

Solutions to Problem Set 6

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Efficient Algorithms

Problem 6.1. Fibonacci numbers

1) The pseudocode given in Algorithm 1 implements a function computing the Fibonacci numbers in a top-down manner with the help of memoization.

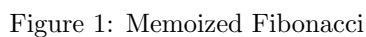
Algorithm 1 computes the Fibonacci numbers with memoization.

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1: procedure FIB( $n, F[1...n]$ )
2:   if  $n \leq 1$  then
3:     return  $n$ 
4:   else
5:     if  $F[n] > 0$  then
6:       return  $F[n]$ 
7:      $F[n] = \text{FIB}(n-1, F) + \text{FIB}(n-2, F)$ 
8:     return  $F[n]$ 
```

What is the recursion depth and what is the space complexity of $\text{FIB}(n)$?

Solution: The recursion depth is the same as the number of distinct subproblems generated by the call $\text{Fib}(n)$. Figure 1 shows that there are exactly n distinct subproblems. Therefore, the recursion depth is n . Time complexity $T(n)$ is linear in the number of distinct subproblems times work per subproblem. Work per subproblem is $\Theta(1)$. Thus, $T(n) = \Theta(n) \cdot \Theta(1) = \Theta(n)$.

Space complexity $S(n)$ is linear in the number of elements of the table $F[1...n]$ and is also linear in the recursion depth, which determines the maximum number of nested stack frames during the execution of $\text{Fib}(n)$. Thus, $S(n) = \Theta(n)$.



Algorithm 2 computes the Fibonacci numbers bottom-up.

Algorithm 3 computes the Fibonacci numbers bottom-up using $\Theta(1)$ space.

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8×3 , 3×10 and 10×6 in a bottom-up approach.

Solution: Base Cases:

(0): $M[1, 1] = M[2, 2] = M[3, 3] = M[4, 4] = M[5, 5] = 0$

Inductive Cases:

The table is filled in the following order: $(1) \rightarrow (2) \rightarrow (3) \rightarrow (4)$

(1): $M[1, 2], M[2, 3], M[3, 4], M[4, 5]$

(2): $M[1, 3], M[2, 4], M[3, 5]$

(3): $M[1, 4], M[2, 5]$

(4): $M[1, 5]$

		j				
		1	2	3	4	5
i	1	0	336	294	474	582
	2		0	168	378	474
	3			0	240	324
	4				0	180
	5					0

Figure 2: Bottom-up Table

$M[1, 3]$ is the optimal number of scalar multiplications for the matrix chain $A_1 \cdot A_2 \cdot A_3$. The parenthesization $A_1 \cdot (A_2 \cdot A_3)$ yields the optimal value of 294.

$M[2, 4]$ is the optimal number of scalar multiplications for the matrix chain $A_2 \cdot A_3 \cdot A_4$. The parenthesization $(A_2 \cdot A_3) \cdot A_4$ yields the optimal value of 378.

$M[3, 5]$ is the optimal number of scalar multiplications for the matrix chain $A_3 \cdot A_4 \cdot A_5$. The parenthesization $A_3 \cdot (A_4 \cdot A_5)$ yields the optimal value of 324.

$M[1, 4]$ is the optimal number of scalar multiplications for the matrix chain $A_1 \cdot A_2 \cdot A_3 \cdot A_4$. The parenthesization $(A_1 \cdot A_2 \cdot A_3) \cdot A_4$ yields the optimal value of 474.

$M[2, 5]$ is the optimal number of scalar multiplications for the matrix chain $A_2 \cdot A_3 \cdot A_4 \cdot A_5$. The parenthesization $(A_2 \cdot A_3) \cdot (A_4 \cdot A_5)$ yields the optimal value of 474.

$M[1, 5]$ is the optimal number of scalar multiplications for the matrix chain $A_1 \cdot A_2 \cdot A_3 \cdot A_4 \cdot A_5$. The parenthesization $(A_1 \cdot A_2 \cdot A_3) \cdot (A_4 \cdot A_5)$ yields the optimal value of 582.

The optimal number of scalar multiplications can be harvested from $M[1, 5]$.

Here, the optimal number of scalar multiplications is 582, and an optimal parenthesization is $(A_1 \cdot (A_2 \cdot A_3))(A_4 \cdot A_5)$.

2) Show that the number of ways of parenthesization $C(n)$ is $\Omega(2^n)$, where n is the matrix chain length. You may use induction to show that $C(n) \geq c \cdot 2^n$ for some $c \in \mathbb{R}^+$ and $n_0 \in \mathbb{Z}^+$ for all $n \geq n_0$.

Proof: We know that

$$C(n) = \begin{cases} 1 & n = 1 \\ \sum_{k=1}^{n-1} C(k)C(n-k) & n \geq 2 \end{cases}$$

