Algorithm Analysis and Design

Divide and Conquer strategy

(Matrix Multiplication by Strassen's Algorithm)

Lecture -16

Overview

- *Learn the implementation techniques of "divide and conquer" in the context of the Strassen's Matrix multiplication with analysis.*
- $Conventional\ strategy \Rightarrow\ \mathrm{O}(n^3)$.
- $Divide\ and\ Coques\ strategy \Rightarrow\ \mathrm{O}(n^3)$.
- $Strassen's\ strategy \Rightarrow\ \mathrm{O}(n^{2.81})$.

Matrix Multiplication

- Problem definition:

Input: Two $n \times n$ (square) matrices, $A = (a_{ij})$ and $B = (b_{ij})$.

Output: $n \times n$ matrix $C = (c_{ij})$, where $C = A \cdot B$, i.e.,

$$c_{ij} = \sum_{k=1}^{n} a_{ik} b_{kj}$$

for $i, j = 1, 2, \ldots, n$.

Need to compute n^2 entries of C. Each entry is the sum of n values.

Matrix Multiplication

- Conventional strategy:

SQUARE-MAT-MULT(A, B, n)

```
let C be a new n × n matrix
for i = 1 to n
    for j = 1 to n
        c_ij = 0
        for k = 1 to n
            c_ij = c_ij + a_ik · b_kj
return C
```

Analysis: Three nested loops, each iterates n times, and innermost loop body takes constant time $\Rightarrow \Theta(n^3)$.

Matrix Multiplication

- Question is

  $Is\ \Theta(n^3)$ is the best or we can multiply the matrix in $o(n^3)$ time?

  (i.e. can we solve it in $< \Theta(n^3)$)
- Let's see with Divide and Conquer strategy………

Matrix Multiplication

- Divide-and-conquer strategy :
  - As with the other divide-and-conquer algorithms, assume that n is a power of 2.
  - Partition each of A,B, C into four $\boldsymbol{n/2\ x\ n/2}$ matrices:

$$A = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix},\ B = \begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix}, C = \begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix}$$

For multiplication we can write $C = A\,.\,B$ as

$$\begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} . \begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix}$$

Matrix Multiplication

- Divide-and-conquer strategy :

For multiplication we can write $C = A\,.\,B$ as

$$\begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{pmatrix} \cdot \begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix}$$

Which create four equations. They are

$$C_{11} = A_{11}\,.\,B_{11} + A_{12}\,.\,B_{21}$$
$$C_{12} = A_{11}\,.\,B_{12} + A_{12}\,.\,B_{22}$$
$$C_{21} = A_{21}\,.\,B_{11} + A_{22}\,.\,B_{21}$$
$$C_{22} = A_{21}\,.\,B_{12} + A_{22}\,.\,B_{22}$$

Each of these equations multiplies two $\boldsymbol{n/2\ x\ n/2}$ matrices and then adds their $\boldsymbol{n/2\ x\ n/2}$ products.

Matrix Multiplication

- Divide-and-conquer strategy :

By using the equations of previous slide we ca write the Divide and conquer algorithm.

REC-MAT-MULT (A, B, n)

Let C be a n x n matrix

If n== 1

$C_{11} = A_{11} \times B_{11}$

else partition A,B, and C into **n/2 x n/2** submatrices.

$C_{11} = \text{REC-MAT-MULT}(A_{11}, B_{11}, N/2) + \text{REC-MAT-MULT}(A_{12}, B_{21}, N/2)$

$C_{12} = \text{REC-MAT-MULT}(A_{11}, B_{12}, N/2) + \text{REC-MAT-MULT}(A_{12}, B_{22}, N/2)$

$C_{21} = \text{REC-MAT-MULT}(A_{21}, B_{11}, N/2) + \text{REC-MAT-MULT}(A_{22}, B_{21}, N/2)$

$C_{22} = \text{REC-MAT-MULT}(A_{21}, B_{12}, N/2) + \text{REC-MAT-MULT}(A_{22}, B_{22}, N/2)$

Return C

Matrix Multiplication

- Analysis of Divide-and-conquer strategy :

Let T(n) be the time to multiply two **n/2 x n/2** matrices.

