

CE100 Algorithms and Programming II

Week-5 (Dynamic Programming)

Spring Semester, 2021-2022

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Quicksort Sort

Outline

- Convex Hull (Divide & Conquer)
- Dynamic Programming
 - Introduction
 - Divide-and-Conquer (DAC) vs Dynamic Programming (DP)

- Fibonacci Numbers
 - Recursive Solution
 - Bottom-Up Solution
- Optimization Problems
- Development of a DP Algorithms

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 - Counting the Number of Parenthesizations

- The Structure of Optimal Parenthesization
 - Characterize the structure of an optimal solution
 - A Recursive Solution
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 - Computing the optimal Cost of Matrix-Chain Multiplication
 - Bottom-up Computation

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 - MATRIX-CHAIN-ORDER
- Construction and Optimal Solution
 - MATRIX-CHAIN-MULTIPLY
- Summary

Dynamic Programming - Introduction

- An algorithm design paradigm like divide-and-conquer
- **Programming:** A tabular method (not writing computer code)
 - Older sense of planning or scheduling, typically by filling in a table
- **Divide-and-Conquer (DAC):** subproblems are independent
- **Dynamic Programming (DP):** subproblems are not independent
- **Overlapping subproblems:** subproblems share sub-subproblems
 - In solving problems with overlapping subproblems
 - A DAC algorithm **does redundant** work
 - Repeatedly solves common subproblems
 - A DP algorithm solves each problem just once
 - **Saves its result in a table**

Problem 1: Fibonacci Numbers

Recursive Solution

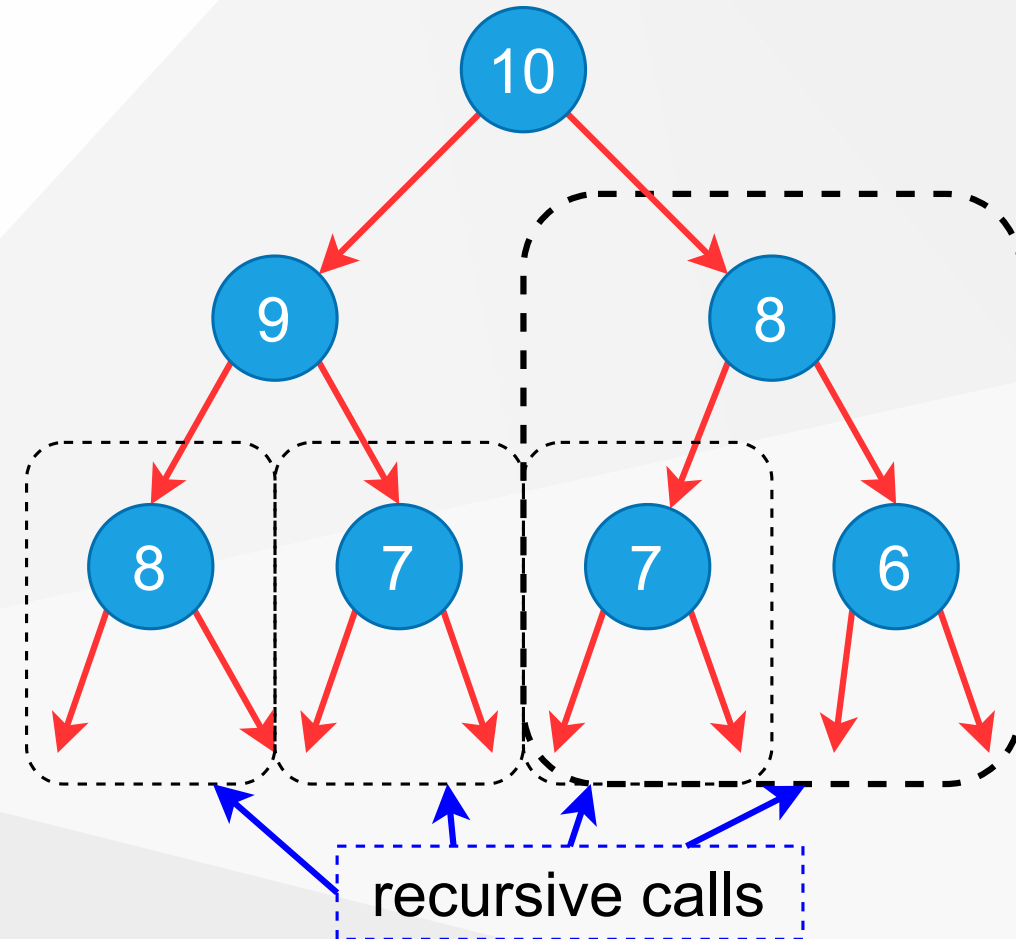
- Reminder:

$$F(0) = 0 \text{ and } F(1) = 1$$

$$F(n) = F(n - 1) + F(n - 2)$$

```
REC-FIBO( $n$ ) {  
  if  $n < 2$   
    return  $n$   
  else  
    return REC-FIBO( $n - 1$ ) + REC-FIBO( $n - 2$ ) }
```

- Overlapping subproblems in different recursive calls. Repeated work!



Problem 1: Fibonacci Numbers Recursive Solution

- Recurrence:
 - *exponential runtime*

$$T(n) = T(n - 1) + T(n - 2) + 1$$

- Recursive algorithm inefficient because it recomputes the same $F(i)$ repeatedly in different branches of the recursion tree.

Problem 1: Fibonacci Numbers

Bottom-up Computation

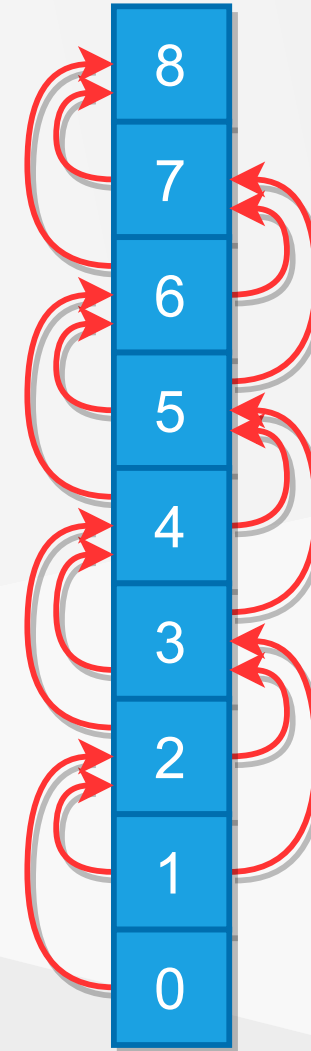
- Reminder:

$$F(0) = 0 \text{ and } F(1) = 1$$

$$F(n) = F(n - 1) + F(n - 2)$$

- Runtime $\Theta(n)$

```
ITER-FIBO(n)
  F[0] = 0
  F[1] = 1
  for i = 2 to n do
    F[i] = F[i-1] + F[i-2]
  return F[n]
```



Optimization Problems

- **DP** typically applied to optimization problems
- In an optimization problem
 - There are many possible solutions (feasible solutions)
 - Each solution has a value
 - Want to find an optimal solution to the problem
 - *A solution with the optimal value (min or max value)*
 - Wrong to say **the** optimal solution to the problem
 - *There may be several solutions with the same optimal value*

Development of a DP Algorithm

Step-1. Characterize the structure of an optimal solution

Step-2. Recursively define the value of an optimal solution

Step-3. Compute the value of an optimal solution in a bottom-up fashion

Step-4. Construct an optimal solution from the information computed in **Step 3**

Problem 2: Matrix Chain Multiplication

- **Input:** a sequence (chain) $\langle A_1, A_2, \dots, A_n \rangle$ of n matrices
- **Aim:** compute the product $A_1 \cdot A_2 \cdot \dots \cdot A_n$
- A product of matrices is fully parenthesized if
 - It is either a single matrix
 - Or, the product of two fully parenthesized matrix products surrounded by a pair of parentheses.

$$\left(\begin{array}{l} A_i(A_{i+1}A_{i+2} \dots A_j) \\ (A_iA_{i+1}A_{i+2} \dots A_{j-1})A_j \\ (A_iA_{i+1}A_{i+2} \dots A_k)(A_{k+1}A_{k+2} \dots A_j) \end{array} \right) \text{ for } i \leq k < j$$

- All parenthesizations yield the same product; matrix product is associative

Matrix-chain Multiplication: An Example Parenthesization

- Input: $\langle A_1, A_2, A_3, A_4 \rangle$ (5 distinct ways of full parenthesization)

$$\left(A_1 \left(A_2 (A_3 A_4) \right) \right)$$

$$\left(A_1 \left((A_2 A_3) A_4 \right) \right)$$

$$\left((A_1 A_2) (A_3 A_4) \right)$$

$$\left(\left(A_1 (A_2 A_3) A_4 \right) \right)$$

$$\left(\left((A_1 A_2) A_3 \right) A_4 \right)$$

- The way we parenthesize a chain of matrices can have a dramatic effect on the cost of computing the product

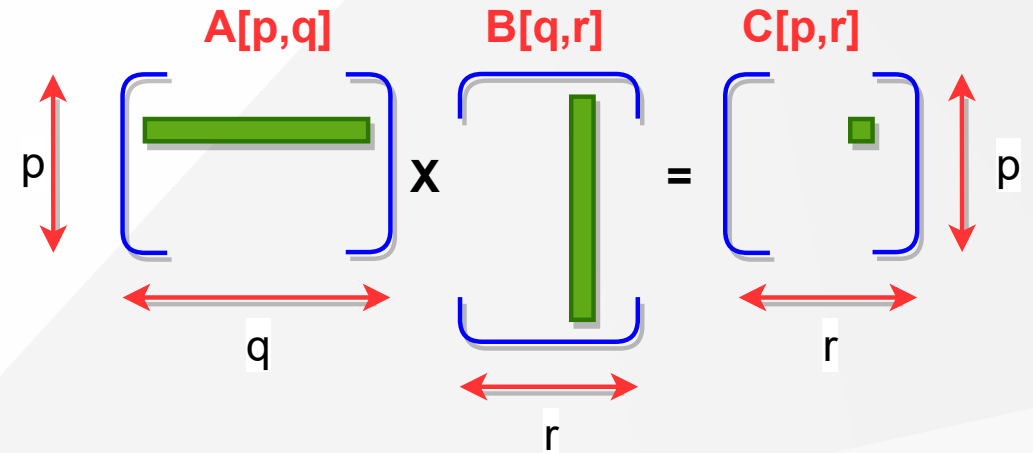
Matrix-chain Multiplication:

