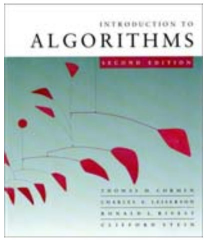
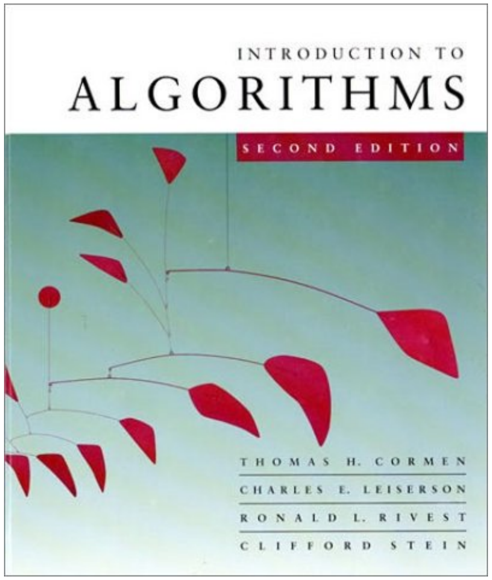
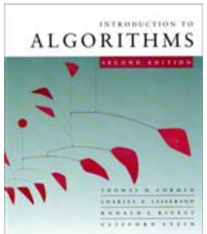


CS 5633 -- Spring 2010



Matrix-chain multiplication

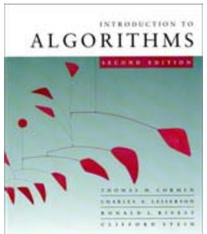
Carola Wenk



Matrix-chain multiplication

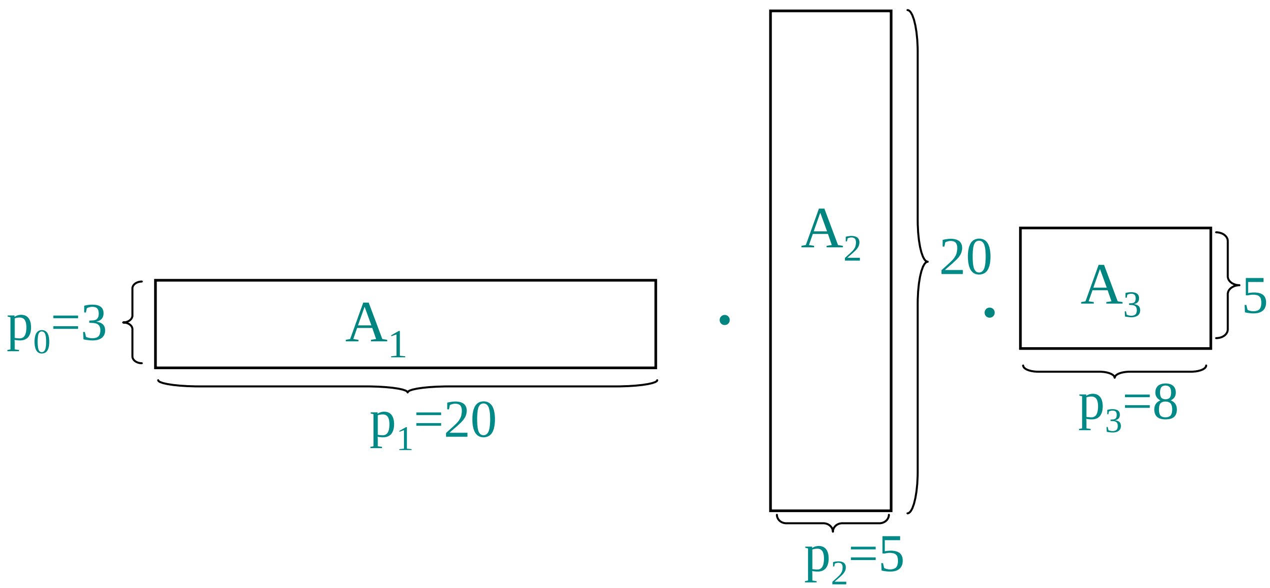
Given: A sequence/chain of *n* matrices $A_1, A_2, \ldots, A_n$, where A_i is a $p_{i-1} \times p_i$ matrix

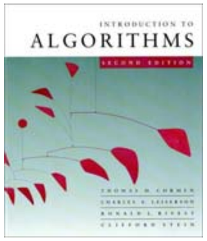
Task: Compute their product $A_1 \cdot A_2 \cdot \ldots \cdot A_n$ using the minimum number of scalar multiplications.



