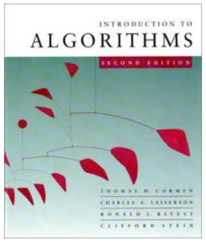

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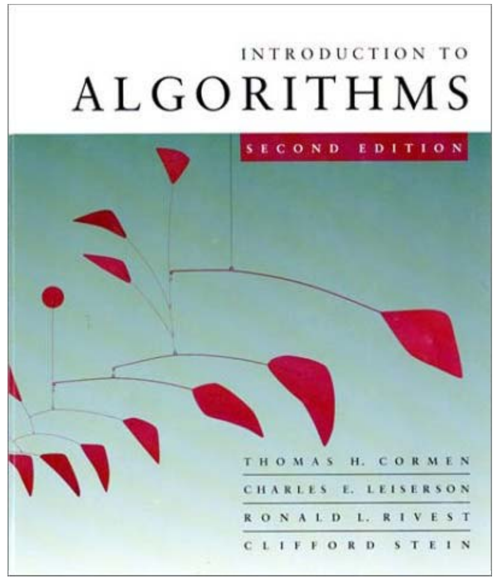
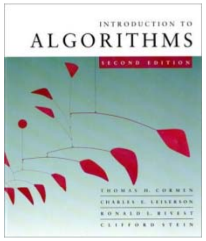


Dynamic Programming

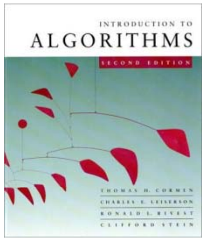
Carola Wenk

Slides courtesy of Charles Leiserson with small changes by Carola Wenk



Dynamic programming

- Algorithm design technique
- A technique for solving problems that have
  - overlapping subproblems
  - and, when used for optimization, have an optimal substructure property
- **Idea:** Do not repeatedly solve the same subproblems, but solve them only once and store the solutions in a **dynamic programming table**



Example: Fibonacci numbers

- F(0)=0; F(1)=1; F(n)=F(n-1)+F(n-2) for $n \geq 2$
- Implement this recursion naively:

F(n)

F(n-1) F(n-2)

F(n-2) F(n-3) F(n-3) F(n-4)

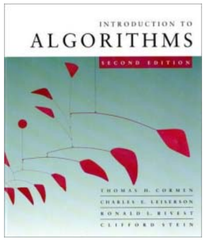
Solve same subproblems many times !

Runtime is exponential in n.

- Store 1D DP-table and fill bottom-up in $O(n)$ time:

F:

0	1	1	2	3	5	8				



Longest Common Subsequence

Example: ***Longest Common Subsequence (LCS)***

- Given two sequences $x[1 \,.\,.\, m]$ and $y[1 \,.\,.\, n]$, find a longest subsequence common to them both.

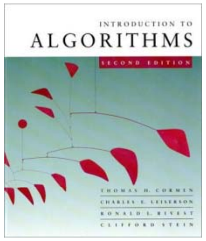
“a” *not* “the”

x: A B C B D A B

y: B D C A B A

BCBA = LCS(x, y)

functional notation, but not a function

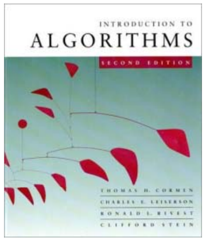


Brute-force LCS algorithm

Check every subsequence of $x[1 \,.\,.\, m]$ to see if it is also a subsequence of $y[1 \,.\,.\, n]$.

Analysis

- 2^m subsequences of x (each bit-vector of length m determines a distinct subsequence of x).
- Hence, the runtime would be exponential !



Towards a better algorithm

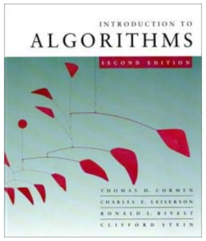
Two-Step Approach:

1. Look at the *length* of a longest-common subsequence.
2. Extend the algorithm to find the LCS itself.

Notation: Denote the length of a sequence s by $|s|$.

Strategy: Consider ***prefixes*** of x and y.

- Define $c[i, j] = |\mathrm{LCS}(x[1\,..\,i], y[1\,..\,j])|$.
- Then, $c[m, n] = |\mathrm{LCS}(x, y)|$.

