



香港電腦奧林匹克競賽
Hong Kong Olympiad in Informatics

Dynamic Programming (I)

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2026-03-21

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Tasks on HKOJ will be discussed today

[B300 Recurrence](#)

[01010 Diamond Chain](#)

[B301 Jumper](#)

[B302 Longest Common Subsequence](#)

[01054 Matrix-chain Multiplication](#)

[M1222 Longest Increasing Subsequence](#)

If you are too strong then

(Provided by Benson last year)

JOI18_asceticism Asceticism

JOI21_ho_t3 Group Photo

IOI20_biscuits Packing Biscuits

And/Or literally do ALL of the tasks in AtCoder DP

<https://atcoder.jp/contests/dp/tasks>

Introduction to DP

Why DP?

- DP is a very common technique in OI
- Some tasks may divide subtasks into different levels of DP.
- In this session, we will discuss about what is DP and then get us familiar with DP by solving some DP problems.

How to DP?

Prerequisites:

- Recursion
- Divide & Conquer
- Big O notation - to analyze Time and Memory complexities

How to DP?

Memorization - The Key of DP

- Basically, DP is 'exhaustion' but 'don't calculate something that has been calculated again'.
- How? 'Remember' what have been calculated.
- We often care Time complexity more than Memory complexity.
- Memorization is a method that "trades-off" Time with Memory.

How to DP?

What problems can DP?

- Have optimal substructure
 - The optimal solution of a problem can be constructed **efficiently** from the optimal solutions of its **sub**problems.
- Have overlapping subproblems
 - Some the optimal solutions a subproblems can be **reused** to constructed a larger subproblems

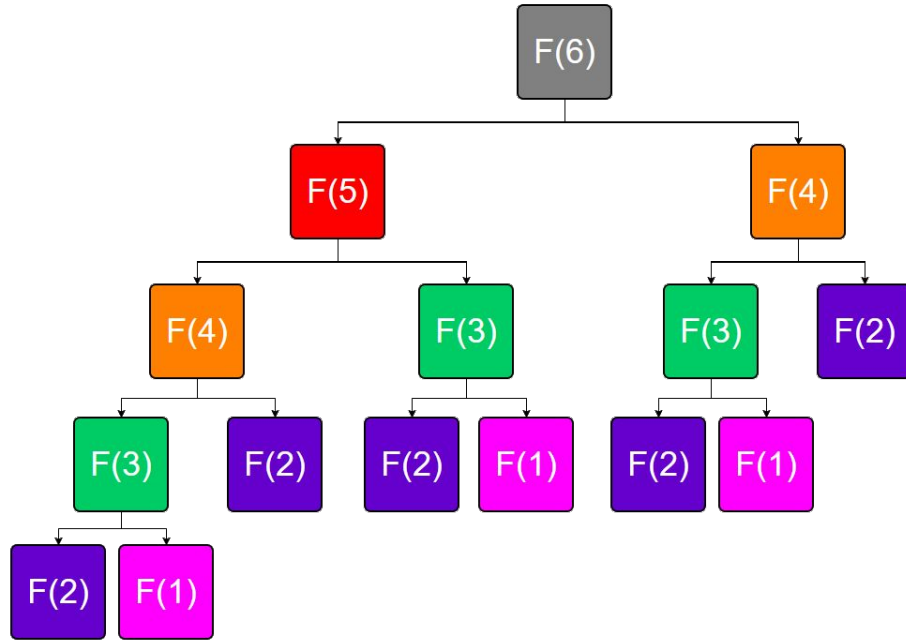
Fibonacci Sequence

Use plain text to understand DP is painful. So let's talk about some examples.

Fibonacci Sequence, a recursive function:

- $F(1) = 1$
- $F(2) = 1$
- $F(n) = F(n-1) + F(n-2)$ for $n > 2$

Fibonacci Sequence



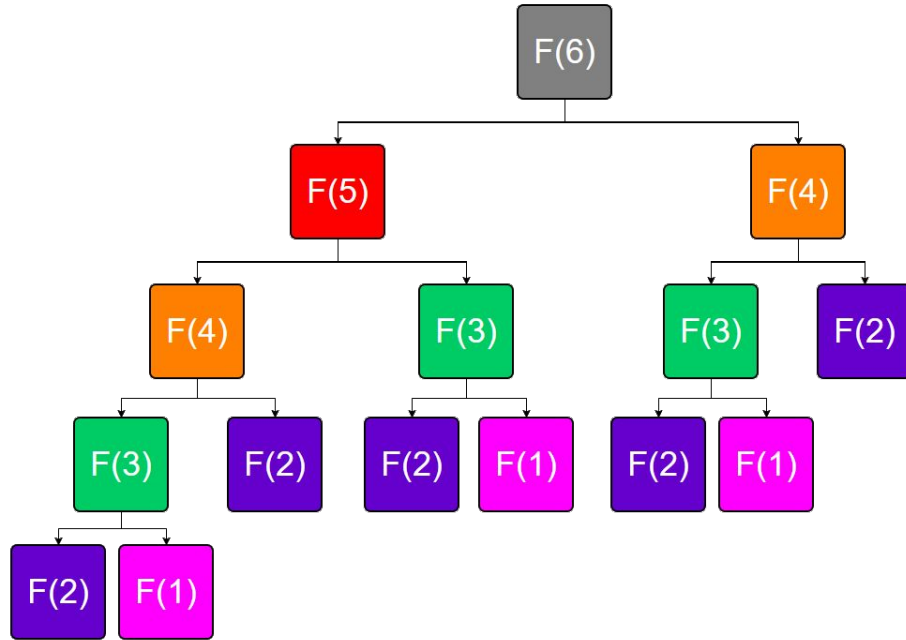
Fibonacci Sequence

Use recursion to solve a recursive function.

```
int F(int n) {  
    if(n == 1 || n == 2)  
        return 1;  
    int tmp = F(n-1);  
    return tmp + F(n-2);  
}
```

(ps: If you really want to write a program to calculate Fibonacci Sequence, please be reminded that $F(n)$ grow really fast, $F(50) \approx 1e10$, you may use some method to store it or just use other language.)

Fibonacci Sequence



Fibonacci Sequence

How efficient? Let's count how many times `int F()` have been called.

```
int count = 0;
int F(int n) {
    count++;
    if(n == 1 || n == 2)
        return 1;
    int tmp = F(n-1);
    return tmp + F(n-2);
}
```

Fibonacci Sequence

$F(n)$: count

$F(10)$: 109

$F(20)$: 13529

$F(30)$: 1664079

$F(40)$: 204668309

$F(50)$: TLE :(

Fibonacci Sequence

It's very slow! How to speed up???

- $F(n)$ can be constructed easily by $F(n-1)$ and $F(n-2)$.
 - $F(n-1)$ and $F(n-2)$ are **sub**problems of $F(n)$!
- Both $F(n)$ & $F(n-1)$ will call $F(n-2)$.
 - $F(n-2)$ can be reused!

DP can be used! But how?

Fibonacci Sequence

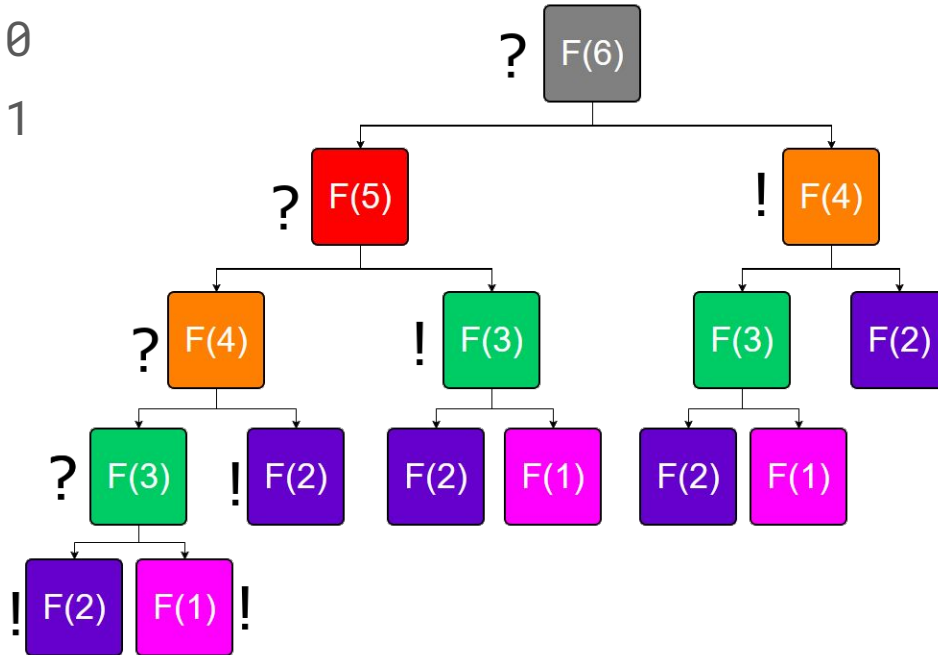
If $F(n)$ is not calculated, calculate it. Else, just return the value $F(n)$ stored.

```
bool caled[101]; // calculated?, let's assume caled[1] = caled[2] = 1, else = 0
int f[101]; // values of F(n), let's assume f[1] = f[2] = 1
int F(int n) {
    if(!caled[n]) {
        f[n] = F(n-1);
        f[n] += F(n-2);
        caled[n] = 1;
    }
    return f[n];
}
```

Fibonacci Sequence

? : `called[n] = 0`

! : `called[n] = 1`



Fibonacci Sequence

There are some time saved, but how much?

Each $F(n)$ will be call almost 2 times. (called by $F(n+1)$ & $F(n+2)$)

$F(n)$ was called about $n*2$ times, which is $O(n)$

We successfully reduce the time complexity to $O(n)$ by using $O(n)$ amount of memory!