Reminder

```

MATRIX-MULTIPLY(A, B)
  if cols[A] != rows[B] then
    error("incompatible dimensions")
  for i=1 to rows[A] do
    for j=1 to cols[B] do
      C[i,j]=0
      for k=1 to cols[A] do
        C[i,j]=C[i,j]+A[i,k]·B[k,j]
      return C

```



$\text{rows}(A) = p$ $\text{rows}(B) = q$ $\text{rows}(C) = p$
 $\text{cols}(A) = q$ $\text{cols}(B) = r$ $\text{cols}(C) = r$

Note : matrix[row,column]

A: $p \times q$

B: $q \times r$

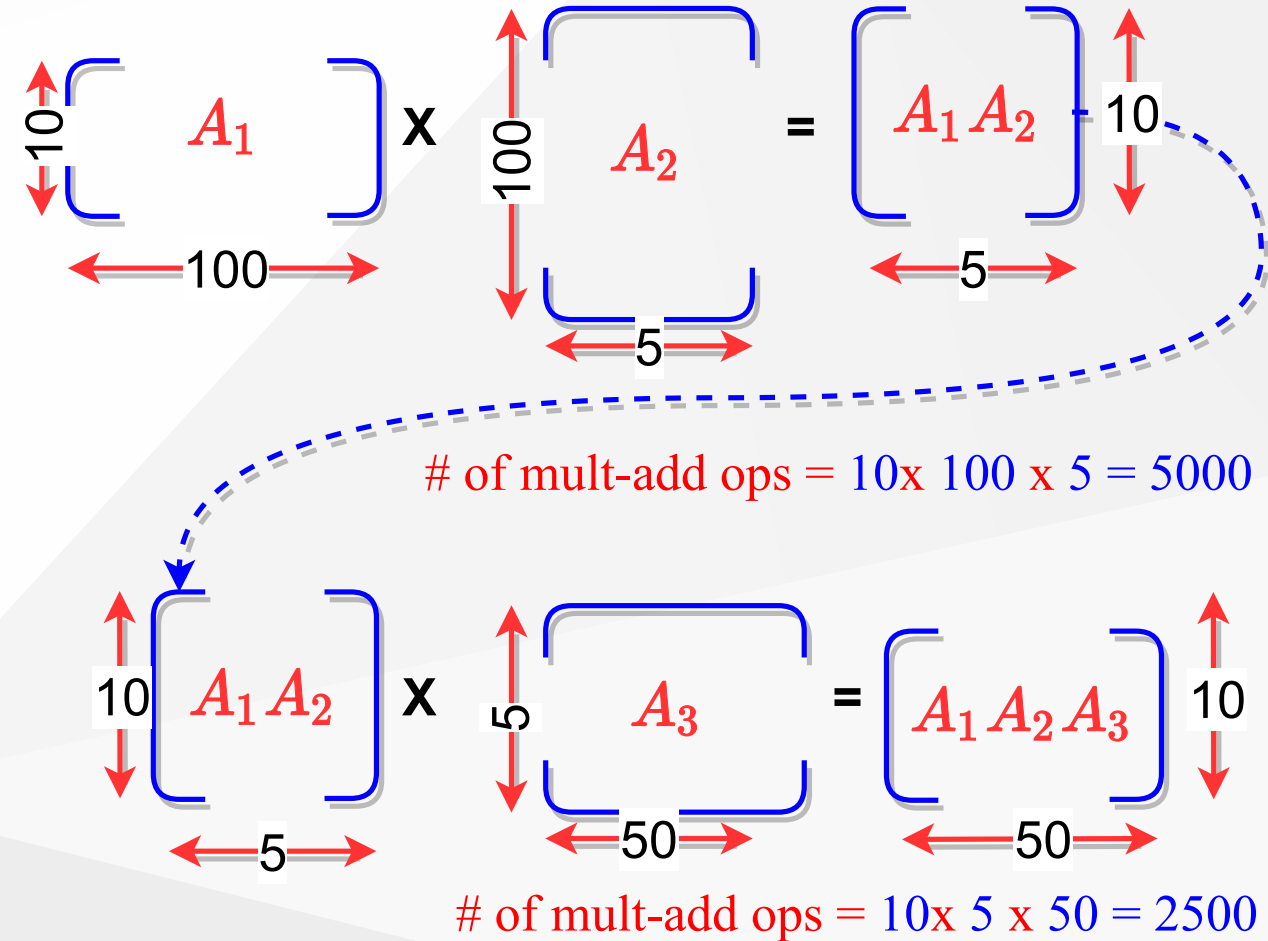
C: $p \times r$

of mult-add ops = $\text{rows}[A] \times \text{cols}[B] \times \text{cols}[A]$

of mult-add ops = $p \times q \times r$

Matrix Chain Multiplication: Example

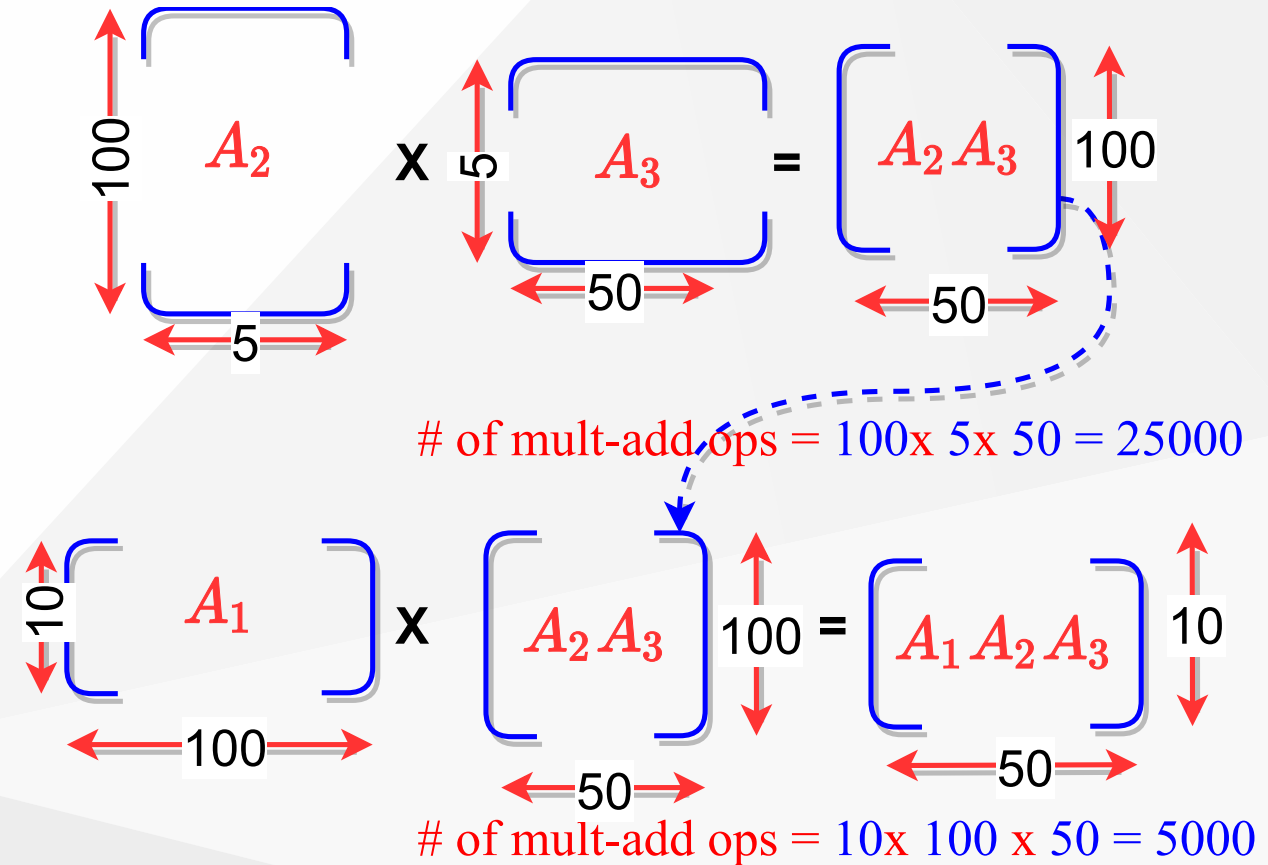
- $A_1 : 10 \times 100$, $A_2 : 100 \times 5$,
 $A_3 : 5 \times 50$
 - Which paranthesization is better? $(A_1 A_2) A_3$ or $A_1 (A_2 A_3)$?



$$\# \text{ of mult-add ops} = 5000 + 2500 = 7500$$

Matrix Chain Multiplication: Example

- $A_1 : 10 \times 100$, $A_2 : 100 \times 5$,
 $A_3 : 5 \times 50$
 - Which paranthesization is better? $(A_1 A_2) A_3$ or $A_1 (A_2 A_3)$?



of multi-add ops = $25000 + 5000 = 75000$

Matrix Chain Multiplication: Example

- $A1 : 10 \times 100, A2 : 100 \times 5, A3 : 5 \times 50$
 - Which paranthesization is better? $(A1A2)A3$ or $A1(A2A3)$?

In summary:

- $(A1A2)A3 = \#$ of multiply-add ops: 7500
- $A1(A2A3) = \#$ of multiple-add ops: 75000

First paranthesization yields **10x faster** computation

Matrix-chain Multiplication Problem

- **Input:** A chain $\langle A_1, A_2, \dots, A_n \rangle$ of n matrices,
 - where A_i is a $p_{i-1} \times p_i$ matrix
- **Objective:** Fully parenthesize the product
 - $A_1 \cdot A_2 \dots A_n$
 - such that the number of **scalar mult-adds** is minimized.

