

Competitive Programming Library

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11.1 Faster implementations

50

11.1.1 hashes

50

11.1.2 Binary Search the value

50

1

Templates

1.1

Setup

1.1.1

IO Manipulation

Input/Output

```
#include <bits/stdc++.h>

freopen("input.txt", "r", stdin);
freopen("output.txt", "w", stdout);

#define fastIO \
    ios_base::sync_with_stdio(false), cin.tie(nullptr), cout.tie(nullptr);
```

1.1.2

GCC Compiler Optimization (Vectorization)

GCC Opt

```
// Ref: USACO guide
// will make GCC auto-vectorize for loops and optimizes floating points
// better (assumes associativity and turns off denormals).
#pragma GCC optimize ("Ofast")
// can double performance of vectorized code, but causes crashes on old
// machines.
#pragma GCC target ("avx,avx2,fma")

// slows down run time but throws a Runtime Error if an overflow occurred
#pragma GCC optimize("trapv")
```

1.2

MOD Template

```
constexpr int MOD = 1e9+7; // must be a prime number

int add(int a, int b) {
    int res = a+b;
    if(res >= MOD) return res -= MOD;
```

```

}

int sub(int a, int b) {
    int res = a-b;
    if(res < 0) return res += MOD;
}

int power(int a, int e) {
    int res = 1;
    while(e) {if(e & 1) res = res * a % MOD; a = a * a % MOD;
    e >>= 1;}
    return res;
}

-----
// note -> from Fermat little theorem, we can deduce that
// a^(BIG) % prime = (a ^ (BIG%(prime - 1)))%prime
// because every a^(prime - 1) is equal to 1
// from the identity says a^(prime - 1) % prime = 1
-----

int inverse(int a) {
    return power(a, MOD-2);
}

int div(int a, int b) {
    return a * inverse(b) % MOD;
}

```

MOD Template

1.3 Macros

Macros

```

#define getBit(n, k) (n >> k) // & 1
#define ON(n, idx) (n | (1ll << idx))
#define OFF(n, idx) (n & ~(1ll << idx))

```

```

#define toggle(n, idx) ((n) ^ (1ll<<(idx)))
#define gray(n) (n ^ (n >> 1))
#define bitCount(x) (__builtin_popcountll(x))
#define clz(x) (__builtin_clzll(x))
#define ctz(x) (__builtin_ctzll(x))
#define uniq(x) x.resize(unique(x.begin(), x.end())-x.begin());

#define angle(a) (atan2((a).imag(), (a).real()))
// #define vec(a, b) ((b)-(a))
#define same(v1, v2) (dp(vec(v1,v2),vec(v1,v2)) < EPS)
#define dotProduct(a, b) ((conj(a)*(b)).real()) // a*b cos(T), if zero ->
    prep
#define crossProduct(a, b) ((conj(a)*(b)).imag()) // a*b sin(T), if zero
    -> parallel
// #define length(a) (hypot((a).imag(), (a).real()))
#define normalize(a) ((a)/length(a))
#define rotate0(v, ang) ((v)*exp(point(0,ang)))
#define rotateA(p, ang, about) (rotate0(vec(about,p),ang)+about)
#define reflect0(v, m) (conj((v)/(m))*(m))
#define ceil_i(a, b) (((1ll)(a)+(1ll)(b-1))/(1ll)(b))
#define floor_i(a, b) (a/b)
#define round_i(a, b) ((a+(b/2))/b) // if a>0
#define round_m(a, b) ((a-(b/2))/b) // if a<0
#define round_multiple(n, m) round_i(n,m)*m // round to multiple if
    specified element

const double PI = acos(-1.0);

```

1.4 Grid Navigation

Grid Nav

```

// knight moves on a chess board
int dx[] = { -2, -1, 1, 2, -2, -1, 1, 2 };
int dy[] = { -1, -2, -2, -1, 1, 2, 2, 1 };

// Grid up, down, right, left (Moves for Chess Rook)
int dx[4] = {1, -1, 0, 0};
int dy[4] = {0, 0, 1, -1};

// Grid cell all neighbours

```

```
const int dx[8] = {1, 0, -1, 0, 1, 1, -1, -1}
const int dy[8] = {0, 1, 0, -1, -1, 1, -1, 1};
```

```
// Grid Diagonal (Moves for Chess Bishop)
int dx[] = {1, 1, -1, -1};
int dy[] = {1, -1, 1, -1};
```

1.5 Integer 128

i128

```
typedef __int128 i128;

__int128 read() {
    __int128 x = 0, f = 1;
    char ch = getchar();
    while (ch < '0' || ch > '9') {
        if (ch == '-') f = -1;
        ch = getchar();
    }
    while (ch >= '0' && ch <= '9') {
        x = x * 10 + ch - '0';
        ch = getchar();
    }
    return x * f;
}

void print(__int128 x) {
    if (x < 0) {
        putchar('-');
        x = -x;
    }
    if (x > 9) print(x / 10);
    putchar(x % 10 + '0');
}

bool cmp(__int128 x, __int128 y) { return x > y; }
```

1.6 Matrix Expo

MExpo

```
constexpr int MAX_N = 201, MOD = 1e9+7;
struct Matrix { int mat[MAX_N][MAX_N]; }; // we return a 2D array
ll mod(ll a, ll m) { return ((a%m)+m) % m; } // ensure positive answer
Matrix matMul(Matrix a, Matrix b) { // normally O(n^3)
    Matrix ans{}; // but O(1) as n = 2
    for (auto & i : ans.mat)
        for (int & j : i)
            j = 0;

    for (int i = 0; i < MAX_N; ++i)
        for (int k = 0; k < MAX_N; ++k) {
            if (a.mat[i][k] == 0) continue; // optimization
            for (int j = 0; j < MAX_N; ++j) {
                ans.mat[i][j] += mod(a.mat[i][k], MOD) * mod(b.mat[k][j],
                    MOD);
                ans.mat[i][j] = mod(ans.mat[i][j], MOD);
            }
        }
    return ans;
}

Matrix matPow(Matrix base, int p) { // normally O(n^3 log p)
    Matrix ans{}; // but O(log p) as n = 2
    for (int i = 0; i < MAX_N; ++i)
        for (int j = 0; j < MAX_N; ++j)
            ans.mat[i][j] = (i == j); // prepare identity matrix
    while (p) { // iterative D&C version
        if (p&1) // check if p is odd
            ans = matMul(ans, base); // update ans
        base = matMul(base, base); // square the base
        p >>= 1; // divide p by 2
    }
    return ans;
}

Matrix matMul(Matrix a, Matrix b, int p, int q, int r) { // O(pqr)
    Matrix c{};
    for (int i = 0; i < p; ++i)
        for (int j = 0; j < r; ++j) {
            c.mat[i][j] = 0;
            for (int k = 0; k < q; ++k)
```

```

        c.mat[i][j] += a.mat[i][k] + b.mat[k][j];
    }
    return c;
}

