Representing Big Integers

Multiple-precision integers can't be stored in a single machine word like an 'int'.

Why are these important computationally?

Example: `4391354067575026` represented as an array:

- `[6, 2, 0, 5, 7, 5, 7, 6, 0, 4, 5, 3, 1, 9, 3, 4]` in base $B = 10$
- `[242, 224, 71, 203, 233, 153, 15]` in base $B = 256$

Base of representation

General form of a multiple-precision integer:
$d_0 + d_1 B + d_2 B^2 + d_3 B^3 + \cdots + d_{n-1} B^{n-1}$,

Does the choice of base B matter?

Addition

How would you add two n-digit integers?

- Remember, every digit is in a separate machine word.
- How big can the "carries" get?
- What if the inputs don't have the same size?
- How fast is your method?

Standard Addition

```
carry := 0
A := new array of length n+1
for i from 0 to n-1
  A[i] := (X[i] + Y[i] + carry) mod B
  carry := (X[i] + Y[i] + carry) / B
end for
A[n] := carry
return A
```


Linear-time lower bounds

Remember the $\Omega(n \log n)$ lower bound for comparison-based sorting?

Much easier lower bounds exist for many problems!

Linear lower bounds

For any problem with input size n,
where **changing any part of the input could change the answer**,
any correct algorithm must take $\Omega(n)$ time.

What does this tell us about integer addition?

Multiplication

Let's remember how we multiplied multi-digit integers in grade school.

Standard multiplication

```
A := new array of length (2*n)
A := [0 0 .. 0]
T := new array of length (n+1)
for i from 0 to n-1
  -- set T to X times Y[i] --
  carry := 0
  for j from 0 to n-1
    T[j] := (X[j] * Y[i] + carry) mod B
    carry := (X[j] * Y[i] + carry) / B
  end for
  T[n] := carry
  -- Add T to A, the running sum --
  A[i..i+n] := add(A[i..i+n-1], T[0..n])
end for
return A
```


Divide and Conquer

Maybe a divide-and-conquer approach will yield a faster multiplication algorithm.

Let's split the digit-lists in half. Let $m = \lfloor \frac{n}{2} \rfloor$ and write $x = x_0 + B^m x_1$ and $y = y_0 + B^m y_1$.
Then we multiply $xy = x_0 y_0 + x_0 y_1 B^m + x_1 y_0 B^m + x_1 y_1 B^{2m}$.

For example, if $x = 7407$ and $y = 2915$, then we get

```
 Integers  | Array representation
-----------|---------------------
 x = 7407  |  X = [7, 0, 4, 7]
 y = 2915  |  Y = [5, 1, 9, 2]
x0 =   07  | X0 = [7, 0]
x1 =   74  | X1 = [4, 7]
y0 =   15  | Y0 = [5, 1]
y1 =   29  | Y1 = [9, 2]
```


Recurrences for Multiplication

Standard multiplication has running time

$$T(n) = \begin{cases} 1, & n = 1 \\ n + T(n-1), & n \geq 2 \end{cases}$$

The divide-and-conquer way has running time

$$T(n) = \begin{cases} 1, & n = 1 \\ n + 4T(\frac{n}{2}), & n \geq 2 \end{cases}$$

Karatsuba's Algorithm

The equation:

$$(x_0+x_1B^m)(y_0+y_1B^m) = x_0y_0+x_1y_1B^{2m}+((x_0+x_1)(y_0+y_1)-x_0y_0-x_1y_1)B^m$$

leads to an algorithm:

1. Compute two sums: $u = x_0 + x_1$ and $v = y_0 + y_1$.
2. Compute three m-digit products: x_0y_0, x_1y_1, and uv.
3. Sum them up and multiply by powers of B to get the answer: $xy = x_0y_0 + x_1y_1B^{2m} + (uv - x_0y_0 - x_1y_1)B^m$

Karatsuba Example

```
    x = 7407 = 7 + 74*100
    y = 2915 = 15 + 29*100

    u = x0 + x1 =  7 + 74 = 81
    v = y0 + y1 = 15 + 29 = 44

x0*y0 =  7*15 =  105
x1*x1 = 74*29 = 2146
 u*v  = 81*44 = 3564

 x*y  = 105 + 2146*10000 + (3564 - 105 - 2146)*100
      =        105
        +   1313
        + 2146
      =   21591405
```


Analyzing Karatsuba

$$T(n) = \begin{cases} 1, & n \leq 1 \\ n + 3T(\frac{n}{2}), n \geq 2 & \end{cases}$$

Crucial difference: The coefficient of $T(\frac{n}{2})$.

Beyond Karatsuba

History Lesson:

- 1962: Karatsuba: $O(n^{1.59})$
- 1963: Toom & Cook: $O(n^{1.47})$, $O(n^{1+\epsilon})$
- 1971: Schönhage & Strassen: $O(n(\log n)(\log\log n))$
- 2007: Fürer: $O(n(\log n)2^{\log* n})$

Lots of work to do in algorithms!