Base Case: n=1. Perform one scalar multiplication: $\Theta(1)$**.**

Recursive Case: n>1

- Dividing takes b $\Theta(1)$ time, using index calculations.
- Conquering makes 8 recursive calls, each multiplying $\boldsymbol{n/2\ x\ n/2}$ matrices.
  (i.e. $8T(n/2)$)
- Combining Takes $\Theta(n^2)$ time to add $\boldsymbol{n/2\ x\ n/2}$ matrices four items.

Hence the Recurrence is

$$T(n) = \begin{cases} \Theta(1) & if\ n = 1 \\ 8T\left(\frac{n}{2}\right) + \Theta(n^2) & if n > 1 \end{cases}$$

The Complexity is $\Theta(n^3)$ (Apply Master Method)

Can we do better?

Matrix Multiplication

- Strassen’s strategy :

  The Idea:

  - Make the recursion tree less bushy.
  - Perform only 7(seven) recursive multiplications of n/2 x n/2 matrices, rather than 8(Eight).

Matrix Multiplication

- Strassen's strategy :

The Algorithm:

1. As in the recursive method, partition each of the matrices into four n/2 x n/2 submatrices. Time: $\Theta(1)$
2. Compute 7 matrix products P, Q, R, S, T, U, V for each n/2 x n/2.
3. Compute n/2 x n/2 submatrices of C by adding and subtracting various combinations of the P_i . Time: $\Theta(n^2)$.

Matrix Multiplication

- Strassen's strategy :

  Details of Step 2:

  Compute 7 matrix products:

  $P = (A_{11} + A_{22}).(B_{11} + B_{22})$

  $Q = (A_{21} + A_{22}).B_{11}$

  $R = A_{11}.(B_{12} - B_{22})$

  $S = A_{22}.(B_{21} - B_{11})$

  $T = (A_{11} + A_{12}).B_{22}$

  $U = (A_{21} - A_{11}).(B_{11} + B_{12})$

  $V = (A_{12} - A_{22}).(B_{21} + B_{22})$

Matrix Multiplication

- Strassen's strategy :

  Details of Step 3:

  Compute C with 4 adding and subtracting :

  $$\boldsymbol{C_{11} = P + S - T + V}$$

  $$\boldsymbol{C_{12} = R + T}$$

  $$\boldsymbol{C_{21} = Q + S}$$

  $$\boldsymbol{C_{22} = P + R - Q + U}$$

Matrix Multiplication

- Strassen's strategy :

  Analysis:

  The Recurrence is

$$T(n) = \begin{cases} \Theta(1) & if\ n = 1 \\ 7T\left(\frac{n}{2}\right) + \Theta(n^2) & if n > 1 \end{cases}$$

  The Complexity is $\Theta(n^{\log_2 7}) = \Theta(n^{2.81})$ (By using Master Method)

Matrix Multiplication

Example 1

- Compute Matrix multiplication of the following two matrices with the help of Strassen's strategy

$$A = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} \text{ and } B = \begin{bmatrix} 5 & 6 \\ 7 & 8 \end{bmatrix}$$

Matrix Multiplication

Example 1

- Compute Matrix multiplication of the following two matrices with the help of Strassen's strategy

$$A = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} \text{ and } B = \begin{bmatrix} 5 & 6 \\ 7 & 8 \end{bmatrix}$$

Ans:

A_{11}=1, A_{12}=2, A_{21}=3, and A_{22}=4

B_{11}=5, B_{12}=6, B_{21}=7, and B_{22}=8

Matrix Multiplication

Example 1

Calculate the value of P, Q, R, S, T, U and V

- $P=(A_{11} + A_{22}).\,(B_{11}+B_{22}) = (1+4)(5+8)=5 \times 13=65$
- $Q=(A_{21} + A_{22}).\,B_{11}= (3+4)5=7 \times 5=35$
- $R= A_{11}.(B_{12} - B_{22})=1(6-8)=1 \times -2=-2$
- $S= A_{22}.(B_{21} - B_{11}) = 4(7-5)=4 \times 2=8$
- $T=(A_{11} + A_{12}).\,B_{22}=(1+2)8=3 \times 8=24$
- $U= (A_{21} - A_{11}).(B_{11} + B_{12})=(3-1)(5+6)=2 \times 11=22$
- $V=(A_{12} - A_{22}).(B_{21} + B_{22})=(2-4)(7+8)=-2 \times 15=-30$