```

2 Dynamic Programming

2.1 Some dp patterns

Maximum/Minimum path cost

```

const int MAX = 21;
int grid[MAX][MAX];
int mem[MAX][MAX];
int n = 20;
bool valid(int r, int c){
    return r >= 0 && r < n && c >= 0 && c < n;
}

int maxPathSum(int r, int c){
    if(!valid(r,c)){
        return 0;
    }

    if(r == n-1 && c == n-1){
        return mem[r][c] = grid[r][c];
    }
    // available moves
    int path1 = maxPathSum(r+1,c);
    int path2 = maxPathSum(r,c+1);

    return grid[r][c] + max(path1,path2);
}

```

add operators between numbers to get max prod/sum

// put +, -, between sequence of numbers such that the sum is divisible by k, and maximum as possible

```

const int MAX = 21;
long long mem[MAX][MAX];
const int n = 20;
int k = 4; // example
int v[20];
int fix(int a){
    return (a % k + k) % k;
}

long long tryAll(int pos, int mod){
    long long &ret = mem[pos][mod];
    if(ret != -1){
        return ret;
    }
    if(pos == n){
        return ret = mod == 0;
    }
    if(tryAll(pos+1,fix(mod + v[pos])) || tryAll(pos+1,fix(mod-v[pos]))){
        return ret = 1;
    }
    return ret = 0;
}

```

pick choices with no two similar consecutive choices

```

// pick minimum of choinces costs with no two similar consecutive choices
const int choices = 4;
const int n = 20;
int MAX = n;
int mem[MAX][choices];
const int OO = 1e6+1;
int minCost(int pos, int lastChoice){
    if(pos == n){
        return 0; // invalid move
    }
    int &ret = mem[pos][lastChoice];

    if(ret != -1){
        return ret;
    }

    ret = OO; // want to minimize

```

```

// let choices are 0, 1, 2
if(lastChoice != 0){
    ret = min(ret, minCost(pos+1,0));
}
if(lastChoice != 1){
    ret = min(ret, minCost(pos+1,1));
}
if(lastChoice != 2){
    ret = min(ret, minCost(pos+1,2));
}
return ret;
}

```

sum S and max/min Product

```

int maxK;

ll mem[21][101]; // k, and s

// You are given an integer s and an integer k. Find k positive integers
// a1, a2, ..., ak
// such that their sum is equal to s and their product is the maximal
// possible. Return their product.

ll maxProd(int k, int rem)
{
    if(k == maxK){
        // base case
        if(rem == 0)
            return 1;
        return 0;
    }

    if(rem == 0) // invalid case
        return 0;

    ll &ret = mem[k][rem];

    if(ret != -1)
        return ret;

    ret = 0;

```

```

for (int i = 1; i <= rem; ++i) {
    ll sol = maxProd(k+1, rem - i) * i;
    ret = max(ret, sol);
}

return ret;
}

```

2.2 DP solutions

2.2.1 Max Subarray sum (Kadane's Algorithm)

Max Subarray sum

```

int maxSubarraySum(vector<int>& arr, int len) {
    int ans = INT_MIN, cur = 0;

    for (int i = 0; i < len; i++) {
        cur = cur + arr[i];
        if (ans < cur)
            ans = cur;

        if (cur < 0)
            cur = 0;
    }

    return ans;
}

```

2.2.2 Maximum Subarray Alternating Sum

Maximum Subarray Alternating Sum

```

/* REF: GeeksForGeeks
Input: arr[] = {-4, -10, 3, 5}
Output: 9
Explanation: Subarray {arr[0], arr[2]} = {-4, -10, 3}. Therefore, the sum
of this subarray is 9.

```

```

*/
int maxSubarraySumALT(vector<int>& a, int len) {
    int ans = INT_MIN, cur = 0;
    for (int i = 0; i < len; i++) {
        if (i % 2 == 0)
            cur = max(cur + a[i], a[i]);
        else
            cur = max(cur - a[i], -a[i]);

        ans = max(ans, cur);
    }

    cur = 0;

    for (int i = 0; i < len; i++) {
        if (i % 2 == 1)
            cur = max(cur + a[i], a[i]);
        else
            cur = max(cur - a[i], -a[i]);

        ans = max(ans, cur);
    }

    return ans;
}

```

2.2.3 Count number of DISTINCT ordered ways to produce coins sums to x

Count distinct

/*
For example, if the coins are {2,3,5} and the desired sum is 9, there are 3 ways:

2+2+5
3+3+3
2+2+2+3

```

*/
int n, x;
cin >> n >> x;

```

```

vector<int> coins(n);
read(coins);

vector dp(x + 1, 0);

dp[0] = 1;
for (int i = 0; i < n; ++i) {
    for (int j = coins[i]; j <= x; ++j) {
        dp[j] = add(dp[j], dp[j - coins[i]]);
    }
}

cout << dp[x] << endl;

```

2.2.4 Min absolute difference between 2 elements from (L, R) (DP Ranges)

Min absolute difference

```

const int N = 1e4 + 1;

int dp[N][N];

int n;
cin >> n;
vector<int> a(n);
read(a);

for (int i = 0; i < n; ++i) dp[i][i] = 1e6; // INF, you can't take the
// element with it self
for (int i = 1; i < n; ++i) dp[i - 1][i] = abs(a[i] - a[i - 1]);

for (int len = 3; len <= n; ++len) {
    for (int l = 0, r = len - 1; r < n; ++l, ++r) {
        dp[l][r] = min(dp[l][r - 1], dp[l + 1][r]);
        dp[l][r] = min(dp[l][r], abs(a[l] - a[r]));
    }
}

int q;
cin >> q;