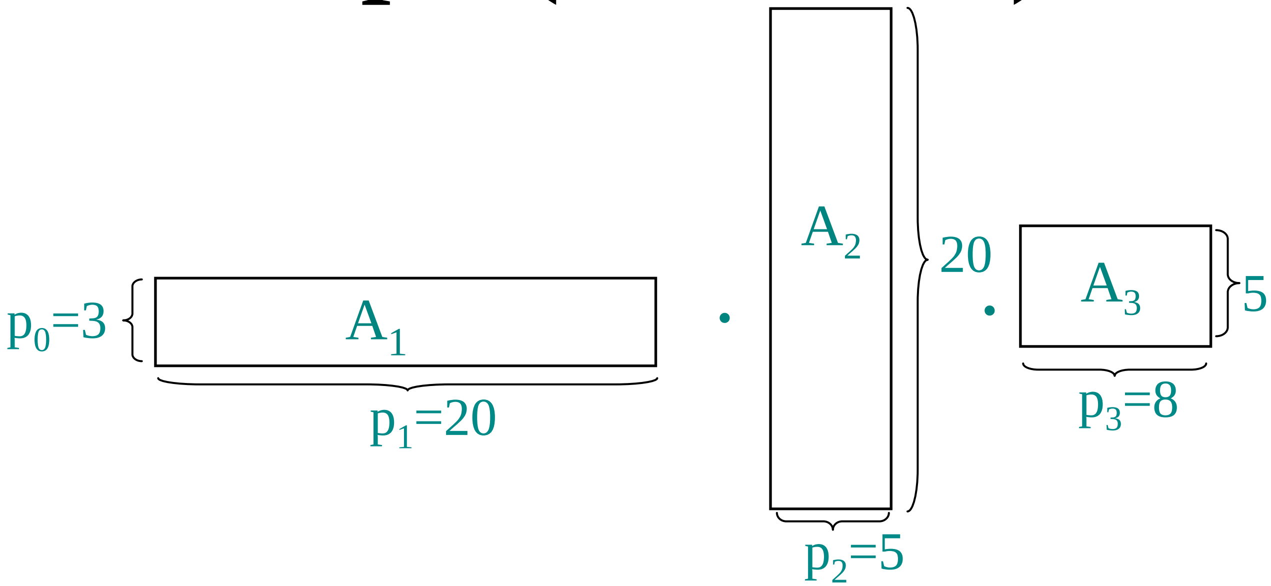
Matrix-chain multiplication example

Example: $n=3$, $p_0=3$, $p_1=20$, $p_2=5$, $p_3=8$. A_1 is a 3×20 matrix, A_2 is a 20×5 matrix, A_3 is a 5×2 matrix. Compute $A_1 \cdot A_2 \cdot A_3$.

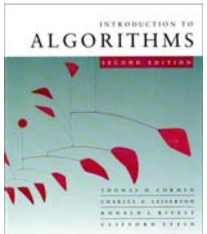




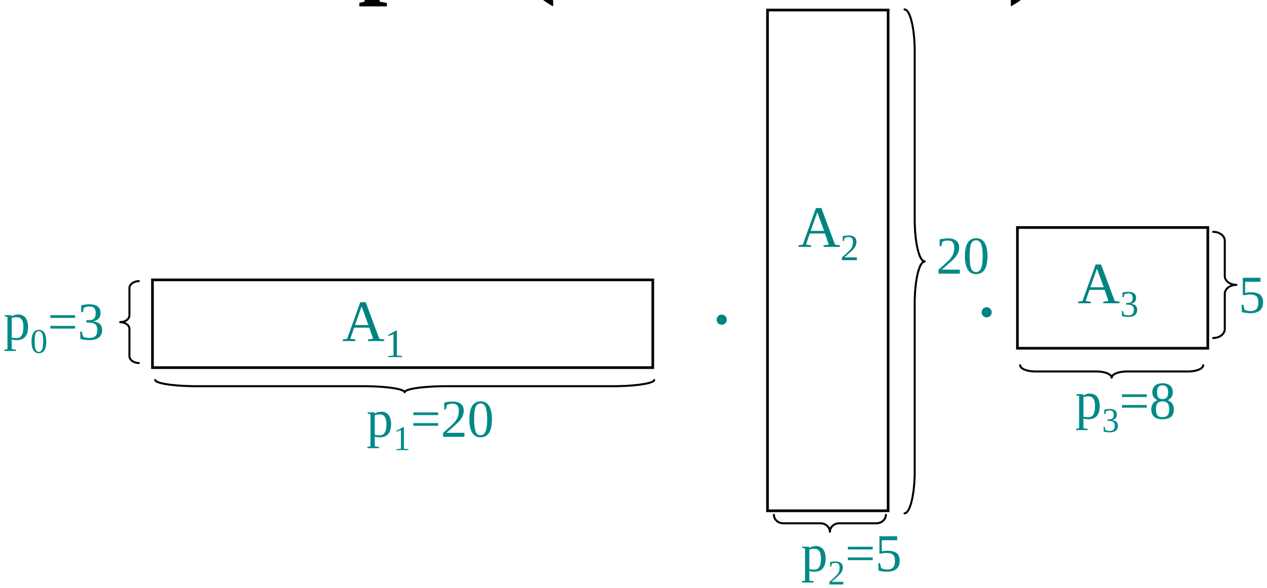
Matrix-chain multiplication example (continued)