Recurrences

Algorithm	Recurrence	Asymptotic big-Θ
BinarySearch	$1 + T(n/2)$	$\log n$
LinearSearch	$1 + T(n-1)$	n
MergeSort (space)	$n + T(n/2)$	n
MergeSort (time)	$n + 2T(n/2)$	$n \log n$
KaratsubaMul	$n + 3T(n/2)$	$n^{\lg 3}$
SelectionSort	$n + T(n-1)$	n^2
StandardMul	$n + 4T(n/2)$	n^2

Master Method A

$$T(n) = aT(\frac{n}{b}) + n^c(\log n)^d$$

Write $e = \log_b a = \frac{\lg a}{\lg b}$

Three cases:

1. $\mathbf{c = e}$. Then $T(n) \in \Theta(n^c(\log n)^{d+1})$.
2. $\mathbf{c < e}$. Then $T(n) \in \Theta(n^e) = \Theta(n^{\log_b a})$.
3. $\mathbf{c > e}$. Then $T(n) \in \Theta(n^c(\log n)^d)$.

Master Method B

$$T(n) = aT(n-b) + n^c(\log n)^d$$

Two cases:

1. $\mathbf{a = 1}$. Then $T(n) \in \Theta(n^{c+1}(\log n)^d)$.
2. $\mathbf{a} > \mathbf{1}$. Then $T(n) \in \Theta(e^n)$, where e is the positive constant $a^{1/b}$.

Matrix Multiplication

Review: **Dimensions** = number of rows and columns.

Multiplication of 4×3 and 4×2 matrices:

$$\underset{A}{\begin{bmatrix} 7 & 1 & 2 \\ 6 & 2 & 8 \\ 9 & 6 & 3 \\ 1 & 1 & 4 \end{bmatrix}} \underset{B}{\begin{bmatrix} 2 & 0 \\ 6 & 3 \\ 4 & 3 \end{bmatrix}} = \underset{AB}{\begin{bmatrix} 28 & 9 \\ 56 & 30 \\ 66 & 27 \\ 24 & 15 \end{bmatrix}}$$

Middle dimensions **must** match.

Running time:

Divide and Conquer Matrix Multiplication

$$\left[\begin{array}{c|c} S & T \\ \hline U & V \end{array}\right] \left[\begin{array}{c|c} W & X \\ \hline Y & Z \end{array}\right] = \left[\begin{array}{c|c} SW + TY & SX + TZ \\ \hline UW + VY & UX + VZ \end{array}\right]$$

Is this faster?

Strassen's Algorithm

Step 1: Seven products

$$P_1 = S(X - Z) \qquad P_5 = (S + V)(W + Z)$$
$$P_2 = (S + T)Z \qquad P_6 = (T - V)(Y + Z)$$
$$P_3 = (U + V)W \qquad P_7 = (S - U)(W + X)$$
$$P_4 = V(Y - W)$$

Step 2: Add and subtract

$$\left[\begin{array}{c|c} S & T \\ \hline U & V \end{array}\right] \left[\begin{array}{c|c} W & X \\ \hline Y & Z \end{array}\right] = \left[\begin{array}{c|c} P_5 + P_4 - P_2 + P_6 & P_1 + P_2 \\ \hline P_3 + P_4 & P_1 + P_5 - P_3 - P_7 \end{array}\right]$$

Fibonacci

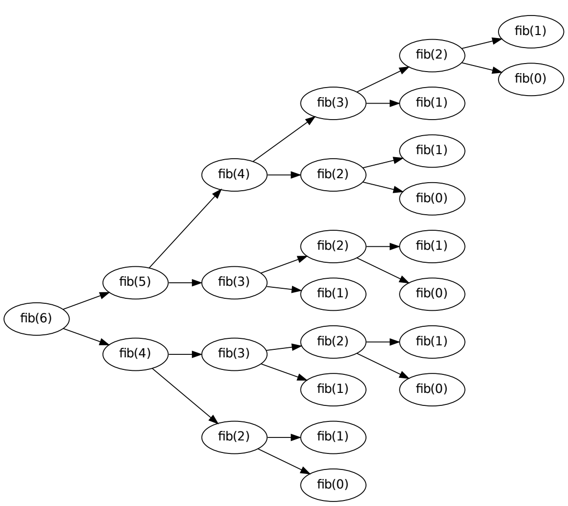
Here's a basic algorithm to compute f_n:

`fib(n)`
Input: Non-negative integer n
Output: f_n

```
if n <= 1 then return n
else return fib(n-1) + fib(n-2)
```

Is this fast?

Recursion tree for `fib(6)`



Memoization

How to avoid **repeated, identical function calls**?