```



```

while (q--) {
    int l, r;
    cin >> l >> r;
    --l, --r;

    cout << dp[l][r] << el;
}

```

2.2.5 Longest common subsequence between 2 Strings

$$dp[i][j] = \begin{cases} \max(dp[i-1][j], dp[i][j-1]) & \text{if } A_i \neq B_j \\ dp[i-1][j-1] + 1 & \text{if } A_i = B_j \end{cases}$$

LIS 2 Strings

```

// REF: USACO guide
int longestCommonSubsequence(string a, string b) {
    int dp[a.size()][b.size()];
    for (int i = 0; i < a.size(); i++) { fill(dp[i], dp[i] + b.size(), 0); }
    for (int i = 0; i < a.size(); i++) {
        if (a[i] == b[0]) dp[i][0] = 1;
        if (i != 0) dp[i][0] = max(dp[i][0], dp[i-1][0]);
    }
    for (int i = 0; i < b.size(); i++) {
        if (a[0] == b[i]) dp[0][i] = 1;
        if (i != 0) dp[0][i] = max(dp[0][i], dp[0][i-1]);
    }
    for (int i = 1; i < a.size(); i++) {
        for (int j = 1; j < b.size(); j++) {
            if (a[i] == b[j]) {
                dp[i][j] = dp[i-1][j-1] + 1;
            } else {
                dp[i][j] = max(dp[i-1][j], dp[i][j-1]);
            }
        }
    }
    return dp[a.size()-1][b.size()-1];
}

```

2.2.6 Longest common subsequence $\mathcal{O}(n^2)$

LIS

```

// REF: cp-algorithms
int lis(vector<int> const& a) {
    int n = a.size();
    vector<int> d(n, 1);
    for (int i = 0; i < n; i++) {
        for (int j = 0; j < i; j++) {
            if (a[j] < a[i])
                d[i] = max(d[i], d[j] + 1);
        }
    }

    int ans = d[0];
    for (int i = 1; i < n; i++) {
        ans = max(ans, d[i]);
    }
    return ans;
}

// Restoring
vector<int> lis(vector<int> const& a) {
    int n = a.size();
    vector<int> d(n, 1), p(n, -1);
    for (int i = 0; i < n; i++) {
        for (int j = 0; j < i; j++) {
            if (a[j] < a[i] && d[i] < d[j] + 1) {
                d[i] = d[j] + 1;
                p[i] = j;
            }
        }
    }

    int ans = d[0], pos = 0;
    for (int i = 1; i < n; i++) {
        if (d[i] > ans) {
            ans = d[i];
            pos = i;
        }
    }
}

```

```

vector<int> subseq;
while (pos != -1) {
    subseq.push_back(a[pos]);
    pos = p[pos];
}
reverse(subseq.begin(), subseq.end());
return subseq;
}

```

2.2.7 Longest common subsequence Binary Search $\mathcal{O}(n + \log N)$

LIS

```

int lisBS(vector<int> const& a) {
    int n = a.size();
    const int INF = 1e9;
    vector<int> d(n+1, INF);
    d[0] = -INF;

    for (int i = 0; i < n; i++) {
        int l = upper_bound(d.begin(), d.end(), a[i]) - d.begin();
        if (d[l-1] < a[i] && a[i] < d[l])
            d[l] = a[i];
    }

    int ans = 0;
    for (int l = 0; l <= n; l++) {
        if (d[l] < INF)
            ans = l;
    }
    return ans;
}

```

3 Bit Manipulation

3.1 Subset Operations

count subsets with give sum

```

int countDistinctSubsetsWithSum(vector<int>& arr, int n, int k) {
    // Count distinct subsets of array arr that sum up to k
    vector<int> dp(k + 1, 0);
    dp[0] = 1;
    for (int i = 0; i < n; ++i) {
        for (int j = k; j >= arr[i]; --j) {
            dp[j] += dp[j - arr[i]];
        }
    }
    return dp[k]; // Number of distinct subsets with sum k
}

```

max xor of any subset of elements in the array

```

int maximalSubsetXOR(vector<int>& arr, int n) {
    // Find the maximum XOR of any subset of elements in array arr
    int maxXor = 0;
    for (int mask = 0; mask < (1 << n); ++mask) {
        int xorSum = 0;
        for (int i = 0; i < n; ++i) {
            if (mask & (1 << i)) {
                xorSum ^= arr[i];
            }
        }
        maxXor = max(maxXor, xorSum);
    }
    return maxXor;
}

```

min xor of any subset

```

int minimumSubsetXOR(vector<int>& arr, int n) {
    // Find the minimum XOR of any pair of elements in array arr
    int minSubsetXor = INT_MAX;
    for (int mask = 0; mask < (1 << n); ++mask) {
        int xorSum = 0;
        for (int i = 0; i < n; ++i) {
            if (mask & (1 << i)) {
                xorSum ^= arr[i];
            }
        }
    }
    return minSubsetXor;
}

```

```

    }
}
minSubsetXor = min(minSubsetXor, xorSum);
}
return minSubsetXor;
}

```

subset generation

```

void subsetGeneration(int x, int n) {
    // Generate all non-empty subsets of a set represented by an integer x
    for (int subset = x; subset > 0; subset = (subset - 1) & x) {
        // Process subset
        cout << subset << endl;
    }
}

```

check if subset of elements in the array sum up to k

```

void subsetSumCheck(vector<int>& arr, int n, int k) {
    // Check if a subset of elements in array arr sums up to k
    for (int subset = 0; subset < (1 << n); ++subset) {
        int sum = 0;
        for (int i = 0; i < n; ++i) {
            if (subset & (1 << i)) {
                sum += arr[i];
            }
        }
        if (sum == k) {
            // Found subset with sum k
            cout << "Subset with sum " << k << ": " << subset << endl;
        }
    }
}