Matrix Multiplication

Example 1

Compute $\boldsymbol{C_{11}, C_{12}, C_{21}, and\ C_{22}}$:

$C_{11} = P + S - T + V$= 65+8-24-30=19

$C_{12} = R + T$=-2+24=22

$C_{21} = Q + S$=35+8=43

$C_{22} = P + R - Q + U$=65-2-35+22=50

Hence,

$$C = \begin{bmatrix} 19 & 22 \\ 43 & 50 \end{bmatrix}$$

Matrix Multiplication

Example 2

Compute Matrix multiplication of the following two matrices with the help of Strassen's strategy.

$$A = \begin{bmatrix} 4 & 2 & 0 & 1 \\ 3 & 1 & 2 & 5 \\ 3 & 2 & 1 & 4 \\ 5 & 2 & 6 & 7 \end{bmatrix}, \mathrm{B} = \begin{bmatrix} 2 & 1 & 3 & 2 \\ 5 & 4 & 2 & 3 \\ 1 & 4 & 0 & 2 \\ 3 & 2 & 4 & 1 \end{bmatrix}$$

Matrix Multiplication

Example 2

First we partition the input matrices into sub matrices as shown below:

$$A_{11} = \begin{bmatrix} 4 & 2 \\ 3 & 1 \end{bmatrix}, A_{12} = \begin{bmatrix} 0 & 1 \\ 2 & 5 \end{bmatrix} \qquad B_{11} = \begin{bmatrix} 2 & 1 \\ 5 & 4 \end{bmatrix}, B_{12} = \begin{bmatrix} 3 & 2 \\ 2 & 3 \end{bmatrix}$$

$$A_{21} = \begin{bmatrix} 3 & 2 \\ 5 & 2 \end{bmatrix}, A_{22} = \begin{bmatrix} 1 & 4 \\ 6 & 7 \end{bmatrix} \qquad B_{21} = \begin{bmatrix} 1 & 4 \\ 3 & 2 \end{bmatrix}, B_{22} = \begin{bmatrix} 0 & 2 \\ 4 & 1 \end{bmatrix}$$

Matrix Multiplication

Example 2

Calculate the value of P, Q, R, S, T, U and V

$P = (\mathrm{A}_{11} + \mathrm{A}_{22}).(B_{11}+B_{22})$

$= \begin{bmatrix} 5 & 6 \\ 9 & 8 \end{bmatrix} \begin{bmatrix} 2 & 3 \\ 9 & 5 \end{bmatrix}$

$= \begin{bmatrix} 64 & 45 \\ 90 & 67 \end{bmatrix}$

$\mathrm{Q}=(A_{21} + A_{22}).\ B_{11}$

$= \begin{bmatrix} 4 & 6 \\ 11 & 9 \end{bmatrix} \begin{bmatrix} 2 & 1 \\ 5 & 4 \end{bmatrix}$

$= \begin{bmatrix} 38 & 28 \\ 67 & 47 \end{bmatrix}$

Matrix Multiplication

Example 2

R$= \mathrm{A}_{11}.(B_{12} - B_{22})$

$$= \begin{bmatrix} 4 & 2 \\ 3 & 1 \end{bmatrix} \begin{bmatrix} 3 & 0 \\ -2 & 2 \end{bmatrix}$$

$$= \begin{bmatrix} 8 & 4 \\ 7 & 2 \end{bmatrix}$$

S$= A_{22}.(B_{21} - B_{11})$

$$= \begin{bmatrix} 1 & 4 \\ 6 & 7 \end{bmatrix} \begin{bmatrix} -1 & 3 \\ -2 & -2 \end{bmatrix}$$