We would like to show that

$$C(n) = \Omega(2^n)$$

Suppose that we choose $n_0 = 1$ and $c = \frac{1}{4}$.

In other words, we want to show

$$C(n) \geq \frac{1}{4} \cdot 2^n \quad \forall n \geq 1$$

Base Case: $n = 1$

$$C(1) \geq \frac{1}{4} \cdot 2^1 = \frac{1}{2}$$

Since $C(1) = 1$, the proposition is true when $n = 1$.

Induction Hypothesis: Assume true for $k = 1, 2, 3, \dots, n-1$.

$$C(k) \geq \frac{1}{4} \cdot 2^k$$

Inductive Step:

$$\begin{aligned} C(n) &= \sum_{k=1}^{n-1} C(k)C(n-k) \\ &\geq C(1)C(n-1) + C(n-1) \\ &= 2C(1)C(n-1) \\ &= 2C(n-1) & [C(1) = 1] \\ &\geq 2 \cdot \frac{1}{4} \cdot 2^{(n-1)} & [\text{Invoking I.H. at } n-1] \\ &= \frac{1}{4} \cdot 2^n \end{aligned}$$

Thus, we have shown that the proposition is true for all $n \geq 1$ with $c = \frac{1}{4}$.
Therefore, $C(n) = \Omega(2^n)$. \square

3) Calculate the exact number of distinct subproblems for a matrix chain of length n .

Solution: Let $M[i, j]$ be the minimum number of scalar multiplications required to compute the matrix chain $A_i \cdot A_{i+1} \cdot \dots \cdot A_{j-1} \cdot A_j$.

For $i = 1$, there are n ways to choose j .

For $i = 2$, there are $n-1$ ways to choose j .

For $i = 3$, there are $n-2$ ways to choose j .

...

For $i = n$, there are 1 ways to choose j .

The number of ways to choose i and j is the number of distinct subproblems.

Therefore, there are $n + (n - 1) + (n - 2) + \dots + 1 = \frac{n(n+1)}{2}$ distinct subproblems. \square

4) Does the maximum matrix chain problem also exhibit optimal substructure? If it is the case, prove your claim using a cut-and-paste argument.

Proof: The maximum chain problem also exhibits optimal substructure as we will show using a cut-and-paste argument as follows.

It is given that $M[i, j]$ is an optimal solution to $A_i \dots A_j$. Suppose the solution $M[i, k] = m_{i,k}$ to the prefix subchain $A_i \dots A_k$ is not optimal. We can then replace this solution to $A_i \dots A_k$ a better solution (better means larger in value) $M[i, k] = m'_{i,k} > m_{i,k}$ to obtain a better solution $M[i, j] = m'_{i,j}$ to $A_i \dots A_j$:

$$m'_{i,j} = m'_{i,k} + m_{k+1,j} + p_i p_k p_j < m_{i,j}$$

,which contradicts the optimality of the solution $m_{i,j}$ to $A_i \dots A_j$. An identical cut-and-paste argument can be used to show optimality of the suffix subchain $A_{k+1} \dots A_j$. \square .

Problem 6.3. Longest Common Subsequence

1) Give a memoized version of LCS-LENGTH that runs in $\mathcal{O}(mn)$ time.

Solution: The table c in Algorithm 4 is assumed to be a **global** variable, and all $c[i, j]$ are initialized to -1 . Given two sequences X and Y of length m and n , respectively, we run $\text{LCS}(X, Y, m, n)$ to compute the length of a longest-common subsequence.

Algorithm 4 Longest-Common Subsequence

```

1: procedure LCS( $X, Y, i, j$ )
2:   if  $c[i, j] > -1$  then
3:     return  $c[i, j]$ 
4:   if  $i = 0 \vee j = 0$  then
5:      $c[i, j] = 0$ 
6:     return 0
7:   if  $X[i] == Y[j]$  then
8:      $c[i, j] = 1 + \text{LCS}(X, Y, i - 1, j - 1)$ 
9:     return  $c[i, j]$ 
10:   $c[i, j] = \max(\text{LCS}(X, Y, i - 1, j), \text{LCS}(X, Y, i, j - 1))$ 
11:  return  $c[i, j]$ 
12:
```

2) What is the maximum recursion depth of LCS?

Solution: Observe that, at each recursive call $\text{LCS}(X, Y, i, j)$, either i or j or both decrease by one.

An unlucky case can happen, for example, when i decreases by one at each recursive call whereas j stays at n all the way until $i = 1$, from which point i stays at 1 whereas j decreases by one at each recursive call.

This means that it takes at most $m + n$ recursive calls to bring either i or j (whichever one becomes 0 first does not matter) to 0, which is a base case, where recursion bottoms out.

Thus, this means that the maximum number of recursive calls is $m + n$, which means the maximum recursion depth is also $m + n$.