

Algorithm Design and Analysis

Homework Assignment 1

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1 Recursion and Dynamic Programming

Exercise 1.1. This complexity of the recursion process mainly depends on the additions. Let's define $F_{i,j}$ as when such recursion process start at calculating $\binom{i}{j}$, the number of additions it will do.

obviously, $F_{i,j}$ consists of three parts below:

- $F_{i-1,j-1}$: add the number of addition operations in $\binom{i-1}{j-1}$ to the current answer.
- $F_{i-1,j}$: add the $\binom{i-1}{j-1}$'s answer.
- 1: the number of additions which used to add $\binom{i-1}{j-1}$ and $\binom{i-1}{j}$ up.

Thus we have

$$F_{i,j} = F_{i-1,j-1} + F_{i-1,j} + 1 \quad (1)$$

This is a quite strange and Pascal-like equation. Consider

$$(F_{i,j} + 1) = (F_{i-1,j-1} + 1) + (F_{i-1,j} + 1)$$

We can easily find out that

$$F_{i,j} + 1 = \binom{i}{j} + \binom{i}{j-1} + \binom{i}{j+1}$$

Therefore

$$F_{i,j} = \binom{i}{j} + \binom{i}{j-1} + \binom{i}{j+1} - 1 \quad (2)$$

Hence, the total number of addition operation is

$$\binom{n}{k} + \binom{n}{k-1} + \binom{n}{k+1} - 1$$

The lower bound of the complexity of adding two numbers together being $O(1)$ and the upper bound being $O(n)$, we can easily figure out that the lower bound of the complexity of this algorithm is

$$O\left(\binom{n}{k} + \binom{n}{k-1} + \binom{n}{k+1}\right) = O\left(\binom{n}{k}\right)$$

While the upper bound is

$$O\left(n\binom{n}{k}\right)$$

When $n = 50, k = 25$, this algorithm needs to do about 1.3×10^{16} additions, which is too slow. Hence this algorithm is inefficient.

Exercise 1.2. Since we use dynamic programming, the running time depends on how many binomial coefficients we calculate. Consider the formula

$$\binom{n}{k} = \binom{n-1}{k-1} + \binom{n-1}{k}$$

It's easy to see that the area we calculate is an parallelogram in Pascal's triangle. More specifically, in order to get the answer of $\binom{n}{k}$, there are exactly $n - k$ numbers we calculate in the columns from 1 to k , so we need to do $O(k \cdot (n - k))$ additions.

The time we need for a single addition depends on the length of the result, namely $\log \binom{n}{k}$. Since

$$\sum \binom{n}{k} = 2^n$$

We can easily see that $\binom{n}{k}$ has a length up to n . So the upper bound of the running time is $O(nk \cdot (n - k))$, which is not very efficient.

Exercise 1.3. The additions we need is the same as Ex2, $O(k \cdot (n - k))$. But this time the addition can be done in $O(1)$ time because we only need to keep the result modulo 2. So the running time is $O(k \cdot (n - k))$, which is quite efficient.

Exercise 1.4.

1. Proof by introduction

Proof. We can easily prove the lemma using induction:

(a) Basic step

When $n = 2^1$, the lemma obviously holds because

$$\binom{2}{1} = 0$$

(b) Induction step

Assume that the lemma holds where n equals to 2^d , namely

$$\binom{n}{k} = 0$$

when $1 \leq k \leq n - 1$.

Then we will show that the lemma holds when n equals to 2^{d+1} .

According to the hints, on the one hand, the number of paths to the n -th line and the k -th grid equals to

$$\binom{n}{k}$$

On the other hand, we can also calculate the number by Multiplication Principle and Addition Principle, namely

$$\binom{n}{k} = \sum_{i=0}^{n/2} \binom{n/2}{i} * \binom{n/2}{k-i} \quad (3)$$

Then our proof divides into three cases:

- When $1 \leq k \leq n/2 - 1$, it is obviously that

$$\binom{n/2}{k} = 0$$

and

$$\binom{n/2}{0} = \binom{n/2}{n/2} = 1$$

According to the equation (3), we have

$$\binom{n}{k} = \binom{n/2}{k-0} + \binom{n/2}{k-n/2}$$

By assumption, when $1 \leq k < n/2$, we have

$$\binom{n/2}{k} = 0$$

Notice that $k - n/2 < n/2$, so we have

$$\binom{n/2}{k-n/2} = 0$$

Therefore

$$\binom{n}{k} = 0$$

- When $k = n/2$, it is obviously that

$$\binom{n/2}{k} = \binom{n/2}{k-n/2} = 1$$

Therefore

$$\binom{n}{k} = (1 + 1) = 2 \equiv 0 \pmod{2}$$

- When $n/2 \leq k < n$, it is easy to see that

$$\binom{n/2}{k} = 0$$

And by assumption

$$\binom{n/2}{k-n/2} = 0$$

So that we have

$$\binom{n}{k} = 0$$

(c) Conclusion

By induction, we have

$$\binom{n}{k} \equiv 0 \pmod{2}$$

where $1 \leq k \leq n-1$ and $n = 2^d$ ($d \geq 1$).