Fibonacci Sequence

Let's change the direction of thinking.

If we know we have to calculate smaller $F(n)$ first to get a bigger $F(n)$,
why don't we start from $F(3)$ to $F(n)$?

Fibonacci Sequence

```
int f[101]; // values of F(n)
int F(int n) {
    f[1] = f[2] = 1;
    for(int i = 3; i <= n; i++) {
        f[i] = f[i-1] + f[i-2];
    }
    return f[n];
}
```

Top-down & Bottom-up DP

We have just seen two approach of DP.

The First one is call Top-down DP, and

The second one is call Bottom-up DP.

What's the difference?

Top-down & Bottom-up DP

Top-down:

```
bool caled[101]; // calculated?, let's assume caled[1] = caled[2] = 1, else = 0
int f[101]; // values of F(n), let's assume f[1] = f[2] = 1
int F(int n) {
    if(!caled[n]) {
        f[n] = F(n-1);
        f[n] += F(n-2);
        caled[n] = 1;
    }
    return f[n];
}
```

Top-down & Bottom-up DP

Bottom-up:

```
int f[101]; // values of F(n)
int F(int n) {
    f[1] = f[2] = 1;
    for(int i = 3; i <= n; i++) {
        f[i] = f[i-1] + f[i-2];
    }
    return f[n];
}
```

Top-down & Bottom-up DP

Top-down DP

- Intuitive (I think)
- No need to care the order of computation.
- Messy (I think) and harder to debug.

Top-down & Bottom-up DP

Bottom-up DP

- So clean
- The subproblems must be solved first when transitioning
- Some techniques and tricks will be discussed in DP (II) & (III) can only been done easily in Bottom-up DP - **important**
- We will mainly focus on Bottom-up DP.

Demo!

B300 Recurrence

A slightly different recursive function but it works the same.

Let's ~~play the game~~ take attendance

Some classical DP problems

Maximum Subarray Sum

[HKOI 01010 Diamond Chain](#)

Let $a[]$ be an array with n values of a_1, a_2, \dots, a_n .

A subarray of $a[]$ is defined by deleting some prefix of $a[]$ and deleting some suffix of $a[]$.

- If $a[] = [0, 1, 2, 3]$;
 $[0, 1, 2, 3]$, $[0, 1]$, $[2]$ and $[]$ are the subarray of $a[]$ but $[0, 3]$ isn't.

Maximum Subarray Sum

What is the naive solution? Just loop all the possible subarrays in this array.

```
int ans = 0;
for(int i = 1; i <= n; i++) { // all subarray start with index i
    for(int j = i; j <= n; j++) { // all subarray end with index j
        int sum = 0;
        for(int k = i; k <= j; k++) { // calculate the sum from i to j
            sum += a[k];
        }
        ans = max(ans, sum);
    }
}
```

Maximum Subarray Sum

Time complexity: $O(n^3)$

Way to slow for $n = 100000$.

If you know partial sum before, you may reduce it to $O(n^2)$ by replacing the innermost loop.

Still TLE.

Maximum Subarray Sum

($A[i : j]$) = the subarray of A that start at i and end at j)

For example if the length of A is 2.

We can choose the answer from $A[1 : 1]$, $A[1 : 2]$ or $A[2 : 2]$.

What if we want to add another element end the back of A .

We can choose the answer from $A[1 : 1]$, $A[1 : 2]$, $A[2 : 2]$, $A[1 : 3]$, $A[2 : 3]$ or $A[3 : 3]$.

Note that of those new options, $A[1 : 3]$ and $A[2 : 3]$ can be calculated easily by $A[1 : 2]$ and $A[2 : 2]$ by adding A_3 , and $A[3 : 3]$ is just A_3 itself.

Maximum Subarray Sum

To know $A[1 : 3]$ or $A[2 : 3]$ is better, we only need to care which is the better one between $A[1 : 2]$ and $A[2 : 2]$.

That mean we only need to store the better one between $A[1 : 2]$ and $A[2 : 2]$.

And that compare it to the value $A[3 : 3] = \mathbf{A}_3$.

There we have the optimal subarray that end with \mathbf{A}_3 .

In general, we only need to store the optimal value of all subarray that subarray that end with \mathbf{A}_i to compute the optimal value of $\mathbf{i+1}$ one!

Maximum Subarray Sum

For each a_i , we can decide added it to some subarrays that end with a_{i-1} .

Or we just start a new subarray that start with a_i .

For each a_i , we can decide added it to some subarrays that end with a_{i-1} .

What if we somehow know the optimal subarray that end with a_{i-1} ?

We can choose connecting a_i to the optimal subarray that end with a_{i-1} or just a_i itself become the subarray that end with a_i .

Maximum Subarray Sum

Ok, but how?

Let $dp[i]$ = the Maximum Subarray Sum that end with a_i .

For $i = 1$, **$dp[1]$** is **a_1** itself only.

For $i = 2$, **$dp[2]$** is the choose between adding **$dp[1]$** to **a_2** and **a_2** itself only.

