

# Dynamic Programming Chain Matrix Multiply

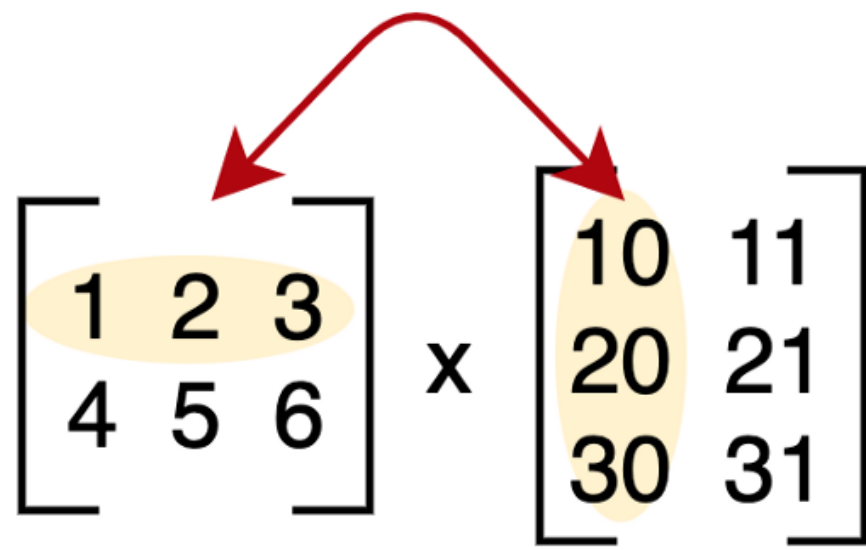
(Class 19)

From Book's Page No 373 (Chapter 14)

- Suppose we wish to multiply a series of matrices:

$$A_1 A_2 \dots A_n$$

- Problem Statement: In what order should the multiplication be done?
- A  $p \times q$  matrix  $A$  can be multiplied with a  $q \times r$  matrix  $B$ .
- The result will be a  $p \times r$  matrix  $C$ .
- For example, multiplying  $A[2,3]$  with  $B[3,2]$  will result in  $C[2,2]$ .



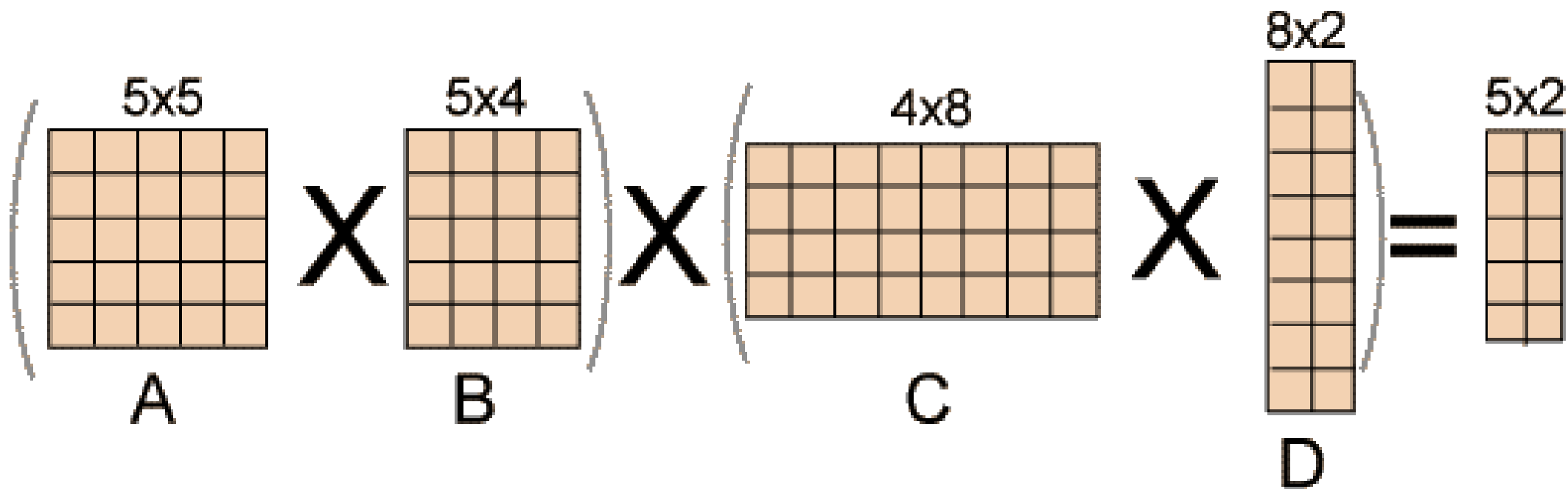
$$\begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix} \times \begin{bmatrix} 10 & 11 \\ 20 & 21 \\ 30 & 31 \end{bmatrix}$$

$$= \begin{bmatrix} 1 \times 10 + 2 \times 20 + 3 \times 30 & 1 \times 11 + 2 \times 21 + 3 \times 31 \\ 4 \times 10 + 5 \times 20 + 6 \times 30 & 4 \times 11 + 5 \times 21 + 6 \times 31 \end{bmatrix}$$

$$= \begin{bmatrix} 10 + 40 + 90 & 11 + 42 + 93 \\ 40 + 100 + 180 & 44 + 105 + 186 \end{bmatrix} = \begin{bmatrix} 140 & 146 \\ 320 & 335 \end{bmatrix}$$

"Dot Product"

$$\begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix} \times \begin{bmatrix} 7 & 8 \\ 9 & 10 \\ 11 & 12 \end{bmatrix} = \begin{bmatrix} 58 \\ \end{bmatrix}$$