□

2. Direct Proof

Proof. We can denote the binomial coefficient as $2^p * q$, namely

$$\binom{n}{k} = \frac{n!}{k!(n-k)!} = 2^p * q \quad (4)$$

where $2 \nmid q$, $n = 2^d$ ($d \geq 1$) and $1 \leq k \leq (n-1)$.

We can easily calculate the exponent p with the formular below

$$p = \sum_{i=1}^d \left\lfloor \frac{n}{2^i} \right\rfloor - \sum_{i=1}^d \left\lfloor \frac{k}{2^i} \right\rfloor - \sum_{i=1}^d \left\lfloor \frac{n-k}{2^i} \right\rfloor$$

Specially when $i = d$, we have

$$\left\lfloor \frac{n}{2^d} \right\rfloor = 1 \text{ and } \left\lfloor \frac{k}{2^d} \right\rfloor = \left\lfloor \frac{n-k}{2^d} \right\rfloor = 0$$

According to the equation (4), we have

$$\begin{aligned} p &= 1 - 0 - 0 + \sum_{i=1}^{d-1} \left\lfloor \frac{n}{2^i} \right\rfloor - \left\lfloor \frac{k}{2^i} \right\rfloor - \left\lfloor \frac{n-k}{2^i} \right\rfloor \\ &\geq 1 + \sum_{i=1}^{d-1} \frac{n}{2^i} - \frac{k}{2^i} - \frac{n-k}{2^i} = 1 \end{aligned}$$

Hence we have

$$2 \mid \binom{n}{k}$$

That is

$$\binom{n}{k} \equiv 0 \pmod{2}$$

□

Exercise 1.5. We can easily come out an algorithm using the formular which is proved in Ex5.

Algorithm 1 An efficient method calculating the binomial coefficient

```

1: function BINOM( $n, k, p$ )
2:   if  $m > n$  or  $m < 0$  then
3:     return 0
4:   end if
5:   if  $n < 2$  then :
6:     return 1
7:   end if
8:   if  $p = 0$  then :
9:      $p = 1$ 
10:    while  $p * 2 \geq n$  do
11:       $p \leftarrow p * 2$ 
12:    end while
13:  else
14:    while  $p \geq n$  do
15:       $p \leftarrow p / 2$ 
16:    end while
17:  end if
18:  return (BINOM( $n - p, m - p, p$ ) + BINOM( $n - p, m, p$ )) mod2
19: end function

```

The implementation in python is displayed below

```

1  def binom(n, m, p = 0):
2      if(m > n or m < 0):
3          return 0;
4      if(n < 2):
5          return 1;
6      if(p == 0):
7          p = 1;
8          while(p * 2 < n):
9              p = p * 2;
10     else:
11         while(p >= n):
12             p = p / 2;
13     return binom(n - p, m - p, p) ^ binom(n - p, m, p);

```

Exercise 1.6. Assume it will form a rho-like process. Considering i is the entrance of the “circle” of the process, we have

$$F'_i = F'_j \text{ and } F'_{i+1} = F'_{j+1}$$

But

$$F'_{i-1} \neq F'_{j-1}$$

If not, you can easily see that $i - 1$ is the entrance of the “circle”.

But according to the formula

$$F'_{i+1} = F'_i + F'_{i-1}$$

We have

$$F'_i = F'_j \text{ and } F'_{i+1} = F'_{j+1} \Rightarrow F'_{i-1} = F'_{j-1}$$

which is a contradictory. Thus the assumption does not hold.

Consider every F'_i, F'_{i+1} can form a pair $\{F'_i, F'_{i+1}\}$. Because $F'_i \in [0, k)$, the number of such pair will not exceed k^2 . According to the Pigeon's Theorem, there must be a cycle-like process whose length doesn't exceed k^2 , so we can find j which satisfied $F'_0 = F'_j$, $F'_1 = F'_{j+1}$ and $F'_n = F'_{n \bmod j}$ within the complexity $O(k^2)$.

Exercise 1.7. The theorem in the homework is the direct inference of **Lucas's Theorem**. However Lucas's Theorem holds only when the module number is a prime. Our question is that what if the module number is a composite number?