For $i > 2$, **$dp[i]$** is the choose between adding **$dp[i-1]$** to **a_i** and **a_i** itself only.

Maximum Subarray Sum

- **dp[i]** can be constructed easily by **dp[i-1]**
- **dp[i]** will be used by **dp[i+1]**

It can DP!

```
dp[1] = a[1];
int ans = max(0, dp[1]);
for(int i = 2; i <= n; i++) {
    dp[i] = dp[i-1] + a[i]; // connecting a[i] to the optimal subarray before
    dp[i] = max(dp[i], a[i]); // leave a[i] alone
    ans = max(ans, dp[i]); // choose the best subarray
}
```

Maximum Subarray Sum

There is a top-down version for your reference.

```
bool caled[100001]; // let's assume caled[1] = 1, else = 0
int dp[100001]; // let's assume dp[1] = a[1]
int DP(int i) {
    if(!caled[i]) {
        dp[i] = DP(i-1) + a[i];
        dp[i] = a[i];
        caled[i] = 1;
    }
    return dp[i];
}
```

Maximum Subarray Sum

Time Complexity become $O(n)$ by using $O(n)$ extra memory. So good.

To discuss DP solution more formally, we can use something call transitional formula:

$$dp[i] = \max(dp[i-1] + a[i], a[i])$$

Be carefully how to define the transition formula and the base cases(in this case $dp[1]$).

Maximum Subarray Sum

Be Careful that this DP solution only apply on this “offline” problem. (i.e. the values of a_i won't change)

“Online” problem like M0923 require some special Data Structure.

Jumper

B301 Jumper

There n building on a line and the height of i -th building is h_i .

There is a man who wants to go to building n from building 1 by jumping rooftop to rooftop.

He can jump really high and each jump cost him $|h_i - h_j|$ from i to j .

But he can't jump too far, so the gaps between building he can jump is limited to k . I.e. $j - i \leq k$.

Also he can only jump forward.

What is the minimum energy costed?

Jumper

The “Naive” solution:

```
int sol(int i) {
    if(i == n)
        return 0;
    int tmp = INF; // some very big number
    for(int j = i+1; j <= min(n, i+k); j++) {
        tmp = min(tmp, sol(j) + abs(h[i] - h[j]));
    }
    return tmp;
}
```

Jumper

It is kind of like the solution of Fibonacci Sequence.

Which mean it is really really really slow.

But it also mean it can be improved. Right?

Jumper

```
int sol(int i) {  
    if(i == n)  
        return 0;  
  
    int tmp = INF; // some very big number  
    for(int j = i+1; j <= min(n, i+k); i++) {  
        tmp = min(tmp, sol(j) + abs(h[i] - h[j]));  
    }  
    return tmp;  
}
```

sol() has been called many times.

Jumper

Let's think about what is $\text{sol}(i)$.

$\text{sol}(i)$ is the minimum cost jumping from building i to n .

$\text{sol}(i)$ will be called by $\text{sol}(i-k)$ to $\text{sol}(i-1)$.

Why don't we just memorize the value of $\text{sol}(i)$?

Jumper

Let's $dp[i]$ = the minimum cost from i to n .

$dp[n]$ i.e. the minimum cost from n to n is 0 .

$dp[i] = \min(dp[j] + |h_i - h_j|)$ for each j he can jump from i , i.e. $i+1$ to $i+k$.

$dp[1]$ will become the answer.

Jumper

```
dp[n] = 0;
for(int i = n-1; i >= 1; i--) {
    dp[i] = INF; // some really big number
    for(int j = i+1; j <= min(n, i+k); j++) {
        dp[i] = min(dp[i], dp[j] + abs(h[i] - h[j]));
    }
}
cout << dp[1];
```

Jumper

There is a top-down version for your reference.

```
bool caled[100001]; // let's assume caled[n] = 1, else = 0
int dp[100001]; // let's assume dp[n] = 0
int DP(int i) {
    if(!caled[i]) {
        dp[i] = INF; // some really big number
        for(int j = i+1; j <= min(n, i+k); j++) {
            dp[i] = min(dp[i], DP(j) + abs(h[i] - h[j]));
        }
        caled[i] = 1;
    }
    return dp[i];
}
```

Jumper

Time complexity become $O(n*k)$.

Note that you may take $dp[i]$ = the minimum cost from 1 to i , and try work on the transition formula and the base case. Both should work perfectly ok.

Longest Common Subsequence

B302 Longest Common Subsequence

Given two strings **S** & **T**, find the Longest Common Subsequence.

Let a subsequence of S is the result of deleting some(0 to All) characters in S.

E.g. **S** = "abcde"; "", "abcde", "ae" are the subsequences of **S**, but "aeb" is not.

Remind that **Subsequence** != **Substring**. (Substring is contiguous)

If S = "abcdef", T = "ebdaf",

There Longest Common Subsequence = "bdf"

Longest Common Subsequence

I give up on thinking the brute force solution.

Let's think about a DP solution.

