XCPC-Template

Created by

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Supervisor: Dr Dan Huang
Co-Supervisor: Dr Zhiguang Chen

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Contents

Part I: Basic Template

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0 ⋆ Preface

0.1 Template

```cpp
#define itn int
#define nit int
#define nti int
#define tin int
#define tni int
#define retrun return
#define reutrn return
#define rutren return
#define fastin                        \
    ios_base::sync_with_stdio(0); \
    cin.tie(0), cout.tie(0);
#include <bits/stdc++.h>
using namespace std;
typedef long long LL;
typedef long double LD;
typedef pair<int, int> PII;
typedef pair<long long, long long> PLL;
typedef pair<double, double> PDD;
typedef vector<int> VI;
#ifndef ONLINE_JUDGE
#define dbg(args...)    \
    do                  \
    {                   \
        cout << "\033[32;1m" << #args << " -> "; \
        err(args);      \
    } while (0)
#else
#define dbg(...)
#endif
void err()
{ cout << "\033[39;0m" << endl; }
template <template <typename...> class T, typename t, typename... Args>
void err(T<t> a, Args... args)
{
    for (auto x : a) cout << x << ' ';
    err(args...);
}
template <typename T, typename... Args>
void err(T a, Args... args)
{ cout << a << ' '; err(args...); }
const int INF = 0x3f3f3f3f;
const int mod = 1e9 + 7;
const double eps = 1e-6;
int main()
{
#ifndef ONLINE_JUDGE
    freopen("test.in", "r", stdin);
    freopen("test.out", "w", stdout);
#endif
    fastin;

    return 0;
}
```

0.2 Operator Precedence

- **括号成员排第一；全体单目排第二；**
- **乘除余三加减四；移位五，关系六；**
- **等于不等排第七；位与异或和位或；**
- **三分天下八九十；逻辑与或十一二；**
- **条件赋值十三四；逗号十五最末尾。**

0.3 Time Complexity

- In most ACM or coding interview problems, the time limit is usually 1 or 2 seconds. Under such constraints, C++ programs should aim to stay within about $\mathbf{10^7} \sim \mathbf{10^8}$ operations.
- Below is a guide on how to choose algorithms based on different input sizes ranges:

1. $\mathbf{n \le 30} \to$ Exponential complexity: DFS with pruning, State Compression DP
2. $\mathbf{n \le 100} \to \mathbf{O(n^3)}$: Floyd, DP, Gaussian Elimination
3. $\mathbf{n \le 1000} \to \mathbf{O(n^2)}, \mathbf{O(n^2 \log n)}$: DP, Binary Search, Naive Dijkstra, Naive Prim, Bellman-Ford
4. $\mathbf{n \le 10000} \to \mathbf{O(n^{\frac{3}{2}})}$: Block Linked List, Mo's Algorithm
5. $\mathbf{n \le 100000} \to \mathbf{O(n \log n)}$: sort, Segment Tree, Fenwick Tree (BIT), set/map, Heap, Topological Sort, Dijkstra (heap optimized), Prim (heap optimized), Kruskal, SPFA, Convex Hull, Half Plane Intersection, Binary Search, CDQ Divide and Conquer, Overall Binary Search, Suffix Array, Heavy-Light Decomposition, Dynamic Trees
6. $\mathbf{n \le 1000000} \to \mathbf{O(n)}$, or small-constant $\mathbf{O(n \log n)}$: Monotonic Queue, Hashing, Two Pointers, BFS, Union Find, KMP, Aho-Corasick Automaton
7. $\mathbf{n \le 10000000} \to \mathbf{O(n)}$: Two Pointers, KMP, Aho-Corasick Automaton, Linear Sieve for Primes
8. $\mathbf{n \le 10^9} \to \mathbf{O(\sqrt{n})}$: Primality Testing
9. $\mathbf{n \le 10^{18}} \to \mathbf{O(\log n)}$: GCD, Fast Exponentiation, Digit DP
10. $\mathbf{n \le 10^{1000}} \to \mathbf{O((\log n)^2)}$: Big Integer Arithmetic (Add/Subtract/Multiply/Divide)
11. $\mathbf{n \le 10^{100000}} \to \mathbf{O(\log k \cdot \log\log k)}$, where k is the number of digits: Big Integer Add/Subtract, FFT/NTT

0.4 If <bits/stdc++.h> Failed

Replace it with:

```
#include <algorithm>
#include <bitset>
#include <complex>
#include <deque>
#include <exception>
#include <fstream>
#include <functional>
#include <iomanip>
#include <ios>
#include <iosfwd>
#include <iostream>
#include <istream>
#include <iterator>
#include <limits>
#include <list>
#include <locale>
#include <map>
#include <memory>
#include <numeric>
#include <ostream>
#include <queue>
#include <set>
#include <sstream>
#include <stack>
#include <stdexcept>
#include <streambuf>
#include <string>
#include <typeinfo>
#include <utility>
#include <valarray>
#include <vector>
#include <unordered_map>
#include <unordered_set>
```

1 ⋆ Basic Algorithm

1.1 Quick Sort

Sort the given array from index 1 to n.

```
void quick_sort(int l, int r)
{
    if (l >= r) return;
    int x = a[(l + r) >> 1], i = l - 1, j = r + 1;
    while (i < j)
    {
        do i++; while (a[i] < x);
        do j--; while (a[j] > x);
        if (i < j) swap(a[i], a[j]);
    }
    quick_sort(l, j);
    quick_sort(j + 1, r);
    return;
}
```

1.2 Binary Search

```
// 区间 [l, r] 被划分成 [l, mid] 和 [mid + 1, r] 时使用
// 大于等于区间的最小值, check 应为 target <= a[mid]
int bsearch_1(int l, int r)
{
    while (l < r)
    {
        int mid = l + r >> 1;
        if (check(mid)) r = mid;
        else l = mid + 1;
    }
    return l;
}
// 区间 [l, r] 被划分成 [l, mid - 1] 和 [mid, r] 时使用
// 小于等于区间的最大值, check 应为 target >= a[mid]
int bsearch_2(int l, int r)
{
    while (l < r)
    {
        // 为什么要 l + r + 1: 因为 l 的更新条件是 mid 本身
        // 当 r == l + 1 时 mid 向下取整必定取 l, 有可能在满足 check(mid) 时导致无限循环
        int mid = l + r + 1 >> 1;
        if (check(mid)) l = mid;
        else r = mid - 1;
    }
    return l;
}
// 浮点数二分
double bsearch_3(double l, double r)
{
    // eps 表示精度, 取决于题目对精度的要求
    const double eps = 1e-6;
    while (r - l > eps)
    {
        double mid = (l + r) / 2;
        if (check(mid))  r = mid;
        else l = mid;
    }
    return l;
}
```

1.3 Ternary Search

```
// 整数三分
void tsearch_1(int l, int r)
{
    while (l < r)
    {
        int lmid = l + (r - l) / 3, rmid = r - (r - l) / 3;
        lans = cal(lmid), rans = cal(rmid);
        if (lans <= rans) r = rmid - 1;
        else l = lmid + 1;
        if (lans <= rans) l = lmid + 1;
        else r = rmid - 1;
    }
    // 求凹函数的极小值
    cout << min(lans, rans) << endl;
    // 求凸函数的极大值
    cout << max(lans, rans) << endl;
}
// 浮点数三分
void tsearch_2(int l, int r)
{
    const double eps = 1e-6;
    while (r - l < eps)
    {
        double lmid = l + (r - l) / 3;
        double rmid = r - (r - l) / 3;
        lans = cal(lmid), rans = cal(rmid);
        // 求凹函数的极小值
        if (lans <= rans) r = rmid;
        else l = lmid;
        // 求凸函数的极大值
        if (lans <= rans) l = lmid;
        else r = rmid;
    }
}
```

1.4 High Precision

1.4.1 High Precision Add

```
string s1, s2;
vector<int> a, b, c;
void add(vector<int> &a, vector<int> &b)
{
    if (a.size() < b.size())
    { add(b, a); return; }
    int t = 0;
```

```
    for (int i = 0; i < a.size(); i++)
    {
        t += a[i];
        if (i < b.size()) t += b[i];
        c.push_back(t % 10);
        t /= 10;
    }
    while (t)
        c.push_back(t % 10), t /= 10;
}
int main()
{
    cin >> s1 >> s2;
    for (int i = s1.size() - 1; i >= 0; i--)
        a.push_back(s1[i] - '0');
    for (int i = s2.size() - 1; i >= 0; i--)
        b.push_back(s2[i] - '0');
    add(a, b);
    for (int i = c.size() - 1; i >= 0; i--)
        cout << c[i];
    return 0;
}
```

1.4.2 High Precision Subsection

```
vector<int> a, b, c;
string s1, s2;
void sub(vector<int> &a, vector<int> &b)
{
    int t = 0;
    for (int i = 0; i < a.size(); i++)
    {
        t = a[i] - t;
        if (i < b.size()) t -= b[i];
        c.push_back((t + 10) % 10);
        if (t < 0) t = 1;
        else t = 0;
    }
    while (c.size() > 1 && c.back() == 0)
        c.pop_back();
}
int main()
{
    cin >> s1 >> s2;
    for (int i = s1.size() - 1; i >= 0; i--)
        a.push_back(s1[i] - '0');
    for (int i = s2.size() - 1; i >= 0; i--)
        b.push_back(s2[i] - '0');
    if (s1.size() < s2.size())
        cout << '-', sub(b, a);
    else if (s1.size() == s2.size() && s1 < s2)
        cout << '-', sub(b, a);
    else sub(a, b);
    for (int i = c.size() - 1; i >= 0; i--)
        cout << c[i];
    return 0;
}
```

1.4.3 High Precision Multiply

```
string s1, s2;
vector<int> a, c;
int b;
void mul(vector<int> &a, int b)
{
    for (int i = 0, t = 0; i < a.size() || t; i++)
    {
        if (i < a.size()) t += a[i] * b;
        c.push_back(t % 10);
        t /= 10;
    }
    while (c.size() > 1 && c.back() == 0)
        c.pop_back();
}
int main()
{
    cin >> s1 >> b;
    for (int i = s1.size() - 1; i >= 0; i--)
        a.push_back(s1[i] - '0');
    mul(a, b);
    for (int i = c.size() - 1; i >= 0; i--)
        cout << c[i];
    return 0;
}
```

1.4.4 High Precision Divide

```
string s1, s2;
vector<int> a, c;
int b, r;
void divide(vector<int> &a, int b, int &r)
{
    r = 0;
    for (int i = a.size() - 1; i >= 0; i--)
    {
        r = r * 10 + a[i];
        c.push_back(r / b);
        r %= b;
    }
    reverse(c.begin(), c.end());
    while (c.size() > 1 && c.back() == 0)
        c.pop_back();
}
int main()
{
    cin >> s1 >> b;
    for (int i = s1.size() - 1; i >= 0; i--)
        a.push_back(s1[i] - '0');
    divide(a, b, r);
    for (int i = c.size() - 1; i >= 0; i--)
        cout << c[i];
    cout << '\n' << r;
    return 0;
}
```

1.5 Prefix Sum & Difference Array

1.5.1 1D Prefix Sum

```
S[i] = a[1] + a[2] + ... a[i]
a[l] + ... + a[r] = S[r] - S[l - 1]
```

1.5.2 2D Prefix Sum

```
// S[i, j] = i 行 j 列左上部分所有元素和为:
s[i - 1][j] + s[i][j - 1] - s[i - 1][j - 1] + a[i][j]
// 以 (x1, y1) 为左上角, (x2, y2) 为右下角的子矩阵的和为:
S[x2][y2] - S[x1 - 1][y2] - S[x2][y1 - 1] + S[x1 - 1][y1 - 1]
```

1.5.3 1D Difference Array

```
const int N = 100010;
int n, m;
int a[N], b[N];
void insert(int l, int r, int c)
{ b[l] += c; b[r + 1] -= c; }
int main()
{
    cin >> n >> m;
    for (int i = 1; i <= n; i++)
        cin >> a[i];
    for (int i = 1; i <= n; i++)
        insert(i, i, a[i]);
    while (m--)
    {
        int l, r, c;
        cin >> l >> r >> c;
        insert(l, r, c);
    }
    for (int i = 1; i <= n; i++)
        b[i] += b[i - 1],
        cout << b[i] << ' ';
    return 0;
}
```

1.5.4 2D Difference Array

```
const int N = 1010;
int n, m, q, a[N][N], b[N][N];
void insert(int x1, int y1, int x2, int y2, int c)
{
    b[x1][y1] += c;
    b[x2 + 1][y2 + 1] += c;
    b[x1][y2 + 1] -= c;
    b[x2 + 1][y1] -= c;
}
int main()
{
    cin >> n >> m >> q;
    for (int i = 1; i <= n; i++)
        for (int j = 1; j <= m; j++)
            cin >> a[i][j];
    for (int i = 1; i <= n; i++)
        for (int j = 1; j <= m; j++)
            insert(i, j, i, j, a[i][j]);
    while (q--)
    {
        int x1, x2, y1, y2, c;
        cin >> x1 >> y1 >> x2 >> y2 >> c;
        insert(x1, y1, x2, y2, c);
    }
    // 其他过程略
}
```

2 ⋆ Basic Data Structures

2.1 Linked List

2.1.1 Singly Linked List

```
const int N = 100010;
int n, h[N], e[N], ne[N], idx = 1;
void init() { ne[0] = -1; }
void insert(int k, int x) //  第 k 个节点后插入
{ e[idx] = x, ne[idx] = ne[k], ne[k] = idx++; }
void del(int k) // 第 k 个节点后删除
{ ne[k] = ne[ne[k]]; }
```

2.1.2 Bidirectional Linked List

```
const int N = 100010;
int n, r[N], l[N], e[N], idx = 2;
void init() { r[0] = 1; l[1] = 0; }
void insert(int k, int x) // 第 k 个节点后插入
{
    e[idx] = x;
    r[idx] = r[k];
    l[idx] = k;
    l[r[k]] = idx;
    r[k] = idx++;
}
void remove(int k) // 删除 k 本身
{ r[l[k]] = r[k]; l[r[k]] = l[k]; }
```

2.2 Stack & Queue

2.2.1 Monotonic Stack

```
// 常见模型：找出每个数左边离它最近的比它大/小的数
int tt = 0;
for (int i = 1; i <= n; i ++ )
{
    while (tt && check(stk[tt], i)) tt --;
    stk[++tt] = i;
}
```

