CS 362, Lecture 7

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Today's Outline

- Matrix Multiplication

Matrix Chain Multiplication

Problem:

- We are given a sequence of n matrices, $A_1, A_2, \ldots, A_n$, where for $i = 1, 2, \ldots, n$, matrix A_i has dimension p_{i-1} by p_i
- We want to compute the product, $A_1 A_2, \ldots, A_n$ as quickly as possible.
- In particular, we want to fully *paranthesize* the expression above so there are no ambiguities about the how the matrices are multiplied
- A product of matrices is *fully parenthisized* if it is either a single matrix, or the product of two fully parenthesized matrix products, sorrounded by parantheses

Paranthesizing Matrices

- There are many ways to paranthesize the matrices
- Each way gives the same output (because of associativity of matrix multiplications)
- However the way we paranthesize will effect the *time* to compute the output
- Our Goal: Find a paranthesization which requires the minimal number of scalar multiplications

Example

- In this example, it's much better to multiply the last two matrices first (this gives us a short, narrow matrix on the right)
- Worse to multiply the first two matrices first (this gives us a short wide matrix on the left)
- In general, our goal is to find ways to always create narrow and short resulting matrices.

A Problem

Problem: There can be many ways to paranthesize. E.g.

- $(A_1(A_2(A_3A_4)))$
- $(A_1((A_2A_3)A_4))$
- $((A_1A_2)(A_3A_4))$
- $((A_1(A_2A_3))A_4)$
- $(((A_1A_2)A_3)A_4)$

A Problem

- Let $P(n)$ be the number of ways to paranthesize n matrices. Then $P(1) = 1$
- For $n \geq 2$, we know that a fully paranthesized product is the product of two fully paranthesized products, and the split can occur anywhere from $k = 1$ to $k = n - 1$.
- Hence for $n \geq 2$:

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

- In the hw, you will show that the solution to this recurrence is $\Omega(2^n)$

The Pattern

Q: Can we develop a DP Solution to this problem?

- **Formulate the problem recursively.**. Write down a formula for the whole problem as a simple combination of answers to smaller subproblems
- **Build solutions to your recurrence from the bottom up.** Write an algorithm that starts with the base cases of your recurrence and works its way up to the final solution by considering the intermediate subproblems in the correct order.

Key Observation

- Let $A_{i..j}$ (for $i \leq j$) be the matrix that results from evaluating the product $A_i A_{i+1}, \ldots A_j$
- Imagine we are computing $A_{i..j}$
- The last multiplication we do must look like this:

$$A_{i..j} = (A_{i..k}) * (A_{k+1..j})$$

  for some k between i and $j-1$
- Then total cost to compute $A_{i..j}$ is:

  cost to compute $A_{i..k}$ +
  cost to compute $A_{k+1..j}$ +
  cost to multiply $A_{i..k}$ and $A_{k+1..j}$

Recursive Formulation

- For any integers x, y, let $m(x, y)$ be the minimum cost of computing $A_{x..y}$
- Then for any k between i and $j-1$,
  $m(i,j) \leq$ optimal cost to compute $A_{i..k}$ +
  optimal cost to compute $A_{k+1..j}$ +
  cost to multiply $A_{i..k}$ and $A_{k+1..j}$
- In other words:

  $m(i,j) \leq m(i,k) +$
  $m(k+1,j) +$
  cost to multiply $A_{i..k}$ and $A_{k+1..j}$

Cost to Multiply

- $A_{i..k}$ is a p_{i-1} by p_k matrix
- $A_{k+1..j}$ is a p_k by p_j matrix
- Thus multiplying $A_{i..k}$ and $A_{k+1..j}$ takes $p_{i-1}p_kp_j$ operations
- Hence we have:

$$\begin{aligned} m(i,j) \leq\ & m(i,k) + \\ & m(k+1,j) + \\ & p_{i-1}p_kp_j \end{aligned}$$

Recursive Formulation

- We've shown that $m(i,j) \leq m(i,k) + m(k+1,j) + p_{i-1}p_kp_j$ for any $k = i, i+1, \ldots, j-1$
- Further note that the optimal parenthesization must use some value of $k = i, i+1, \ldots, j-1$. So we need only pick the best
- Thus we have:

$$\boxed{\begin{array}{l} m(i,j) = 0 \text{ if } i = j \\ m(i,j) = \min_{i \leq k < j}\{m(i,k) + m(k+1,j) + p_{i-1}p_kp_j\} \end{array}}$$

The Recursive Algorithm

- We now have enough information to write a recursive function to solve the problem
- The recursive solution will have runtime given by the following recurrence:
- $T(1) = 1$,
- $T(n) = 1 + \sum_{k=1}^{n-1}(T(k) + T(n-k) + 1)$
- Unfortunately, the solution to this recurrence is $\Omega(2^n)$ (as shown on p. 346 of the text)

