

CSC373 Worksheet 3 Solution

July 30, 2020

1. Using the following formula

$$M[i, j] = \begin{cases} 0 & \text{if } i = j \\ \min_{i \leq k \leq j} M[i, k] + M[k + 1, j] + p_{i-1}p_kp_j & \text{if } i < j \end{cases} \quad (1)$$

we have

| C | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|-----|-----|-----|------|------|
| 1 | 0 | 350 | 770 | 612 | 1212 | 1422 |
| 2 | x | 0 | 840 | 462 | 1662 | 1362 |
| 3 | x | x | 0 | 252 | 1092 | 1098 |
| 4 | x | x | x | 0 | 1440 | 936 |
| 5 | x | x | x | x | 0 | 720 |
| 6 | x | x | x | x | x | 0 |

And an optimal parenthesization is

My Work:

$(A_1A_2)(A_3A_4)(A_5A_6)$

Correct Solution:

Using the following formula

$$M[i, j] = \begin{cases} 0 & \text{if } i = j \\ \min_{i \leq k \leq j} M[i, k] + M[k + 1, j] + p_{i-1}p_kp_j & \text{if } i < j \end{cases} \quad (2)$$

we have

| m (i/j) | 1 | 2 | 3 | 4 | 5 | 6 |
|---------|---|-----|-----|-----|------|------|
| 1 | 0 | 350 | 770 | 612 | 1212 | 1422 |
| 2 | x | 0 | 840 | 462 | 1662 | 1362 |
| 3 | x | x | 0 | 252 | 1092 | 1098 |
| 4 | x | x | x | 0 | 1440 | 936 |
| 5 | x | x | x | x | 0 | 720 |
| 6 | x | x | x | x | x | 0 |

| s (i/j) | 1 | 2 | 3 | 4 | 5 | 6 |
|---------|---|---|---|---|---|---|
| 1 | 0 | 1 | 2 | 1 | 4 | 4 |
| 2 | x | 0 | 2 | 2 | 4 | 4 |
| 3 | x | x | 0 | 3 | 4 | 4 |
| 4 | x | x | x | 0 | 4 | 4 |
| 5 | x | x | x | x | 0 | 5 |
| 5 | x | x | x | x | x | 0 |

And an optimal parenthesization is

My Work:

$(A_1(A_2(A_3A_4)))(A_5A_6)$

Notes:

- Sequence of Dimensions

The sequence of dimensions $\langle p_0 = 5, p_1 = 10, p_2 = 3, p_3 = 12, p_4 = 5, p_5 = 50, p_6 = 6 \rangle$ means there are 6 matrices with dimensions $p_{i-1} \times p_i$

- $A_1 \rightarrow 5 \times 10$
- $A_2 \rightarrow 10 \times 3$
- $A_3 \rightarrow 3 \times 12$
- $A_4 \rightarrow 12 \times 5$
- $A_5 \rightarrow 5 \times 50$
- $A_6 \rightarrow 50 \times 6$

- Dynamic Programming

- Is applied to optimization problems
- Applies when the subproblems overlap
- Uses the following sequence of steps
 1. Characterize the structure of an optimal solution

2. Recursively define the value of an optimal solution
 3. Construct an optimal solution from computed information
- Matrix-chain Multiplication
 - Is an optimization problem solved using dynamic programming
 - Goal is to find matrix parenthesis with fewest number of operations

Example:

Given chain of matrices $\langle A, B, C \rangle$, it's fully parenthesized product is:

- * $(AB)C$ needs $(10 \times 30 \times 5) + (10 \times 5 \times 60) = 1500 + 3000 = 4500$ operations
- * $A(BC)$ needs $(30 \times 5 \times 60) + (10 \times 30 \times 60) = 27000$ operations

Thus, $(AB)C$ performs more efficiently than $A(BC)$.

- Is stated as: given a chain $\langle A_1, A_2, \dots, A_n \rangle$ of n matrices, where for $i = 1, 2, \dots, n$ matrix A_i has dimension $p_{i-1} \times p_i$, fully parenthesize the product $A_1 A_2 \dots A_n$ in a way that minimizes the number of scalar multiplications.
- Steps

1. Check is the problem has Optimal Substructure

Let us adopt the notation $A_{i\dots j}$ where $i \leq j$, for the matrix that results from evaluating the product $A_i A_{i+1} \dots A_j$.

Assume the solution has the following parentheses:

$$(A_{i\dots k})(A_{k+1\dots j})$$

If there is a better way to multiply $(A_{i\dots k})$, then we would have a more optimal solution.