2.2.2 Monotonic Queue

```
// 常见模型：找出滑动窗口中的最大值/最小值
int hh = 0, tt = -1;
for (int i = 0; i < n; i ++ )
{
    while (hh <= tt && check_out(q[hh]))
        hh++; // 判断队头是否滑出窗口
    while (hh <= tt && check(q[tt], i))
        tt-- ;
    q[++tt] = i;
}
```

2.3 KMP

```
const int N = 100010, M = 1000010;
int n, m;
char p[N], s[M];
void getNext(int ne[])
{
    for (int i = 2, j = 0; i <= n; i++)
    {
        while (j && p[j + 1] != p[i])
            j = ne[j];
        if (p[j + 1] == p[i]) j++;
        ne[i] = j;
    }
}
int KMP()
{
    int *ne = new int[n + 1];
    getNext(ne);
    for (int i = 1, j = 0; i <= m; i++)
    {
        while (j && p[j + 1] != s[i])
            j = ne[j];
        if (p[j + 1] == s[i]) j++;
        if (j == n) cout << i - n << ' ';
    }
    return -1;
}
```

2.4 Trie

```
const int N = 100010;
int trie[N][26], cnt[N], idx = 0;
void insert(string &str)     // 插入到 Trie 数组
{
    int p = 0;
    for (auto c : str)
    {
        int u = c - 'a';
        if (!trie[p][u])
            trie[p][u] = ++idx;
        p = trie[p][u];
    }
    cnt[p]++;
}
int query(string &str)      // 查询字符串出现的次数
{
    int p = 0;
    for (auto c : str)
    {
        int u = c - 'a';
        if (!trie[p][u]) return 0;
        p = trie[p][u];
    }
```

```
    return cnt[p];
}
```

2.5 Disjoint-Set

```
const int N = 100010;
int n, m, p[N], Size[N], D[N];
void init()
{
    for (int i = 1; i <= n; i ++ )
        p[i] = i, Size[i] = 1, D[i] = 0;
}
int find(int x)
{
    if (p[x] != x)
    {
        int u = find(p[x]);
        D[x] += D[p[x]];  // 视具体情况计算
        p[x] = u;
    }
    return p[x];
}
void merge(int a, int b, int distance)
{
    int x = find(a), y = find(b);
    if(x != y)
    {
        p[x] = y;
        D[x] = distance;  // 视具体情况计算
        Size[y] += Size[x];
    }
}
```

2.6 Hash

2.6.1 Simple Hash

```
// (1) 拉链法
int h[N], e[N], ne[N], idx;
void insert(int x)
{
    int k = (x % N + N) % N;
    e[idx] = x, ne[idx] = h[k], h[k] = idx ++ ;
}
bool find(int x)
{
    for (int i = h[(x % N + N) % N]; i != -1; i = ne[i])
        if (e[i] == x) return true;
    return false;
}
// (2) 开放寻址法
int find(int x)
{
    int t = (x % N + N) % N;
    while (h[t] != null && h[t] != x)
    { t ++ ; if (t == N) t = 0; }
    return t;
}
```

2.6.2 String Hash

```
typedef unsigned long long ULL;
ULL h[N], p[N];
void init()
{
    p[0] = 1;
    for (int i = 1; i <= n; i ++ ) { h[i] = h[i - 1] * P + str[i]; p[i] = p[i - 1] * P; }
}
ULL get(int l, int r) { return h[r] - h[l - 1] * p[r - l + 1]; }
```

2.7 STL

```
// vector
size()       返回元素个数
empty()      返回是否为空
clear()      清空
front()/back()
push_back()/pop_back()
begin()/end()
[]
支持比较运算，按字典序
// pair<int, int>
first        第一个元素
second       第二个元素
支持比较运算，以first为第一关键字，以second为第二关键字（字典序）
// string
size()/length()  返回字符串长度
empty()
clear()
substr(起始下标，(子串长度))  返回子串
c_str()  返回字符串所在字符数组的起始地址
// queue
size()
empty()
push()       向队尾插入一个元素
front()      返回队头元素
back()       返回队尾元素
pop()        弹出队头元素
// priority_queue
size()
empty()
push()       插入一个元素
top()        返回堆顶元素
pop()        弹出堆顶元素
定义成小根堆的方式：priority_queue<int, vector<int>, greater<int>> q;
// stack
size()
empty()
push()       向栈顶插入一个元素
top()        返回栈顶元素
pop()        弹出栈顶元素
// deque
size()
empty()
clear()
front()/back()
push_back()/pop_back()
```

```
push_front()/pop_front()
begin()/end()
[]
// set, map, multiset, multimap: 基于平衡二叉树（红黑树）动态维护有序序列
size()
empty()
clear()
begin()/end()
++, -- 返回前驱和后继，时间复杂度 O(logn)
// set/multiset
    insert()  插入一个数
    find()    查找一个数
    count()   返回某一个数的个数
    erase()
        (1) 输入是一个数x，删除所有x，O(k + logn)
        (2) 输入一个迭代器，删除这个迭代器
    lower_bound()/upper_bound()
        lower_bound(x)  返回大于等于x的最小的数的迭代器
        upper_bound(x)  返回大于x的最小的数的迭代器
// map/multimap
    insert()  插入的数是一个pair
    erase()   输入的参数是pair或者迭代器
    find()
    []         注意multimap不支持此操作。 时间复杂度是 O(logn)
    lower_bound()/upper_bound()
// unordered_set, unordered_map, unordered_multiset, unordered_multimap
增删改查的时间复杂度是 O(1)
不支持 lower_bound()/upper_bound()， 迭代器的++，--
// bitset
bitset<10000> s;
~, &, |, ^
>>, <<
==, !=
[]
count()     返回有多少个1
any()       判断是否至少有一个1
none()      判断是否全为0
set()       把所有位置成1
set(k, v)   将第k位变成v
reset()     把所有位变成0
flip()      等价于~
flip(k)     把第k位取反
```

3 ⋆ Search & Graph Theory

3.1 Representation of Tree & Graph

3.1.1 Adjacency Matrix

```
// g[a][b] = a->b
```

3.1.2 Adjacency List

```
int h[N], e[N], ne[N], idx;
void init() { memeset(h, -1, sizeof h); }
void add(int a, int b) { e[idx] = b, ne[idx] = h[a], h[a] = idx++ ; }
```

3.2 DFS & BFS

3.2.1 DFS

```
int dfs(int u)
{
    st[u] = true; // 表示点 u 已经被遍历过
    for (int i = h[u]; i != -1; i = ne[i])
    { int j = e[i]; if (!st[j]) dfs(j); }
}
```

3.2.2 BFS

```
queue<int> q;
st[1] = true; q.push(1);
while (q.size())
{
    int t = q.front(); q.pop();
    for (int i = h[t]; i != -1; i = ne[i])
        if (!st[e[i]]) { st[e[i]] = true; q.push(e[i]); }
}
```

3.3 Topological Sort

```
const int N = 100010;
int e[2 * N], ne[2 * N], h[N], d[N], idx;
int n, m, q[N];
void init() { memset(h, -1, sizeof h); }
void add(int a, int b) { e[idx] = b, ne[idx] = h[a], h[a] = idx++, d[b]++; }
bool topSort()
{
    int hh = 0, tt = -1;
    for (int i = 1; i <= n; i++)
        if (!d[i]) q[++tt] = i;
    while (hh <= tt)
        for (int i = h[q[hh++]]; ~i; i = ne[i])
            if (--d[e[i]] == 0) q[++tt] = e[i];
    return tt == n - 1;
}
```

3.4 Shortest Path

3.4.1 Dijkstra

```
const int N = 1010;
int n, dist[N];
int h[N], w[N], e[N], ne[N], idx;
bool st[N];
void add(int a, int b, int c) { e[idx] = b, w[idx] = c, ne[idx] = h[a], h[a] = idx++; }
int dijkstra()      // 需要初始化 dist 与 h
{
    dist[1] = 0;
    priority_queue<PII, vector<PII>, greater<PII>> heap;
    heap.push({0, 1});
    while (heap.size())
    {
        auto t = heap.top();
        heap.pop();
        int ver = t.second, distance = t.first;
        if (st[ver]) continue;
        st[ver] = true;
        for (int i = h[ver]; i != -1; i = ne[i])
            if (dist[e[i]] > distance + w[i])
            {
                dist[e[i]] = distance + w[i];
                heap.push({dist[e[i]], e[i]});
            }
    }
    if (dist[n] == 0x3f3f3f3f) return -1;
    return dist[n];
}
```

3.4.2 Bellman-Ford

```
const int N = 100010;
int n, m, dist[N], backup[N];
struct Edge
{
    int a, b, w;
}edges[N];
int bellman_ford()
{
    memset(dist, 0x3f, sizeof dist);
    dist[1] = 0;
    for (int i = 0; i < n; i ++ )
    {
```

```cpp
        memcpy(backup, dist, sizeof dist);
        for (int j = 0; j < m; j++)
        {
            int a = edges[j].a, b = edges[j].b, w = edges[j].w;
            dist[b] = min(dist[b], backup[a] + w);
        }
    }
    if (dist[n] > 0x3f3f3f3f / 2) return -1;
    return dist[n];
}
```

3.4.3 SPFA

```cpp
const int N = 100010;
int n, m, dist[N];
int e[2 * N], ne[2 * N], w[2 * N], h[N], idx;
bool vis[N];
void spfa()     // 需要初始化 dist 与 h
{
    queue<int> q;
    q.push(1); vis[1] = true;
    while (q.size())
    {
        int t = q.front();
        q.pop();
        vis[t] = false;
        for (int i = h[t]; ~i; i = ne[i])
            if (dist[e[i]] > dist[t] + w[i])
            {
                dist[e[i]] = dist[t] + w[i];
                if (!vis[e[i]]) vis[e[i]] = true, q.push(j);
            }
    }
    dist[n] > INF / 2 ? cout << "impossible" : cout << dist[n];
}
```

3.4.4 Detecting Negative Circle in SPFA

```cpp
void spfa()     // 只需要初始化 h
{
    queue<int> q;
    // 基于虚拟原点假设，所有点放入队列
    for (int i = 1; i <= n; i++) q.push(i), st[i] = true;
    while (q.size())
    {
        int t = q.front();
        q.pop();
        vis[t] = false;
        for (int i = h[t]; ~i; i = ne[i])
            if (dist[e[i]] > dist[t] + w[i])
```

```cpp
            {
                dist[e[i]] = dist[t] + w[i];
                // 新增
                cnt[j] = cnt[t] + 1;
                if (cnt[j] >= n) return true;
                if (!st[j]) q.push(j), st[j] = true;
            }
    }
    return false;
}
```

3.4.5 Floyd

```cpp
const int N = 210;
int g[N][N], n, m, k;
int main()
{
    cin >> n >> m >> k;
    memset(g, 0x3f, sizeof g);
    for (int i = 1; i <= n; i++) g[i][i] = 0;
    while (m--)
    {
        int a, b, c;
        cin >> a >> b >> c;
        g[a][b] = min(g[a][b], c);
    }
    for (int k = 1; k <= n; k++)
        for (int i = 1; i <= n; i++)
            for (int j = 1; j <= n; j++)
                g[i][j] = min(g[i][k] + g[k][j], g[i][j]);
    // 后续代码略
    return 0;
}
```

3.5 Minimum Spanning Tree

3.5.1 Prim

```cpp
const int N = 510;
int n, m, g[N][N], dist[N];
bool vis[N];
void prim()
{
    int res = 0;
    for (int i = 0; i < n; i++)
    {
        int t = -1;
        for (int j = 1; j <= n; j++)
            if (!vis[j] && (t == -1 || dist[j] < dist[t])) t = j;
        if (i && dist[t] == INF) { res = INF; break; }
        if (i) res += dist[t];
        vis[t] = true;
        for (int j = 1; j <= n; j++) dist[j] = min(dist[j], g[t][j]);
```

```
    }
    res == INF ? cout << "impossible" : cout << res;
}
int main()
{
    memset(g, 0x3f, sizeof g);
    memset(dist, 0x3f, sizeof dist);
    cin >> n >> m;
    while (m--)
    {
        int a, b, c;
        cin >> a >> b >> c;
        g[a][b] = min(g[a][b], c);
        g[b][a] = min(g[b][a], c);
    }
    prim();
    return 0;
}
```

3.5.2 Kruskal

```
const int N = 100010;
int n, m;
int p[N];
struct Edge
{
    int a, b, w;
    bool operator<(const Edge &e) const { return w < e.w; };
} edge[2 * N];
void init() { for (int i = 1; i <= n; i++) p[i] = i; }
int find(int x)
{
    if (x != p[x]) p[x] = find(p[x]);
    return p[x];
}
void merge(int x, int y) { p[find(x)] = find(y); }
void kruskal()
{
    int res = 0, cnt = 0;
    for (int i = 1; i <= m; i++)
        if (find(edge[i].a) != find(edge[i].b))
        {
            merge(edge[i].a, edge[i].b);
            res += edge[i].w;
            cnt++;
        }
    if (cnt < n - 1) res = INF;
    res == INF ? cout << "impossible" : cout << res;
}
int main()
{
    init();
    cin >> n >> m;
    for (int i = 1; i <= m; i++) cin >> edge[i].a >> edge[i].b >> edge[i].w;
    sort(edge + 1, edge + m + 1);
    kruskal();
    return 0;
}
```

3.6 Bipartite Graph

3.6.1 Coloring Method

To check if a given graph is bipartite.

```
const int N = 100010, M = 200010;
int n, m;
int e[M], ne[M], h[N], color[N], idx;
bool dfs(int u, int c)
{
color[u] = c;
for (int i = h[u]; ~i; i = ne[i])
    if (color[e[i]] == -1)
    {
        if (!dfs(e[i], !c)) return false;
    }
    else if (color[e[i]] == c) return false;
return true;
}
bool check()
{
for (int i = 1; i <= n; i++)
    if (color[i] == -1)
        if (!dfs(i, 0)) return false;
return true;
}
int main()
{
// 注意另外初始化 h 与 color
cin >> n >> m;
while (m--)
{
    int a, b;
    cin >> a >> b;
    add(a, b), add(b, a);
}
// 其余过程略
}
```

3.6.2 Hungarian Algorithm

To find the maximum matching for a given graph.

```cpp
const int N = 510, M = 100010;
int n1, n2, m;
int e[M], ne[M], h[N], match[N], idx;
bool vis[N];
bool find(int x)
{
for (int i = h[x]; ~i; i = ne[i])
    if (!vis[e[i]])
    {
        vis[e[i]] = true;
        if (match[e[i]] == 0 || find(match[e[i]]))
        {
            match[e[i]] = x;
            return true;
        }
    }
return false;
}
int main()
{
// 注意初始化 h
cin >> n1 >> n2 >> m;
while (m--)
{
    int a, b;
    cin >> a >> b;
    add(a, b);
}
int res = 0;
for (int i = 1; i <= n1; i++)
{
    memset(vis, false, sizeof vis);
    if (find(i)) res++;
}
cout << res;
return 0;
}
```