$$= \begin{bmatrix} -9 & -5 \\ -20 & 4 \end{bmatrix}$$

Matrix Multiplication

Example 2

T=$(A_{11}+A_{12}).\ B_{22}$

$$=\begin{bmatrix}4 & 3\\5 & 6\end{bmatrix}\begin{bmatrix}0 & 2\\4 & 1\end{bmatrix}$$

$$=\begin{bmatrix}12 & 11\\24 & 16\end{bmatrix}$$

U= $(A_{21}-A_{11}).(B_{11}+B_{12})$

$$=\begin{bmatrix}-1 & 0\\2 & 1\end{bmatrix}\begin{bmatrix}5 & 3\\7 & 7\end{bmatrix}$$

$$=\begin{bmatrix}-5 & -3\\17 & 13\end{bmatrix}$$

V=$(A_{12}-A_{22}).(B_{21}+B_{22})$

$$=\begin{bmatrix}-1 & -3\\-4 & -2\end{bmatrix}\begin{bmatrix}1 & 6\\7 & 3\end{bmatrix}$$

$$=\begin{bmatrix}-22 & -15\\-18 & -30\end{bmatrix}$$

Matrix Multiplication

Example 2

Now, Compute $\boldsymbol{C_{11}}, \boldsymbol{C_{12}}, \boldsymbol{C_{21}}, \boldsymbol{and}\ \boldsymbol{C_{22}}$:

$C_{11} = P + S - T + V$

$C_{11} = \begin{bmatrix} 64 & 45 \\ 90 & 67 \end{bmatrix} + \begin{bmatrix} -9 & -5 \\ -20 & 4 \end{bmatrix} - \begin{bmatrix} 12 & 11 \\ 24 & 16 \end{bmatrix} + \begin{bmatrix} -22 & -15 \\ -18 & -30 \end{bmatrix} = \begin{bmatrix} 21 & 14 \\ 28 & 25 \end{bmatrix}$

$C_{12} = R + T$

$C_{12} = \begin{bmatrix} 8 & 4 \\ 7 & 2 \end{bmatrix} + \begin{bmatrix} 12 & 11 \\ 24 & 16 \end{bmatrix} = \begin{bmatrix} 20 & 15 \\ 31 & 18 \end{bmatrix}$

Matrix Multiplication

Example 2

Now, Compute $\boldsymbol{C_{11}}, \boldsymbol{C_{12}}, \boldsymbol{C_{21}}, \boldsymbol{and}\ \boldsymbol{C_{22}}$:

$$C_{21} = Q + S$$

$$C_{21} = \begin{bmatrix} 38 & 28 \\ 67 & 47 \end{bmatrix} + \begin{bmatrix} -9 & -5 \\ -20 & 4 \end{bmatrix} = \begin{bmatrix} 29 & 23 \\ 47 & 51 \end{bmatrix}$$

$$C_{22} = P + R - Q + U$$

$$C_{22} = \begin{bmatrix} 64 & 45 \\ 90 & 67 \end{bmatrix} + \begin{bmatrix} 8 & 4 \\ 7 & 2 \end{bmatrix} - \begin{bmatrix} 38 & 28 \\ 67 & 47 \end{bmatrix} + \begin{bmatrix} -5 & -3 \\ 17 & 13 \end{bmatrix} = \begin{bmatrix} 29 & 18 \\ 47 & 35 \end{bmatrix}$$

Matrix Multiplication

Example 2

So the values of $\boldsymbol{C_{11}, C_{12}, C_{21}, and\ C_{22}}$ are:

$C_{11} = \begin{bmatrix} 21 & 14 \\ 28 & 25 \end{bmatrix}$, $C_{12} = \begin{bmatrix} 20 & 15 \\ 31 & 18 \end{bmatrix}$, $C_{21} = \begin{bmatrix} 29 & 23 \\ 47 & 51 \end{bmatrix}$ and $C_{22} = \begin{bmatrix} 29 & 18 \\ 47 & 35 \end{bmatrix}$

Hence the resultant Matrix C is =

$$C = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} = \begin{bmatrix} 21 & 14 & 20 & 15 \\ 28 & 25 & 31 & 18 \\ 29 & 23 & 29 & 18 \\ 47 & 51 & 47 & 35 \end{bmatrix}$$

Thank u