```

max subset sum mod m

```

int subsetWithMaxSumModuloM(vector<int>& arr, int n, int m) {
    // Find the maximum subset sum modulo m

```

```

vector<int> dp(m, -1);
dp[0] = 0;
int currentMod = 0;
for (int i = 0; i < n; ++i) {
    currentMod = (currentMod + arr[i]) % m;
    for (int j = 0; j < m; ++j) {
        if (dp[j] != -1) {
            dp[(j + currentMod) % m] = max(dp[(j + currentMod) % m], dp[j] + arr[i]);
        }
    }
    dp[currentMod] = max(dp[currentMod], arr[i]);
}
return dp[0]; // Maximum subset sum modulo m
}

```

iterate over all supersets represented by x

```

void iterateOverSupersets(int x, int n) {
    // Iterate over all supersets of a set represented by x
    int subset = x;
    do {
        // Process subset
        cout << subset << endl;
        subset = (subset + 1) | x;
    } while (subset <= (1 << n) - 1);
}

```

4 Algorithms

4.1 FFT

FFT Algorithm

```

constexpr ll mod = 998244353, root = 3;

ll modpow(ll b, ll e, ll m) {
    ll ans = 1;
    for (; e; b = b * b % m, e /= 2)

```

```

        if (e & 1) ans = ans * b % m;
    return ans;
}

// Primitive Root of the mod of form 2^a * b + 1
int generator () {
    vector<int> fact;
    int phi = mod-1, n = phi;
    for (int i=2; i*i<=n; ++i)
        if (n % i == 0) {
            fact.push_back (i);
            while (n % i == 0)
                n /= i;
        }
    if (n > 1)
        fact.push_back (n);

    for (int res=2; res<=mod; ++res) {
        bool ok = true;
        for (size_t i=0; i<fact.size() && ok; ++i)
            ok &= modpow(res, phi / fact[i], mod) != 1;
        if (ok) return res;
    }
    return -1;
}

void ntt(vector<ll> &a) {
    int n = a.size(), L = 31 - __builtin_clz(n);
    static vector<ll> rt(2, 1); // erase the static if you want to use two moduli;
    for (static int k = 2, s = 2; k < n; k *= 2, s++) { // erase the static if you want to use two moduli;
        rt.resize(n);
        ll z[] = {1, modpow(root, mod >> s, mod)};
        for (int i = k; i < 2*k; ++i) rt[i] = rt[i / 2] * z[i & 1] % mod;
    }
    vector<int> rev(n);
    for (int i = 0; i < n; ++i) rev[i] = (rev[i / 2] | (i & 1) << L) / 2;
    for (int i = 0; i < n; ++i) if (i < rev[i]) swap(a[i], a[rev[i]]);
    for (int k = 1; k < n; k *= 2) {
        for (int i = 0; i < n; i += 2 * k) {
            for (int j = 0; j < k; ++j) {
                ll z = rt[j + k] * a[i + j + k] % mod, &ai = a[i + j];

```

```

                a[i + j + k] = ai - z + (z > ai ? mod : 0);
                ai += (ai + z >= mod ? z - mod : z);
            }
        }
    }
}

vector<ll> multi(const vector<ll> &a, const vector<ll> &b) {
    if (a.empty() || b.empty()) return {};
    int s = static_cast<ll>(a.size()) + static_cast<ll>(b.size()) - 1, B =
        32 - __builtin_clz(s), n = 1 << B;
    int inv = modpow(n, mod - 2, mod);
    vector<ll> L(a), R(b), out(n);
    L.resize(n), R.resize(n);
    ntt(L), ntt(R);
    for (int i = 0; i < n; ++i) out[-i & (n - 1)] = L[i] * R[i] % mod *
        inv % mod;
    ntt(out);
    return {out.begin(), out.begin() + s};
}

vector<int> poly_pow(vector<int> poly, int p, int limit = 1e9) {
    vector<int> ans{1};
    while (p) {
        if(p&1) ans = multi(ans, poly);
        poly = multi(poly, poly);
        ans.resize(limit + 1);
        poly.resize(limit + 1);
        p >>= 1;
    }
    return ans;
}

```

4.2 MO

MO Algorithm

// MO → $O(N+Q \sqrt{N}) \leq 10^5$

```

const int N = 1e5+5, M = 1e5+5;
int n, m;

```

```

int nums[N], q_ans[M];

struct query {
    int idx, block_idx, l, r;

    query() = default;
    query(int _l, int _r, int _idx) {
        idx = _idx;
        r = _r - 1;
        l = _l - 1;
        block_idx = _l / sqrt(n);
    }

    bool operator <(const query & y) const {
        if(y.block_idx == block_idx) return r < y.r;
        return block_idx < y.block_idx;
    }
};

int freq[N], ans;

void add(int idx) {
    freq[nums[idx]]++;
    if (freq[nums[idx]] == 2) ans++;
}

void remove(int idx) {
    freq[nums[idx]]--;
    if (freq[nums[idx]] == 1) ans--;
}

cin >> n >> m;
for (int i = 0; i < n; ++i) cin >> nums[i];

vector<query> Query(m);
for (int i = 0; i < m; ++i) {
    int l, r; cin >> l >> r;
    Query[i] = query(l, r, i);
}

sort(Query.begin(), Query.end());
int l0 = 1, r0 = 0;
for (int i = 0; i < m; ++i) {

```

```

    while (l0 < Query[i].l) remove(l0++);
    while (l0 > Query[i].l) add(--l0);
    while (r0 < Query[i].r) add(++r0);
    while (r0 > Query[i].r) remove(r0--);
    q_ans[Query[i].idx] = ans;
}
for (int i = 0; i < m; ++i) {
    cout << q_ans[i] << '\n';
}

```

4.3 Intervals

4.3.1 Prefix Sum (L, R) intervals

Prefix Sum (L, R) intervals

// NOTE: works fine with small n or with large memory

```

int main() {
    int n, k;
    cin >> n >> k;

    vector<int> a(n + 1);
    vector<vector<int>> rangesPrefix(n + 1, vector<int>(n + 1, 0));
    for (int i = 1; i <= n; ++i)
        cin >> a[i];

    int l = 1, r = 1, sum = 0;
    // validate your intervals
    // here the intervals are the ones that have a sum of k
    while (r <= n) {
        sum += a[r];

        while (sum > k) {
            sum -= a[l];
            ++l;
        }

        while (l <= r && a[l] == 0) {
            if (sum != k)