4 ⋆ Basic Math

4.1 Prime Numbers

4.1.1 Judging Prime Numbers

$O(\sqrt{n})$

```
bool is_prime(int x)
{
    if (x < 2) return false;
    for (int i = 2; i <= x / i; i ++ )
        if (x % i == 0) return false;
    return true;
}
```

4.1.2 Prime Factorization

```
void divide(int x)
{
    for (int i = 2; i <= x / i; i ++ )
        if (x % i == 0)
        {   // 此条件成立时 i 一定是质数
            int s = 0;
            while (x % i == 0) x /= i, s ++ ;
            cout << i << ' ' << s << '\n';
        }
    if (x > 1) cout << x << ' ' << 1 << '\n'
}
```

4.1.3 Euler's Sieve

```
int primes[N], cnt;
bool st[N];
void get_primes(int n)
{
    for (int i = 2; i <= n; i ++ )
    {
        if (!st[i]) primes[cnt++] = i;
        for (int j = 0; primes[j] <= n / i; j ++ )
        {
            st[primes[j] * i] = true;
            if (i % primes[j] == 0) break;
        }
    }
}
```

4.2 Divisor

4.2.1 Find All Divisors

```
vector<int> get_divisors(int x)
{
    vector<int> res;
    for (int i = 1; i <= x / i; i ++ )
        if (x % i == 0)
        {
            res.push_back(i);
            if (i != x / i) res.push_back(x / i);
        }
    sort(res.begin(), res.end());
    return res;
}
```

4.2.2 The Number of Divisors

```
const int mod = 1e9 + 7;
int n;
int main()
{
    cin >> n;
    unordered_map<int, int> h;
    while (n--)
    {
        int x;
        cin >> x;
        for (int i = 2; i <= x / i; i++)
            while (x % i == 0) { h[i]++; x = x / i; }
        if (x > 1) h[x]++;
    }
    long long res = 1;
    for (auto iter = h.begin(); iter != h.end(); iter++)
        res = res * (iter->second + 1) % mod;
    cout << res;
    return 0;
}
```

4.2.3 The Sum of Divisors

```
const int mod = 1e9 + 7;
int n;
long long getSum(int x, int c)
{
    long long s = 1;
    while(c--) s = (s * x + 1) % mod;
    return s;
}
int main()
{
    cin >> n;
    unordered_map<int, int> h;
    while (n--)
    {
        int x;
        cin >> x;
        for (int i = 2; i <= x / i; i++)
            while (x % i == 0) { h[i]++; x = x / i; }
        if (x > 1) h[x]++;
    }
    long long res = 1;
```

```cpp
    for (auto iter = h.begin(); iter != h.end(); iter++)
        res = res * getSum(iter->first, iter->second) % mod;
    cout << res;
    return 0;
}
```

4.2.4 Euclidean Algorithm

```cpp
int gcd(int a, int b)
{ return a % b == 0 ? b : gcd(b, a % b); }
```

4.3 Euler Function

4.3.1 Simple Method

```cpp
int phi(int x)
{
    int res = x;
    for (int i = 2; i <= x / i; i ++ )
        if (x % i == 0)
        {
            res = res / i * (i - 1);
            while (x % i == 0) x /= i;
        }
    if (x > 1) res = res / x * (x - 1);
    return res;
}
```

4.3.2 Euler's Sieve Method

```cpp
const int N = 1000010;
int n, primes[N], phi[N], cnt;
bool st[N];
void getEuler()
{
    phi[1] = 1;
    for (int i = 2; i <= n; i++)
    {
        if (!st[i])
        {
            primes[cnt++] = i;
            // i 是质数，它只会被本身整除，所以直接赋值 i - 1
            phi[i] = i - 1;
        }
        for (int j = 0; primes[j] <= n / i; j++)
        {
            st[i * primes[j]] = true;
            if (i % primes[j] == 0)
            {
                // 如果 i % primes[j] == 0 成立表示 primes[j] 是 i 的最小质因子
                // 也是 primes[j] * i 的最小质因子
                // 1 - 1 / primes[j] 这一项在 phi[i] 中计算过了，只需将基数 N 修正为 primes[j] 倍
                phi[primes[j] * i] = phi[i] * primes[j];
                break;
            }
            // 否则，primes[j] 不是 i 的质因子，只是 primes[j] * i 的最小质因子
            // 不仅需要将基数 N 修正为 primes[j] 倍
            // 还需要补上 1 - 1 / primes[j] 的分子项，因此最终结果为 phi[i] * (primes[j] - 1)
            phi[primes[j] * i] = phi[i] * (primes[j] - 1);
        }
    }
}
```

4.4 Exponentiating by Squaring

```cpp
LL qmi(int m, int k, int p)
{
    LL res = 1 % p, t = m;
    while (k)
    {
        if (k&1) res = res * t % p;
        t = t * t % p;
        k >>= 1;
    }
    return res;
}
```

4.5 Extended Euclidean Algorithm

```cpp
int exgcd(int a, int b, int &x, int &y)
{
    if (!b)
    {
        x = 1;
        y = 0;
        return a;
    }
    int d = exgcd(b, a % b, y, x);
    y -= (a / b) * x;
    return d;
}
```

4.6 Chinese Remainder Theorem

```cpp
LL exgcd(LL a, LL b, LL &x, LL &y)
{
    if (!b) { x = 1, y = 0; return a; }
```

```
    LL d = exgcd(b, a % b, y, x);
    y -= a / b * x;
    return d;
}
int main()
{
    int n;
    cin >> n;
    LL x = 0, m1, a1;
    cin >> m1 >> a1;
    for (int i = 0; i < n - 1; i++)
    {
        LL m2, a2;
        cin >> m2 >> a2;
        LL k1, k2;
        LL d = exgcd(m1, m2, k1, k2);
        if ((a2 - a1) % d) { x = -1; break; }
        k1 *= (a2 - a1) / d;
        k1 = (k1 % (m2 / d) + m2 / d) % (m2 / d);
        x = k1 * m1 + a1;
        LL m = abs(m1 / d * m2);
        a1 = k1 * m1 + a1;
        m1 = m;
    }
    if (x != -1)
        x = (a1 % m1 + m1) % m1;
    cout << x << '\n';
    return 0;
}
```

4.7 Gauss-Jordan Elimination

4.7.1 Linear Equation Group

```
int gauss()
{
    int c, r;
    for (c = 0, r = 0; c < n; c++)
    {
        int t = r;
        for (int i = r; i < n; i++)      // 找绝对值最大的行
            if (fabs(a[i][c]) > fabs(a[t][c]))
                t = i;
        if (fabs(a[t][c]) < eps)         // 此时没必要对该列该行处理
            continue;
        for (int i = c; i <= n; i++)
            swap(a[t][i], a[r][i]);      // 将绝对值最大的行换到最顶端
        for (int i = n; i >= c; i--)
            a[r][i] /= a[r][c];          // 将当前行的首位变成1
        for (int i = r + 1; i < n; i++) // 用当前行将下面所有的列消成0
            if (fabs(a[i][c]) > eps)
                for (int j = n; j >= c; j--)
                    a[i][j] -= a[r][j] * a[i][c];
        r++;
    }
    if (r < n)
    {
        for (int i = r; i < n; i++)
            if (fabs(a[i][n]) > eps)
                return 2; // 无解
        return 1;         // 有无穷多组解
    }
    for (int i = n - 1; i >= 0; i--)
        for (int j = i + 1; j < n; j++)
            a[i][n] -= a[i][j] * a[j][n];
    return 0;            // 有解
}
```

4.7.2 XOR Linear Equation Group

```
int gauss()
{
    int c, r;
    for (c = 0, r = 0; c < n; c++)
    {
        int t = r;
        for (int i = r; i < n; i++)
            if (a[i][c])
                t = i;
        if (!a[t][c])
            continue;
        for (int i = c; i <= n; i++)
            swap(a[r][i], a[t][i]);
        for (int i = r + 1; i < n; i++)
            if (a[i][c])
                for (int j = n; j >= c; j--)
                    a[i][j] ^= a[r][j];
        r++;
    }
    if (r < n)
    {
        for (int i = r; i < n; i++)
            if (a[i][n])
                return 2;
        return 1;
    }
    for (int i = n - 1; i >= 0; i--)
        for (int j = i + 1; j < n; j++)
            a[i][n] ^= a[i][j] * a[j][n];
    return 0;
}
```

4.8 Combinatorial Counting

4.8.1 Recurrence Relation

```
void init()
{
    for (int i = 0; i < N; i++)
        for (int j = 0; j <= i; j++)
            if (!j) c[i][j] = 1;
            else c[i][j] = (c[i - 1][j] + c[i - 1][j - 1]) % mod;
```

```
}
```

4.8.2 Preprocessing & Inverse Element

```
const int N = 100010, mod = 1e9 + 7;
int n, fact[N], infact[N];
int qmi(int a, int b, int p)
{
    int res = 1;
    while (b)
    {
        if (b & 1)
            res = (LL)res * a % p;
        a = (LL)a * a % p;
        b >>= 1;
    }
    return res;
}
int main()
{
    fact[0] = infact[0] = 1;
    for (int i = 1; i < N; i++)
    {
        fact[i] = (LL)fact[i - 1] * i % mod;
        infact[i] = (LL)infact[i - 1] * qmi(i, mod - 2, mod) % mod;
    }
    // 此后 C(a, b) = (LL)fact[a] * infact[b] % mod * infact[a - b] % mod
}
```

4.8.3 Lucas Theorem

```
int qmi(int a, int k, int p)
{
    int res = 1 % p;
    while (k)
    {
        if (k & 1)
            res = (LL)res * a % p;
        a = (LL)a * a % p;
        k >>= 1;
    }
    return res;
}
int C(int a, int b, int p)
{
    if (a < b) return 0;
    LL x = 1, y = 1;
    // x = a * (a - 1) * (a - 2) * ... * (a - b + 1) = a! / (a - b)! (mod p)
    // y = 1 * 2 * ... * b = b! (mod p)
    for (int i = a, j = 1; j <= b; i--, j++)
    { x = (LL)x * i % p; y = (LL)y * j % p; }
    return x * (LL)qmi(y, p - 2, p) % p;
}
int lucas(LL a, LL b, int p)
{
    if (a < p && b < p)
        return C(a, b, p);
    return (LL)C(a % p, b % p, p) * lucas(a / p, b / p, p) % p;
}
```

4.8.4 Factorization Method

```
const int N = 5010;
int n, primes[N], sum[N], cnt;
bool st[N];
void getPrimes(int n) { // 略 }
// 求 n! 中 p 的幂次
int get(int n, int p)
{
    int res = 0;
    while (n) { res += n / p; n /= p; }
    return res;
}
void mul(vector<int> &a, int b) { // 高精度乘，略 }
int main()
{
    int a, b;
    cin >> a >> b;
    getPrimes(a);
    for (int i = 0; i < cnt; i++)
    {
        int p = primes[i];
        sum[i] = get(a, p) - get(b, p) - get(a - b, p);
    }
    vector<int> res;
    res.push_back(1);
    for (int i = 0; i < cnt; i++)
        for (int j = 0; j < sum[i]; j++)
            mul(res, primes[i]);
    for (int i = res.size() - 1; i >= 0; i--)
        cout << res[i];
}
```

4.8.5 Catalan Number

```
const int N = 100010, mod = 1e9 + 7;
int qmi(int a, int k, int p) { // 略 }
int main()
{
    int n;
    cin >> n;
    int a = n * 2, b = n, res = 1;
    for (int i = a; i > a - b; i--)
        res = (LL)res * i % mod;
    for (int i = 1; i <= b; i++)
        res = (LL)res * qmi(i, mod - 2, mod) % mod;
    res = (LL)res * qmi(n + 1, mod - 2, mod) % mod;
}
```

4.9 Inclusion-Exclusion Principle

```cpp
const int N = 20;
int n, m, res = 0, p[N];
int main()
{
    cin >> n >> m;
    for (int i = 0; i < m; i++)
        cin >> p[i];
    // 使用二进制数字表示数字选取情况
    for (int i = 1; i < 1 << m; i++)
    {
        int t = 1, cnt = 0;
        // 遍历每个被选取的质数
        for (int j = 0; j < m; j++)
            if (i >> j & 1)
            {
                cnt++;
                // 一个质数能被选取的条件应该是其累乘积不超过目标数字
                if ((LL)t * p[j] > n)
                { t = -1; break; }
                t *= p[j];
            }
        if (t != -1)
            // 容斥原理公式中奇数个并集系数为 1，反之为 -1
            if (cnt % 2) res += n / t;
            else res -= n / t;
    }
    cout << res;
}
```

4.10 Game Theory

4.10.1 NIM Game

```cpp
const int N = 110, M = 100010;
int k, n,  s[N], f[M];
int sg(int x)
{
    if (f[x] != -1) return f[x];
    // 到达节点得 SG 函数集合
    unordered_set<int> S;
    // 能取走石子就说明能到达，并且递归向下求解
    for (int i = 0; i < k; i++)
    {
        int sum = s[i];
        if (x >= sum) S.insert(sg(x - sum));
    }
    // SG 从小到达遍历并返回，找到最小的、不包含在 SG 函数集合中的自然数
    for (int i = 0;; i++)
        if (!S.count(i))
            return f[x] = i;
}

int main()
{
    cin >> k;
    for (int i = 0; i < k; i++) cin >> s[i];
    cin >> n;
    memset(f, -1, sizeof f);
    int res = 0;
    // 每一堆石子都是一个入度为 0 的起始点
    for (int i = 0; i < n; i++)
    {
        int x;
        cin >> x;
        res ^= sg(x);
    }
    res ? cout << "Yes" : cout << "No";
    return 0;
}
```

5 ⋆ Basic DP

5.1 Knapsack Problem

5.1.1 01 Knapsack

```
const int N = 1010;
int n, m, v[N], w[N], f[N];
int main()
{
    cin >> n >> m;
    for (int i = 1; i <= n; i++)
        cin >> v[i] >> w[i];
    for (int i = 1; i <= n; i++)
        for (int j = m; j >= v[i]; j++)
            f[j] = max(f[j], f[j - v[i]] + w[i]);
    cout << f[m];
}
```