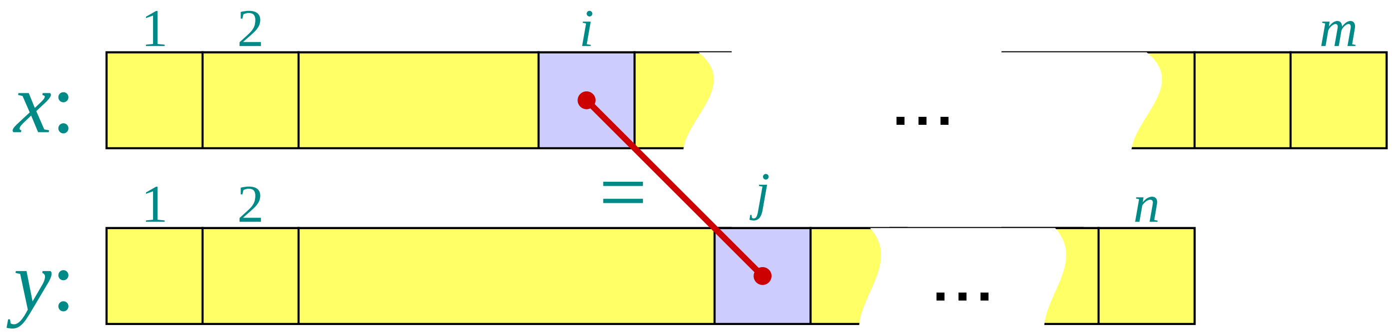


Recursive formulation

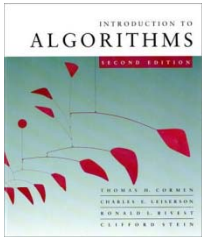
Theorem.

$$c[i, j] = \begin{cases} c[i-1, j-1] + 1 & \text{if } x[i] = y[j], \\ \max\{c[i-1, j], c[i, j-1]\} & \text{otherwise.} \end{cases}$$

Proof. Case $x[i] = y[j]$:



Let $z[1 \,.\,.\, k] = \mathrm{LCS}(x[1 \,.\,.\, i], y[1 \,.\,.\, j])$, where $c[i, j] = k$. Then, $z[k] = x[i]$, or else z could be extended. Thus, $z[1 \,.\,.\, k-1]$ is CS of $x[1 \,.\,.\, i-1]$ and $y[1 \,.\,.\, j-1]$.



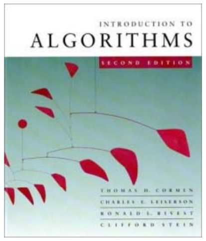
Proof (continued)

Claim: $z[1\,.\,.\,k-1] = \mathrm{LCS}(x[1\,.\,.\,i-1], y[1\,.\,.\,j-1])$.

Suppose w is a longer CS of $x[1\,.\,.\,i-1]$ and $y[1\,.\,.\,j-1]$, that is, $|w| > k-1$. Then, ***cut and paste***: $w \,||\, z[k]$ (w concatenated with $z[k]$) is a common subsequence of $x[1\,.\,.\,i]$ and $y[1\,.\,.\,j]$ with $\left|w \,||\, z[k]\right| > k$. Contradiction, proving the claim.

Thus, $c[i-1, j-1] = k-1$, which implies that $c[i, j] = c[i-1, j-1] + 1$.

Other cases are similar. □



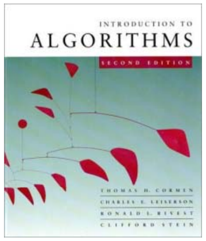
Dynamic-programming hallmark #1

Optimal substructure

An optimal solution to a problem (instance) contains optimal solutions to subproblems.

Recurrence

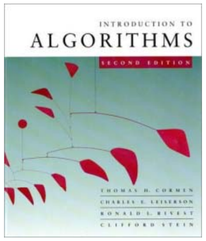
If $z = \mathrm{LCS}(x, y)$, then any prefix of z is an LCS of a prefix of x and a prefix of y.