What if we define **dp[i]** = the length of Longest Common Subsequence of $S_1 \dots S_i$ and **T**?

dp[i] doesn't help because we don't know where it end on **T**. :(

Well just add another dimension. :)

Longest Common Subsequence

(1-based)

Let $\mathbf{dp}[i][j]$ = the length of Longest Common Subsequence of $S_1 \dots S_i$ and $T_1 \dots T_j$.

If $S[i] \neq T[j]$, we consider $\mathbf{dp}[i-1][j]$ and $\mathbf{dp}[i][j-1]$.

I.e. $\mathbf{dp}[i][j] = \max(\mathbf{dp}[i-1][j], \mathbf{dp}[i][j-1])$.

If $S[i] == T[j]$, other then consider $\mathbf{dp}[i-1][j]$ and $\mathbf{dp}[i][j-1]$, we may add this character to the Longest Common Subsequence of $S_1 \dots S_{i-1}$ and $T_1 \dots T_{j-1}$.

I.e. $\mathbf{dp}[i][j] = \max(\mathbf{dp}[i-1][j], \mathbf{dp}[i][j-1], \mathbf{dp}[i-1][j-1] + 1)$.

$\mathbf{dp}[0][j] = \mathbf{dp}[i][0] = 0$ for all i, j because of empty string.

Longest Common Subsequence

		T[]	e	b	b	d	a	f
i\j		0	1	2	3	4	5	6
S[]	0	0	0	0	0	0	0	0
a	1	0	0	0	0	0	1	1
b	2	0	0	1	1	1	1	1
c	3	0	0	1	1	1	1	1
d	4	0	0	1	1	2	2	2
e	5	0	1	1	1	2	2	2
f	6	0	1	1	1	2	2	3

Longest Common Subsequence

(Let $SL = |S|$ and $TL = |T|$)

```
for(int i = 1; i <= SL; i++) {
    for(int j = 1; j <= TL; j++) {
        dp[i][j] = max(dp[i-1][j], dp[i][j-1]);
        if(S[i] == T[j]) {
            dp[i][j] = max(dp[i][j], dp[i-1][j-1] + 1);
        }
    }
}
cout << dp[SL][TL];
```

Longest Common Subsequence

Time complexity: $O(|S| * |T|)$.

This program only give us longest length of the Longest Common Subsequence. What if we want to know the actually Subsequence?

- For each i and j , we **choose** the optimal $dp[i][j]$ between $dp[i-1][j]$, $dp[i][j-1]$ and $dp[i-1][j-1] + 1$.
- Why don't we **memorize** what we had chose for each i and j ?
- Finally, **Backtrack** it from $i = |S|, j = |T|$ and record where we choose $dp[i-1][j-1] + 1$.
- You may try it as exercise. :)

Knapsack Problem

There are N items. Each with a Weight w_i and a value v_i .

You have a bag that can only carry **at most** total weight of K . I.e. For any set of items that can be put in the bag, the sum of w_i is smaller than or equal to K .

Note that you can't duplicate or divide the items.

We want to find a set of N such that **total weight** $\leq K$, the total value is the largest.

Knapsack Problem

Let's Brute force it.

(0-based)

For i from 0 to $(1 \ll N)-1$ ($00\dots0_2$ to $11\dots1_2$), if the j -th bit of i is 1 , we put the j -th item into the bag.

E.g. if $i = 5_{10}$ (101_2), we put item 0 and 2 into the bag.

Knapsack Problem

```
for(int i = 0; i < (1 << N); i++) {
    int sum_w = 0, sum_v = 0;
    for(int j = 0; j < N; j++) {
        if(i & (1<<j) != 0) { // is the j-th bit is 1
            sum_w += w[j];
            sum_v += v[j];
        }
    }
    if(sum_w <= K) // is this set valid
        ans = max(ans, sum_v);
}
```

Knapsack Problem

Time Complexity: $O(2^N)$

So slow, let's improve it.

Intuitively, we may think about put the items with largest v_i/w_i first.

But it will WA on this version of the problem. Why?

Remind that we **can't** divide the items.

You may think about a counter example.

Knapsack Problem

For each Item i , we can choose to put it into the bag or not.

Let assume after putting item i into the bag, total weight of the set is j .

What if we know about the optimal solution of using a set of items $0...(i-1)$ which the **total weight = $j - w[i]$** ?

Here we find the subproblem of this problem.

Knapsack Problem

(1-based)

Let $\mathbf{dp}[i][j]$ = the optimal solution of using a set of items $\mathbf{0\dots i}$ which the total weight is \mathbf{j} .

For each $\mathbf{dp}[i][j]$, we consider put item \mathbf{i} or not.

I.e. $\mathbf{dp}[i][j] = \max(\mathbf{dp}[i-1][j], \mathbf{dp}[i-1][j-w[i]] + v[i])$

$\mathbf{dp}[0][j] = 0$

The answer will be $\max(\mathbf{dp}[N][j])$ for each j from 0 to K .