5.1.2 Complete Knapsack

```
const int N = 1010;
int n, m, v[N], w[N], f[N];
int main()
{
    cin >> n >> m;
    for (int i = 1; i <= n; i++)
        cin >> v[i] >> w[i];
    for (int i = 1; i <= n; i++)
        for (int j = v[i]; j <= m; j++)
            f[j] = max(f[j], f[j - v[i]] + w[i]);
    cout << f[m];
}
```

5.1.3 Mutiple Knapsack

```
const int N = 25000;
int n, m, v[N], w[N], f[N];
int main()
{
    cin >> n >> m;
    int cnt = 0;
    for (int i = 1; i <= n; i++)
    {
        int a, b, s;
        cin >> a >> b >> s;
        int k = 1;
        while (k <= s)
        {
            cnt++;
            v[cnt] = a * k, w[cnt] = b * k;
            s -= k, k *= 2;
        }
        if (s > 0)
        {
            cnt++;
            v[cnt] = a * s, w[cnt] = b * s;
        }
    }
    n = cnt;
    for (int i = 1; i <= n; i++)
        for (int j = m; j >= v[i]; j--)
            f[j] = max(f[j], f[j - v[i]] + w[i]);
    cout << f[m];
}
```

5.1.4 Grouped Knapsack

```
const int N = 120;
int n, m, s[N], v[N][N], w[N][N], f[N];
int main()
{
    cin >> n >> m;
    for (int i = 1; i <= n; i++)
    {
        cin >> s[i];
        for (int j = 1; j <= s[i]; j++)
            cin >> v[i][j] >> w[i][j];
    }
    for (int i = 1; i <= n; i++)
        for (int j = m; j >= 0; j--)
            for (int k = 1; k <= s[i]; k++)
                if (v[i][k] <= j)
                    f[j] = max(f[j], f[j - v[i][k]] + w[i][k]);
    cout << f[m];
}
```

5.2 Linear DP

5.2.1 LIS

Here is an $O(n^2)$ solution:

```
const int N = 1010;
int n, a[N], f[N];
int main()
{
    cin >> n;
    for (int i = 1; i <= n; i++)
        cin >> a[i];
    for (int i = 1; i <= n; i++)
    {
        f[i] = 1;
        for (int j = 1; j < i; j++)
            if (a[j] < a[i])
                f[i] = max(f[i], f[j] + 1);
    }
    int res = 0;
    for (int i = 1; i <= n; i++)
        res = max(res, f[i]);
    cout << res;
}
```

Another is an $O(nlogn)$ solution:

```
const int N = 100010;
int n, a[N], q[N];
int main()
{
    cin >> n;
    for (int i = 1; i <= n; i++) cin >> a[i];
    int len = 0;
    q[len] = -INF;
    for (int i = 1; i <= n; i++)
    {
        int l = 0, r = len;
        while (l < r)
        {
            int mid = l + r + 1 >> 1;
            if (q[mid] < a[i]) l = mid;
            else r = mid - 1;
        }
        len = max(r + 1, len);
        q[r + 1] = a[i];
    }
    cout << len;
}
```

5.2.2 LCS

```
const int N = 1010;
int n, m, f[N][N];
char a[N], b[N];
int main()
{
    cin >> n >> m >> (a + 1) >> (b + 1);
    for (int i = 1; i <= n; i++)
        for (int j = 1; j <= m; j++)
        {
            f[i][j] = max(f[i - 1][j], f[i][j - 1]);
            if (a[i] == b[j])
                f[i][j] = max(f[i][j], f[i - 1][j - 1] + 1);
        }
    cout << f[n][m];
}
```

5.3 Interval DP

In this case we focus on an interval, whose sum of its elements can represent the answer we want to find:

```
const int N = 310;
int n, s[N], f[N][N];
int main()
{
    cin >> n;
    for (int i = 1; i <= n; i++)
        cin >> s[i], s[i] += s[i - 1];
    for (int len = 2; len <= n; len++)
        for (int i = 1; i + len - 1 <= n; i++)
        {
            int l = i, r = i + len - 1;
            f[l][r] = INF;
            for (int k = l; k < r; k++)
                f[l][r] = min(f[l][r], f[l][k] + f[k + 1][r] + s[r] - s[l - 1]);
        }
    cout << f[1][n];
}
```

5.4 Counting DP

```
const int N = 1010, M = 1e9 + 7;
int n, f[N][N];
int main()
{
    cin >> n;
    f[0][0] = 1;
    for (int i = 1; i <= n; i++)
        for (int j = 1; j <= i; j++)
            f[i][j] = (f[i - 1][j - 1] + f[i - j][j]) % M;
    int ans = 0;
    for (int i = 1; i <= n; i++)
        ans = (ans + f[n][i]) % M;
    cout << ans;
}
```

5.5 Digit DP

```
// 求数 n 的位数
int get(int n)
{
    int res = 0;
    while (n) n /= 10, res++;
    return res;
}
int count(int n, int i)
{
    int res = 0, dgt = get(n);
    for (int j = 1; j <= dgt; j++)
    {
        // p 为当前遍历位次(第 j 位)的数大小 <10^(右边的数的位数)>, Ps: 从左往右(从高位到低位)
        // l 为第 j 位的左边的数, r 为右边的数, dj 为第 j 位上的数
        int p = pow(10, dgt - j), l = n / p / 10, r = n % p, dj = n / p % 10;
        // 求要选的数在 i 的左边的数小于 l 的情况:
        //      1)、当 i 不为 0 时 xxx : 0...0 ~ l - 1, 即 l * (右边的数的位数) == l * p 种选法
        //      2)、当 i 为 0 时 由于不能有前导零 故 xxx: 0....1 ~ l - 1, 即 (l - 1) * (右边的数的位数) == (l - 1) * p 种选法
        if (i) res += l * p;
        else res += (l - 1) * p;
        // 求要选的数在 i 的左边的数等于 l 的情况: (即视频中的xxx == l 时)
```

```cpp
        //      1)、i > dj 时 0 种选法
        //      2)、i == dj 时 yyy : 0...0 ~ r 即 r + 1 种选法
        //      3)、i < dj 时 yyy : 0...0 ~ 9...9 即 10^(右边的数的位数) == p 种选法 */
        if (i == dj) res += r + 1;
        if (i < dj) res += p;
    }
    return res;
}
int main()
{
    int a, b;
    while (cin >> a >> b, a)
    {
        if (a > b) swap(a, b);
        for (int i = 0; i <= 9; ++i)
            cout << count(b, i) - count(a - 1, i) << ' ';
        // 利用前缀和思想: [l, r] 的和 = s[r] - s[l - 1]
        cout << '\n';
    }
}
```

5.6 State Compression DP

```cpp
const int N = 12, M = 1 << 12;
int n, m;
LL f[N][M];
bool st[M];
int main()
{
    while (cin >> n >> m, n || m)
    {
        memset(f, 0, sizeof f);
        for (int i = 0; i < 1 << n; i++)
        {
            st[i] = true;
            // 统计连续 0 的个数, 若连续 0 为奇数个就不能正好放得下竖放的方格
            int cnt = 0;
            for (int j = 0; j < n && st[i]; j++)
                if (i >> j & 1)
                {
                    // 当前格子被使用
                    // 如果连续 0 的数量为奇数个, 当前格子被使用的后果就是导致格子重合, 所以不可取
                    if (cnt & 1)
                        st[i] = false;
                    // 刷新状态
                    cnt = 0;
                }
                else cnt++;
            // 最后再判断一次, 防止漏判
            if (cnt & 1)
                st[i] = false;
        }
        // 没有摆放任何棋子的状态默认只有 1 种取法
        f[0][0] = 1;
        // 遍历每一列
        for (int i = 1; i <= m; i++)
            // 遍历当前列的每一种用二进制数字表示的摆放状态: 1 指横向摆放, 0 指空位
            for (int j = 0; j < 1 << n; j++)
                // 遍历上一列的每一种用二进制数字表示的摆放状态: 1 指横向摆放, 0 指空位
                for (int k = 0; k < 1 << n; k++)
                    // 满足两个条件: 两列的摆放互不冲突; 两列摆放状态的结合状态是一个可取的状态则累加情况数
                    if (!(j & k) && st[j | k])
                        f[i][j] += f[i - 1][k];
        // 输出摆放好第 m 列且第 (m + 1) 列没有任何方格的状态数
        cout << f[m][0] << '\n';
    }
}
```

5.7 Tree DP

```cpp
// Don't use I/O functions from stdio.h!!!
#define itn int
#define nit int
#define nti int
#define tin int
#define tni int
#define retrun return
#define reutrn return
#define rutren return
#define INF 0x3f3f3f3f
#include <bits/stdc++.h>
using namespace std;
typedef pair<int, int> PII;
typedef long long LL;

const int N = 6010;

int n;
int e[N], ne[N], happy[N], h[N], idx;
int f[N][2];
bool has_father[N];
void add(int a, int b)
{ e[idx] = b, ne[idx] = h[a], h[a] = idx++; }
void dfs(int u)
{
    f[u][1] = happy[u];
    for (int i = h[u]; ~i; i = ne[i])

        dfs(e[i]);
        f[u][0] += max(f[e[i]][0], f[e[i]][1]);
        f[u][1] += f[e[i]][0];
    }
}
```

```
int main()
{
    memset(h, -1, sizeof h);
    cin >> n;
    for (int i = 1; i <= n; i++) cin >>
    happy[i];
    for (int i = 0; i < n - 1; i++)
    {
        int a, b;
        cin >> a >> b;
        has_father[a] = true;
        add(b, a);
    }
    int root = 1;
    while (has_father[root]) root++;
    dfs(root);
    cout << max(f[root][0], f[root][1]);
}
```

5.8 Memoized Search

```
const int N = 310;
int n, m,
h[N][N], f[N][N],
dx[4] = {0, 1, 0, -1}, dy[4] = {1, 0, -1,
    0};
int dp(int x, int y)
{
    int &v = f[x][y];
    if (v != -1) return v;
    v = 1;
    for (int i = 0; i < 4; i++)
    {
        int a = x + dx[i], b = y + dy[i];
        if (a >= 1 && a <= n && b >= 1 &&
    b <= m && h[a][b] < h[x][y])
            v = max(v, dp(a, b) + 1);
    }
    return v;
}
int main()
{
    cin >> n >> m;
    for (int i = 1; i <= n; i++)
        for (int j = 1; j <= m; j++)
            cin >> h[i][j];
    memset(f, -1, sizeof f);
    int res = 0;
    for (int i = 1; i <= n; i++)
        for (int j = 1; j <= m; j++)
            res = max(res, dp(i, j));
    cout << res;
}
```

Part II: Advanced Template

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6 ⋆ Advanced Basic

6.1 Slow Multiplication

```
LL mul(LL a, LL b, LL p)
{
    LL ans = 0;
    while (b)
    {
        if (b & 1) ans = (ans + a) % p;
        a = a * 2 % p; b >>= 1;
    }
    return ans;
}
```

6.2 Sum of Geometric Series

```
const int mod = 9901;
int a, b;
int qmi(int a, int k)
{
    int res = 1;
    a %= mod;
    while (k)
    {
        if (k & 1)
            res = res * a % mod;
        a = a * a % mod;
        k >>= 1;
    }
    return res;
}
int sum(int p, int k)
{
    if (k == 1) return 1;
    if (k % 2 == 0)
        return (1 + qmi(p, k / 2)) * sum(p, k / 2) % mod;
    return (sum(p, k - 1) + qmi(p, k - 1)) % mod;
}
int main()
{
    // 以 a^b 约数之和为例求等比数列和
    cin >> a >> b;
    int res = 1;
    for (int i = 2; i <= a / i; i++)
        if (a % i == 0)
        {
            int s = 0;
            while (a % i == 0) a /= i, s++;
            res = res * sum(i, b * s + 1) % mod;
        }
    if (a > 1) res = res * sum(a, b + 1) % mod;
}
```

6.3 Sort

6.3.1 Card Balancing Problem

```
cin >> n;
for (int i = 1; i <= n; i++)
    cin >> a[i], avg += a[i];
avg /= n;
for (int i = 1; i <= n; i++)
    if (a[i] != avg)
        a[i + 1] += a[i] - avg, ans++;
cout << ans;
```

6.3.2 2D Card Balancing Problem

```
const int N = 100010;
int row[N], col[N], c[N], s[N];
LL work(int n, int a[])
{
    for (int i = 1; i <= n; i++)
        s[i] = s[i - 1] + a[i];
    if (s[n] % n) return -1;
    int avg = s[n] / n;
    c[1] = 0;
    for (int i = 2; i <= n; i++)
        c[i] = s[i - 1] - (i - 1) * avg;
    sort(c + 1, c + n + 1);
    LL res = 0;
    for (int i = 1; i <= n; i++)
        res += abs(c[i] - c[(n + 1) / 2]);
    return res;
}
int main()
{
    int n, m, cnt;
    cin >> n >> m >> cnt;
    while (cnt--)
    {
        int x, y;
        cin >> x >> y;
        row[x]++; col[y]++;
    }
    LL r = work(n, row);
    LL c = work(m, col);
    if (r != -1 && c != -1)
        cout << "both " << r + c;
    else if (r != -1)
        cout << "row " << r;
    else if (c != -1)
        cout << "column " << c;
    else cout << "impossible";
}
```

6.3.3 Dual Heaps

```
if (down.empty() || x <= down.top())
          down.push(x);
else up.push(x);
if (down.size() > up.size() + 1)
    up.push(down.top()), down.pop();
```

```
if (up.size() > down.size())
    down.push(up.top()), up.pop();
if (i % 2)
{
    cout << down.top() << ' ';
    if (++cnt % 10 == 0) cout << '\n';
}
```

6.4 RMQ

```
const int N = 200010, M = 18;
int n, m, w[N], f[N][M];
void init()
{
    for (int j = 0; j < M; j++)
        for (int i = 1; i + (1 << j) - 1 <= n; i++)
            if (!j) f[i][j] = w[i];
            else    // 也可以是最小值
                f[i][j] = max(f[i][j - 1], f[i + (1 << j - 1)][j - 1]);
}
int query(int l, int r)
{
    int len = r - l + 1;
    int k = log(len) / log(2);
    return max(f[l][k], f[r - (1 << k) + 1][k]);
}
```