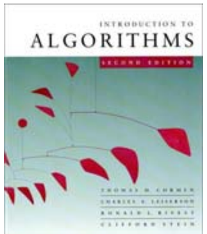
- Computing $A_1 \cdot A_2$ takes $3 \cdot 20 \cdot 5$ multiplications and results in a 3×5 matrix.
- Computing $A_i \cdot A_{i+1}$ takes $p_{i-1} \cdot p_i \cdot p_{i+1}$ multiplications and results in a $p_{i-1} \times p_{i+1}$ matrix.



Matrix-chain multiplication example (continued)



- Computing $(A_1 \cdot A_2) \cdot A_3$ takes $3 \cdot 20 \cdot 5 + 3 \cdot 5 \cdot 8 = 300 + 120 = 420$ multiplications
- Computing $A_1 \cdot (A_2 \cdot A_3)$ takes $20 \cdot 5 \cdot 8 + 3 \cdot 20 \cdot 8 = 800 + 480 = 1280$ multiplications

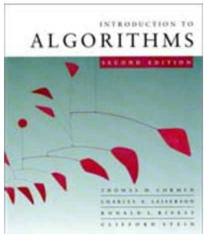


Matrix-chain multiplication

Given: A sequence/chain of n matrices $A_1, A_2, \ldots, A_n$, where A_i is a $p_{i-1} \times p_i$ matrix

Task: Compute their product $A_1 \cdot A_2 \cdot \ldots \cdot A_n$ using the minimum number of scalar multiplications.

$\Rightarrow$ Find a parenthesization that minimizes the number of multiplications



Would greedy work?

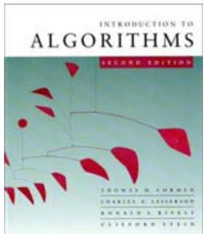
1. Parenthesizing like this $(\ldots((A_1 \cdot A_2) \cdot A_3) \ldots \cdot A_n)$ does not work (e.g., reverse our running example).
2. Recursively parenthesize like this:

$$\underbrace{(A_1 \cdot \ldots \cdot A_k)}_{p_0 \times p_k} \cdot \underbrace{(A_{k+1} \ldots \cdot A_n)}_{p_k \times p_n}$$

Find the k that minimizes $p_0 \cdot p_k \cdot p_n$.

Does not work either (example: $p_0=1$, $p_1=2$, $p_2=3$, $p_3=4$)

$\Rightarrow$ Try dynamic programming



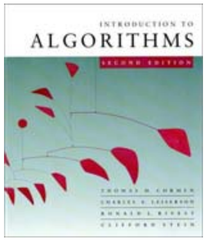
1) Optimal substructure

Let $A_{i,j} = A_i \cdot \ldots \cdot A_j$ for $i \leq j$

- Consider an optimal parenthesization for $A_{i,j}$. Assume it splits it at k, so

$$A_{i,j} = (A_i \cdot \ldots \cdot A_k) \cdot (A_{k+1} \cdot \ldots \cdot A_j)$$

- Then, the par. of the prefix $A_i \cdot \ldots \cdot A_k$ within the optimal par. of $A_{i,j}$ must be an optimal par. of $A_{i,k}$. (Assume it is not optimal, then there exists a better par. for $A_{i,k}$. **Cut and paste** this par. into the par. for $A_{i,j}$. This yields a better par. for $A_{i,j}$. Contradiction.)

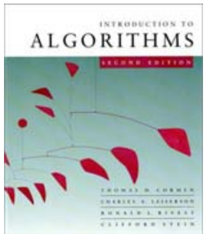


2) Recursive solution

a) First compute the minimum number of multiplications

b) Then compute the actual parenthesization

We will concentrate on solving a) now.



2) Recursive solution (cont.)