Knapsack Problem

```
for(int i = 1; i <= N; i++) {  
    for(int j = 0; j <= K; j++) {  
        dp[i][j] = dp[i-1][j];  
        if(j >= w[i]) {  
            dp[i][j] = max(dp[i][j], dp[i-1][j - w[i]] + v[i]);  
        }  
    }  
}
```

Knapsack Problem

Time Complexity: $O(N \cdot K)$

There are some variations you may think about it (from 2019 Materials):

- The bag and the items have volume now, both weight and volume can't exceed.
- There are infinite amount of each item. (J181 subtasks 2 & 4)
- There are some amount of each item.
- Some items i can be picked only if item j has been picked before.

Let's take attendance again and have a Break

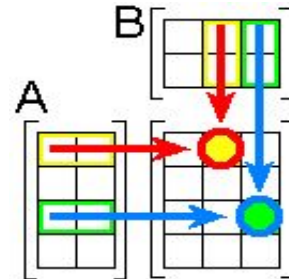
Matrix Multiplication

For whom may not know what Matrix Multiplication is, Let's briefly talk about it first.

A $m \times n$ matrix is like a 2D array of numbers with m rows and n columns.

Let A_1 and A_2 be matrices, $A_1 A_2$ only exist **if and only if** no. of **columns** of A_1 = no. of **rows** A_2

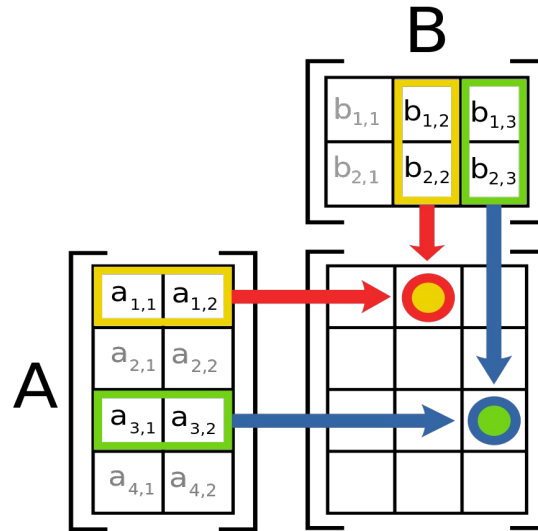
Let A_1 is an $m \times p$ matrix and A_2 is an $p \times n$ matrix, by some operation, $A_1 A_2$ will be a $m \times n$ matrix.



(from Wikipedia)

Matrix Multiplication

(from Wikipedia)



Matrix Multiplication

Properties of matrix multiplication:

- Matrix multiplication is **associative**, i.e. $\mathbf{A}_1(\mathbf{A}_2\mathbf{A}_3) = (\mathbf{A}_1\mathbf{A}_2)\mathbf{A}_3$
- But matrix multiplication is **not commutative**, i.e. $\mathbf{A}_1\mathbf{A}_2 \neq \mathbf{A}_2\mathbf{A}_1$ generally.

Matrix Multiplication

[HKOI 01054 Matrix-chain Multiplication](#)

Let define the cost of performing multiplication of two matrix A_1 - $m \times p$ matrix and A_2 - $p \times n$ matrix is equal to $m * p * n$.

There $N+1$ number p_i which the i -th matrix A_i is a $p_i \times p_{i+1}$ matrix.

Find the minimum cost to finish this matrix multiplication.

Remind that Matrix multiplication is **associative**.

Matrix Multiplication

Sample test case:

	Input	Output
1	3 5 10 15 5	1000

	Matrices			Total cost
1.	5x10	10x15	15x5	0
2.	5x15	15x5		750
3.	5x5			1125
	Matrices			Total cost
1.	5x10	10x15	15x5	0
2.	5x10	10x5		750
3.	5x5			1000

Matrix Multiplication

Brute Force:

- Let's think about it, if we to perform the Multiplication of a chain $A_i \dots A_j$, where $i < j$, the **final** operation must be the Multiplication of the **resultant** matrix of chain $A_i \dots A_{k-1}$ and the **resultant** matrix of chain $A_k \dots A_j$, for some k where $i < k \leq j$. Which is the Multiplication of between an $p_i \times p_k$ matrix and an $p_k \times p_{j+1}$ matrix, the resultant matrix would be $p_i \times p_{j+1}$ with cost $p_i * p_k * p_{j+1}$.
- Same as $A_i \dots A_j$, $A_i \dots A_{k-1}$ and $A_k \dots A_j$ can obtain in a same process as above.
- We can solve it recursively!

Matrix Multiplication

```
int sol(int i, int j) {
    if(i == j)
        return 0;

    int tmp = INF; // some really big number
    for(int k = i+1; k <= j; k++) {
        tmp = min(tmp, sol(i, k-1) + sol(k, j) + p[i] * p[k] * p[j+1]);
    }
    return tmp;
}
```

Matrix Multiplication

The time complexity is large by having a look at it. :(

Again, `sol()` had been call so many time.