7 ⋆ Advanced Data Structures

7.1 Binary Indexed Tree

```cpp
// 支持区间修改、区间查询
// 利用变差分求二阶区间和
const int N = 100010;
int n, m, a[N];
LL tr1[N], tr2[N];
int lowbit(int x) { return x & -x; }
void add(LL tr[], LL x, LL c)
{
    for (int i = x; i <= n; i += lowbit(i))
        tr[i] += c;
}
LL sum(LL tr[], LL x)
{
    LL res = 0;
    for (int i = x; i; i -= lowbit(i))
        res += tr[i];
    return res;
}
LL prefix_sum(LL x)
{ return sum(tr1, x) * (x + 1) - sum(tr2, x); }
int main()
{
    cin >> n >> m;
    for (int i = 1; i <= n; i++)
        cin >> a[i];
    for (int i = 1; i <= n; i++)
    {
        int b = a[i] - a[i - 1];
        add(tr1, i, b);
        add(tr2, i, (LL)i * b);
    }
    while (m--)
    {
        char op[2];
        int l, r, d;
        cin >> op >> l >> r;
        if (*op == 'Q')
            cout << prefix_sum(r) - prefix_sum(l - 1) << '\n';
        else
        {
            cin >> d;
            add(tr1, l, d), add(tr2, l, (LL)l * d),
            add(tr1, r + 1, -d),
            add(tr2, r + 1, (LL)-(r + 1) * d);
        }
    }
}
```

7.2 Segment Tree

7.2.1 Maintain the Maximum

```cpp
struct Node
{ int l, r, v; } tr[N * 4];
void pushup(int u)
{
    tr[u].v = max(tr[u << 1].v, tr[u << 1 | 1].v);
}
void build(int u, int l, int r)
{
    tr[u] = {l, r};
    if (l == r) return;
    int mid = l + r >> 1;
    build(u << 1, l, mid),
    build(u << 1 | 1, mid + 1, r);
}
int query(int u, int l, int r)
{
    if (tr[u].l >= l && tr[u].r <= r)
        return tr[u].v;
    int mid = tr[u].l + tr[u].r >> 1;
    int v = 0;
    if (l <= mid)
        v = query(u << 1, l, r);
    if (r > mid)
        v = max(v, query(u << 1 | 1, l, r));
    return v;
}
void modify(int u, int x, int v)
{
    if (tr[u].l == x && tr[u].r == x)
        tr[u].v = v;
    else
    {
        int mid = tr[u].l + tr[u].r >> 1;
        if (x <= mid)
            modify(u << 1, x, v);
        else
            modify(u << 1 | 1, x, v);
        pushup(u);
    }
}
```

7.2.2 Maintain the Maximum Subarray Sum

```cpp
struct Node
{ int l, r, sum, lmax, rmax, tmax; } tr[N * 4];
void pushup(Node &u, Node &l, Node &r)
{
    u.sum = l.sum + r.sum;
    u.lmax = max(l.lmax, l.sum + r.lmax);
    u.rmax = max(r.rmax, r.sum + l.rmax);
    u.tmax = max(max(l.tmax, r.tmax), l.rmax + r.lmax);
}
void pushup(int u)
{ pushup(tr[u], tr[u << 1], tr[u << 1 | 1]); }
void build(int u, int l, int r)
{
    if (l == r)
```

```cpp
        tr[u] = {l, r, w[r], w[r], w[r], w[r]};
    else
    {
        tr[u] = {l, r};
        int mid = l + r >> 1;
        build(u << 1, l, mid),
        build(u << 1 | 1, mid + 1, r);
        pushup(u);
    }
}
void modify(int u, int x, int v)
{
    if (tr[u].l == x && tr[u].r == x)
        tr[u] = {x, x, v, v, v, v};
    else
    {
        int mid = tr[u].l + tr[u].r >> 1;
        if (x <= mid)
            modify(u << 1, x, v);
        else
            modify(u << 1 | 1, x, v);
        pushup(u);
    }
}
Node query(int u, int l, int r)
{
    if (tr[u].l >= l && tr[u].r <= r)
        return tr[u];
    else
    {
        int mid = tr[u].l + tr[u].r >> 1;
        if (r <= mid)
            return query(u << 1, l, r);
        else if (l > mid)
            return query(u << 1 | 1, l, r);
        else
        {
            auto left = query(u << 1, l, r);
            auto right = query(u << 1 | 1, l, r);
            Node res;
            pushup(res, left, right);
            return res;
        }
    }
}
```

7.2.3 Maintain the GCD

```cpp
struct Node
{ int l, r; LL sum, d; } tr[N * 4];
LL gcd(LL a, LL b)
{ return b ? gcd(b, a % b) : a; }
void pushup(Node &u, Node &l, Node &r)
{
    u.sum = l.sum + r.sum;
    u.d = gcd(l.d, r.d);
}
void pushup(int u)
{ pushup(tr[u], tr[u << 1], tr[u << 1 | 1]); }
void build(int u, int l, int r)
{
    if (l == r)
    {
        LL b = w[r] - w[r - 1];
        tr[u] = {l, r, b, b};
    }
    else
    {
        tr[u].l = l, tr[u].r = r;
        int mid = l + r >> 1;
        build(u << 1, l, mid),
        build(u << 1 | 1, mid + 1, r);
        pushup(u);
    }
}
void modify(int u, int x, LL v)
{
    if (tr[u].l == x && tr[u].r == x)
    {
        LL b = tr[u].sum + v;
        tr[u] = {x, x, b, b};
    }
    else
    {
        int mid = tr[u].l + tr[u].r >> 1;
        if (x <= mid)
            modify(u << 1, x, v);
        else
            modify(u << 1 | 1, x, v);
        pushup(u);
    }
}
Node query(int u, int l, int r)
{
    if (tr[u].l >= l && tr[u].r <= r)
        return tr[u];
    else
    {
        int mid = tr[u].l + tr[u].r >> 1;
        if (r <= mid)
            return query(u << 1, l, r);
        else if (l > mid)
            return query(u << 1 | 1, l, r);
        else
        {
            auto left = query(u << 1, l, r);
            auto right = query(u << 1 | 1, l, r);
            Node res;
            pushup(res, left, right);
            return res;
        }
    }
}
```

7.2.4 Optimize Range Updates

Use this when you need to get summary of a specific range of an array but you also need to modify a specific range of an array:

```cpp
struct Node
```

```cpp
{ int l, r; LL sum, add; } tr[N * 4];
void pushup(int u)
{ tr[u].sum = tr[u << 1].sum + tr[u << 1 | 1].sum; }
void pushdown(int u)
{
    auto &root = tr[u],
         &left = tr[u << 1],
         &right = tr[u << 1 | 1];
    if (root.add)
    {
        left.add += root.add,
        left.sum += (LL)(left.r - left.l + 1) * root.add;
        right.add += root.add,
        right.sum += (LL)(right.r - right.l + 1) * root.add;
        root.add = 0;
    }
}
void build(int u, int l, int r)
{
    if (l == r) tr[u] = {l, r, w[r], 0};
    else
    {
        tr[u] = {l, r};
        int mid = l + r >> 1;
        build(u << 1, l, mid);
        build(u << 1 | 1, mid + 1, r);
        pushup(u);
    }
}
void modify(int u, int l, int r, int d)
{
    if (tr[u].l >= l && tr[u].r <= r)
    {
        tr[u].sum += (LL)(tr[u].r - tr[u].l + 1) * d;
        tr[u].add += d;
    }
    else
    {
        pushdown(u);
        int mid = tr[u].l + tr[u].r >> 1;
        if (l <= mid)
            modify(u << 1, l, r, d);
        if (r > mid)
            modify(u << 1 | 1, l, r, d);
        pushup(u);
    }
}
LL query(int u, int l, int r)
{
    if (tr[u].l >= l && tr[u].r <= r)
        return tr[u].sum;
    pushdown(u);
    int mid = tr[u].l + tr[u].r >> 1;
    LL sum = 0;
    if (l <= mid)
        sum += query(u << 1, l, r);
    if (r > mid)
        sum += query(u << 1 | 1, l, r);
    return sum;
}
```

7.3 Persistent Data Structure

7.3.1 Persistent Trie

```cpp
const int N = 600010, M = N * 25;
int n, m, s[N], root[N], idx;
int trie[M][2], max_id[M];
void insert(int i, int k, int p, int q)
{
    if (k < 0)
    {
        max_id[q] = i;
        return;
    }
    int v = s[i] >> k & 1;
    if (p)
        trie[q][v ^ 1] = trie[p][v ^ 1];
    trie[q][v] = ++idx;
    insert(i, k - 1, trie[p][v], trie[q][v]);
    max_id[q] = max(max_id[trie[q][0]], max_id[trie[q][1]]);
}
int query(int root, int C, int L)
{
    int p = root;
    for (int i = 23; i >= 0; i--)
    {
        int v = C >> i & 1;
        if (max_id[trie[p][v ^ 1]] >= L)
            p = trie[p][v ^ 1];
        else
            p = trie[p][v];
    }
    return C ^ s[max_id[p]];
}
// insert(i, 23, root[i - 1], root[i]);
// query(root[r - 1], l - 1, x ^ s[n]);
```

7.3.2 Persistent Segment Tree

```cpp
const int N = 100010, M = 10010;
int n, m, a[N], root[N], idx;
vector<int> nums;
struct Node
{
    int l, r;
    int cnt;
} tr[N * 4 + N * 17];
int find(int x)
{
    return lower_bound(nums.begin(), nums.end(), x) - nums.begin();
}
int build(int l, int r)
{
    int p = ++idx;
    if (l == r)
        return p;
    int mid = l + r >> 1;
    tr[p].l = build(l, mid), tr[p].r = build(mid + 1, r);
    return p;
```

```
}
int insert(int p, int l, int r, int x)
{
    int q = ++idx;
    tr[q] = tr[p];
    if (l == r)
    {
        tr[q].cnt++;
        return q;
    }
    int mid = l + r >> 1;
    if (x <= mid)
        tr[q].l = insert(tr[p].l, l, mid, x);
    else
        tr[q].r = insert(tr[p].r, mid + 1, r, x);
    tr[q].cnt = tr[tr[q].l].cnt + tr[tr[q].r].cnt;
    return q;
}
int query(int q, int p, int l, int r, int k)
{
    if (l == r)
        return r;
    int cnt = tr[tr[q].l].cnt - tr[tr[p].l].cnt;
    int mid = l + r >> 1;
    if (k <= cnt)
        return query(tr[q].l, tr[p].l, l, mid, k);
    else
        return query(tr[q].r, tr[p].r, mid + 1, r, k - cnt);
}
```

7.4 Treap

```
const int N = 100010, INF = 1e8;
int n, root, idx;
struct Node
{ int l, r, key, val, cnt, size; } tr[N];
void pushup(int p)
{
    tr[p].size = tr[tr[p].l].size +
                 tr[tr[p].r].size + tr[p].cnt;
}
int get_node(int key)
{
    tr[++idx].key = key;
    tr[idx].val = rand();
    tr[idx].cnt = tr[idx].size = 1;
    return idx;
}
void zig(int &p)
{
    int q = tr[p].l;
    tr[p].l = tr[q].r, tr[q].r = p, p = q;
    pushup(tr[p].r), pushup(p);
}
void zag(int &p)
{
    int q = tr[p].r;
    tr[p].r = tr[q].l, tr[q].l = p, p = q;
    pushup(tr[p].l), pushup(p);
}
void build()
{
    get_node(-INF), get_node(INF);
    root = 1, tr[1].r = 2;
    pushup(root);
    if (tr[1].val < tr[2].val) zag(root);
}
void insert(int &p, int key)
{
    if (!p) p = get_node(key);
    else if (tr[p].key == key) tr[p].cnt++;
    else if (tr[p].key > key)
    {
        insert(tr[p].l, key);
        if (tr[tr[p].l].val > tr[p].val)
            zig(p);
    }
    else
    {
        insert(tr[p].r, key);
        if (tr[tr[p].r].val > tr[p].val)
            zag(p);
    }
    pushup(p);
}
void remove(int &p, int key)
{
    if (!p) return;
    if (tr[p].key == key)
    {
        if (tr[p].cnt > 1) tr[p].cnt--;
        else if (tr[p].l || tr[p].r)
        {
            if (!tr[p].r || tr[tr[p].l].val > tr[tr[p].r].val)
            {
                zig(p);
                remove(tr[p].r, key);
            }
            else
            {
                zag(p);
                remove(tr[p].l, key);
            }
        }
        else p = 0;
    }
    else if (tr[p].key > key)
        remove(tr[p].l, key);
    else remove(tr[p].r, key);
    pushup(p);
}
int get_rank_by_key(int p, int key)
{
    if (!p) return 0;
    if (tr[p].key == key)
        return tr[tr[p].l].size + 1;
    if (tr[p].key > key)
        return get_rank_by_key(tr[p].l, key);
```

```
    return tr[tr[p].l].size + tr[p].cnt + get_rank_by_key(tr[p].r, key);
}
int get_key_by_rank(int p, int rank)
{
    if (!p) reutrn INF;
    if (tr[tr[p].l].size >= rank)
        reutrn get_key_by_rank(tr[p].l, rank);
    if (tr[tr[p].l].size + tr[p].cnt >= rank)
        reutrn tr[p].key;
    return get_key_by_rank(tr[p].r, rank - tr[tr[p].l].size - tr[p].cnt);
}
int get_prev(int p, int key)
{
    if (!p) return -INF;
    if (tr[p].key >= key)
        reutrn get_prev(tr[p].l, key);
    return max(tr[p].key, get_prev(tr[p].r, key));
}
int get_next(int p, int key)
{
    if (!p) reutrn INF;
    if (tr[p].key <= key)
        return get_next(tr[p].r, key);
    return min(tr[p].key, get_next(tr[p].l, key));
}
```

7.5 AC Automaton

```
const int N = 10010, M = 1000010, S = 55;
int n, tr[N * S][26], cnt[N * S], idx;
int q[N * S], ne[N * S];
char str[M];
void insert()
{
    int p = 0;
    for (int i = 0; str[i]; i++)
    {
        int t = str[i] - 'a';
        if (!tr[p][t]) tr[p][t] = ++idx;
        p = tr[p][t];
    }
    cnt[p]++;
}
void build()
{
    int hh = 0, tt = -1;
    for (int i = 0; i < 26; i++)
        if (tr[0][i]) q[++tt] = tr[0][i];
    while (hh <= tt)
    {
        int t = q[hh++];
        for (int i = 0; i < 26; i++)
        {
            int p = tr[t][i];
            if (!p) tr[t][i] = tr[ne[t]][i];
            else
            {
                ne[p] = tr[ne[t]][i];
                q[++tt] = p;
            }
        }
    }
}
```