Counting the Number of Parenthesizations

- **Brute force approach:** exhaustively check all parenthesizations
- $P(n)$: # of parenthesizations of a sequence of n matrices
- We can split sequence between k^{th} and $(k + 1)^{st}$ matrices for any $k = 1, 2, \dots, n - 1$, then parenthesize the two resulting sequences independently, i.e.,

$$(A_1 A_2 A_3 \dots A_k \quad \overbrace{\hspace{1cm}}^{\text{break-point}}) (A_{k+1} A_{k+2} \dots A_n)$$

- We obtain the recurrence

$$P(1) = 1 \text{ and } P(n) = \sum_{k=1}^{n-1} P(k)P(n-k)$$

Number of Parenthesizations:

- $P(1) = 1$ and $P(n) = \sum_{k=1}^{n-1} P(k)P(n-k)$
- The recurrence generates the sequence of **Catalan Numbers** Solution is $P(n) = C(n-1)$ where

$$C(n) = \frac{1}{n+1} \binom{2n}{n} = \Omega(4^n / n^{3/2})$$

- The number of solutions is **exponential** in n
- Therefore, brute force approach is a poor strategy

The Structure of Optimal Parenthesization

- **Notation:** $A_{i..j}$: The matrix that results from evaluation of the product:
 $A_i A_{i+1} A_{i+2} \dots A_j$
- **Observation:** Consider the last multiplication operation in any parenthesization:
 $(A_1 A_2 \dots A_k) \cdot (A_{k+1} A_{k+2} \dots A_n)$
 - There is a k value ($1 \leq k < n$) such that:
 - First, the product $A_1 \dots k$ is computed
 - Then, the product $A_{k+1..n}$ is computed
 - Finally, the matrices $A_{1..k}$ and $A_{k+1..n}$ are multiplied

Step 1: Characterize the Structure of an Optimal Solution

- An optimal parenthesization of product $A_1 A_2 \dots A_n$ will be:
 $(A_1 A_2 \dots A_k) \cdot (A_{k+1} A_{k+2} \dots A_n)$ for some k value
- The cost of this optimal parenthesization will be:
 - $=$ Cost of computing $A_{1\dots k}$
 - $+$ Cost of computing $A_{k+1\dots n}$
 - $+$ Cost of multiplying $A_{1\dots k} \cdot A_{k+1\dots n}$

Step 1: Characterize the Structure of an Optimal Solution

- **Key observation:** Given optimal parenthesization
 - $(A_1 A_2 A_3 \dots A_k) \cdot (A_{k+1} A_{k+2} \dots A_n)$
- Parenthesization of the subchain $A_1 A_2 A_3 \dots A_k$
- Parenthesization of the subchain $A_{k+1} A_{k+2} \dots A_n$

should both be optimal

- Thus, optimal solution to an instance of the problem contains optimal solutions to subproblem instances
 - **i.e.**, optimal substructure within an optimal solution exists.

Step 2: A Recursive Solution

- **Step 2:** Define the value of an optimal solution recursively in terms of optimal solutions to the subproblems
- Assume we are trying to determine the min cost of computing $A_{i..j}$
- $m_{i,j}$: min # of scalar multiply-add opns needed to compute $A_{i..j}$
 - **Note:** *The optimal cost of the original problem: $m_{1,n}$*
- How to compute $m_{i,j}$ recursively?

Step 2: A Recursive Solution

- Base case: $m_{i,i} = 0$ (single matrix, no multiplication)
- Let the size of matrix A_i be $(p_{i-1} \times p_i)$
- Consider an optimal parenthesization of chain
 - $A_i \dots A_j : (A_i \dots A_k) \cdot (A_{k+1} \dots A_j)$
- The optimal cost: $m_{i,j} = m_{i,k} + m_{k+1,j} + p_{i-1} \times p_k \times p_j$
- where:
 - $m_{i,k}$: Optimal cost of computing $A_{i..k}$
 - $m_{k+1,j}$: Optimal cost of computing $A_{k+1..j}$
 - $p_{i-1} \times p_k \times p_j$: Cost of multiplying $A_{i..k}$ and $A_{k+1..j}$

Step 2: A Recursive Solution

- In an optimal parenthesization: k must be chosen to minimize m_{ij}
- The recursive formulation for m_{ij} :

$$m_{ij} = \begin{cases} 0 & \text{if } i = j \\ \underset{i \leq k < j}{MIN} \{m_{ik} + m_{k+1,j} + p_{i-1}p_kp_j\} & \text{if } i < j \end{cases}$$

Step 2: A Recursive Solution

- The m_{ij} values give the **costs of optimal solutions** to subproblems
- In order to keep track of how to construct an optimal solution
 - Define s_{ij} to be the value of k which yields the optimal split of the subchain $A_{i..j}$
 - That is, $s_{ij} = k$ such that
 - $m_{ij} = m_{ik} + m_{k+1,j} + p_{i-1}p_kp_j$ holds

Direct Recursion: Inefficient!

- Recursive Matrix-Chain (RMC) Order

```
RMC(p,i,j)

  if (i == j) then
    return 0

  m[i, j] = INF

  for k=i to j-1 do

    q = RMC(p, i, k) + RMC(p, k+1, j) + p_{i-1} p_k p_j

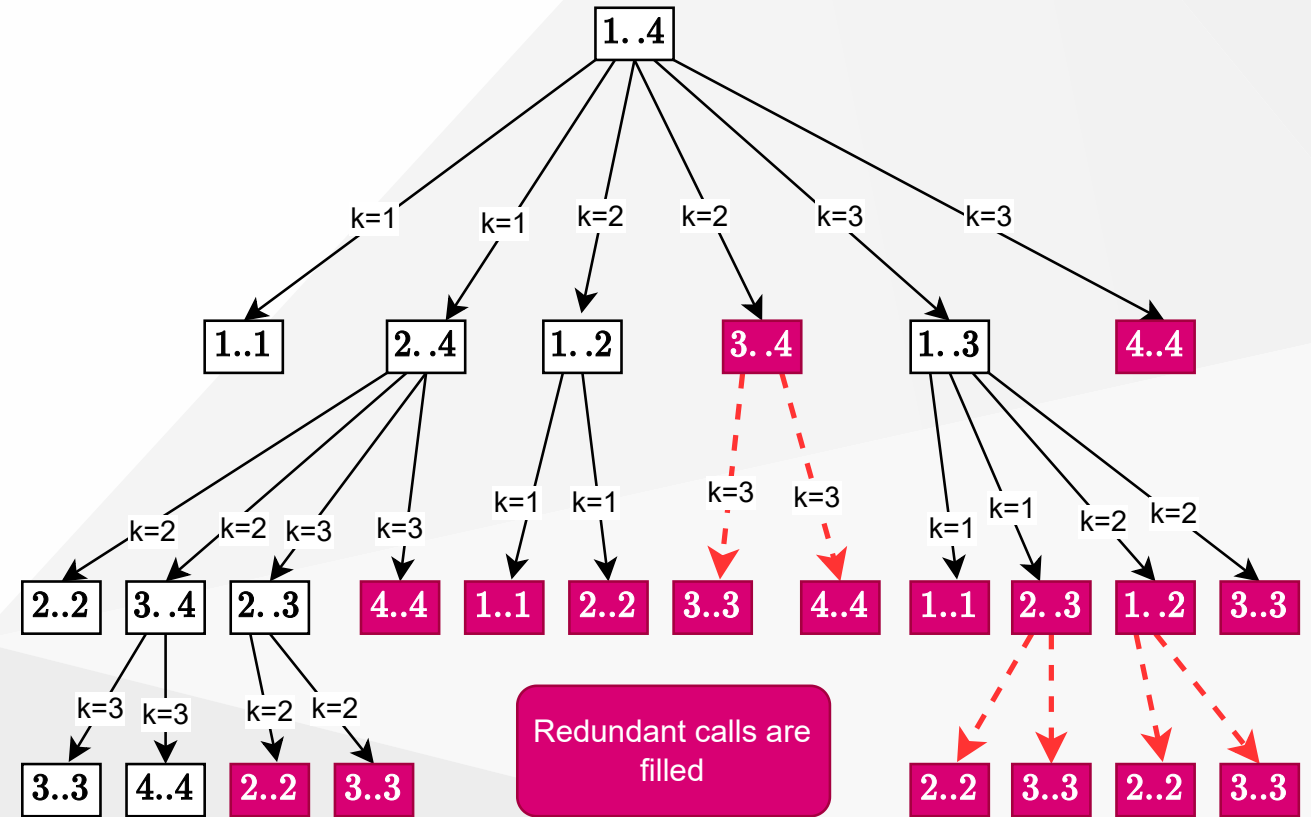
    if q < m[i, j] then
      m[i, j] = q

  endfor

  return m[i, j]
```

Direct Recursion: Inefficient!

- Recursion tree for $RMC(p, 1, 4)$
- Nodes are labeled with i and j values



Computing the Optimal Cost (Matrix-Chain Multiplication)

An important observation:

- We have **relatively few subproblems**
 - one problem for each choice of i and j satisfying $1 \leq i \leq j \leq n$
 - total $n + (n - 1) + \dots + 2 + 1 = \frac{1}{2}n(n + 1) = \Theta(n^2)$ subproblems
- We can write a **recursive** algorithm based on recurrence.
- However, a recursive algorithm may encounter each subproblem many times in different branches of the recursion tree
- This property, **overlapping subproblems**, is the **second important feature** for applicability of **dynamic programming**

Computing the Optimal Cost (Matrix-Chain Multiplication)

- Compute the value of an optimal solution in a **bottom-up** fashion
 - matrix A_i has dimensions $p_{i-1} \times p_i$ for $i = 1, 2, \dots, n$
 - the input is a sequence $\langle p_0, p_1, \dots, p_n \rangle$ where $length[p] = n + 1$
- Procedure uses the following auxiliary tables:
 - $m[1 \dots n, 1 \dots n]$: for storing the $m[i, j]$ costs
 - $s[1 \dots n, 1 \dots n]$: records which index of k achieved the optimal cost in computing $m[i, j]$