This would be a contradiction, as we already stated that we have the optimal solution for $A_{i\dots j}$.

Therefore, this problem has optimal substructure.

2. Find the Recursive Solution

Let $M[i, j]$ be the cost of multiplying matrices from A_i to A_j

We want to find out at which k' returns the fewest number of multiplications, or the minimum number of M .

The recursive formula for the cost of multiplying from A_i to A_j is

$$M[i, j] = \begin{cases} 0 & \text{if } i = j \\ \min_{i \leq k \leq j} M[i, k] + M[k + 1, j] + p_{i-1}p_kp_j & \text{if } i < j \end{cases} \quad (3)$$

3. Computing the Estimated Cost

* Steps

- 1) Fill the table for $i = j$
- 2) Fill the table for $i < j$ with a spread of 1
- 3) Repeat 2 with the increased value of spread

Example:

Given

$\langle A_1, A_2, A_3, A_4, A_5 \rangle$

where

- * $A_1 \rightarrow 4 \times 10$
- * $A_2 \rightarrow 10 \times 3$
- * $A_3 \rightarrow 3 \times 12$
- * $A_4 \rightarrow 12 \times 20$
- * $A_5 \rightarrow 20 \times 7$

we have:

- 1) Fill the table for $i = j$

1) $i = j$

| $i \backslash j$ | 1 | 2 | 3 | 4 | 5 |
|------------------|---|---|---|---|---|
| 1 | 0 | | | | |
| 2 | x | 0 | | | |
| 3 | x | x | 0 | | |
| 4 | x | x | x | 0 | |
| 5 | x | x | x | x | 0 |

$$M[i, j] = \begin{cases} 0 & \text{if } i = j \\ \min_{i \leq k \leq j} M[i, k] + M[k + 1, j] + p_{i-1}p_kp_j & \text{if } i < j \end{cases}$$

- 2) Fill the table for $i < j$ with a spread of 1

2) ($i = 1, j = 2$), ($i = 2, j = 3$), ($i = 3, j = 4$), ($i = 4, j = 5$)

| i \ j | 1 | 2 | 3 | 4 | 5 |
|-------|---|-----|-----|-----|------|
| 1 | 0 | 120 | | | |
| 2 | x | 0 | 360 | | |
| 3 | x | x | 0 | 720 | |
| 4 | x | x | x | 0 | 1680 |
| 5 | x | x | x | x | 0 |

since

* $i = 1, j = 2$

$$M[1, 2] = \min_{1 \leq k \leq 2} (M[1, 1] + M[1, 2] + p_{i-1}p_kp_j) \quad (4)$$

$$= \min_{1 \leq k \leq 2} (0 + 0 + p_0p_1p_2) \quad (5)$$

$$= \min_{1 \leq k \leq 2} (0 + 0 + 4 \cdot 10 \cdot 3) \quad (6)$$

$$= 120 \quad (7)$$

where $p_0 = 3$ is from the dimension 3×10 of A_1 , $p_k = 10$ is from the dimension of 3×10 of A_1 .

* $i = 2, j = 3$

$$M[2, 3] = \min_{2 \leq k \leq 3} (M[2, 2] + M[3, 3] + p_{i-1}p_kp_j) \quad (8)$$

$$= \min_{2 \leq k \leq 3} (0 + 0 + p_1p_2p_3) \quad (9)$$

$$= \min_{2 \leq k \leq 3} (0 + 0 + 10 \cdot 3 \cdot 12) \quad (10)$$

$$= 360 \quad (11)$$

* $i = 3, j = 4$

$$M[3, 4] = \min_{3 \leq k \leq 4} (M[3, 3] + M[4, 4] + p_{i-1}p_kp_j) \quad (12)$$

$$= \min_{3 \leq k \leq 4} (0 + 0 + p_2p_3p_4) \quad (13)$$

$$= \min_{3 \leq k \leq 4} (0 + 0 + 3 \cdot 12 \cdot 20) \quad (14)$$

$$= 720 \quad (15)$$

* $i = 4, j = 5$

$$M[4, 5] = \min_{4 \leq k \leq 5} (M[4, 4] + M[5, 5] + p_{i-1}p_kp_j) \quad (16)$$

$$= \min_{4 \leq k \leq 5} (0 + 0 + p_3p_4p_5) \quad (17)$$

$$= \min_{4 \leq k \leq 5} (0 + 0 + 12 \cdot 20 \cdot 7) \quad (18)$$

$$= 1680 \quad (19)$$

3) Repeat 2 with the increased value of spread

2) $(i = 1, j = 2), (i = 2, j = 3), (i = 3, j = 4), (i = 4, j = 5)$

| i \ j | 1 | 2 | 3 | 4 | 5 |
|-------|---|-----|-----|------|------|
| 1 | 0 | 120 | 264 | 1080 | 1344 |
| 2 | x | 0 | 360 | 1320 | 1350 |
| 3 | x | x | 0 | 720 | 1140 |
| 4 | x | x | x | 0 | 1680 |
| 5 | x | x | x | x | 0 |