8 ⋆ Advanced Search

8.1 Flood-Fill

```
const int N = 1010, M = N * N;
int n, m;
char g[N][N];
PII q[M];
bool st[N][N];
void bfs(int sx, int sy)
{
    int hh = 0, tt = 0;
    q[0] = {sx, sy}; st[sx][sy] = true;
    while (hh <= tt)
    {
        PII t = q[hh++];
        for (int i = t.first - 1; i <= t.first + 1; i++)
            for (int j = t.second - 1; j <= t.second + 1; j++)
            {
                if (i == t.first && j == t.second)
                    continue;
                if (i < 0 || i >= n || j < 0 || j >= m)
                    continue;
                if (g[i][j] == '.' || st[i][j])
                    continue;
                q[++tt] = {i, j};
                st[i][j] = true;
            }
    }
}
int main()
{
    int cnt = 0;
    for (int i = 0; i < n; i++)
        for (int j = 0; j < m; j++)
            if (g[i][j] == 'W' && !st[i][j])
            { bfs(i, j); cnt++; }
}
```

8.2 Multi-source BFS

```
const int N = 1010, M = N * N;
int n, m, dist[N][N];
char g[N][N];
PII q[M];
int dx[4] = {-1, 0, 1, 0},
    dy[4] = {0, 1, 0, -1};
void bfs()
{
    memset(dist, -1, sizeof dist);
    int hh = 0, tt = -1;
    for (int i = 1; i <= n; i++)
        for (int j = 1; j <= m; j++)
            if (g[i][j] == '1')
            {
                dist[i][j] = 0;
                q[++tt] = {i, j};
            }
    while (hh <= tt)
    {
        auto t = q[hh++];
        for (int i = 0; i < 4; i++)
        {
            int a = t.x + dx[i], b = t.y + dy[i];
            if (a < 1 || a > n | b < 1 || b > m) continue;
            if (dist[a][b] != -1) continue;
            dist[a][b] = dist[t.x][t.y] + 1;
            q[++tt] = {a, b};
        }
    }
}
```

8.3 BFS with Deque

```
const int N = 510, M = N * N;
int n, m, dist[N][N];
char g[N][N];
bool st[N][N];
int dx[4] = {-1, -1, 1, 1},
    dy[4] = {-1, 1, 1, -1},
    ix[4] = {-1, -1, 0, 0},
    iy[4] = {-1, 0, 0, -1};
int bfs()
{
    memset(dist, 0x3f, sizeof dist);
    memset(st, 0, sizeof st);
    dist[0][0] = 0;
    deque<PII> q;
    q.push_back({0, 0});
    char cs[] = "\\/\\/";
    while (q.size())
    {
        PII t = q.front();
        q.pop_front();
        if (st[t.x][t.y]) continue;
        st[t.x][t.y] = true;
        for (int i = 0; i < 4; i++)
        {
            int a = t.x + dx[i], b = t.y + dy[i];
            if (a < 0 || a > n || b < 0 || b > m) continue;
            int ca = t.x + ix[i], cb = t.y + iy[i];
            int d = dist[t.x][t.y] +
            (g[ca][cb] != cs[i]);
            if (d < dist[a][b])
            {
                dist[a][b] = d;
                if (g[ca][cb] != cs[i])
                    q.push_back({a, b});
                else
                    q.push_front({a, b});
            }
```

```
        }
    }
    return dist[n][m];
}
```

8.4 Bidirectional BFS

```
int bfs()
{
    if (A == B) return 0;
    queue<string> qa, qb;
    unordered_map<string, int> da, db;
    qa.push(A), qb.push(B);
    da[A] = db[B] = 0;
    int step = 0;
    while (qa.size() && qb.size())
    {
        int t;
        if (qa.size() < qb.size())
            // PROCESS
        else
            // PROCESS
        if (t <= 10) return t;
        if (++step == 10) return -1;
    }
    return -1;
}
```

8.5 A*

```
const int N = 1010, M = 200010;
int n, m, S, T, K;
int h[N], rh[N], e[M], w[M], ne[M], idx;
int dist[N], cnt[N];
bool st[N];
void dijkstra()
{
    priority_queue<PII, vector<PII>, greater<PII>> heap;
    heap.push({0, T});
    memset(dist, 0x3f, sizeof dist);
    dist[T] = 0;
    while (heap.size())
    {
        auto t = heap.top();
        heap.pop();
        int ver = t.y;
        if (st[ver]) continue;
        st[ver] = true;
        for (int i = rh[ver]; ~i; i = ne[i])
        {
            int j = e[i];
            if (dist[j] > dist[ver] + w[i])
            {
                dist[j] = dist[ver] + w[i];
                heap.push({dist[j], j});
            }
        }
    }
}

int astar()
{
    priority_queue<PIII, vector<PIII>, greater<PIII>> heap;
    heap.push({dist[S], {0, S}});
    while (heap.size())
    {
        auto t = heap.top();
        heap.pop();
        int ver = t.y.y, distance = t.y.x;
        cnt[ver]++;
        if (cnt[T] == K) return distance;
        for (int i = h[ver]; ~i; i = ne[i])
        {
            int j = e[i];
            if (cnt[j] < K)
                heap.push({distance + w[i] + dist[j], {distance + w[i], j}});
        }
    }
    return -1;
}
int main()
{
    // PROCESS
    dijkstra(); cout << astar();
    // PROCESS
}
```

8.6 DFS Connectivity Model

```
char g[N][N];
int xa, ya, xb, yb;
int dx[4] = {-1, 0, 1, 0}, dy[4] = {0, 1, 0, -1};
bool st[N][N];
bool dfs(int x, int y)
{
    if (g[x][y] == '#') return false;
    if (x == xb && y == yb) return true;
    st[x][y] = true;
    for (int i = 0; i < 4; i++)
    {
        int a = x + dx[i], b = y + dy[i];
        if (a < 0 || a >= n || b < 0 || b >= n) continue;
        if (st[a][b]) continue;
        if (dfs(a, b)) return true;
    }
    return false;
}
```

8.7 Iterative Deepening

```
const int N = 110;
```

```cpp
int n, path[N];
bool dfs(int u, int k)
{
    if (u == k)
        return path[u - 1] == n;
    bool st[N] = {0};
    for (int i = u - 1; i >= 0; i--)
        for (int j = i; j >= 0; j--)
        {
            int s = path[i] + path[j];
            if (s > n || s <= path[u - 1] || st[s]) continue;
            st[s] = true;
            path[u] = s;
            if (dfs(u + 1, k)) return true;
        }

    return false;
}
```

8.8 Bidirectional DFS

```cpp
const int N = 1 << 24;
int n, m, k, cnt = 0, ans;
int g[50], weights[N];
void dfs(int u, int s)
{
    if (u == k)
    {
        weights[cnt++] = s;
        return;
    }
    if ((LL)s + g[u] <= m)
        dfs(u + 1, s + g[u]);
    dfs(u + 1, s);
}
void dfs2(int u, int s)
{
    if (u == n)
    {
        int l = 0, r = cnt - 1;
        while (l < r)
        {
            int mid = l + r + 1 >> 1;
            if (weights[mid] + (LL)s <= m)
                l = mid;
            else r = mid - 1;
        }
        if (weights[l] + (LL)s <= m)
            ans = max(ans, weights[l] + s);
        return;
    }
    if ((LL)s + g[u] <= m)
        dfs2(u + 1, s + g[u]);
    dfs2(u + 1, s);
}
```

8.9 IDA*

```cpp
const int N = 1e2;
int n, a[N];
string t;
int f()
{
    int tot = 0;
    for (int i = 1; i < n; i++)
        if (t[i - 1] != t[i] - 1)
            tot++;
    return (tot + 2) / 3;
}
bool IDAstar(int u, int maxn)
{
    if (f() > maxn - u) return false;
    if (u == maxn) return true;
    string temp = t;
    for (int len = 1; len <= n - 1; len++)
    {
        for (int l = 0; l <= n - len; l++)
        {
            int r = l + len - 1;
            string substr = temp.substr(l, r - l + 1);
            for (int k = r + 1; k < n; k++)
            {
                t.insert(k + 1, substr);
                t.erase(l, r - l + 1);
                if (IDAstar(u + 1, maxn))
                    return true;
                t = temp;
            }
        }
    }
    return false;
}
```

9 ⋆ Advanced Graph Theory

9.1 Detecting Negative Cycles

```
int n, m1, m2;
int h[N], e[M], w[M], ne[M], idx;
int dist[N], q[N], cnt[N];
bool st[N];
bool spfa()
{
    memset(dist, 0, sizeof dist);
    memset(cnt, 0, sizeof cnt);
    memset(st, 0, sizeof st);
    int hh = 0, tt = 0;
    for (int i = 1; i <= n; i++)
    { q[tt++] = i; st[i] = true; }
    while (hh != tt)
    {
        int t = q[hh++];
        if (hh == N) hh = 0;
        st[t] = false;
        for (int i = h[t]; ~i; i = ne[i])
        {
            int j = e[i];
            if (dist[j] > dist[t] + w[i])
            {
                dist[j] = dist[t] + w[i];
                cnt[j] = cnt[t] + 1;
                if (cnt[j] >= n)
                    return true;
                if (!st[j])
                {
                    q[tt++] = j;
                    if (tt == N) tt = 0;
                    st[j] = true;
                }
            }
        }
    }
    return false;
}
```

9.2 SPFA-SLF

Using deque to solve SPFA question.

```
void spfa()
{
    memset(dist, 0x3f, sizeof dist);
    memset(st, 0, sizeof st);
    deque<int> q;
    q.push_back(s);
    st[s] = 1, dist[s] = 0;
    while (q.size())
    {
        int t = q.front();
        q.pop_front();
        st[t] = 0;
        for (int i = h[t]; ~i; i = ne[i])
        {
            int j = e[i];
            if (dist[j] > dist[t] + w[i])
            {
                dist[j] = dist[t] + w[i];
                if (!st[j])
                {
                    st[j] = true;
                    if (q.size() && dist[j] < dist[q.front()])
                        q.push_front(j);
                    else q.push_back(j);
                }
            }
        }
    }
}
```

9.3 SPFA-Stack

```
bool spfa()
{
    int hh = 0, tt = 1;
    memset(dist, -0x3f, sizeof dist);
    dist[0] = 0; q[0] = 0;
    while (hh != tt)
    {
        int t = q[--tt];
        st[t] = false;
        for(int i = h[t]; ~i; i = ne[i])
        {
            int j = e[i];
            if (dist[j] < dist[t] + w[i])
            {
                dist[j] = dist[t] + w[i];
                cnt[j] = cnt[t] + 1;
                if (cnt[j] >= n + 1) return true;
                if (!st[j])
                {
                    st[j] = true; q[tt++] = j;
                }
            }
        }
    }
    return false;
}
```

9.4 SPFA & MIN & MAX

Using SPFA to maintain the minimum and maximum. In this case we need **Original Graph** and **Reverse Graph**, in which we can use **type == 0** or **type == 1** to describe.

```
void spfa(int h[], int dist[], int type)
{
    int hh = 0, tt = 1;
    if (type == 0)
    {
        memset(dist, 0x3f, sizeof dmin);
        dist[1] = w[1]; q[0] = 1;
    }
```

```
    else
    {
        memset(dist, -0x3f, sizeof dmax);
        dist[n] = w[n]; q[0] = n;
    }
    while (hh != tt)
    {
        int t = q[hh++];
        if (hh == N) hh = 0;
        st[t] = false;
        for (int i = h[t]; ~i; i = ne[i])
        {
            int j = e[i];
            if (type == 0 && dist[j] > min(dist[t], w[j]) || type == 1 && dist[j] < max(dist[t], w[j]))
            {
                if (type == 0)
                    dist[j] = min(dist[t], w[j]);
                else
                    dist[j] = max(dist[t], w[j]);
                if (!st[j])
                {
                    q[tt++] = j;
                    if (tt == N) tt = 0;
                    st[j] = true;
                }
            }
        }
    }
}
```

9.5 Second Shortest Path

```
const int N = 1010, M = 20010;
struct Ver
{
    int id, type, dist;
    bool operator>(const Ver &W) const
    { return dist > W.dist; }
};
int n, m, S, T, dist[N][2], cnt[N][2];
int h[N], e[M], w[M], ne[M], idx;
bool st[N][2];
void add(int a, int b, int c)
{
    e[idx] = b, w[idx] = c, ne[idx] = h[a], h[a] = idx++;
}
int dijkstra()
{
    memset(st, 0, sizeof st);
    memset(dist, 0x3f, sizeof dist);
    memset(cnt, 0, sizeof cnt);
    dist[S][0] = 0, cnt[S][0] = 1;
    priority_queue<Ver, vector<Ver>, greater<Ver>> heap;
    heap.push({S, 0, 0});
    while (heap.size())
    {
        Ver t = heap.top();
        heap.pop();
        int ver = t.id, type = t.type, distance = t.dist, count = cnt[ver][type];
        if (st[ver][type]) continue;
        st[ver][type] = true;
        for (int i = h[ver]; ~i; i = ne[i])
        {
            int j = e[i];
            if (dist[j][0] > distance + w[i])
            {
                dist[j][1] = dist[j][0], cnt[j][1] = cnt[j][0];
                heap.push({j, 1, dist[j][1]});
                dist[j][0] = distance + w[i], cnt[j][0] = count;
                heap.push({j, 0, dist[j][0]});
            }
            else if (dist[j][0] == distance + w[i])
                cnt[j][0] += count;
            else if (dist[j][1] > distance + w[i])
            {
                dist[j][1] = distance + w[i], cnt[j][1] = count;
                heap.push({j, 1, dist[j][1]});
            }
            else if (dist[j][1] == distance + w[i])
                cnt[j][1] += count;
        }
    }
    int res = cnt[T][0];
    if (dist[T][0] + 1 == dist[T][1])
        res += cnt[T][1];
    return res;
}
```