Bottom-Up Computation

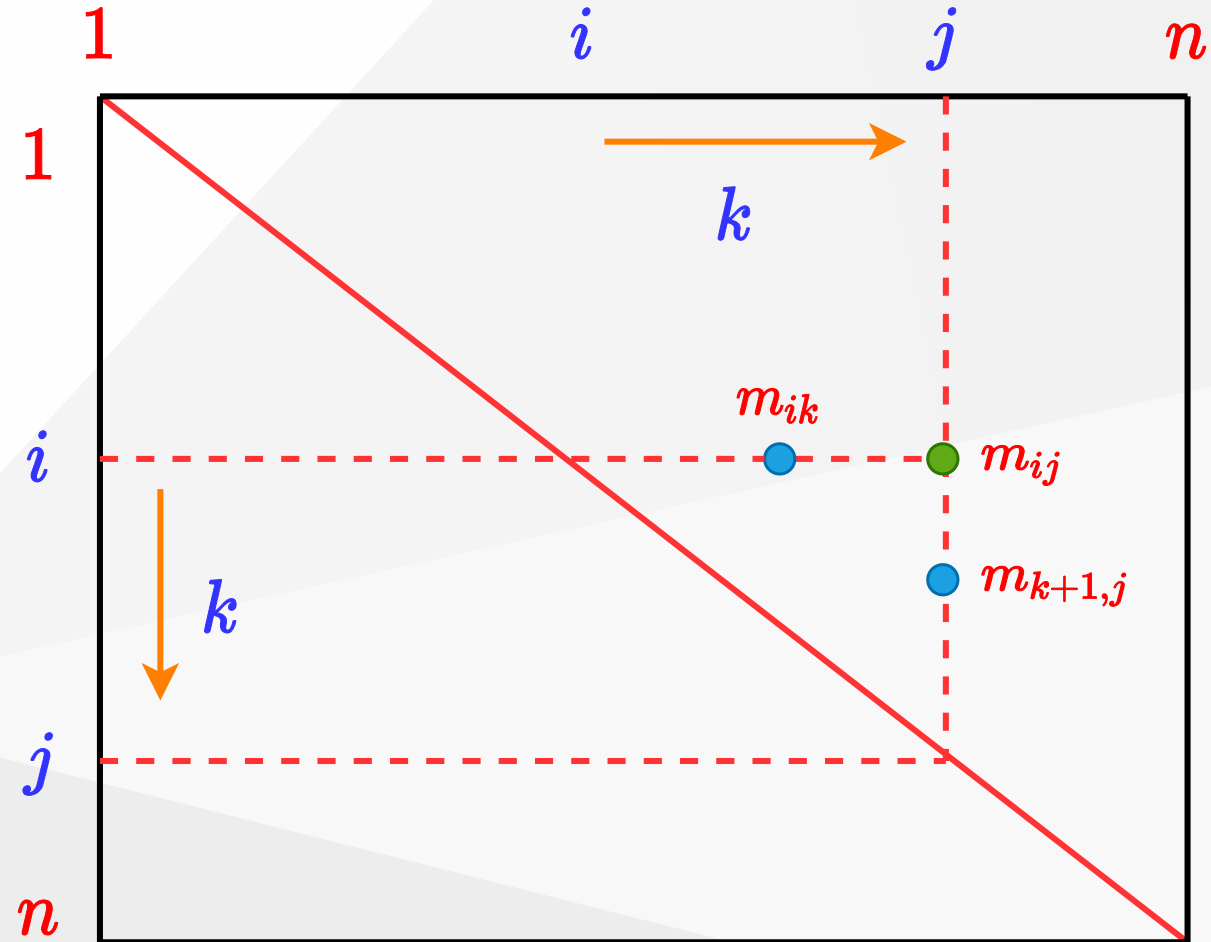
- How to choose the order in which we process m_{ij} values?
- Before computing m_{ij} , we have to make sure that the values for m_{ik} and $m_{k+1,j}$ have been computed for all k .

$$m_{ij} = \underset{i \leq k < j}{MIN} \{m_{ik} + m_{k+1,j} + p_{i-1}p_kp_j\}$$

Bottom-Up Computation

$$m_{ij} = \underset{i \leq k < j}{\text{MIN}} \{m_{ik} + m_{k+1,j} + p_{i-1}p_kp_j\}$$

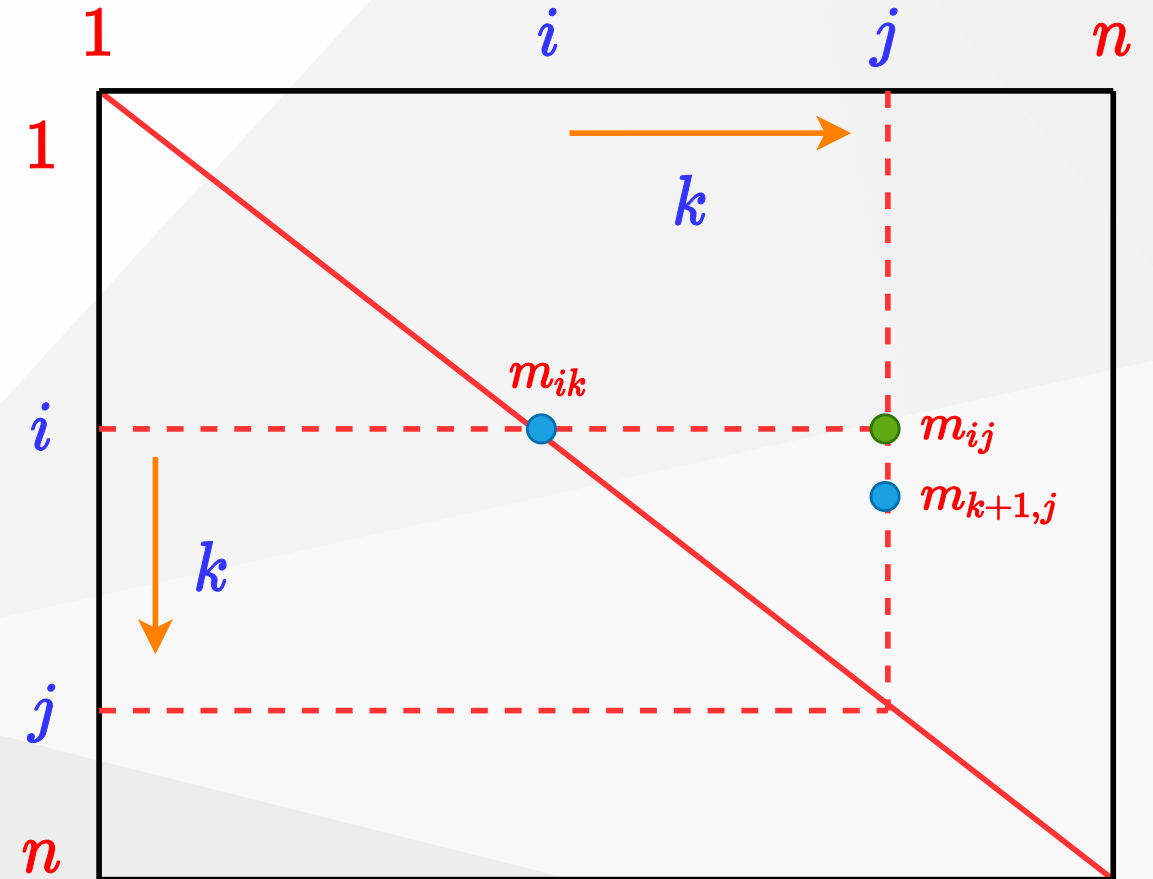
- m_{ij} must be processed after m_{ik} and $m_{j,k+1}$
- **Reminder:** m_{ij} computed only for $j > i$



Bottom-Up Computation

$$m_{ij} = \underset{i \leq k < j}{MIN} \{m_{ik} + m_{k+1,j} + p_{i-1}p_kp_j\}$$

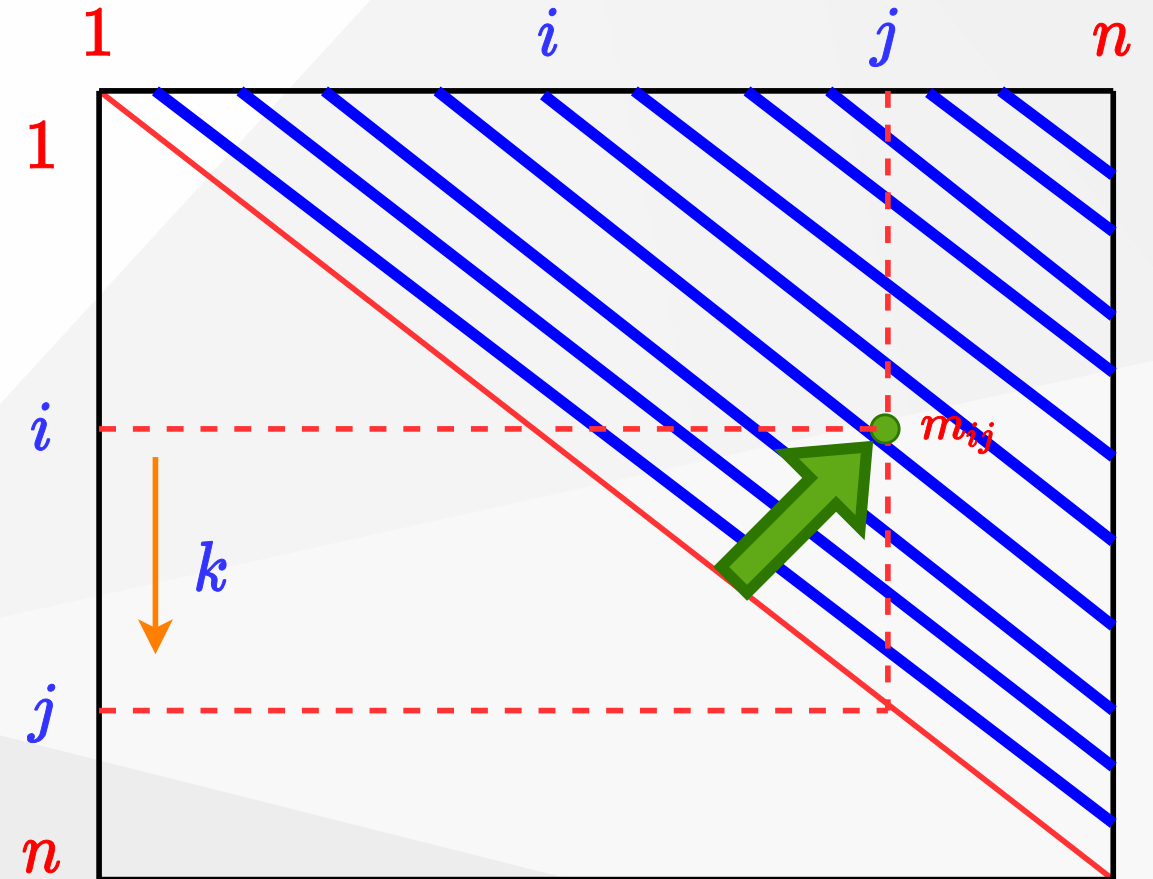
- m_{ij} must be processed after m_{ik} and $m_{j,k+1}$
- How to set up the iterations over i and j to compute m_{ij} ?