- In particular, for  $1 \leq i \leq p$  and  $1 \leq j \leq r$ ,

$$C[i, j] = \sum_{k=1}^q A[i, k]B[k, j]$$

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RECTANGULAR-MATRIX-MULTIPLY .A;B;C; p; q; r/  
1 for i ← 1 to p  
2   for j ← 1 to r  
3     for k ← 1 to q  
4        $c_{ij} \leftarrow c_{ij} + a_{ik} * b_{kj}$ 
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- There are  $(p \cdot r)$  total entries in  $C$  and each takes  $O(q)$  to compute.
- Thus, the total number of multiplications is  $p \cdot q \cdot r$ .

$$\begin{array}{c}
 \text{A} \qquad \qquad \text{B} \\
 \left[ \begin{array}{cc} 1 & 2 \\ 3 & 4 \end{array} \right] \times \left[ \begin{array}{c} 5 \quad 6 \\ 7 \quad 8 \end{array} \right] = \left[ \begin{array}{cc} 19 & 22 \\ 43 & 50 \end{array} \right]
 \end{array}$$


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$$\begin{array}{l}
 1 \times 6 + 2 \times 8 = 22 \\
 1 \times 5 + 2 \times 7 = 19 \\
 3 \times 5 + 4 \times 7 = 43 \\
 3 \times 6 + 4 \times 8 = 50
 \end{array}$$

$\uparrow \qquad \qquad \uparrow$   
 8 multiplications

- Consider the case of 3 matrices:

$$A_1 = 5 \times 4$$

$$A_2 = 4 \times 6$$

$$A_3 = 6 \times 2$$

- The multiplication can be carried out either as  $((A_1A_2)A_3)$  or  $(A_1(A_2A_3))$ .
- The cost of the two is:

$$((A_1A_2)A_3) = (5 \cdot 4 \cdot 6) + (5 \cdot 6 \cdot 2) = 180$$

$$(A_1(A_2A_3)) = (5 \cdot 4 \cdot 2) + (4 \cdot 6 \cdot 2) = 88$$

- There is considerable savings achieved even for this simple example.
- In general, however, in what order should we multiply a series of matrices  $A_1 A_2 \dots A_n$ ?
- Matrix multiplication is associative but not commutative operation.
- We are free to add parenthesis the above multiplication, but the order of matrices cannot be changed.



- The *Chain Matrix Multiplication* problem is stated as follows:

“Given a chain of  $n$  matrices  $A_1, A_2, \dots, A_n$  and dimensions

$p_0, p_1, \dots, p_n$ ,

where matrix  $A_i$  has dimension  $p_{i-1} \times p_i$ , determine the order of multiplication that minimizes the number of scalar multiplications.”

# Counting the Number of Parenthesizations

- We could write a procedure that tries all possible parenthesizations.
- Unfortunately, the number of ways of parenthesizing an expression is very large.
- If there are  $n$  items, there are  $n - 1$  ways in which outer most pair of parentheses can be placed.

$$(A_1)(A_2A_3A_4 \dots A_n)$$

or  $(A_1A_2)(A_3A_4 \dots A_n)$

or  $(A_1A_2A_3)(A_4 \dots A_n)$

...

or  $(A_1A_2A_3A_4 \dots A_{n-1})(A_n)$

- Once we split just after the  $k^{th}$  matrix, we create two sub lists to be parenthesized.
- One with  $k$  and other with  $n - k$  matrices.

$$(A_1 A_2 \dots A_k)(A_{k+1} \dots A_n)$$

- We could consider all the ways of parenthesizing these two.

- Since these are independent choices, if there are  $L$  ways of parenthesizing the left sublist and  $R$  ways to parenthesize the right sublist, then the total is  $L \cdot R$ .
- For which value of  $k$  the result  $L \cdot R$  will be minimum?
- This suggests the following recurrence for  $P(n)$ , the number of different ways of parenthesizing  $n$  items:

$$T(n) = \begin{cases} 1, & \text{if } n = 1 \\ \sum_{k=1}^{n-1} P(k)P(n-k), & \text{if } n \geq 2 \end{cases}$$

- This is related to a function called the *Catalan Numbers*.
- Catalan numbers are related the number of different binary trees on  $n$  nodes.
- We will get the running time:

$$P(n) \in O(4^n / n^{3/2})$$

$$\mathbf{P(n) \in O(4^n)}$$

- The dominating term is the exponential  $4^n$  thus  $P(n)$  will grow large very quickly.
- So, this brute-force method of exhaustive search makes for a poor strategy when determining how to optimally parenthesize a matrix chain.

# Chain Matrix Multiplication - Dynamic Programming Formulation

- The dynamic programming solution involves breaking up the problem into subproblems whose solutions can be combined to solve the global problem.
- Let  $A_{i..j}$  be the result of multiplying matrices  $i$  through  $j$ .
- It is easy to see that  $A_{i..j}$  is a  $p_{i-1} \times p_j$  matrix.

$$\begin{matrix} A_3 & A_4 & A_5 & A_6 \\ 4 \times 5 & 5 \times 2 & 2 \times 8 & 8 \times 7 \end{matrix} = \begin{matrix} A_{3..6} \\ 4 \times 7 \end{matrix}$$

- At the highest level of parenthesization, we multiply two matrices:

$$A_{1..n} = A_{1..k} \cdot A_{k+1..n} \text{ where } 1 \leq k \leq n - 1$$

- The question is what is the optimum value of  $k$  for the split?
- And how do we parenthesis the sub-chains  $A_{1..k}$  and  $A_{k+1..n}$ .



- We cannot use divide and conquer because we do not know that what is the optimum value of  $k$ .
- We will have to consider all possible values of  $k$  and take the best of them.
- We will apply this strategy to solve the subproblems optimally.
- We will store the solutions to the subproblem in a table and build the table bottom-up.