Let's define **`dp[i][j]`** like before.

Matrix Multiplication

Let $dp[i][j]$ = the minimum cost to perform the multiplication to the chain of matrices $A_i \dots A_j$.

Similar to the brute force solution, the transition formula is:

$dp[i][j] = \min(dp[i][k-1] + dp[k][j] + p[i]*p[k]*p[j+1])$ for all k where $i < k \leq j$.

$dp[i][i]$ (i.e. the chain have A_i only) = 0

Matrix Multiplication

```
for(int i = 1; i <= N; i++) {
    for(int j = i; j <= N; j++) {
        dp[i][j] = INF; // some really big number
        for(int k = i+1; k <= j; k++) {
            dp[i][j] = min(dp[i][j], dp[i][k-1] + dp[k][j] + p[i] * p[k] * p[j+1]);
        }
    }
}
```

Matrix Multiplication

WA why??? :(

Dynamic Programming (I)

Top-down & Bottom-up DP

Bottom-up DP

- So clean
- The subproblems must be solved first when transitioning
- Some techniques and tricks will be discussed in DP (II) & (III) can only be done easily in Bottom-up DP - **important**
- We will mainly focus on Bottom-up DP.

Matrix Multiplication

It will be somewhat complicated to design the subproblems to be solved first in this problem. (You may try it).

Don't forget we still have top-down approach.

Matrix Multiplication

```
int sol(int i, int j) {
    if(i == j)
        return 0;
    if(!caled[i][j]) {
        dp[i][j] = INF; // some really big number
        for(int k = i+1; k <= j; k++) {
            dp[i][j] = min(dp[i][j], sol(i, k-1) + sol(k, j) + p[i]*p[k]*p[j+1]);
        }
        caled[i][j] = 1;
    }
    return dp[i][j];
}
```

Matrix Multiplication

Time Complexity:

- Each state have a time complexity of $O(N)$
- There are $O(N^2)$ state
- The resultant time complexity: $O(N * N^2) = O(N^3)$

Longest Increasing Subsequence

[HKOI M1222 Longest Increasing Subsequence](#)

Given a sequence $a_1, a_2, a_3, \dots, a_N$, find the length of the Longest Increasing Subsequence

Subsequence again.

Increasing Subsequence is the subsequence of a , such that for elements of this subsequence b , $b[i] < b[i+1]$ for all applicable i .

E.g. the LIS of $\{3, 4, 2, 9, 1, 9, 6, 7\}$ is $\{3, 4, 6, 7\}$

Longest Increasing Subsequence

Let $dp[i]$ = the LIS of $a[1], \dots, a[i]$ that **ended with $a[i]$** .

Is this enough to compute $dp[i]$ by $dp[i-1]$ only?

No, it is because $a[i]$ may not be larger than $a[i-1]$.

We need to consider all $dp[j]$ where $1 \leq j < i$.

Longest Increasing Subsequence

```
for(int i = 1; i <= N; i++) {  
    dp[i] = 1; // a[i] itself is a increasing subsequence  
    for(int j = 1; j < i; j++) {  
        if(a[i] > a[j]) {  
            dp[i] = max(dp[i], dp[j] + 1);  
        }  
    }  
}
```

Longest Increasing Subsequence

Time Complexity: $O(N^2)$

Is not hard right?

CONSTRAINTS

In all test cases, $1 \leq N \leq 100000$, $1 \leq a_i \leq 10^9$.

In 50% test cases, $1 \leq N \leq 3000$.

Oh no! Let's improve it.

Longest Increasing Subsequence

Imagine there are some Increasing Subsequence S of a_1, \dots, a_{i-1} with length k .

If we want to append a_i to the one of the S to form an Increasing Subsequence of a_1, \dots, a_i with length $k+1$. What will we choose?

A_i can only append to the Subsequence that the **last** element of that is **smaller** than A_i . If it is possible, the **last** element of the **new** Subsequence become A_i .

Because only the last element can only affect our choice, we can consider the S with the **smallest last element only** right? In which the elements is not the lastest doesn't matter right?

Longest Increasing Subsequence

Let $f[i][k]$ = the smallest last element of the Increasing Subsequence of a_1, \dots, a_i such that the length of this Increasing Subsequence is k .

For every $f[i][k]$, if $f[i-1][k-1]$ is smaller than $a[i]$, we can append $a[i]$ to it and form a Increasing Subsequence with length k . That mean we can compare $a[i]$ to $f[i-1][k]$, i.e. $f[i][k] = \min(a[i], f[i-1][k])$.

If $f[i-1][k-1]$ is not smaller than $a[i]$, $f[i][k]$ can only be $f[i-1][k]$,
i.e. $f[i][k] = f[i-1][k]$.

At start, $f[i][0] = -\text{INF}$ (Always possible to append $a[i]$ in to an empty subsequence.), and other = INF (Indicate there no such subsequence)

Longest Increasing Subsequence

Each column is increasing right? Why?