Bottom-Up Computation

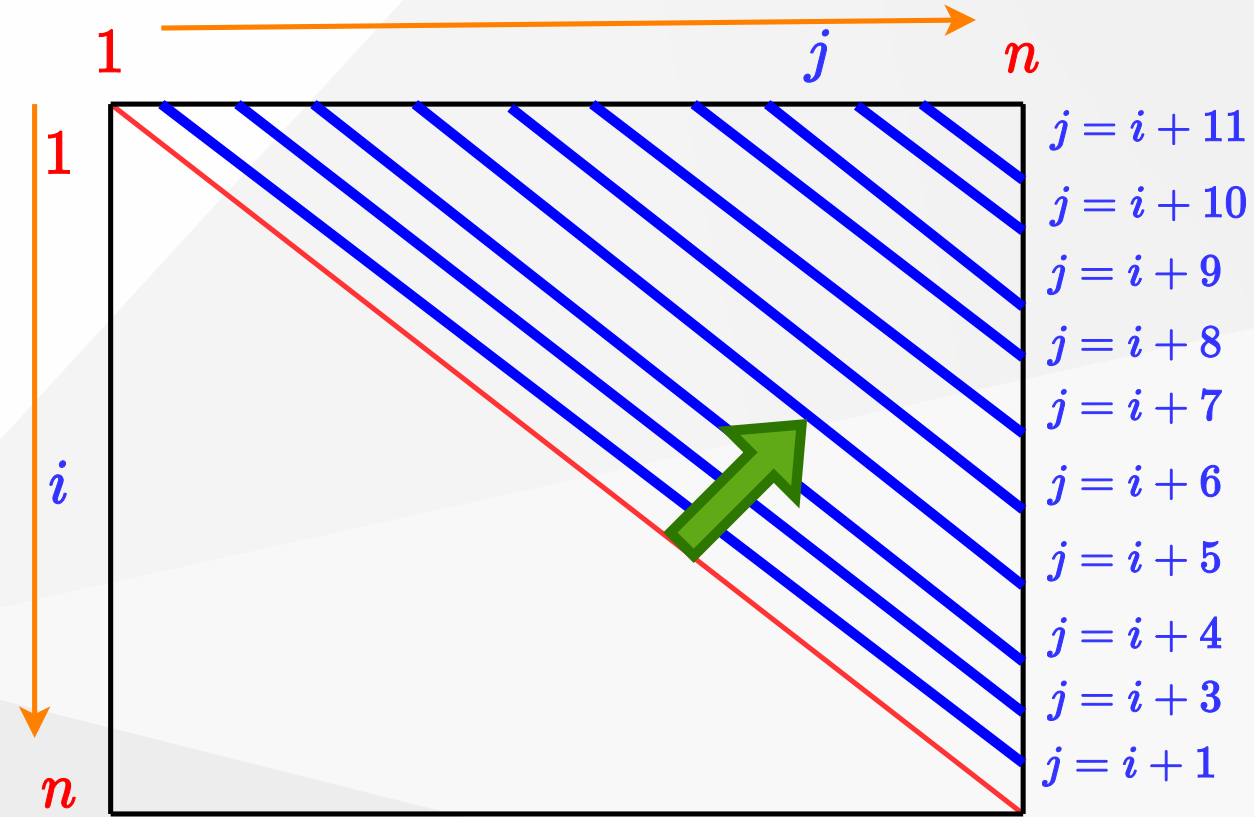
$$m_{ij} = \underset{i \leq k < j}{MIN} \{m_{ik} + m_{k+1,j} + p_{i-1}p_kp_j\}$$

- If the entries m_{ij} are computed in the shown order, then m_{ik} and $m_{k+1,j}$ values are guaranteed to be computed before m_{ij} .



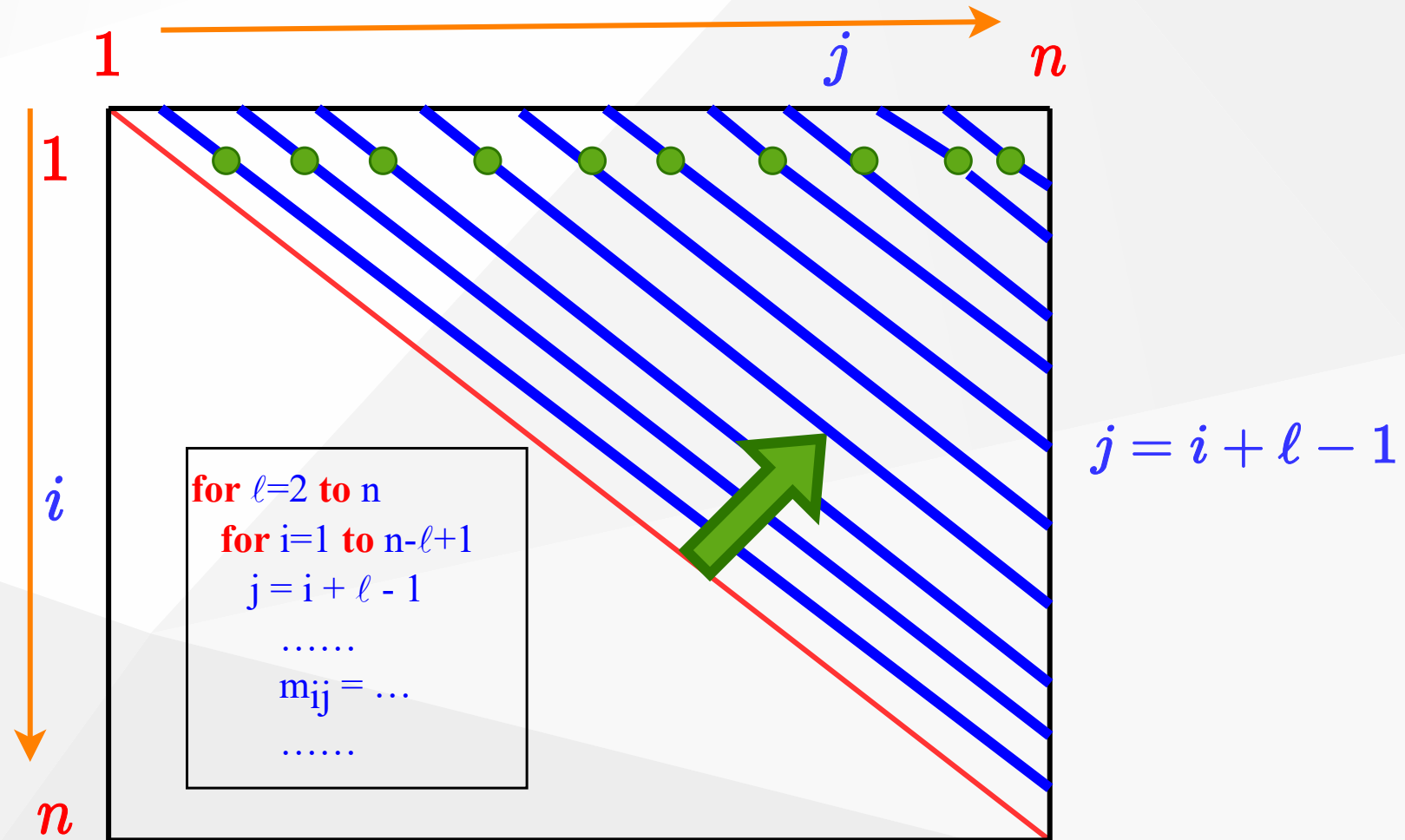
Bottom-Up Computation

$$m_{ij} = \underset{i \leq k < j}{MIN} \{m_{ik} + m_{k+1,j} + p_{i-1}p_kp_j\}$$



Bottom-Up Computation

$$m_{ij} = \underset{i \leq k < j}{\text{MIN}} \{m_{ik} + m_{k+1,j} + p_{i-1}p_kp_j\}$$



Algorithm for Computing the Optimal Costs

- Note: $l = \ell$ and $p_{\{i-1\}} p_k p_j = p_{i-1} p_k p_j$

```

MATRIX-CHAIN-ORDER(p)
  n = length[p]-1
  for i=1 to n do
    m[i, i]=0
  endfor
  for l=2 to n do
    for i=1 to n-l+1 do
      j=i+l-1
      m[i, j]=INF
      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
        endif
      endfor
    endfor
  endfor
  return m and s

```

Algorithm for Computing the Optimal Costs

- The algorithm first computes
 - $m[i, i] \leftarrow 0$ for $i = 1, 2, \dots, n$ min costs for all chains of length 1
- Then, for $\ell = 2, 3, \dots, n$ computes
 - $m[i, i + \ell - 1]$ for $i = 1, \dots, n - \ell + 1$ min costs for all chains of length ℓ
- For each value of $\ell = 2, 3, \dots, n$,
 - $m[i, i + \ell - 1]$ depends only on table entries $m[i, k]$ & $m[k + 1, i + \ell - 1]$ for $i \leq k < i + \ell - 1$, which are already computed

Algorithm for Computing the Optimal Costs

$$\begin{array}{l}
 \underbrace{\{\text{compute } m[i, i+1], m[1, 2], m[2, 3], \dots, m[n-1, n]\}}_{(n-1) \text{ values}} \left\{ \begin{array}{l} \ell = 2 \\ \text{for } i = 1 \text{ to } n - 1 \text{ do} \\ \quad m[i, i+1] = \infty \quad (1) \\ \quad \text{for } k = i \text{ to } i \text{ do} \\ \quad \quad \vdots \end{array} \right. \\
 \underbrace{\{\text{compute } m[i, i+2], m[1, 3], m[2, 4], \dots, m[n-2, n]\}}_{(n-2) \text{ values}} \left\{ \begin{array}{l} \ell = 3 \\ \text{for } i = 1 \text{ to } n - 2 \text{ do} \\ \quad m[i, i+2] = \infty \quad (1) \\ \quad \text{for } k = i \text{ to } i + 1 \text{ do} \\ \quad \quad \vdots \end{array} \right. \\
 \underbrace{\{\text{compute } m[i, i+3], m[1, 4], m[2, 5], \dots, m[n-3, n]\}}_{(n-3) \text{ values}} \left\{ \begin{array}{l} \ell = 4 \\ \text{for } i = 1 \text{ to } n - 3 \text{ do} \\ \quad m[i, i+3] = \infty \quad (1) \\ \quad \text{for } k = i \text{ to } i + 2 \text{ do} \\ \quad \quad \vdots \end{array} \right.
 \end{array}$$