```

```

        break;

        rangesPrefix[r][l]++;

        ++l;
    }

    if (sum == k) {
        rangesPrefix[r][l]++;
    }

    ++r;
}

// prefix sum the columns
for (int i = 1; i <= n; ++i) {
    for (int j = n - 1; j >= 0; --j) {
        rangesPrefix[i][j] += rangesPrefix[i][j + 1];
    }
}

// prefix sum the rows
for (int i = 0; i <= n; ++i) {
    for (int j = 1; j <= n; ++j) {
        rangesPrefix[j][i] += rangesPrefix[j - 1][i];
    }
}

int q; cin >> q;

while (q--) {
    cin >> l >> r;
    // answer the number of intervals (X, Y) X <= Y that are included
    // between L, R
    cout << rangesPrefix[r][l] - rangesPrefix[l - 1][l] << endl;
}

```

4.3.2 Find subarrays intervals that sum to K Using Map

Find subarray intervals that sum to K Using Map

```

int n, k;
cin >> n >> k;

vector<int> a(n + 1);
vector<pair<int, int>> rng;
for (int i = 1; i <= n; ++i)
    cin >> a[i];

map<int, set<int>> prev;
int currSum = 0;

for (int i = 1; i <= n; ++i) {
    currSum += a[i];
    if (currSum == k) {
        rng.push_back({1, i});
    }
    if (prev.find(currSum - k) != prev.end()) {
        for (auto &j : prev[currSum - k]) {
            rng.push_back({j + 1, i});
        }
    }
    prev[currSum].insert(i);
}

```

4.4 Ad-hoc

4.4.1 Find duplicate

Find duplicate using XOR

```

int findDuplicate(int arr[] , int n)
{
    int answer=0;
    //XOR all the elements with 0
    for(int i=0; i<n; i++){
        answer=answer^arr[i];
    }
    //XOR all the elements with no from 1 to n
    // i.e  answer^0 = answer
    for(int i=1; i<n; i++){

```

```

    answer=answer^i;
}
return answer;
}

```

4.5 Sorting Algorithms

4.5.1 Radix Sort

Radix Sort

```

// O(n + b), where n is the number of elements and b is the base of the
// number system
// A function to do counting sort of arr[] according to the digit
// represented by exp.
void countingSort(vector<int>& arr, int exp) {
    int n = arr.size();
    vector<int> output(n); // output array
    int count[10] = {0};

    // Store count of occurrences in count[]
    for (int i = 0; i < n; i++)
        count[(arr[i] / exp) % 10]++;

    // Change count[i] so that count[i] now contains the actual
    // position of this digit in output[]
    for (int i = 1; i < 10; i++)
        count[i] += count[i - 1];

    // Build the output array
    for (int i = n - 1; i >= 0; i--) {
        output[count[(arr[i] / exp) % 10] - 1] = arr[i];
        count[(arr[i] / exp) % 10]--;
    }

    // Copy the output array to arr[], so that arr now
    // contains sorted numbers according to the current digit
    for (int i = 0; i < n; i++)
        arr[i] = output[i];
}

```

```

// The main function to that sorts arr[] of size n using Radix Sort
void radixSort(vector<int>& arr) {
    // Find the maximum number to know the number of digits
    int mx = *max_element(arr.begin(), arr.end());

    // Do counting sort for every digit. Note that instead
    // of passing the digit number, exp is passed. exp is 10^i
    // where i is the current digit number
    for (int exp = 1; mx / exp > 0; exp *= 10)
        countingSort(arr, exp);
}

```

4.5.2 Counting Sort

Counting Sort

```

// O(N+M), where N and M are the size of inputArray[] and countArray[]
// The main function that sorts arr[] of size n using Counting Sort
void countingSort(vector<int>& arr) {
    int maxElement = *max_element(arr.begin(), arr.end());
    int minElement = *min_element(arr.begin(), arr.end());
    int range = maxElement - minElement + 1;

    vector<int> count(range), output(arr.size());
    for (int i = 0; i < arr.size(); i++)
        count[arr[i] - minElement]++;

    for (int i = 1; i < count.size(); i++)
        count[i] += count[i - 1];

    for (int i = arr.size() - 1; i >= 0; i--) {
        output[count[arr[i] - minElement] - 1] = arr[i];
        count[arr[i] - minElement]--;
    }

    for (int i = 0; i < arr.size(); i++)
        arr[i] = output[i];
}

```

4.6 Apply permutation k times

permutation k times

```
// Applying a permutation k times
// n log k

vector<int> applyPermutation(vector<int> sequence, vector<int> permutation)
{
    vector<int> newSequence(sequence.size());
    for(int i = 0; i < sequence.size(); i++) {
        newSequence[i] = sequence[permutation[i]];
    }
    return newSequence;
}

vector<int> permute(vector<int> sequence, vector<int> permutation, long
long k) {
    while (k > 0) {
        if (k & 1) {
            sequence = applyPermutation(sequence, permutation);
        }
        permutation = applyPermutation(permutation, permutation);
        k >>= 1;
    }
    return sequence;
}
```