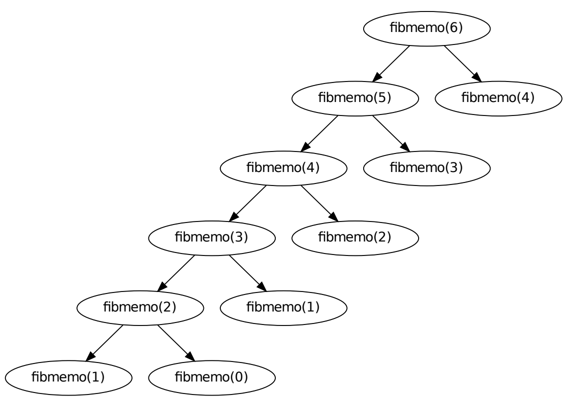
Memoization means saving the results of calls in a table:

`fibmemo(n)`
Input: Non-negative integer n
Output: f_n

```
if T[n] is unset then
  if n <= 1 then T[n] := n
  else T[n] := fibmemo(n-1) + fibmemo(n-2)
end if
return T[n]
```

See the original function?

Recursion tree for `fibmemo(6)`



Cost of Memoization

- How should the table `T` be implemented?
- Analysis

Matrix Chain Multiplication

Problem

Given n matrices $A_1, A_2, \ldots, A_n$, find the best **order of operations** to compute the product $A_1 A_2 \cdots A_n$.

Matrix multiplication is associative but *not* commutative.

In summary: where should we put the parentheses?

Example

$$\underset{\substack{X \\ 5\times 2}}{\begin{bmatrix} 4 & 9 \\ 1 & 6 \\ 9 & 7 \\ 0 & 9 \\ 2 & 0 \end{bmatrix}} * \underset{\substack{Y \\ 2\times 6}}{\begin{bmatrix} 2 & 1 & 5 & 6 & 4 & 5 \\ 8 & 0 & 9 & 1 & 8 & 4 \end{bmatrix}} * \underset{\substack{Z \\ 6\times 3}}{\begin{bmatrix} 6 & 5 & 4 \\ 8 & 8 & 5 \\ 4 & 4 & 4 \\ 0 & 7 & 0 \\ 6 & 4 & 2 \\ 1 & 7 & 5 \end{bmatrix}}$$

Computing minimal mults

Idea: Figure out the *final* multiplication, then use recursion to do the rest.

`mm(D)`

Input: Dimensions array `D` of length $n+1$

Output: Least number of mults to compute the matrix chain product

```
if n = 1 then return 0
else
  fewest := infinity --(just a placeholder)--
  for i from 1 to n-1 do
    t := mm(D[0..i]) + D[0]*D[i]*D[n] + mm(D[i..n])
    if t < fewest then fewest := t
  end for
  return fewest
end if
```

Analyzing mm(D)

$$T(n) = \begin{cases} 1, & n = 1 \\ n + \sum_{i=1}^{n-1} (T(i) + T(n-i)), & n \geq 2 \end{cases}$$

Memoized minimal mults

Let's use our **general tool** for avoiding repeated recursive calls:

mmm(D)
Input: Dimensions array D of length $n+1$
Output: Least number of mults to compute the matrix chain product

```
if T[D] is unset then
  if n = 1 then T[D] := 0
  else
    T[D] := infinity --(just a placeholder)--
    for i from 1 to n-1 do
      t := mmm(D[0..i]) + D[0]*D[i]*D[n] + mmm(D[i..n])
      if t < T[D] then T[D] := t
    end for
  end if
end if
return T[D]
```


Analyzing mmm(D)

- Cost of each call, not counting recursion:

- Total number of recursive calls:

Problems with Memoization

1. What data structure should `T` be?
2. Tricky analysis
3. Too much memory?

Solution: Dynamic Programming

- Store the table `T` explicitly, for a **single problem**
- Fill in the entries of `T` needed to solve the current problem
- Entries are computed **in order** so recursion is never required
- Final answer can be looked up in the filled-in table

Dynamic Minimal Mults Example

Multiply (8×5) times (5×3) times (3×4) times (4×1) matrices.

$D = [8, 5, 3, 4, 1]$, $n = 4$

Make a table for the value of `mm(D[i..j])`:

	0	1	2	3	4
0					
1					
2					
3					
4					

Dynamic Minimal Mults Algorithm

`dmm(D)`

Input: Dimensions array `D` of length $n+1$

Output: Least number of mults to compute the matrix chain product

```
A := new (n+1) by (n+1) array
for diag from 1 to n do
  for row from 0 to (n-diag) do
    col := diag + row
    --This part just like the original version--
    if diag = 1 then A[row,col] := 0
    else
      A[row,col] := infinity
      for i from row+1 to col-1 do
        t := A[row,i] + D[row]*D[i]*D[col] + A[i,col]
        if t < A[row,col] then A[row,col] := t
      end for
    end if
  end for
end for
return A[0,n]
```