Recursive algorithm for LCS

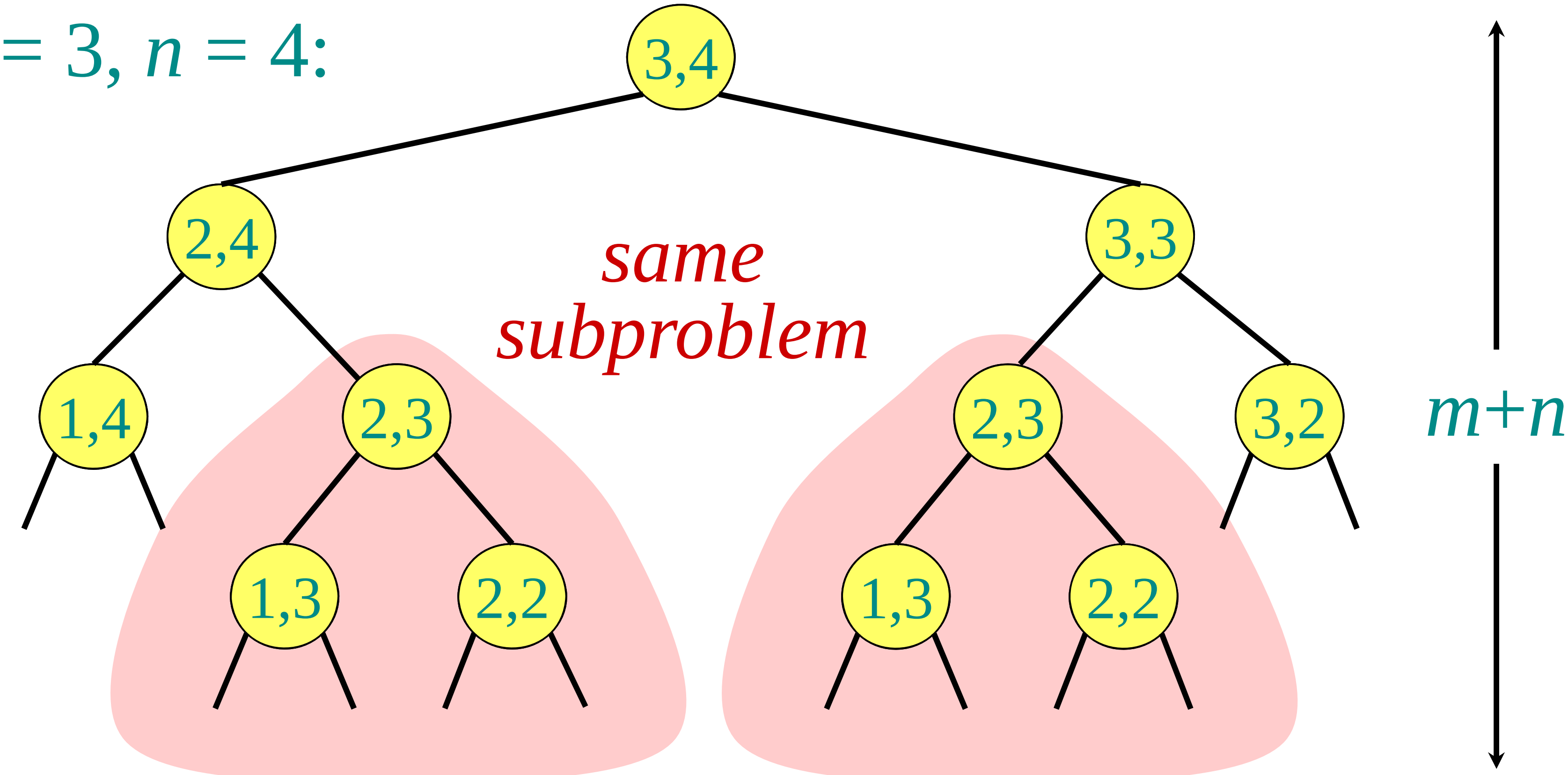
LCS(x, y, i, j)
  if $x[i] = y[j]$
    then $c[i, j] \leftarrow \text{LCS}(x, y, i-1, j-1) + 1$
    else $c[i, j] \leftarrow \max\{\text{LCS}(x, y, i-1, j), \text{LCS}(x, y, i, j-1)\}$

Worst-case: $x[i] \neq y[j]$, in which case the algorithm evaluates two subproblems, each with only one parameter decremented.