* $i = 1, j = 3$

$k = 1$

$$M[1, 3] = M[1, 1] + M[2, 3] + p_{i-1}p_kp_j \quad (20)$$

$$= 0 + 360 + p_0p_1p_3 \quad (21)$$

$$= 0 + 360 + 4 \cdot 10 \cdot 12 \quad (22)$$

$$= 0 + 360 + 480 \quad (23)$$

$$= 840 \quad (24)$$

$k = 2$

$$M[1, 3] = M[1, 2] + M[3, 3] + p_{i-1}p_kp_j \quad (25)$$

$$= 120 + 0 + p_0p_2p_3 \quad (26)$$

$$= 120 + 0 + 4 \cdot 10 \cdot 12 \quad (27)$$

$$= 120 + 0 + 144 \quad (28)$$

$$= 264 \quad (29)$$

Thus, $\min_{1 \leq k \leq 3} M[1, 3] = 264$.

$$* \ i = 2, j = 4$$

$$\underline{k = 2}$$

$$M[2, 4] = M[2, 2] + M[3, 4] + p_{i-1}p_kp_j \quad (30)$$

$$= 0 + 720 + p_1p_2p_4 \quad (31)$$

$$= 0 + 720 + 10 \cdot 3 \cdot 20 \quad (32)$$

$$= 0 + 720 + 600 \quad (33)$$

$$= 1320 \quad (34)$$

$$\underline{k = 3}$$

$$M[2, 4] = M[2, 2] + M[3, 4] + p_{i-1}p_kp_j \quad (35)$$

$$= 360 + 0 + p_1p_3p_4 \quad (36)$$

$$= 360 + 0 + 10 \cdot 12 \cdot 20 \quad (37)$$

$$= 360 + 0 + 2400 \quad (38)$$

$$= 2760 \quad (39)$$

$$\text{Thus, } \min_{2 \leq k \leq 4} M[2, 4] = 1320.$$

$$* \ i = 3, j = 5$$

$$\underline{k = 3}$$

$$M[3, 5] = M[3, 3] + M[3, 5] + p_{i-1}p_kp_j \quad (40)$$

$$= 0 + 1680 + p_2p_3p_5 \quad (41)$$

$$= 0 + 1680 + 3 \cdot 12 \cdot 7 \quad (42)$$

$$= 0 + 1680 + 252 \quad (43)$$

$$= 1932 \quad (44)$$

$$\underline{k = 4}$$

$$M[3, 5] = M[3, 4] + M[5, 5] + p_{i-1}p_kp_j \quad (45)$$

$$= 720 + 0 + p_2p_4p_5 \quad (46)$$

$$= 720 + 0 + 3 \cdot 20 \cdot 7 \quad (47)$$

$$= 720 + 420 \quad (48)$$

$$= 1140 \quad (49)$$

$$\text{Thus, } \min_{3 \leq k \leq 5} M[3, 5] = 1140.$$

$$* \ i = 2, j = 5$$

$$\underline{k = 2}$$

$$M[2, 5] = M[2, 2] + M[3, 5] + p_{i-1}p_kp_j \quad (50)$$

$$= 0 + 1140 + p_1p_2p_5 \quad (51)$$

$$= 0 + 1140 + 10 \cdot 3 \cdot 7 \quad (52)$$

$$= 0 + 1140 + 210 \quad (53)$$

$$= 1350 \quad (54)$$

$$\underline{k = 3}$$

$$M[2, 5] = M[2, 3] + M[4, 5] + p_{i-1}p_kp_j \quad (55)$$

$$= 360 + 1680 + p_1p_3p_5 \quad (56)$$

$$= 2040 + 10 \cdot 12 \cdot 7 \quad (57)$$

$$= 2040 + 840 \quad (58)$$

$$= 2880 \quad (59)$$

$$\underline{k = 4}$$

$$M[2, 5] = M[2, 4] + M[5, 5] + p_{i-1}p_kp_j \quad (60)$$

$$= 1320 + p_1p_3p_5 \quad (61)$$

$$= 1320 + 10 \cdot 20 \cdot 7 \quad (62)$$

$$= 1320 + 1400 \quad (63)$$

$$= 2720 \quad (64)$$

$$\text{Thus, } \min_{2 \leq k \leq 5} M[2, 5] = 1350.$$

$$* \ i = 1, j = 5$$

$$\underline{k = 1}$$

$$M[1, 5] = M[1, 1] + M[3, 5] + p_{i-1}p_kp_j \quad (65)$$

$$= 0 + 1350 + p_0p_1p_5 \quad (66)$$

$$= 0 + 1350 + 4 \cdot 10 \cdot 7 \quad (67)$$

$$= 0 + 1350 + 280 \quad (68)$$

$$= 1630 \quad (69)$$

$$\underline{k = 2}$$

$$M[1, 5] = M[1, 2] + M[3, 5] + p_{i-1}p_kp_j \quad (70)$$

$$= 120 + 1140 + p_0p_2p_5 \quad (71)$$