4.7 Strings

4.7.1 Strings Hashing Utils

Hashing

```
// #define int long long

struct PreHash {
    vector<int> pow, invPow;
    const int MOD, BASE;

    int modExp(int base, int exp) const {
        int res = 1;
```

```
        while (exp > 0) {
            if (exp % 2 == 1)
                res = 1LL * res * base % MOD;
            base = 1LL * base * base % MOD;
            exp /= 2;
        }
        return res;
    }

explicit PreHash(const int n, const int MOD, const int BASE) : MOD(MOD),
BASE(BASE) {
    pow.resize(n);
    invPow.resize(n);

    pow[0] = 1;
    invPow[0] = 1;
    const int invBase = modExp(BASE, MOD - 2);

    for (int i = 1; i < n; ++i) {
        pow[i] = 1LL * pow[i - 1] * BASE % MOD;
        invPow[i] = 1LL * invPow[i - 1] * invBase % MOD;
    }
};

struct Hash {
    vector<int> pref;
    const PreHash* pre;
    int n;

    explicit Hash(const string& s, const PreHash& p) : pre(&p) {
        n = s.size();
        if (s.empty()) return;

        pref.resize(n);
        pref[0] = s[0] % pre->MOD;

        for (int i = 1; i < n; ++i) {
            pref[i] = (pref[i - 1] + 1LL * s[i] * pre->pow[i]) % pre->MOD;
        }

        int getHashRange(int l, int r) const {
```



```

    int ret = pref[r];
    if (l > 0) ret = (ret - pref[l - 1] + pre->MOD) % pre->MOD;
    // if (ret < 0) ret += pre->MOD;
    return 1LL * ret * pre->invPow[l] % pre->MOD;
}

};

struct HashWhole {
    int pref, suff;
    const PreHash* pre;
    int n;

    explicit HashWhole(const string& s, const PreHash& p) : pre(&p) {
        n = s.size();
        if (s.empty()) return;

        pref = s[0] % pre->MOD;
        for (int i = 1; i < n; ++i) {
            pref = (pref + 1LL * s[i] * pre->pow[i]) % pre->MOD;
        }

        suff = s[n - 1] % pre->MOD;
        for (int i = n - 2; i >= 0; --i) {
            suff = (suff + 1LL * s[i] * pre->pow[n - 1 - i]) % pre->MOD;
        }
    }

    void mergeHash(const HashWhole& other) {
        pref = (1LL * pref) + (other.pref * 1LL * (pre->pow[n] % pre->MOD)
            % pre->MOD);
        pref %= pre->MOD;

        suff = ((other.suff * 1LL) + 1LL * suff * (pre->pow[other.n] % pre->MOD)) % pre->MOD;
        suff %= pre->MOD;

        n += other.n;
    }

    bool isPalindrome() const {
        return suff == pref;
    }
}

```

```

};

struct Hasher {
    const PreHash* pre;
    explicit Hasher(const PreHash& p) : pre(&p) {}

    int hash(const string& s, int st, const int end) const {
        if (s.empty() || st > end) return 0;

        int pref = s[st] % pre->MOD, i = 1;
        for (st = st + 1; st < end; ++st) {
            pref = (pref + 1LL * s[st] * pre->pow[i++]) % pre->MOD;
        }

        return pref;
    }
};

constexpr int N = 3e5 + 10;
const PreHash pre2(N, 1e9 + 9, 107);
const PreHash pre1(N, 1e9 + 7, 37);

// #undef int long long

```

4.7.2 KMP

KMP

```

vector<int> kmp(const string& pat) {
    int n = pat.size();
    vector<int> pi(n);
    pi[0] = -1;

    for (int i = 1; i < n; i++){
        int j = pi[i - 1];
        while (j >= 0 && pat[j] != pat[i - 1]) j = pi[j];
        pi[i] = j + 1;
    }

    return pi;
}

```

```

}

vector<int> find_matches(const string& text, const string& pat) {
    int n = pat.size(), m = text.size();
    string s = pat + "$" + text + "$";

    vector<int> pi = kmp(s), ans;
    for (int i = 0; i <= m; i++)
        if (pi[i + n + 1] == n)
            ans.push_back(i - n);

    return ans;
}

```

4.7.3 Manachers Algorithm

Manachers Algorithm

```

struct Manacher {
    vector<int> p[2];
    // p[1][i] = (max odd length palindrome centered at i) / 2 [floor
    // division]
    // p[0][i] = same for even, it considers the right center
    // e.g. for s = "abbabba", p[1][3] = 3, p[0][2] = 2
    Manacher(string s) {
        int n = s.size();
        p[0].resize(n + 1);
        p[1].resize(n);
        for (int z = 0; z < 2; z++)
            for (int i = 0, l = 0, r = 0; i < n; i++) {
                int t = r - i + !z;
                if (i < r) p[z][i] = min(t, p[z][l + t]);
                int L = i - p[z][i], R = i + p[z][i] - !z;
                while (L >= 1 && R + 1 < n && s[L - 1] == s[R + 1]) p[z][i]++, L--,
                    R++;
                if (R > r) l = L, r = R;
            }
    }
    bool is_palindrome(int l, int r) {
        int mid = (l + r + 1) / 2, len = r - l + 1;
        return 2 * p[len % 2][mid] + len % 2 >= len;
    }
}

```

```

}
};

```

5 Data Structures

5.1 Monotonuc

5.1.1 Min Aggregation Deque

Min Aggregation Deque

```

struct minstack {
    stack<pair<int, int>> st;
    int getmin() { return st.top().second; }
    bool empty() { return st.empty(); }
    int size() { return st.size(); }
    void push(int x) {
        int mn = x;
        if (!empty()) mn = min(mn, getmin());
        st.push({x, mn});
    }
    void pop() { st.pop(); }
    int top() { return st.top().first; }
    void swap(minstack &x) { st.swap(x.st); }
};

```

```

struct mindeque {
    minstack l, r, t;
    void rebalance() {
        bool f = false;
        if (r.empty()) {
            f = true;
            l.swap(r);
        }
        int sz = r.size() / 2;
        while (sz-- > 0) {
            t.push(r.top());
            r.pop();
        }
        while (!r.empty()) {

```

```

        l.push(r.top());
        r.pop();
    }
    while (!t.empty()) {
        r.push(t.top());
        t.pop();
    }
    if (f) l.swap(r);
}
int getmin() {
    if (l.empty()) return r.getmin();
    if (r.empty()) return l.getmin();
    return min(l.getmin(), r.getmin());
}
bool empty() { return l.empty() && r.empty(); }
int size() { return l.size() + r.size(); }
void push_front(int x) { l.push(x); }
void push_back(int x) { r.push(x); }
void pop_front() {
    if (l.empty()) rebalance();
    l.pop();
}
void pop_back() {
    if (r.empty()) rebalance();
    r.pop();
}
int front() {
    if (l.empty()) rebalance();
    return l.top();
}
int back() {
    if (r.empty()) rebalance();
    return r.top();
}
void swap(mindeque &x) {
    l.swap(x.l);
    r.swap(x.r);
}
};