9.6 Second Minimum Spanning Tree

9.6.1 brute-force

```
const int N = 510, M = 10010;
int n, m, p[N], dist1[N][N], dist2[N][N];
int h[N], e[N * 2], w[N * 2], ne[N * 2], idx;
struct Edge
{
  int a, b, w;
  bool f;
  bool operator<(const Edge &e) const
  { return w < e.w; }
} edge[M];
void add(int a, int b, int c)
{
```

```
  e[idx] = b, w[idx] = c, ne[idx] = h[a], h[a] = idx++;
}
int find(int x)
{
  if (p[x] != x) p[x] = find(p[x]);
  return p[x];
}
void dfs(int u, int fa, int maxd1, int maxd2, int d1[], int d2[])
{
  d1[u] = maxd1, d2[u] = maxd2;
  for (int i = h[u]; ~i; i = ne[i])
  {
    int j = e[i];
    if (j != fa)
    {
      int td1 = maxd1, td2 = maxd2;
      if (w[i] > td1)
        td2 = td1, td1 = w[i];
      else if (w[i] < td1 && w[i] > td2)
        td2 = w[i];
      dfs(j, u, td1, td2, d1, d2);
    }
  }
}
int main()
{
  cin >> n >> m;
  memset(h, -1, sizeof h);
  for (int i = 0; i < m; i++)
    cin >> edge[i].a >> edge[i].b >> edge[i].w;
  sort(edge, edge + m);
  for (int i = 1; i <= n; i++) p[i] = i;
  LL sum = 0;
  for (int i = 0; i < m; i++)
  {
    int a = edge[i].a, b = edge[i].b, w = edge[i].w;
    int pa = find(a), pb = find(b);
    if (pa != pb)
    {
      p[pa] = pb;
      sum += w;
      add(a, b, w), add(b, a, w);
      edge[i].f = true;
    }
  }
  for (int i = 1; i <= n; i++)
    dfs(i, -1, -1e9, -1e9, dist1[i], dist2[i]);
  LL res = 1e18;
  for (int i = 0; i < m; i++)
    if (!edge[i].f)
    {
      int a = edge[i].a, b = edge[i].b, w = edge[i].w;
      LL t;
      if (w > dist1[a][b])
        t = sum + w - dist1[a][b];
      else if (w > dist2[a][b])
        t = sum + w - dist2[a][b];
      res = min(res, t);
    }
}
```

9.6.2 LCA

```
const int N = 100010, M = 300010;
int n, m, p[N], q[N];
int h[N], e[M], w[M], ne[M], idx;
int depth[N], fa[N][17], d1[N][17], d2[N][17];
struct Edge
{
  int a, b, w;
  bool used;
  bool operator<(const Edge &t) const
  { return w < t.w; }
} edge[M];
void add(int a, int b, int c)
{
  e[idx] = b, w[idx] = c, ne[idx] = h[a], h[a] = idx++;
}
int find(int x)
{
  if (p[x] != x) p[x] = find(p[x]);
  return p[x];
}
LL kruskal()
{
  for (int i = 1; i <= n; i++) p[i] = i;
  sort(edge, edge + m);
  LL res = 0;
  for (int i = 0; i < m; i++)
  {
    int a = find(edge[i].a), b = find(edge[i].b), w = edge[i].w;
    if (a != b)
    {
      p[a] = b; res += w;
      edge[i].used = true;
    }
  }
  return res;
}
void build()
{
  memset(h, -1, sizeof h);
  for (int i = 0; i < m; i++)
    if (edge[i].used)
    {
      int a = edge[i].a, b = edge[i].b, w = edge[i].w;
      add(a, b, w), add(b, a, w);
    }
}
void bfs()
{
  memset(depth, 0x3f, sizeof depth);
  depth[0] = 0, depth[1] = 1, q[0] = 1;
  int hh = 0, tt = 0;
  while (hh <= tt)
  {
    int t = q[hh++];
    for (int i = h[t]; ~i; i = ne[i])
    {
      int j = e[i];
      if (depth[j] > depth[t] + 1)
      {
```

```
        depth[j] = depth[t] + 1;
        q[++tt] = j;
        fa[j][0] = t;
        d1[j][0] = w[i], d2[j][0] = -INF;
        for (int k = 1; k <= 16; k++)
        {
          int anc = fa[j][k - 1];
          fa[j][k] = fa[anc][k - 1];
          int distance[4] = {d1[j][k - 1],
                             d2[j][k - 1],
                             d1[anc][k - 1],
                             d2[anc][k - 1]};
          d1[j][k] = d2[j][k] = -INF;
          for (int u = 0; u < 4; u++)
          {
            int d = distance[u];
            if (d > d1[j][k])
              d2[j][k] = d1[j][k], d1[j][k] = d;
            else if (d != d1[j][k] && d > d2[j][k])
              d2[j][k] = d;
          }
        }
      }
    }
  }
}
int lca(int a, int b, int w)
{
  static int distance[N * 2];
  int cnt = 0;
  if (depth[a] < depth[b])
    swap(a, b);
  for (int k = 16; k >= 0; k--)
    if (depth[fa[a][k]] >= depth[b])
    {
      distance[cnt++] = d1[a][k];
      distance[cnt++] = d2[a][k];
      a = fa[a][k];
    }
  if (a != b)
  {
    for (int k = 16; k >= 0; k--)
      if (fa[a][k] != fa[b][k])
      {
        distance[cnt++] = d1[a][k];
        distance[cnt++] = d2[a][k];
        distance[cnt++] = d1[b][k];
        distance[cnt++] = d2[b][k];
        a = fa[a][k], b = fa[b][k];
      }
    distance[cnt++] = d1[a][0];
    distance[cnt++] = d1[b][0];
  }
  int dist1 = -INF, dist2 = -INF;
  for (int i = 0; i < cnt; i++)
  {
    int d = distance[i];
    if (d > dist1)
      dist2 = dist1, dist1 = d;
    else if (d != dist1 && d > dist2)
      dist2 = d;
  }
  if (w > dist1) return w - dist1;
  if (w > dist2) return w - dist2;
  return INF;
}
int main()
{
  cin >> n >> m;
  for (int i = 0; i < m; i++)
  {
    int a, b, c;
    cin >> a >> b >> c;
    edge[i] = {a, b, c};
  }
  LL sum = kruskal();
  build();
  bfs();
  LL res = 1e18;
  for (int i = 0; i < m; i++)
    if (!edge[i].used)
    {
      int a = edge[i].a, b = edge[i].b, w = edge[i].w;
      res = min(res, sum + lca(a, b, w));
    }
  cout << res;
}
```

9.7 Difference Constraints

- **size == N**: Feasible Solution
- **size == 1**: Maximum/Minimum
- **Maximum**: Shortest Path
- **Minimum**: Longest Path

9.7.1 Maximum-Shortest Path

```
bool spfa(int size)
{
    int hh = 0, tt = 0;
    memset(dist, 0x3f, sizeof dist);
    memset(st, 0, sizeof st);
    memset(cnt, 0, sizeof cnt);
    for (int i = 1; i <= size; i++)
    {
        q[tt++] = i;
        dist[i] = 0;
        st[i] = true;
    }
    while (hh != tt)
    {
        int t = q[hh++];
        if (hh == N) hh = 0;
        st[t] = false;
        for (int i = h[t]; ~i; i = ne[i])
        {
            int j = e[i];
            if (dist[j] > dist[t] + w[i])
            {
                dist[j] = dist[t] + w[i];
                cnt[j] = cnt[t] + 1;
                if (cnt[j] >= n)
```

```
                    return true;
                if (!st[j])
                {
                    st[j] = true;
                    q[tt++] = j;
                    if (tt == N) tt = 0;
                }
            }
        }
    }
    return false;
}
int main()
{
    // add(a, b, k) means x_b <= x_a + k
    // PROCESS
}
```

9.7.2 Minimum-Longest Path

```
bool spfa(int size)
{
    int hh = 0, tt = 0;
    memset(dist, -0x3f, sizeof dist);
    memset(st, 0, sizeof st);
    memset(cnt, 0, sizeof cnt);
    for (int i = 1; i <= size; i++)
    {
        q[tt++] = i;
        dist[i] = 0;
        st[i] = true;
    }
    while (hh != tt)
    {
        int t = q[hh++];
        if (hh == N) hh = 0;
        st[t] = false;
        for (int i = h[t]; ~i; i = ne[i])
        {
            int j = e[i];
            if (dist[j] < dist[t] + w[i])
            {
                dist[j] = dist[t] + w[i];
                cnt[j] = cnt[t] + 1;
                if (cnt[j] >= n)
                    return false;
                if (!st[j])
                {
                    st[j] = true;
                    q[tt++] = j;
                    if (tt == N) tt = 0;
                }
            }
        }
    }
    return ture;
}
int main()
{
    // add(a, b, k) means x_a + k <= x_b
    // PROCESS
}
```

9.8 LCA

```
int n, m, h[N], e[M], ne[M], idx;
int depth[N], fa[N][16], q[N];
void bfs(int root)
{
    memset(depth, 0x3f, sizeof depth);
    depth[0] = 0;
    depth[root] = 1;
    int hh = 0, tt = 0;
    q[0] = root;
    while (hh <= tt)
    {
        int t = q[hh++];
        for (int i = h[t]; ~i; i = ne[i])
        {
            int j = e[i];
            if (depth[j] > depth[t] + 1)
            {
                depth[j] = depth[t] + 1;
                q[++tt] = j;
                fa[j][0] = t;
                for (int k = 1; k <= 15; k
    ++)
                    fa[j][k] = fa[fa[j][k
    - 1]][k - 1];
            }
        }
    }
}
int lca(int a, int b)
{
    if (depth[a] < depth[b])
        swap(a, b);
    for (int k = 15; k >= 0; k--)
        if (depth[fa[a][k]] >= depth[b])
            a = fa[a][k];
    if (a == b)
        return a;
    for (int k = 15; k >= 0; k--)
        if (fa[a][k] != fa[b][k])
        {
            a = fa[a][k];
            b = fa[b][k];
        }
    return fa[a][0];
}
```

9.9 SCC

```
void tarjan(int u)
{
    dfn[u] = low[u] = ++timestap;
    stack[++top] = u, in_stk[u] = true;
    for(int i = h[u]; ~i; i = ne[i])
    {
        int j = e[i];
        if(!dfn[j])
        {
            tarjan(j);
            low[u] = min(low[u], low[j]);
        }
```

```
        else if(in_stk[j])
            low[u] = min(low[u], dfn[j]);
    }
    if(dfn[u] == low[u])
    {
        int y;
        ++scc_cnt;
        do
        {
            y = stk[top--];
            in_stk[y] = false;
            id[y] = scc_cnt;
        } while(y != u);
    }
}
```

9.10 DCC

9.10.1 e-DCC

```
const int N = 5010, M = 20010;
int n, m, h[N], e[M], ne[M], idx;
int dfn[N], low[N], timestamp;
int stk[N], top, id[N], dcc_cnt, d[N];
bool is_bridge[M];
void tarjan(int u, int from)
{
  dfn[u] = low[u] = ++timestamp;
  stk[++top] = u;
  for (int i = h[u]; ~i; i = ne[i])
  {
    int j = e[i];
    if (!dfn[j])
    {
      tarjan(j, i);
      low[u] = min(low[u], low[j]);
      if (dfn[u] < low[j])
        is_bridge[i] = is_bridge[i ^ 1] =
      true;
    }
    else if (i != (from ^ 1))
      low[u] = min(low[u], dfn[j]);
  }
  if (dfn[u] == low[u])
  {
    ++dcc_cnt;
    int y;
    do
    {
      y = stk[top--];
      id[y] = dcc_cnt;
    } while (y != u);
  }
}
```

9.10.2 v-DCC

```
const int N = 1010, M = 1010;
int n, m, h[N], e[M], ne[M], idx;
int dfn[N], low[N], timestamp;
int stk[N], top, dcc_cnt, root;
vector<int> dcc[N];
bool cut[N];
void init()
{
  for (int i = 1; i <= dcc_cnt; i++)
    dcc[i].clear();
  idx = n = timestamp = top = dcc_cnt = 0;
  memset(h, -1, sizeof h);
  memset(dfn, 0, sizeof dfn);
  memset(cut, 0, sizeof cut);
}
void tarjan(int u)
{
  dfn[u] = low[u] = ++timestamp;
  stk[++top] = u;
  if (u == root && h[u] == -1)
  {
    dcc_cnt++;
    dcc[dcc_cnt].push_back(u);
    return;
  }
  int cnt = 0;
  for (int i = h[u]; ~i; i = ne[i])
  {
    int j = e[i];
    if (!dfn[j])
    {
      tarjan(j);
      low[u] = min(low[u], low[j]);
      if (dfn[u] <= low[j])
      {
        cnt++;
        if (u != root || cnt > 1)
          cut[u] = true;
        ++dcc_cnt;
        int y;
        do
        {
          y = stk[top--];
          dcc[dcc_cnt].push_back(y);
        } while (y != j);
        dcc[dcc_cnt].push_back(u);
      }
    }
    else
      low[u] = min(low[u], dfn[j]);
  }
}
```

9.11 Bipartite Graph

The maximum matching
(by the Hungarian algorithm) =
the minimum vertex cover =
total number of vertices -
maximum independent set =
total number of vertices -
minimum path cover.

9.11.1 maximum matching

```
const int N = 110;
```

```
int n, m;
int dx[4] = {-1, 0, 1, 0}, dy[4] = {0, 1,
    0, -1};
PII match[N][N];
bool g[N][N], st[N][N];
bool find(int x, int y)
{
    for (int i = 0; i < 4; i++)
    {
        int a = x + dx[i], b = y + dy[i];
        if (a && a <= n && b && b <= n &&
    !g[a][b] && !st[a][b])
        {
            st[a][b] = true;
            PII t = match[a][b];
            if (t.x == -1 || find(t.x, t.y
    ))
            {
                match[a][b] = {x, y};
                return true;
            }
        }
    }
    return false;
}
int main()
{
    // PROCESS
    memset(match, -1, sizeof match);
    int res = 0;
    for (int i = 1; i <= n; i++)
        for (int j = 1; j <= n; j++)
            if ((i + j) % 2 && !g[i][j])
            {
                memset(st, 0, sizeof st);
                if (find(i, j)) res++;
            }
    // PROCESS
}
```

9.11.2 minimum vertex cover

```
const int N = 110;
int n, m, k, match[N];
bool g[N][N], st[N];
bool find(int x)
{
    for (int i = 0; i < m; i++)
        if (!st[i] && g[x][i])
        {
            st[i] = true;
            if (match[i] == -1 || find(
    match[i]))
            {
                match[i] = x;
                return true;
            }
        }
    return false;
}
int main()
{
    while (cin >> n, n)
    {
        cin >> m >> k;
        memset(g, 0, sizeof g);
        memset(match, -1, sizeof match);
        while (k--)
        {
            int t, a, b;
            cin >> t >> a >> b;
            if (!a || !b) continue;
            g[a][b] = true;
        }
        int res = 0;
        for (int i = 0; i < n; i++)
        {
            memset(st, 0, sizeof st);
            if (find(i)) res++;
        }
        cout << res << '\n';
    }
}
```