Table access pattern in computing $m[i, j]$ s for

$$\ell = j - i + 1$$

for $k \leftarrow i$ to $j - 1$ do

$$q \leftarrow m[i, k] + m[k + 1, j] + p_{i-1}p_kp_j$$

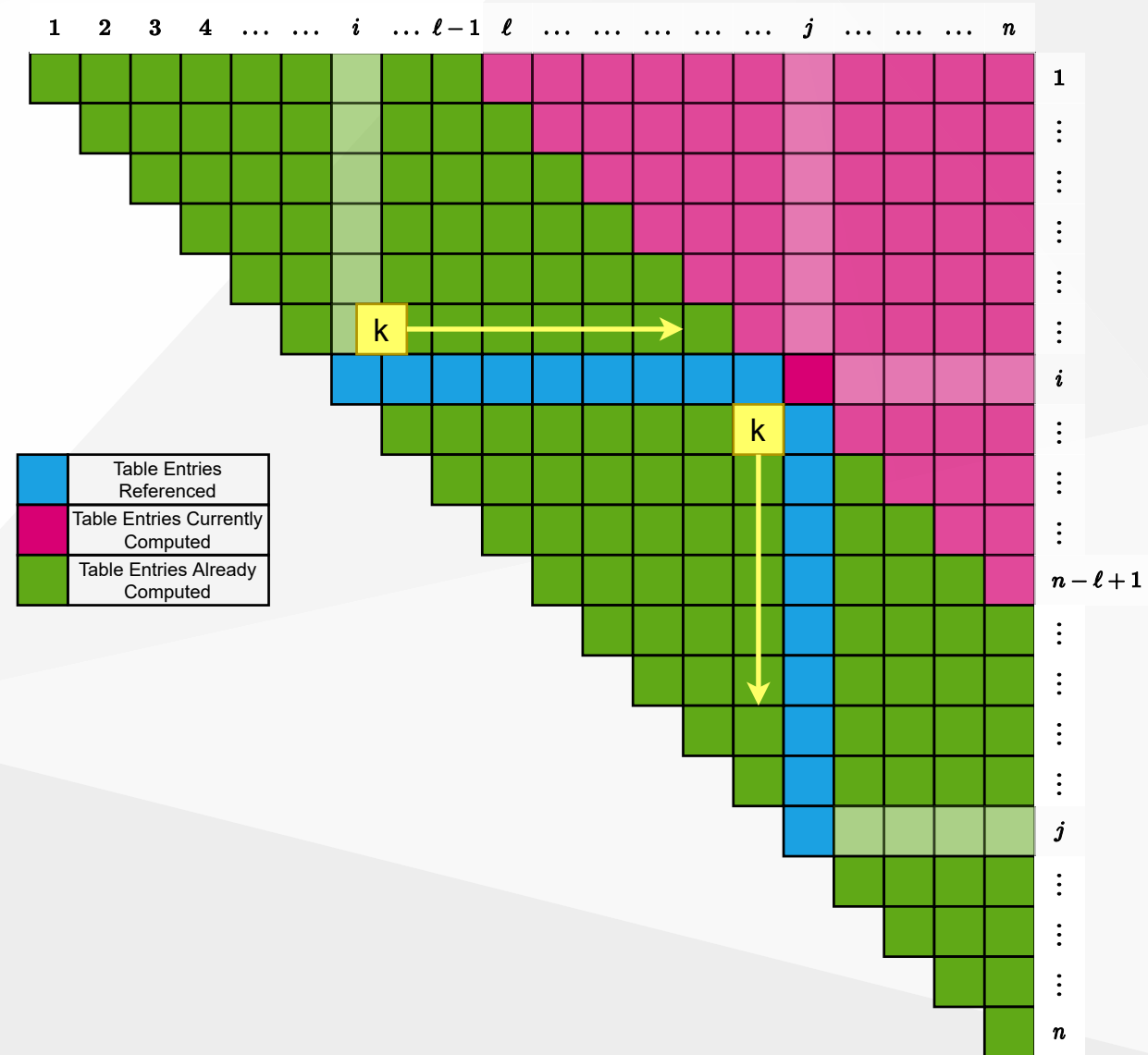
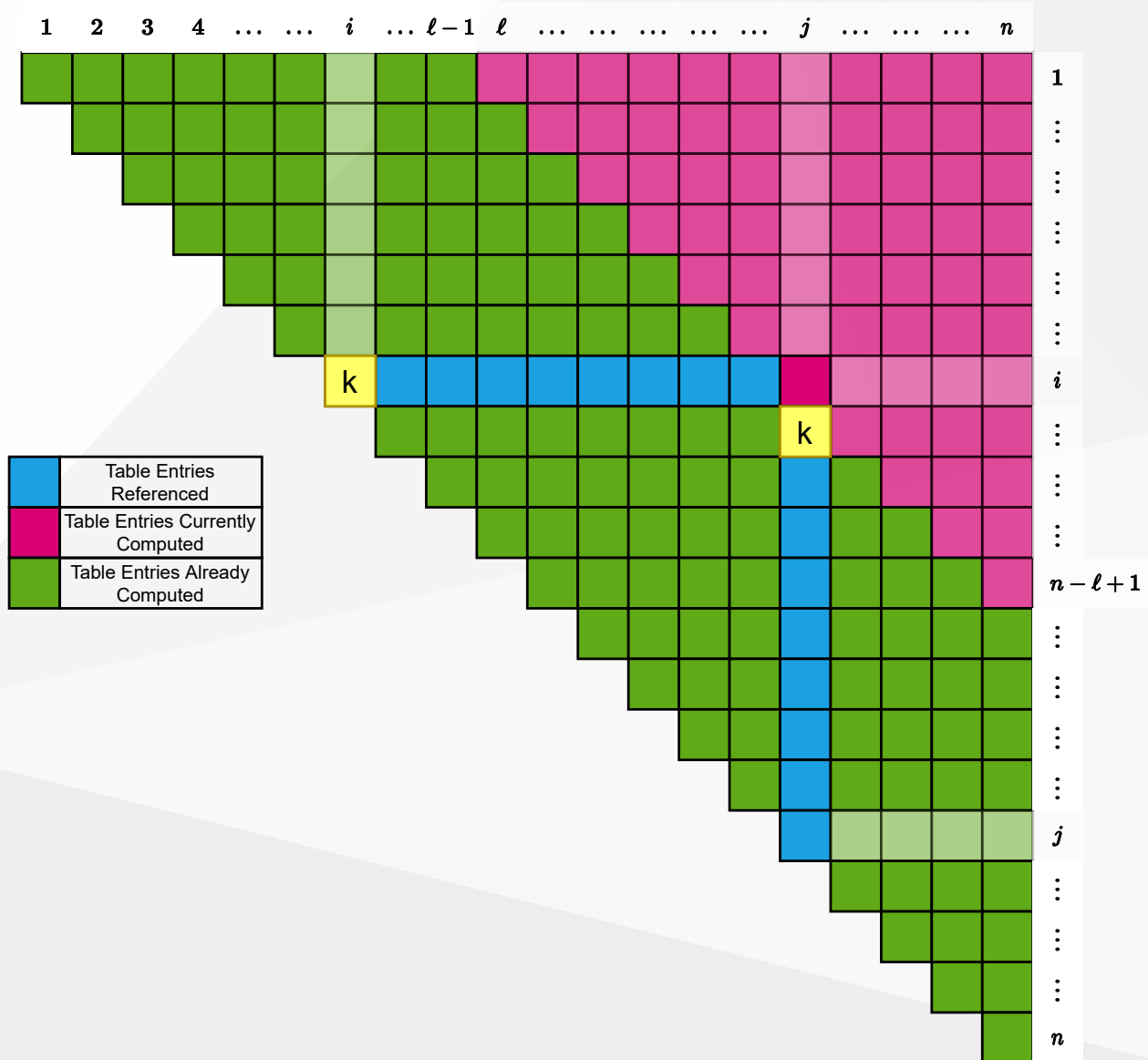


Table access pattern in
computing $m[i, j]$ s for
 $\ell = j - i + 1$

mult.

$$\left((A_i) \vdots (A_{i+1} A_{i+2} \dots A_j) \right)$$



mult.

$$\left(\begin{array}{ccc} (A_i A_{i+1}) & \vdots & (A_{i+2} \dots A_j) \end{array} \right)$$



$$\begin{array}{c} \text{mult.} \\ \left(\begin{array}{ccc} (A_i A_{i+1} A_{i+2}) & \vdots & (A_{i+3} \dots A_j) \end{array} \right) \end{array}$$


$$\begin{pmatrix} (A_i A_{i+1} \dots A_{j-1}) & \vdots & (A_j) \end{pmatrix}^{mult.}$$


Table access pattern Example

- Compute m_{25}
- Choose the k value that leads to min cost

$$m_{ij} = \underset{i \leq k < j}{MIN} \{m_{ik} + m_{k+1,j} + p_{i-1}p_kp_j\}$$

$A_1 : (30 \times 35)$

$A_2 : (35 \times 15)$

$A_3 : (15 \times 5)$

$A_4 : (5 \times 10)$

$A_5 : (10 \times 20)$

$A_6 : (20 \times 25)$

$\underbrace{(k=2)}$
 $((A_2) \vdots (A_3 A_4 A_5))$

$$\begin{aligned}
 \text{cost} &= m_{22} + m_{35} + p_1 p_2 p_5 \\
 &= 0 + 2500 + 35 \times 15 \times 20 \\
 &= 13000
 \end{aligned}$$

	1	2	3	4	5	6	
1	0	15750	7875	9375			1
2		0	2625	4375	???		2
3			0	750	2500		3
4				0	1000	3500	4
5					0	5000	5
6						0	6

Table access pattern Example

- Compute m_{25}
- Choose the k value that leads to min cost

$$m_{ij} = \underset{i \leq k < j}{MIN} \{ m_{ik} + m_{k+1,j} + p_{i-1}p_kp_j \}$$