```

5.2 Strings

5.2.1 Trie (Prefix Tree)

Basic Implementation

```

#define MAX_CHAR 26

struct TrieNode {
    TrieNode *pTrieNode[MAX_CHAR]{};
    bool isWord;

    TrieNode() {
        isWord = false;
        fill(pTrieNode, pTrieNode + 26, (TrieNode *) NULL);
    }

    virtual ~TrieNode() = default;
};

class Trie {
private:
    TrieNode *root;
public:
    Trie() {
        root = new TrieNode();
    }

    virtual ~Trie() = default;

    TrieNode *getTrieNode() {
        return this->root;
    }

    void insert(const string &word) {
        TrieNode *current = root;
        for (char c: word) {
            int i = c - 'a';
            if (current->pTrieNode[i] == nullptr)
                current->pTrieNode[i] = new TrieNode();
            current = current->pTrieNode[i];
        }
        current->isWord = true;
    }

```

```

}

bool search(const string &word) {
    TrieNode *current = root;
    int ch = 0;
    for (char c: word) {
        ch = c - 'a';
        if (current->pTrieNode[ch] == nullptr)
            return false;
        current = current->pTrieNode[ch];
    }
    return current->isWord;
}

bool startsWith(const string &prefix) {
    TrieNode *current = root;
    int ch = 0;
    for (char c: prefix) {
        ch = c - 'a';
        if (current->pTrieNode[ch] == nullptr)
            return false;
        current = current->pTrieNode[ch];
    }
    return true;
}
};

```

5.3 Range Queries

5.3.1 Segment Tree

Basic Implementation

```

struct Node {
    long long val;
};

struct SegTree {
private:
    const Node NEUTRAL = {INT_MIN};

```

```

static Node merge(const Node& x1, const Node& x2) {
    return {x1.val + x2.val};
}

void set(const int& idx, const int& val, int x, int lx, int rx) {
    if (rx - lx == 1) return void(values[x].val = val);

    int mid = (rx + lx) / 2;

    if (idx < mid)
        set(idx, val, 2 * x + 1, lx, mid);
    else
        set(idx, val, 2 * x + 2, mid, rx);

    values[x] = merge(values[2 * x + 1], values[2 * x + 2]);
}

Node query(const int& l, const int& r, int x, int lx, int rx) {
    if (lx >= r || l >= rx) return NEUTRAL;
    if (lx >= l && rx <= r) return values[x];

    int mid = (rx + lx) / 2;

    return merge(query(l, r, 2 * x + 1, lx, mid), query(l, r, 2 * x + 2, mid, rx));
}

void build(vector<int> &a, int x, int lx, int rx) {
    if (rx - lx == 1) {
        if (lx < a.size()) {
            values[x].val = a[lx];
        }
        return;
    }
    int m = (lx + rx) / 2;
    build(a, 2 * x + 1, lx, m);
    build(a, 2 * x + 2, m, rx);
    values[x] = merge(values[2 * x + 1], values[2 * x + 2]);
}

void assign_range(int l, int r, int node, int lx, int rx, int time,
    int val) {
    if (lx > r || l > rx) return;
    if (lx >= l && rx <= r) {

```

```

        lazy[node] = {time, val};
        return;
    }
    int mid = (lx+rx) / 2;

    assign_range(1, r, 2*node+1, lx, mid, time, val);
    assign_range(1, r, 2*node+2, mid+1, rx, time, val);
}

pair<int, int> point_query(int lx, int rx, int node, int idx) {
    if(rx == lx) return lazy[node];
    int mid = (lx+rx) / 2;

    if(idx <= mid) {
        auto x = point_query(lx, mid, 2*node+1, idx);
        if(x.first > lazy[node].first) return x;
        return lazy[node];
    }
    auto x = point_query(mid+1, rx, 2*node+2, idx);
    if(x.first > lazy[node].first) return x;
    return lazy[node];
}

public:
    int size{};
    vector<Node> values;

    void build(vector<int> &a) {
        build(a, 0, 0, size);
    }

    void init(int _size) {
        size = 1;
        while (size < _size) size *= 2;
        values.assign(2 * size, NEUTRAL);
    }

    void set(int idx, int val) {
        set(idx, val, 0, 0, size);
    }

    Node query(const int& l, const int& r) {
        return query(1, r, 0, 0, size);
    }

```

```

    }
};

```

5.3.2 Lazy Propagation

Lazy Propagation

```

struct SegTree {
private:
    void propagate(int lx, int rx, int node) {
        if(!lazy[node]) return;

        if(lx != rx) {
            lazy[2*node+1] = lazy[node];
            lazy[2*node+2] = lazy[node];
        }
        values[node] = lazy[node] * (rx - lx + 1);
        lazy[node] = 0;
    }

    // assign val in range [l, r]
    void update_range(int l, int r, int node, int lx, int rx, int val,
        bool f) {
        propagate(lx, rx, node);
        if (lx > r || l > rx) return;
        if (lx >= l && rx <= r) {
            lazy[node] = val;
            propagate(lx, rx, node);
            return;
        }
        int mid = (lx+rx) / 2;

        update_range(1, r, 2*node+1, lx, mid, val, f);
        update_range(1, r, 2*node+2, mid+1, rx, val, f);
        values[node] = values[2*node+1] + values[2*node+2];
    }

    // get sum in range [l, r]
    int range_query(int l, int r, int lx, int rx, int node) {
        propagate(lx, rx, node);
        if (lx > r || l > rx) return 0;
    }

```

```

        if (lx >= 1 && rx <= r) return values[node];

        int mid = (lx+rx) / 2;
        return range_query(l, r, lx, mid, 2*node+1) + range_query(l, r, mid
            +1, rx, 2*node+2);
    }

public:
    int size{};
    vector<int> values, lazy;

    void init(int _size) {
        size = 1;
        while (size < _size) size *= 2;
        values.assign(2 * size, 0);
        lazy.assign(2 * size, 0);
    }

    void update_range(int l, int r, int v, bool f) {
        update_range(l, r, 0, 0, size-1, v, f);
    }

    int range_query(int l, int r) {
        return range_query(l, r, 0, size-1, 0);
    }
};