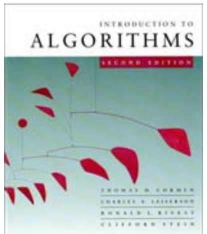
$m[i,j]$ = minimum number of scalar multiplications to compute A_{ij}

Goal: Compute $m[1,n]$

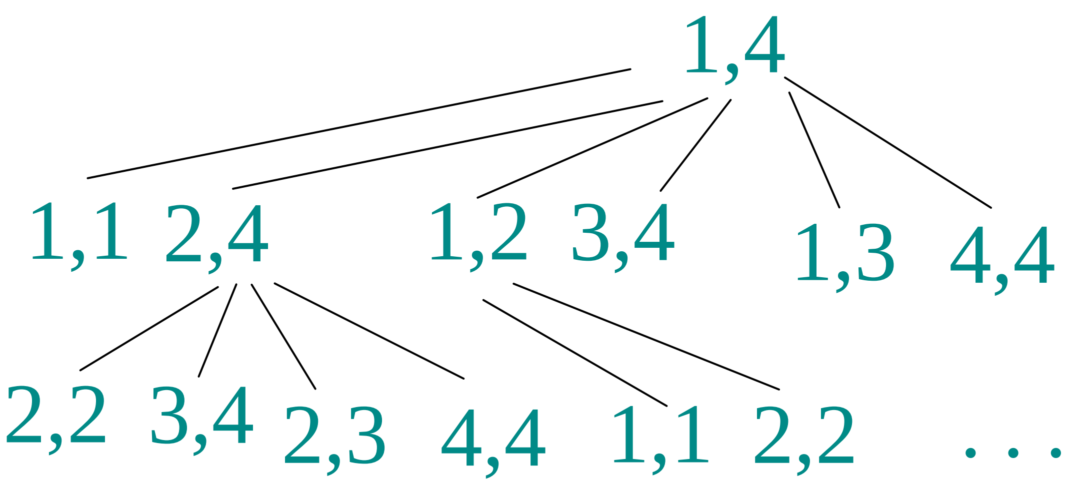
$$A_{i,j} = \underbrace{(A_i \cdot \ldots \cdot A_k)}_{p_{i-1} \times p_k} \cdot \underbrace{(A_{k+1} \ldots \cdot A_j)}_{p_k \times p_j}$$

Recurrence:

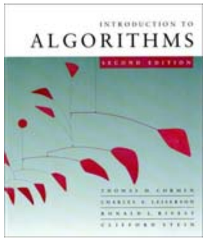
- $m[i,i] = 0$ for $i = 1, 2, \ldots, n$
- $m[i,j] = \min\limits_{i \le k < j} \left(m[i,k] + m[k+1,j] + p_{i-1} p_k p_j \right)$



Recursion tree

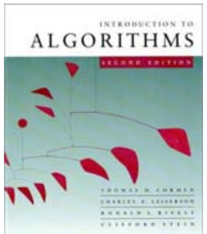


- The runtime of the straight-forward recursive algorithm is $\Omega(2^n)$
- But only $\Theta(n^2)$ different subproblems !



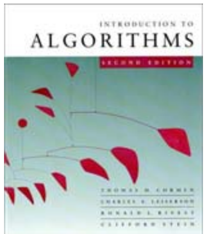
Dynamic programming

```
MATRIX_CHAIN_DP(p, n):
  for i:=1 to n do m[i,i]=0
  for l:=2 to n do // l is length of chain
    for i:=1 to n-l+1 do
      j:=i+l-1
      m[i,j]=∞
      for k:=i to j-1 do
        q:=m[i,k]+m[k+1,j]+p_{i-1}*p_k*p_j
        if q<m[i,j] then
          m[i,j]=q
          s[i,j]:=k //index that optimizes m[i,j]
  return m and s;
```



Dynamic programming

- Use dynamic programming to fill the 2-dimensional $m[i,j]$-table
- Bottom-up: Diagonal by diagonal
- For the construction of the optimal parenthesization, use an additional array $s[i,j]$ that records that value of k for which the minimum is attained and stored in $m[i,j]$
- $O(n^3)$ runtime ($n \times n$ table, $O(n)$ min-computation per entry), $O(n^2)$ space
- $m[1,n]$ is the desired value



Construction of an optimal parenthesization

```
PRINT_PARENS(s,i,j) // initial call: print_parens(s,1,n)
  if i=j then print “A”i
  else print “(“
        PRINT_PARENS(s,i,s[i,j])
        print “)·(”
        PRINT_PARENS(s,s[i,j]+1,j)
        print “)”
```

Runtime: Recursion tree = binary tree with n leaves. Spend $O(1)$ per node. $O(n)$ total runtime.