$$= 120 + 1140 + 4 \cdot 3 \cdot 7 \quad (72)$$

$$= 1260 + 84 \quad (73)$$

$$= 1344 \quad (74)$$

$$\underline{k = 3}$$

$$M[1, 5] = M[1, 3] + M[4, 5] + p_{i-1}p_kp_j \quad (75)$$

$$= 264 + 1680 + p_0p_3p_5 \quad (76)$$

$$= 264 + 1680 + 4 \cdot 12 \cdot 7 \quad (77)$$

$$= 1944 + 336 \quad (78)$$

$$= 2280 \quad (79)$$

$$\underline{k = 4}$$

$$M[1, 5] = M[1, 4] + M[5, 5] + p_{i-1}p_kp_j \quad (80)$$

$$= 1080 + 0 + p_0p_4p_5 \quad (81)$$

$$= 1080 + 4 \cdot 20 \cdot 7 \quad (82)$$

$$= 1080 + 560 \quad (83)$$

$$= 1640 \quad (84)$$

Thus, $\min_{1 \leq k \leq 5} M[1, 5] = 1344$.

4. Constructing the Optimal Solution (Needs revision)

3)

| i \ j | 1 | 2 | 3 | 4 | 5 |
|-------|---|-----|-----|------|------|
| 1 | 0 | 120 | 264 | 1080 | 1344 |
| 2 | x | 0 | 360 | 1320 | 1350 |
| 3 | x | x | 0 | 720 | 1140 |
| 4 | x | x | x | 0 | 1680 |
| 5 | x | x | x | x | 0 |

$(A_1A_2)((A_3A_4)A_5)$

So, the optimal solution is $(A_1A_2)((A_3A_4)A_5)$

References:

- 1) CSBreakdown, Chain Multiplication - Dynamic Programming, link
- 2) University of Maryland, CMSC351 - Fall 2014 Homework # 4, link

```

21 procedure MATRIX-CHAIN-MULTIPLY(A,s,i,j)
2   if i == j then
3       return A[i]
4   end if
5
6   if i < j
7       a = MATRIX-CHAIN-MULTIPLY(A,s,i,s[i,j])
8       b = MATRIX-CHAIN-MULTIPLY(A,s,s[i,j] + 1,j)
9
10      return MATRIX-CHAIN-MULTIPLY(a,b)
11
12   end if
13
14 end procedure
15

```

Example:

- *MATRIX-CHAIN-ORDER* computes the table s containing optimal costs
- s table consists of k value at which $m[i,j]$ is minimum!!

$$A_{1..s[1,n]}A_{s[1,n]+1..n}$$

- Table of optimal costs m is used with table s to construct solution to matrix-chain multiplication problem

3. First, we need to determine the total number of times $m[i,j]$ is referred in the innermost loop.

We know from the header that the loop runs from $k = i$ to $k = j - 1$.

Using this fact, we can write the innermost loop has $j - i = l - 1$ iterations.

Since $m[i,j]$ is referred twice, the total number of $m[i,j]$ referred in the loop is:

$$(l - 1)2 \tag{1}$$

Second, we need to determine the total number of times $m[i, j]$ is referred in the intermediate loop

We know from the header that the loop runs from $i = 1$ to $i = n - l + 1$.

Using this fact, we can write the intermediate loop runs $n - l + 1$ iterations.

Since each iteration refers $m[i, j]$ $(l - 1)2$ many times, the total number of times $m[i, j]$ is referred in the intermediate loop is:

$$(n - l + 1)(l - 1)2 \tag{2}$$

Finally, we need to determine the total number of times $m[i, j]$ is referenced in the outermost loop.

We know from the header that the loop runs from $l = 2$ to n .