$A_1 : (30 \times 35)$

$A_2 : (35 \times 15)$

$A_3 : (15 \times 5)$

$A_4 : (5 \times 10)$

$A_5 : (10 \times 20)$

$A_6 : (20 \times 25)$

$$\overbrace{((A_2 A_3) \vdots (A_4 A_5))}^{(k=3)}$$

$$\begin{aligned} \text{cost} &= m_{23} + m_{45} + p_1 p_3 p_5 \\ &= 2625 + 1000 + 35 \times 5 \times 20 \\ &= 7125 \end{aligned}$$

	1	2	3	4	5	6	
1	0	15750	7875	9375			1
2		0	2625	4375	???		2
3			0	750	2500		3
4				0	1000	3500	4
5					0	5000	5
6						0	6

Table access pattern Example

- Compute m_{25}
- Choose the k value that leads to min cost

$$m_{ij} = \underset{i \leq k < j}{MIN} \{m_{ik} + m_{k+1,j} + p_{i-1}p_kp_j\}$$

$A_1 : (30 \times 35)$

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$A_3 : (15 \times 5)$

$A_4 : (5 \times 10)$

$A_5 : (10 \times 20)$

$A_6 : (20 \times 25)$

$(k=4)$
 $\underbrace{\hspace{1.5cm}}$
 $((A_2 A_3 A_4) \vdots (A_5))$

$$\begin{aligned}
 \text{cost} &= m_{24} + m_{55} + p_1 p_4 p_5 \\
 &= 4375 + 0 + 35 \times 10 \times 20 \\
 &= 11375
 \end{aligned}$$

	1	2	3	4	5	6	
	0	15750	7875	9375			1
		0	2625	4375	???		2
			0	750	2500		3
				0	1000	3500	4
					0	5000	5
						0	6

Table access pattern Example

- Compute m_{25}
- Choose the k value that leads to min cost

$$m_{ij} = \underset{i \leq k < j}{MIN} \{m_{ik} + m_{k+1,j} + p_{i-1}p_kp_j\}$$

$(k=2)$

$$((A_2) \vdots (A_3 A_4 A_5)) \rightarrow m_{22} + m_{35} + p_1 p_2 p_5 = 13000$$

$A_1 : (30 \times 35)$

$A_2 : (35 \times 15)$

$A_3 : (15 \times 5)$

$A_4 : (5 \times 10)$

$A_5 : (10 \times 20)$

$A_6 : (20 \times 25)$

$$((A_2 A_3) \vdots (A_4 A_5)) \rightarrow m_{23} + m_{45} + p_1 p_3 p_5 = \overbrace{7125}^{\text{selected}} \Leftarrow \min$$

$$((A_2 A_3 A_4) \vdots (A_5)) \rightarrow m_{24} + m_{55} + p_1 p_4 p_5 = 11375$$

$$m_{25} = 7125$$

$$s_{25} = 3$$

	1	2	3	4	5	6	
1	0	15750	7875	9375			1
2		0	2625	4375	7125		2
3			0	750	2500		3
4				0	1000	3500	4
5					0	5000	5
6						0	6

Constructing an Optimal Solution

- **MATRIX-CHAIN-ORDER** determines the optimal # of scalar **mults/adds**
 - needed to compute a matrix-chain product
 - it does not directly show how to multiply the matrices
- That is,
 - it determines the cost of the optimal solution(s)
 - it does not show how to obtain an optimal solution
- Each entry $s[i, j]$ records the value of k such that optimal parenthesization of $A_i \dots A_j$ splits the product between A_k & A_{k+1}
- We know that the final matrix multiplication in computing $A_{1..n}$ optimally is $A_{1..s[1,n]} \times A_{s[1,n]+1,n}$

Example: Constructing an Optimal Solution

- **Reminder:** s_{ij} is the optimal top-level split of $A_i \dots A_j$
- What is the optimal top-level split for:
 - $A_1 A_2 A_3 A_4 A_5 A_6$
 - $s_{16} = 3$

2	3	4	5	6	
1	1	3	3	3	1
	2	3	3	3	2
		3	3	3	3
			4	5	4
				5	5

Example: Constructing an Optimal Solution

- **Reminder:** s_{ij} is the optimal top-level split of $A_i \dots A_j$

(k=4)
⏟

- $(A_1 A_2 A_3) \vdots (A_4 A_5 A_6)$
 - What is the optimal split for $A_1 \dots A_3$? ($s_{13} = 1$)
 - What is the optimal split for $A_4 \dots A_6$? ($s_{46} = 5$)

	2	3	4	5	6	
1	1	3	3	3		1
	2	3	3	3		2
		3	3	3		3
			4	5		4
				5		5

Example: Constructing an Optimal Solution

- Reminder: s_{ij} is the optimal top-level split of $A_i \dots A_j$

$(k=1)$

$(k=5)$

- $\left((A_1) \vdots (A_2 A_3) \right) \left((A_4 A_5) \vdots (A_6) \right)$

- What is the optimal split for $A_1 \dots A_3$? (

$$s_{13} = 1)$$

- What is the optimal split for $A_4 \dots A_6$? (

$$s_{46} = 5)$$

	2	3	4	5	6	
1	1	1	3	3	3	1
2		2	3	3	3	2
3			3	3	3	3
4				4	5	4
5					5	5

Example: Constructing an Optimal Solution

- **Reminder:** s_{ij} is the optimal top-level split of $A_i \dots A_j$
- $\left((A_1)(A_2 A_3) \right) \left((A_4 A_5)(A_6) \right)$
 - What is the optimal split for $A_2 A_3$? ($s_{23} = 2$)
 - What is the optimal split for $A_4 A_5$? ($s_{45} = 4$)

	2	3	4	5	6	
1	1	3	3	3	1	
	2	3	3	3	2	
		3	3	3	3	
			4	5	4	
				5	5	

Example: Constructing an Optimal Solution

- **Reminder:** s_{ij} is the optimal top-level split of $A_i \dots A_j$

$$\left(\left(A_1 \right) \overbrace{\left(\left(A_2 \right) \vdots \left(A_3 \right) \right)}^{(k=2)} \right) \left(\overbrace{\left(\left(A_4 \right) \vdots \left(A_5 \right) \right)}^{(k=4)} \left(A_6 \right) \right)$$

- What is the optimal split for $A_2 A_3$? ($s_{23} = 2$)
- What is the optimal split for $A_4 A_5$? ($s_{45} = 4$)

	2	3	4	5	6	
1	1	3	3	3	1	
	2	3	3	3	2	
		3	3	3	3	
			4	5	4	
				5	5	

Constructing an **Optimal Solution**

- Earlier optimal matrix multiplications can be computed recursively
- **Given:**
 - the chain of matrices $A = \langle A_1, A_2, \dots, A_n \rangle$
the s table computed by MATRIX-CHAIN-ORDER
 - The following recursive procedure computes the **matrix-chain product** $A_{i \dots j}$

MATRIX-CHAIN-MULTIPLY(A, s, i, j)

if $j > i$ then

$X \leftarrow \text{MATRIX-CHAIN-MULTIPLY}(A, s, i, s[i, j])$

$Y \leftarrow \text{MATRIX-CHAIN-MULTIPLY}(A, s, s[i, j] + 1, j)$

return MATRIX-MULTIPLY(X, Y)

else

return A_i

- **Invocation:** MATRIX-CHAIN-MULTIPLY($A, s, 1, n$)

Example: Recursive Construction of an Optimal Solution

$MCM(1,6)$
 $X \leftarrow MCM(1,3) = (A_1 A_2 A_3)$
 $Y \leftarrow MCM(4,6) = (A_4 A_5 A_6)$
return(?)

$MCM(1,3)$
 $X \leftarrow MCM(1,1) = (A_1)$
 $Y \leftarrow MCM(2,3) = (A_2 A_3)$
return(?)

return A₁

s[1...6, 1...6]