Everytime we want to append $a[i+1]$, we would like to greedily find the largest $f[i][k]$ such that $f[i][k] < a[i+1]$, which give us $f[i+1][k+1] = a[i+1]$ which is not larger than $f[i][k+1]$. ($f[i][k] < a[i+1] \leq f[i][k+1]$)

Otherwise, let's say $f[i][k-1] < f[i][k] < a[i+1]$, if we choose $f[i][k-1]$, considering $f[i+1][k] = \min(a[i+1], f[i][k])$, $f[i+1][k]$ would not be smaller than $a[i+1]$ since $f[i][k] < a[i+1]$.

As I'd said before, we want to leave the smallest last element of each length K $f[i]$ to compute $f[i+1]$.

Longest Increasing Subsequence

Wait. We need to copy every elements of $f[i]$ to $f[i+1]$. It still cost us at least $O(n^2)$!

Actually we only need to consider $f[i]$ to compute $f[i+1]$, and there will be **almost 1 element** will be change from $f[i]$ to $f[i+1]$, since we only greedily find the **largest $f[i][k]$** such that $f[i][k] < a[i+1]$.

We can use a 1D array $g[]$ to scan through $a[i]$.

$g[0] = -INF$

Longest Increasing Subsequence

```
int search_g(int t); // return the index of largest g[k] which is smaller than t
bool is_last_g(int i); // return is i the last index of g
void push_g(int t); // append t to back of g
int sol() {
    for(int i = 1; i <= N; i++) {
        int tar = search_g(a[i]);
        if(is_last_g(tar))
            push_g(a[i]);
        else
            g[tar+1] = a[i];
    }
}
```

Longest Increasing Subsequence

The Time Complexity is depend on how you **implement search_g()**.

Linear Search will give us $O(N)$ every query.

But Binary Search will give us **$O(\log N)$** every query since $g[]$ is **increasing**.

Total Time Complexity: $O(N \cdot \log N)$

The detail of the code is left as a exercise.

Longest Palindrome Subsequence

Yes, It's subsequence again.

Given a string **S** with length **N**.

The target is to find the longest Palindrome Subsequence.

Here, Palindrome is a string **A** with length **N** such that the reverse of the **A** is equal to the **A** itself. I.e. $A_i = A_{N-i+1}$ for all **i**. (1-based)

E.g. Longest Palindrome Subsequence of "abcabca" is "abcba"

Longest Palindrome Subsequence

Quite similar to Longest Common Subsequence discussed before, right?

Let's define the states and the transitional formal like that.

Let $dp[i][j]$ = the length of the Longest Palindrome Subsequence for the substring $S[i], S[i+1], \dots, S[j-1], S[j]$.

Longest Palindrome Subsequence

For each $dp[i][j]$, we can either concatenate $S[i]$ to $S[i+1], S[i+2], \dots, S[j]$ or concatenate $S[j]$ to $S[i], \dots, S[j-2], S[j-1]$. The values **won't add up**.

It give us $dp[i][j] = \max(dp[i+1][j], dp[i][j-1])$.

If $S[i] == S[j]$, other than above, we can also concatenate $S[i]$ and $S[j]$ to $S[i+1], \dots, S[j-1]$, and the values will be **incremented by 2**, which give us

$$dp[i][j] = \max(dp[i][j], dp[i+1][j-1] + 2)$$

The base cases:

- $dp[i][j] = 0$ if $i > j$ // empty string
- $dp[i][j] = 1$ if $i = j$ // a character itself is a palindrome.

Longest Palindrome Subsequence

Time Complexity: $O(N^2)$

Try to code it as a exercise.

You may find Top-Down approach is more suitable, because it is hard to find the order to compute.

Longest Palindrome Subsequence

(ps: I'd said the problem is similar Longest Common Subsequence, well actually this problem can be solve be find the Longest Common Subsequence of S and it reverse. Try to find out why again!)

Round-up

In this session, we had discussed about a lot of problems. During this, the common theme of the discussion is to define the states, the transitional formula and the base cases.

When encounter a problem, that you believe there are a DP solution, define states and formula clearly which help you to analyze will it TLE or MLE, and code faster with less bug.

More Practice Problems

(CF = CodeForces)

<ul style="list-style-type: none">● Maximum subarray sum<ul style="list-style-type: none">○ 01010 Diamond Chain○ 01016 Diamond Ring○ M0822 Diamond Chain II	<ul style="list-style-type: none">● Parentheses<ul style="list-style-type: none">○ CF 628C FamilDoor and Brackets
<ul style="list-style-type: none">● Knapsack problem<ul style="list-style-type: none">○ 05011 Coin○ T043 Need for speed	<ul style="list-style-type: none">● Combinatorics<ul style="list-style-type: none">○ CF 553A Kyoyaand ColouredBalls
<ul style="list-style-type: none">● Palindrome<ul style="list-style-type: none">○ I0011 Palindrome○ CF 607B Zuma	<ul style="list-style-type: none">● Probabilities<ul style="list-style-type: none">○ CF 540D Bad Luck Island