Since each iteration refers $m[i, j]$ $(n - l + 1)(l - 1)2$ many times, the total number of times $m[i, j]$ is referred in the outermost loop is:

$$\sum_{l=2}^n (n-l+1)(l-1)2 = 2 \sum_{l'=1}^{n-1} (n-l')(l') \quad (3)$$

$$= 2 \left[\sum_{l'=1}^{n-1} nl' - (l')^2 \right] \quad (4)$$

$$= 2 \left[n \sum_{l'=1}^{n-1} l' - \sum_{l'=1}^{n-1} (l')^2 \right] \quad (5)$$

$$= 2 \left[n \sum_{l'=1}^{n-1} l' - \sum_{l'=1}^{n-1} (l')^2 \right] \quad (6)$$

$$= 2 \left[n \sum_{l'=0}^{n-1} l' - \sum_{l'=0}^{n-1} (l')^2 \right] \quad (7)$$

$$= 2 \left[\frac{(n-1)n^2}{2} - \frac{(n-1)n(2n-1)}{6} \right] \quad (8)$$

$$= 2 \left[\frac{n^3 - n^2}{2} - \frac{(n-1)n(2n-1)}{6} \right] \quad (9)$$

$$= 2 \left[\frac{n^3 - n^2}{2} - \frac{(n^2 - n)(2n-1)}{6} \right] \quad (10)$$

$$= 2 \left[\frac{n^3 - n^2}{2} - \frac{(3n^3 - 3n^2 + n)}{6} \right] \quad (11)$$

$$= 2 \left[\frac{3n^3 - 3n^2}{6} - \frac{(3n^3 - 3n^2 + n)}{6} \right] \quad (12)$$

$$= 2 \left[\frac{n^3 - n}{6} \right] \quad (13)$$

$$= \frac{n^3 - n}{3} \quad (14)$$

Notes:

- Hint from equation A.3

$$\sum_{k=0}^n k^2 = \frac{n(n+1)(2n+1)}{6}$$

- I feel the need to gain more insight regarding the question's 'other table entries in a call of MATRIX-CHAIN-ORDER'. What does 'other table entries' mean?

Answer:

The other entries
:)

```

MATRIX-CHAIN-ORDER( $p$ )
1   $n = p.length - 1$ 
2  let  $m[1..n, 1..n]$  and  $s[1..n-1, 2..n]$  be new tables
3  for  $i = 1$  to  $n$ 
4       $m[i, i] = 0$ 
5  for  $l = 2$  to  $n$            //  $l$  is the chain length
6      for  $i = 1$  to  $n - l + 1$ 
7           $j = i + l - 1$ 
8           $m[i, j] = \infty$ 
9          for  $k = i$  to  $j - 1$ 
10              $q = m[i, k] + m[k + 1, j] + p_{i-1}p_kp_j$ 
11             if  $q < m[i, j]$ 
12                  $m[i, j] = q$ 
13                  $s[i, j] = k$ 
14  return  $m$  and  $s$ 

```

- In the problem ‘ $m[i, j]$ is referenced’ refers to $m[i, j]$ used in assignments $q = m[i, j]...$

```


MATRIX-CHAIN-ORDER( $p$ )
1   $n = p.length - 1$ 
2  let  $m[1..n, 1..n]$  and  $s[1..n-1, 2..n]$  be new tables
3  for  $i = 1$  to  $n$ 
4       $m[i, i] = 0$ 
5  for  $l = 2$  to  $n$            //  $l$  is the chain length
6      for  $i = 1$  to  $n - l + 1$ 
7           $j = i + l - 1$ 
8           $m[i, j] = \infty$ 
9          for  $k = i$  to  $j - 1$ 
10              $q = m[i, k] + m[k + 1, j] + p_{i-1}p_kp_j$ 
11             if  $q < m[i, j]$ 
12                  $m[i, j] = q$ 
13                  $s[i, j] = k$ 
14  return  $m$  and  $s$ 

```

4. Notes:


- Elements of Dynamic Programming
 - Optimal Substructure
 - * Is the first step to solving dynamic programming problem
 - * Exists if an optimal solution to the problem contains within it optimal solution to subproblems
 - Overlapping Subproblems

- * Is the second step to solving dynamic programming
 - * Exists when an algorithm revisits the same problem repeatedly
 - Memoization
 - * Maintains an entry in a table for the solution to each subproblem
 - * Ensures that a method doesn't run for the same inputs more than once
- Bottom-Up Dynamic Programming
 - Uses for-loop



images/worksheet_3_solution_8.png

- Top-Down Dynamic Programming
 - Uses recursion



`images/worksheet_3_solution_9.png`