2	3	4	5	6	
1	1	3	3	3	1
	2	3	3	3	2
		3	3	3	3
			4	5	4
				5	5

Example: Recursive Construction of an Optimal Solution

$MCM(1, 6)$

$X \leftarrow MCM(1, 3) = (A_1(A_2 A_3)) \dots \rightarrow MCM(1, 3)$

$Y \leftarrow MCM(4, 6) = (A_4 A_5 A_6)$

$return(?)$

$X \leftarrow MCM(1, 1) = (A_1)$

$Y \leftarrow MCM(2, 3) = (A_2 A_3) \dots \rightarrow MCM(2, 3)$

$return(A_1(A_2 A_3))$

$X \leftarrow MCM(2, 2) = A_2 \dots \rightarrow return(A_2)$

$Y \leftarrow MCM(3, 3) = A_3 \dots \rightarrow return(A_3)$

$return(A_2 A_3)$

$s[1 \dots 6, 1 \dots 6]$

	2	3	4	5	6	
1	1	1	3	3	3	1
2		2	3	3	3	2
3			3	3	3	3
4				4	5	4
5					5	5

Example: Recursive Construction of an Optimal Solution

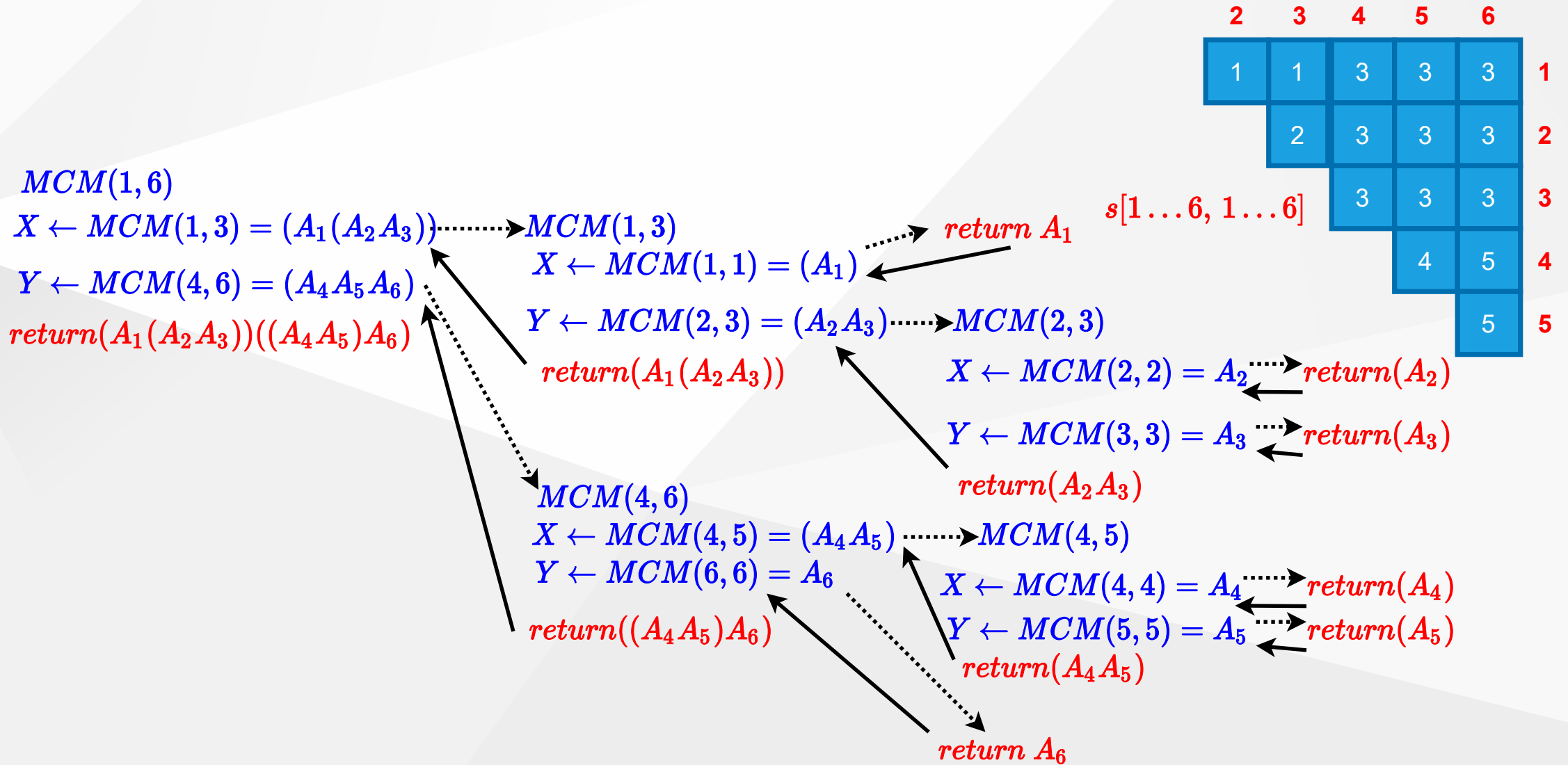


Table reference pattern for $m[i, j]$ ($1 \leq i \leq j \leq n$)

- $m[i, j]$ is referenced for the computation of
 - $m[i, r]$ for $j < r \leq n$ ($n - j$) times
 - $m[r, j]$ for $1 \leq r < i$ ($i - 1$) times

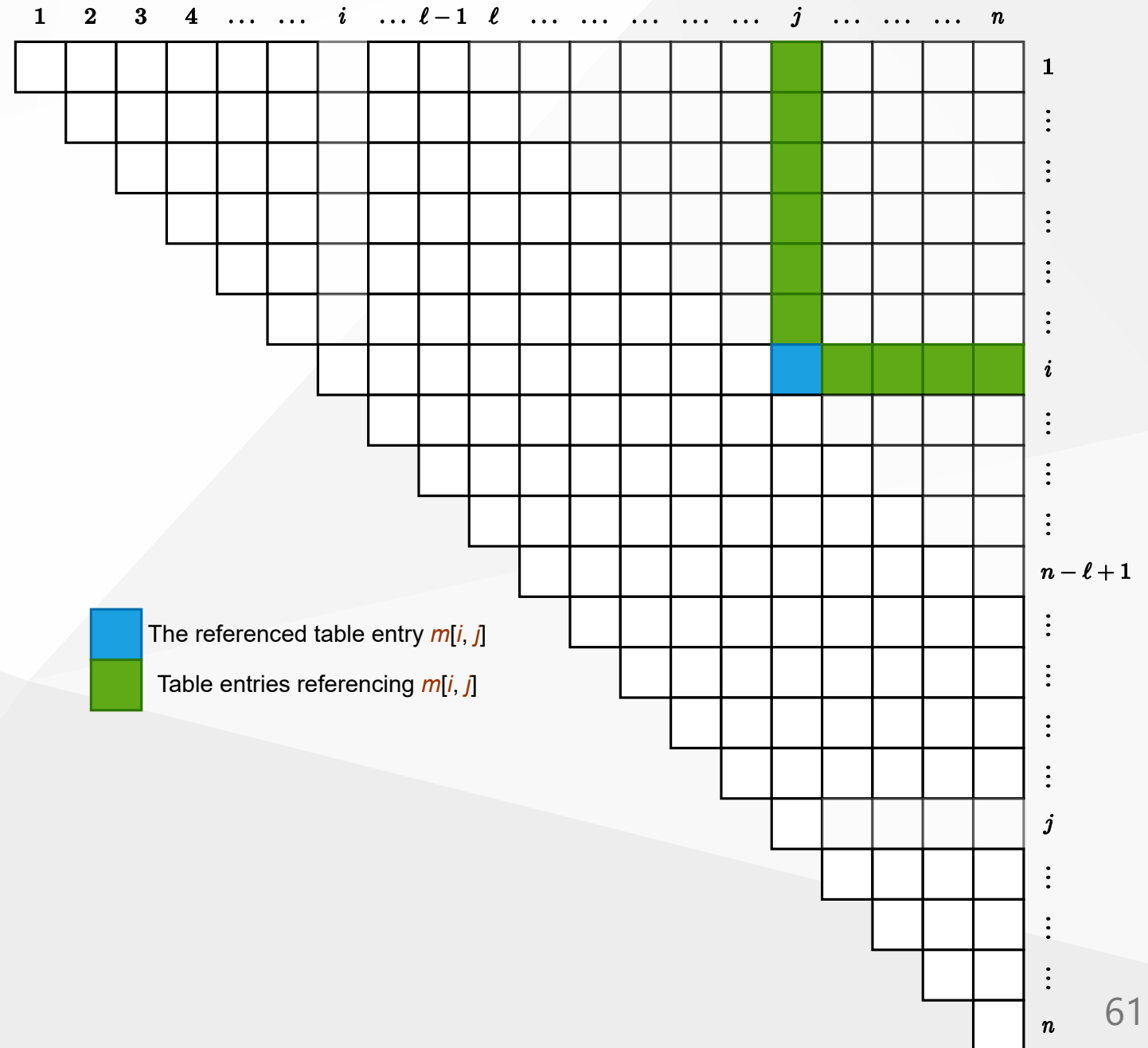


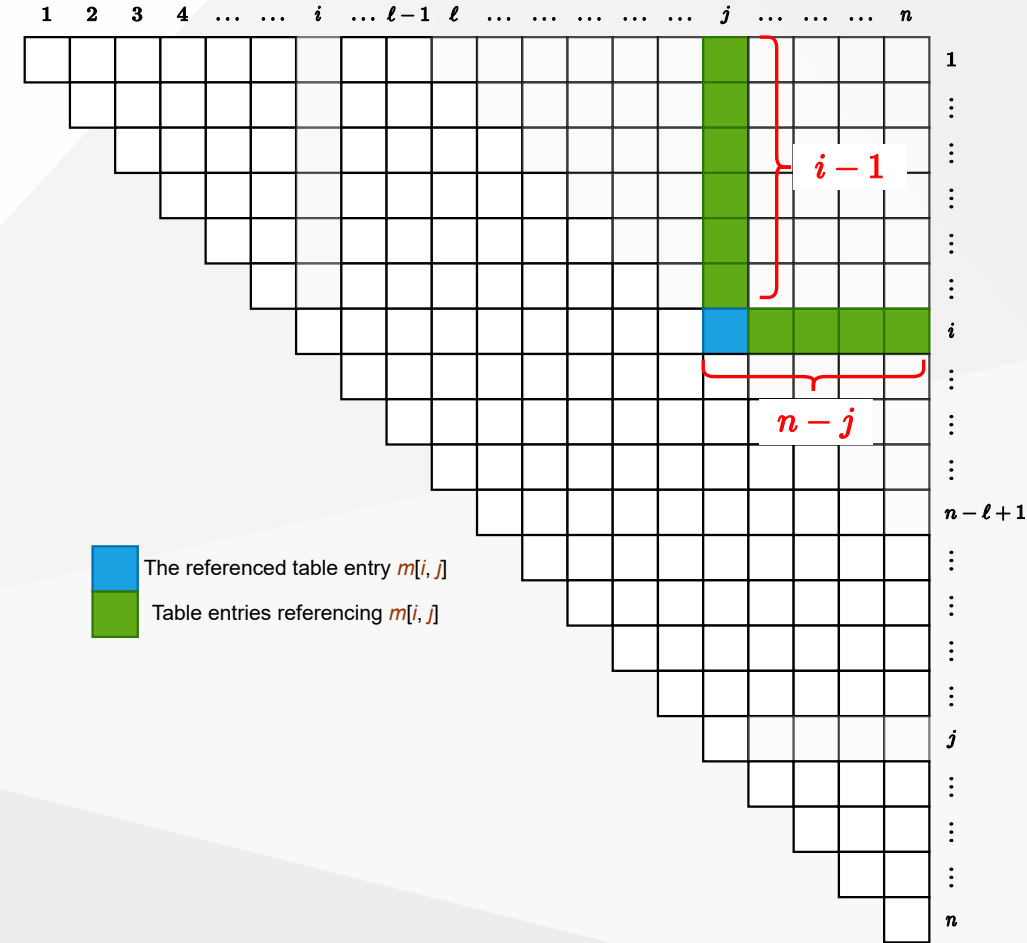
Table reference pattern for $m[i, j]$ $(1 \leq i \leq j \leq n)$

- $R(i, j) = \#$ of times that $m[i, j]$ is referenced in computing other entries

$$\begin{aligned} R(i, j) &= (n - j) + (i - 1) \\ &= (n - 1) - (j - i) \end{aligned}$$

- The total $\#$ of references for the entire

table is: $\sum_{i=1}^n \sum_{j=i}^n R(i, j) = \frac{n^3 - n}{3}$



Summary

- Identification of the optimal substructure property
- Recursive formulation to compute the cost of the optimal solution
- Bottom-up computation of the table entries
- Constructing the optimal solution by backtracing the table entries

References

- [Introduction to Algorithms, Third Edition | The MIT Press](#)
- [Bilkent CS473 Course Notes \(new\)](#)
- [Bilkent CS473 Course Notes \(old\)](#)

–End – Of – Week – 5 – Course – Module–