9.11.3 maximum independent set

```
const int N = 110;
int n, m, k;
PII match[N][N];
bool g[N][N], st[N][N];
int dx[8] = {-2, -1, 1, 2, 2, 1, -1, -2};
int dy[8] = {1, 2, 2, 1, -1, -2, -2, -1};
bool find(int x, int y)
{
    for (int i = 0; i < 8; i++)
    {
        int a = x + dx[i], b = y + dy[i];
        if (a < 1 || a > n || b < 1 || b >
    m)
            continue;
        if (g[a][b]) continue;
        if (st[a][b]) continue;
        st[a][b] = true;
        PII t = match[a][b];
        if (t.x == 0 || find(t.x, t.y))
        {
            match[a][b] = {x, y};
            return true;
        }
    }
    return false;
}
int main()
{
    // PROCESS
    int res = 0;
    for (int i = 1; i <= n; i++)
        for (int j = 1; j <= m; j++)
        {
            if (g[i][j] || (i + j) % 2)
                continue;
            memset(st, 0, sizeof st);
            if (find(i, j)) res++;
        }
    cout << n * m - k - res << '\n';
}
```

9.11.4 minimum path cover

```cpp
const int N = 210, M = 30010;
int n, m, match[N];
bool d[N][N], st[N];
bool find(int x)
{
    for (int i = 1; i <= n; i++)
        if (d[x][i] && !st[i])
        {
            st[i] = true;
            int t = match[i];
            if (t == 0 || find(t))
            {
                match[i] = x;
                return true;
            }
        }
    return false;
}
int main()
{
    // 传递闭包
    for (int k = 1; k <= n; k++)
        for (int i = 1; i <= n; i++)
            for (int j = 1; j <= n; j++)
                d[i][j] |= d[i][k] & d[k][j];
    int res = 0;
    for (int i = 1; i <= n; i++)
    {
        memset(st, 0, sizeof st);
        if (find(i)) res++;
    }
    cout << n - res;
}
```

9.12 Eulerian Circuit & Eulerian Path

9.12.1 Eulerian Circuit

```cpp
int type, n, m;
int h[N], e[M], ne[M], idx;
bool used[M];
int ans[M], cn, din[N], dout[N];
void add(int a, int b)
{
    e[idx] = b, ne[idx] = h[a], h[a] = idx++;
}
void dfs(int u)
{
    for (int &i = h[u]; ~i;)
    {
        if (used[i])
        { i = ne[i]; continue; }
        used[i] = true;
        if (type == 1) used[i ^ 1] = true;
        int t;
        if (type == 1)
        {
            t = i / 2 + 1;
            if (i & 1) t = -t;
        }
        else t = i + 1;
        int j = e[i];
        i = ne[i];
        dfs(j);
        ans[++cnt] = t;
    }
}
int main()
{
    cin >> type >> n >> m;
    memset(h, -1, sizeof h);
    for (int i = 0; i < m; i++)
    {
        int a, b;
        cin >> a >> b;
        add(a, b);
        if (type == 1) add(b, a);
        din[b]++, dout[a]++;
    }
    if (type == 1)
    {
        for (int i = 1; i <= n; i++)
            if (din[i] + dout[i] & 1)
            {
                cout << "NO\n";
                return 0;
            }
    }
    else
    {
        for (int i = 1; i <= n; i++)
            if (din[i] != dout[i])
            {
                cout << "NO\n";
                return 0;
            }
    }
    for (int i = 1; i <= n; i++)
        if (h[i] != -1) { dfs(i); break; }
}
```

9.12.2 Eulerian Path

```cpp
const int N = 510;
int n = 500, m, g[N][N];
int ans[1100], cnt, d[N];
void dfs(int u)
{
    for (int i = 1; i <= n; i++)
        if (g[u][i])
        {
            g[u][i]--, g[i][u]--;
            dfs(i);
        }
    ans[++cnt] = u;
}
int main()
{
    cin >> m;
    while (m--)
    {
```

```
        int a, b;
        cin >> a >> b;
        g[a][b]++, g[b][a]++;
        d[a]++, d[b]++;
    }
    int start = 1;
    while (!d[start]) ++start;
    for (int i = 1; i <= 500; i++)
        if (d[i] % 2)
        { start = i; break; }
    dfs(start);
}
```

10 ⋆ Advanced Math

10.1 Euler's Totient Function

10.1.1 GCD

```
const int N = 1e7 + 10;
int primes[N], cnt, phi[N];
bool st[N];
LL s[N];
void init(int n)
{
    for (int i = 2; i <= n; i++)
    {
        if (!st[i])
        {
            primes[cnt++] = i;
            phi[i] = i - 1;
        }
        for (int j = 0; primes[j] * i <= n; j++)
        {
            st[primes[j] * i] = true;
            if (i % primes[j] == 0)
            {
                phi[i * primes[j]] = phi[i] * primes[j];
                break;
            }
            phi[i * primes[j]] = phi[i] * (primes[j] - 1);
        }
    }
    for (int i = 1; i <= n; i++)
        s[i] = s[i - 1] + phi[i];
}
int main()
{
    int n; cin >> n;
    init(n);
    LL res = 0;
    for (int i = 0; i < cnt; i++)
    {
        int p = primes[i];
        res += s[n / p] * 2 + 1;
    }
}
```

10.2 Matrix Multiplication

```
const int N = 3;
int n, m;
void mul(int c[], int a[], int b[][N])
{
    int temp[N] = {0};
    for (int i = 0; i < N; i++)
        for (int j = 0; j < N; j++)
            temp[i] = (temp[i] + (LL)a[j] * b[j][i]) % m;
    memcpy(c, temp, sizeof temp);
}
void mul(int c[][N], int a[][N], int b[][N])
{
    int temp[N][N] = {0};
    for (int i = 0; i < N; i++)
        for (int j = 0; j < N; j++)
            for (int k = 0; k < N; k++)
                temp[i][j] = (temp[i][j] + (LL)a[i][k] * b[k][j]) % m;
    memcpy(c, temp, sizeof temp);
}
int main()
{
    while (n)
    {
        if (n & 1) mul(f1, f1, a);
        mul(a, a, a); n >>= 1;
    }
}
```

11 ⋆ Advanced DP

11.1 Advanced LIS

11.1.1 MSIS

MSIS means Maximum Sum Increasing Subsequence

```
const int N = 1010;
int n, w[N], f[N];
int main()
{
    cin >> n;
    for (int i = 0; i < n; i++) cin >> w[i];
    int res = 0;
    for (int i = 0; i < n; i++)
    {
        f[i] = w[i];
        for (int j = 0; j < i; j++)
            if (w[i] > w[j])
                f[i] = max(f[i], f[j] + w[i]);
        res = max(res, f[i]);
    }
    cout << res;
}
```

11.1.2 LCIS

LCIS means Longest Common Increasing Subsequence

```
const int N = 3010;
int n, a[N], b[N], f[N][N];
int main()
{
    cin >> n;
    for (int i = 1; i <= n; i++)
        cin >> a[i];
    for (int i = 1; i <= n; i++)
        cin >> b[i];
    for (int i = 1; i <= n; i++)
    {
        int maxv = 1;
        for (int j = 1; j <= n; j++)
        {
            f[i][j] = f[i - 1][j];
            if (a[i] == b[j])
                f[i][j] = max(f[i][j], maxv);
            if (a[i] > b[j])
                maxv = max(maxv, f[i - 1][j] + 1);
        }
    }
    int res = 0;
    for (int i = 1; i <= n; i++)
        res = max(res, f[n][i]);
    cout << res;
}
```

11.2 Knapsack Problem

11.2.1 Multiple Knapsack Problem

```
const int N = 20010;
int n, m, f[N], g[N], q[N];
int main()
{
    cin >> n >> m;
    for (int i = 0; i < n; i++)
    {
        int v, w, s;
        cin >> v >> w >> s;
        memcpy(g, f, sizeof f);
        for (int j = 0; j < v; j++)
        {
            int hh = 0, tt = -1;
            for (int k = j; k <= m; k += v)
            {
                if (hh <= tt && q[hh] < k - s * v)
                    hh++;
                while (hh <= tt && g[q[tt]] - (q[tt] - j) / v * w <= g[k] - (k - j) / v * w)
                    tt--;
                q[++tt] = k;
                f[k] = g[q[hh]] + (k - q[hh]) / v * w;
            }
        }
    }
    cout << f[m] << '\n';
}
```

11.2.2 Two-Dimensional Cost Knapsack Problem

```
const int N = 110;
int n, V, M, f[N][N];
int main()
{
    cin >> n >> V >> M;
    for (int i = 0; i < n; i++)
    {
        int v, m, w;
        cin >> v >> m >> w;
        for (int j = V; j >= v; j--)
            for (int k = M; k >= m; k--)
                f[j][k] = max(f[j][k], f[j - v][k - m] + w);
    }
    cout << f[V][M] << '\n';
}
```

11.2.3 Finding the Actual Solution Set

```
const int N = 1010;
int n, m;
```

```cpp
int v[N], w[N], f[N][N];
int main()
{
    cin >> n >> m;
    for (int i = 1; i <= n; i++)
        cin >> v[i] >> w[i];
    for (int i = n; i >= 1; i--)
        for (int j = 0; j <= m; j++)
        {
            f[i][j] = f[i + 1][j];
            if (j >= v[i])
                f[i][j] = max(f[i][j], f[i + 1][j - v[i]] + w[i]);
        }
    int j = m;
    for (int i = 1; i <= n; i++)
        if (j >= v[i] && f[i][j] == f[i + 1][j - v[i]] + w[i])
        {
            cout << i << ' ';
            j -= v[i];
        }
}
```

11.2.4 Maximum Linearly Independent Subset

```cpp
const int N = 110, M = 25010;
int n, v[N];
bool f[M];
int main()
{
    int T; cin >> T;
    while (T--)
    {
        cin >> n;
        for (int i = 1; i <= n; ++i)
            cin >> v[i];
        sort(v + 1, v + n + 1);
        int m = v[n], res = 0;
        memset(f, 0, sizeof f);
        f[0] = true; // 状态的初值
        for (int i = 1; i <= n; ++i)
        {
            if (f[v[i]]) continue;
            res++;
            for (int j = v[i]; j <= m; ++j)
                f[j] |= f[j - v[i]];
        }
        cout << res << '\n';
    }
}
```

11.2.5 Mixed Knapsack Problem

```cpp
const int N = 1010;
int n, m, f[N];
int main()
{
    cin >> n >> m;
    for (int i = 0; i < n; i++)
    {
        int v, w, s;
        cin >> v >> w >> s;
        if (!s)
        {
            for (int j = v; j <= m; j++)
                f[j] = max(f[j], f[j - v] + w);
        }
        else
        {
            if (s == -1)
                s = 1;
            for (int k = 1; k <= s; k *= 2)
            {
                for (int j = m; j >= k * v; j--)
                    f[j] = max(f[j], f[j - k * v] + k * w);
                s -= k;
            }
            if (s)
            {
                for (int j = m; j >= s * v; j--)
                    f[j] = max(f[j], f[j - s * v] + s * w);
            }
        }
    }
    cout << f[m] << '\n';
}
```

11.2.6 Dependent Knapsack Problem

```cpp
const int N = 110;
int n, m, root;
int h[N], e[N], ne[N], idx;
int v[N], w[N], [N][N];
void add(int a, int b)
{
    e[idx] = b, ne[idx] = h[a], h[a] = idx++;
}
void dfs(int u)
{
    for (int i = h[u]; ~i; i = ne[i])
    {
        int son = e[i];
        dfs(son);
        for (int j = m - v[u]; j >= 0; --j)
            for (int k = 0; k <= j; ++k)
                f[u][j] = max(f[u][j], f[u][j - k] + f[son][k]);
    }
    for (int j = m; j >= v[u]; --j)
        f[u][j] = f[u][j - v[u]] + w[u];
    for (int j = 0; j < v[u]; ++j)
        f[u][j] = 0;
}
int main()
```

```
{
    memset(h, -1, sizeof h);
    cin >> n >> m;
    for (int i = 1; i <= n; ++i)
    {
        int p;
        cin >> v[i] >> w[i] >> p;
        if (p == -1) root = i;
        else add(p, i);
    }
    dfs(root);
    cout << f[root][m] << '\n';
}
```

11.2.7 Number of Solutions

```
const int N = 1010, mod = 1e9 + 7;
int n, m;
int w[N], v[N], f[N], g[N];
int main()
{
    cin >> n >> m;
    for (int i = 1; i <= n; ++i)
        cin >> v[i] >> w[i];
    g[0] = 1;
    for (int i = 1; i <= n; ++i)
    {
        for (int j = m; j >= v[i]; --j)
        {
            int temp = max(f[j], f[j - v[i]] + w[i]), c = 0;
            if (temp == f[j])
                c = (c + g[j]) % mod;
            if (temp == f[j - v[i]] + w[i])
                c = (c + g[j - v[i]]) % mod;
            f[j] = temp, g[j] = c;
        }
    }
    int res = 0;
    for (int j = 0; j <= m; ++j)
        if (f[j] == f[m])
            res = (res + g[j]) % mod;
    cout << res << '\n';
}
```

11.3 FSM

```
const int N = 100010;
int n, w[N], f[N][2];
int main()
{
    int T; cin >> T;
    while (T--)
    {
        cin >> n;
        for (int i = 1; i <= n; i++)
            cin >> w[i];
        for (int i = 1; i <= n; i++)
        {
            // YOUR_FSM_RULES
            // f[i][0] =
            // f[i][1] =
        }
        cout << max(f[n][0], f[n][1]) << '\n';
    }
}
```

11.4 Digit DP

```
const int N = 35;
int l, r, k, b, a[N], al, f[N][N];
int dp(int pos, int st, int op)
{
    if (!pos) return st == k;
    if (!op && ~f[pos][st])
        return f[pos][st];
    int res = 0, maxx = op ? min(a[pos], 1) : 1;
    for (int i = 0; i <= maxx; i++)
    {
        if (st + i > k) continue;
        res += dp(pos - 1, st + i, op && i == a[pos]);
    }
    return op ? res : f[pos][st] = res;
}
int calc(int x)
{
    al = 0;
    memset(f, -1, sizeof f);
    while (x) a[++al] = x % b, x /= b;
    return dp(al, 0, 1);
}
int main()
{
    cin >> l >> r >> k >> b;
    cout << calc(r) - calc(l - 1) << '\n';
}
```

11.5 Queue Optimization for DP

```
int n, m, s[300010], q[300010];
int main()
{
    cin >> n >> m;
    for (int i = 1; i <= n; i++)
        cin >> s[i], s[i] += s[i - 1];
    int res = INT_MIN, hh = 0, tt = 0;
    for (int i = 1; i <= n; i++)
    {
        if (q[hh] < i - m) hh++;
        res = max(res, s[i] - s[q[hh]]);
        while (hh <= tt && s[q[tt]] >= s[i]) tt--;
        q[++tt] = i;
    }
}
```