DP Algorithm

- Note that we must solve one subproblem for each choice of i and j satisfying $1 \leq i \leq j \leq n$
- This is only $\binom{n}{2} + n = \Theta(n^2)$ subproblems
- The recursive algorithm encounters each subproblem many times in the branches of the recursion tree.
- However, we can just compute these subproblems from the bottom up, storing the results in a table (this is the DP solution)

Pseudocode

```
Matrix-Chain-Order(int p[]){
  n = p.length - 1;
  for (i=1;i<=n;i++){
    m(i,i) = 0;
  }
  for (l=2;l<=n;l++){ \\l is chain length
    for (i=1;i<=n-l+1;i++){
      j = i+l-1;
      m[i,j] = MAXINT;
      for(k=i;k<=j-1;k++){
        q = m[i,k] + m[k+1,j] + p[i-1]*p[k]*p[j];
        if(q<m[i,j]){
          m[i,j] = q;
          s[i,j] = k;
        }
      }}}}
```


Pseudocode

- This code computes both the optimal cost and a parenthesization that achieves that cost
- It uses an m array to store the optimal costs of computing $m(i,j)$. It also uses a s array, where $s(i,j)$ stores the k value which gives $m(i,j)$
- The parenthesization can be recovered from the s array using the pseudocode in the book on p. 338.

Analysis

- This code has three nested loops, each of which takes on at most $n-1$ values, and the inner loop takes $O(1)$ time.
- Thus the runtime is $O(n^3)$
- The algorithm also requires $\Theta(n^2)$ space

Example

- Consider the sequence of three matrices, A_1, A_2, A_3 whose dimensions are given by the sequence $3, 1, 2, 1$ (i.e. $p_0 = 3$, $p_1 = 1$, $p_2 = 2$, $p_3 = 1$)
- Let's construct the tables giving the optimal parenthesization
- The (i, j) entry of the first table will give the optimal cost for computing $A_{i..j}$, the (i, j) entry of the second table will give a k value which achieves this optimal cost

Computations

- $m(1,1) = m(2,2) = m(3,3) = 0$
- $m(1,2) = p_0 p_1 p_2 = 6$
- $m(2,3) = p_1 p_2 p_3 = 2$

Computations

$$
\begin{aligned}
m(1,3) &= \min \left\{ \begin{array}{l} m(1,1) + m(2,3) + p_0 p_1 p_3), \\ m(1,2) + m(3,3) + p_0 p_2 p_3) \end{array} \right\} \\
&= \min \left\{ \begin{array}{l} 0 + 2 + 3, \\ 6 + 0 + 6 \end{array} \right\} \\
&= 5
\end{aligned}
$$

Example, m array

	1	2	3
1	0	6	5
2	-	0	2
3	-	-	0

Example, s array

	1	2	3
1	-	1	1
2	-	-	2
3	-	-	-

Example

- Thus an optimal parenthesization is $(A_1(A_2A_3))$
- The cost of this is 5

Example II

- Consider the sequence of three matrices, A_1, A_2, A_3, A_4 whose dimensions are given by the sequence $3, 1, 2, 1, 2$ (i.e. $p_0 = 3$, $p_1 = 1$, $p_2 = 2$, $p_3 = 1$, $p_4 = 2$)
- Let's construct the tables giving the optimal parenthesization
- The (i, j) entry of the first table will give the optimal cost for computing $A_{i..j}$, the (i, j) entry of the second table will give a k value which achieves this optimal cost

Example II, m array

	1	2	3	4
1	0	6	5	10
2	-	0	2	4
3	-	-	0	4
4	-	-	-	0

Example II, s array

	1	2	3	4
1	-	1	1	1
2	-	-	2	3
3	-	-	-	3
4	-	-	-	-

Example Computation

$$\begin{aligned} m(1,4) &= \min \left\{ \begin{array}{l} m(1,1)+m(2,4)+p_0p_1p_4), \\ m(1,2)+m(3,4)+p_0p_2p_4), \\ m(1,3)+m(4,4)+p_0p_3p_4) \end{array} \right\} \\ &= \min \left\{ \begin{array}{l} 0+4+6, \\ 6+4+12, \\ 5+0+6 \end{array} \right\} \\ &= 10 \end{aligned}$$

This minimum is achieved when $k = 1$

Example II

- Thus an optimal parenthesization is $(A_1((A_2A_3)A_4))$
- The cost of this is 10

In-Class Exercise

- Consider the sequence of three matrices, A_1, A_2, A_3 whose dimensions are given by the sequence $1, 2, 1, 2$ (i.e. $p_0 = 1$, $p_1 = 2$, $p_2 = 1$, $p_3 = 2$)
- Q1: What are the m array and s array for these inputs?
- Q2: What is the optimal parenthesization?