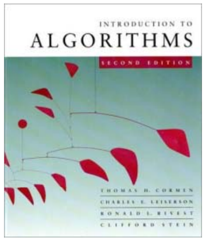


Recursion tree

$m = 3, n = 4$:



Height $= m + n \Rightarrow$ work potentially exponential, but we're solving subproblems already solved!

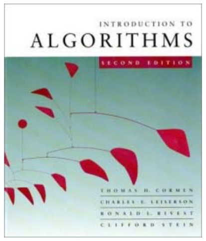


Dynamic-programming hallmark #2

Overlapping subproblems

A recursive solution contains a "small" number of distinct subproblems repeated many times.

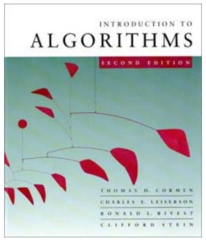
The number of distinct LCS subproblems for two strings of lengths m and n is only mn.



Dynamic-programming

There are two variants of dynamic programming:

1. Memoization
2. Bottom-up dynamic programming (often referred to as “dynamic programming”)



Memoization algorithm

Memoization: After computing a solution to a subproblem, store it in a table. Subsequent calls check the table to avoid redoing work.

for all i, j**:** $c[i,0]=0$ **and** $c[0, j]=0$

LCS(x, y, i, j)

    if $c[i, j] = \mathrm{NIL}$

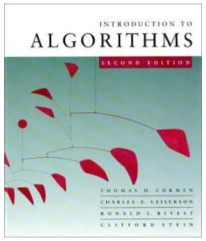
        then if $x[i] = y[j]$

            then $c[i, j] \leftarrow$ LCS$(x, y, i–1, j–1) + 1$

            else $c[i, j] \leftarrow \max\{LCS(x, y, i–1, j)$, LCS$(x, y, i, j–1)\}$

same as before

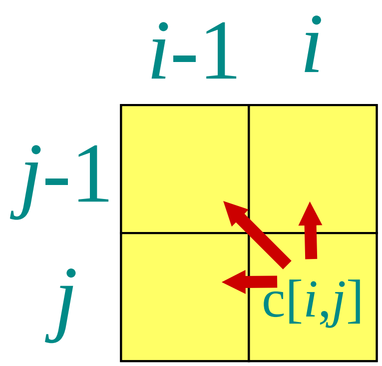
Time $= \Theta(mn) =$ constant work per table entry.
Space $= \Theta(mn)$.

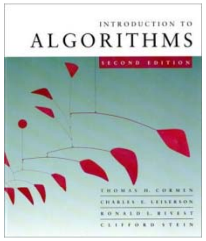


Recursive formulation

$$c[i, j] = \begin{cases} c[i-1, j-1] + 1 & \text{if } x[i] = y[j], \\ \max\{c[i-1, j],\, c[i, j-1]\} & \text{otherwise.} \end{cases}$$

c:





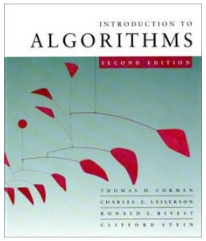
Bottom-up dynamic-programming algorithm

IDEA:

Compute the table bottom-up.

Time = $\Theta(mn)$.

		A	B	C	B	D	A	B
	0	0	0	0	0	0	0	0
B	0	0	1	1	1	1	1	1
D	0	0	1	1	1	2	2	2
C	0	0	1	2	2	2	2	2
A	0	1	1	2	2	2	3	3
B	0	1	2	2	3	3	3	4
A	0	1	2	2	3	3	4	4



Bottom-up dynamic-programming algorithm

IDEA:

Compute the table bottom-up.

Time = $\Theta(mn)$.

Reconstruct LCS by back-tracing.

Space = $\Theta(mn)$.

Exercise: $O(\min\{m, n\})$.

		A	B	C	B	D	A	B
	0	0	0	0	0	0	0	0
B	0	0	1	1	1	1	1	1
D	0	0	1	1	1	2	2	2
C	0	0	1	2	2	2	2	2
A	0	1	1	2	2	2	3	3
B	0	1	2	2	3	3	3	4
A	0	1	2	2	3	3	4	4