```

5.3.3 Fenwick Tree

Fenwick Tree

```

struct Fenwick {
    // One Based
    vector<int> tree;

    explicit Fenwick(int n) {tree.assign(n + 5, {});}

    // Computes the prefix sum from [1, i], O(log(n))
    int query(int i) {
        int res = 0;
        while (i > 0) {

```

```

            res += tree[i];
            i &= ~(i & -i);
        }
        return res;
    }

    int query(int l, int r) {
        return query(r) - query(l-1);
    }

    // Get the value at index i
    int get(int i) {
        return query(i, i);
    }

    // Add 'v' to index 'i', O(log(n))
    void update(int i, int v) {
        while (i < tree.size()) {
            tree[i] += v;
            i += (i & -i);
        }
    }

    // Update range, Point query
    // To get(k) do prefix sum [1, k] and in insert update_range(i, i, a[i
    ])
    void update_range(int l, int r, int v) {
        update(l, v);
        update(r+1, -v);
    }
};

```

5.3.4 Fenwick UpdateRange

BIT UpdateRange

```

struct BITUpdateRange {
private:
    int n;
    vector<int> B1, B2;

```

```

void add(vector<int> &b, int idx, int x) {
    while (idx <= n) {
        b[idx] += x;
        idx += idx & -idx;
    }
}

int sum(vector<int> &b, int idx) {
    int total = 0;
    while (idx > 0) {
        total += b[idx];
        idx &= ~(idx & -idx);
    }
    return total;
}

int prefix(int idx) {
    return sum(B1, idx) * idx - sum(B2, idx);
}

public:
explicit BITUpdateRange(int n) : n(n) {
    B1.assign(n + 1, {});
    B2.assign(n + 1, {});
}

void update(int l, int r, int x) {
    add(B1, l, x);
    add(B1, r + 1, -x);
    add(B2, l, x * (l - 1));
    add(B2, r + 1, -x * r);
}

int query(int i) {
    return prefix(i) - prefix(i - 1);
}

int query(int l, int r) {
    return prefix(r) - prefix(l - 1);
}
};

```

5.3.5 2D BIT

2D BIT

```

struct BIT2D {
    int n, m;
    vector<vector<int>> bit;

    BIT2D(int n, int m) : n(n), m(m) {
        bit.assign(n + 2, vector<int>(m + 2));
    }

    void update(int x, int y, int val) {
        for (; x <= n; x += x & -x) {
            for (int i = y; i <= m; i += i & -i) {
                bit[x][i] += val;
            }
        }
    }

    int prefix(int x, int y) {
        int res = 0;
        for (; x > 0; x &= ~(x & -x)) {
            for (int i = y; i > 0; i &= ~(i & -i)) {
                res += bit[x][i];
            }
        }
        return res;
    }

    int query(int sx, int sy, int ex, int ey) {
        int ans = 0;
        ans += prefix(ex, ey);
        ans -= prefix(ex, sy - 1);
        ans -= prefix(sx - 1, ey);
        ans += prefix(sx - 1, sy - 1);
        return ans;
    }
};

```

5.3.6 Sparse Table

Impl with the index

```
// storing the index also
struct SNode {
    int val;
    int index;
};

class SparseTable {
private:
    vector<vector<SNode>> table;

    function<SNode(const SNode&, const SNode&)> merge;

    static SNode StaticMerge(const SNode& a, const SNode& b) {
        return a.val < b.val ? a : b;
    }

public:
    explicit SparseTable(const vector<int>& arr, const function<SNode(
        const SNode&, const SNode&)>& mergeFunc = StaticMerge) {
        int n = static_cast<int>(arr.size());
        int log_n = static_cast<int>(log2(n)) + 1;
        this->merge = mergeFunc;

        table.resize(n, vector<SNode>(log_n));

        for (int i = 0; i < n; i++) {
            table[i][0] = {arr[i], i};
        }

        for (int j = 1; (1 << j) <= n; j++) {
            for (int i = 0; i + (1 << j) <= n; i++) {
                table[i][j] = mergeFunc(table[i][j - 1], table[i + (1 << (j
                    - 1))] [j - 1]);
            }
        }
    }

    SNode query(int left, int right) {
        int j = static_cast<int>(log2(right - left + 1));
```

```
        return merge(table[left][j], table[right - (1 << j) + 1][j]);
    }

    // query in O(log(n)) if its could't apply to Sparse Table directly
    T query_log(int l, int r){
        int len = r - l + 1;
        T ans;
        for(int i = 0; l <= r; i++){
            if (len & (1 << i)){
                ans = merge(ans, table[i][1]);
                l+= (1 << i);
            }
        }
    }
};

int main(void) {
    int n;
    cin >> n;
    vector<int> arr(n);
    for (auto& element : arr) cin >> element;

    SparseTable minSt(arr, [](const SNode& a, const SNode& b) -> SNode {
        return a.val < b.val ? a : b;
    });

    SparseTable maxSt(arr, [](const SNode& a, const SNode& b) -> SNode {
        return a.val > b.val ? a : b;
    });
}
```

5.3.7 Sparse Table (Shorter Version)

Impl

```
template<class T>
struct Rmq {
    vector<vector<T>> jmp;

    // vector is 0-based indexed
```



```

Rmq(const vector<T>& V) : jmp(1, V) {
    for (int pw = 1, k = 1; pw * 2 <= V.size(); pw *= 2, ++k) {
        jmp.emplace_back(V.size() - pw * 2 + 1);
        for(int j = 0; j < jmp[k].size(); j++)
            jmp[k][j] = (jmp[k - 1][j] | jmp[k - 1][j + pw]);
    }
}

// query (a, b] inclusive exclusive
T query(int a, int b) {
    // assert(a < b);
    int dep = 31 - __builtin_clz(b - a);
    return (jmp[dep][a] | jmp[dep][b - (1 << dep)]);
}
};

```

```

int query(int l, int r){
    int ret = 00;
    while(l <= r) {
        if(l % sq == 0 && l + sq <= r) {
            ret = min(ret, ans[l / sq]);
            l += sq;
        }else {
            ret = min(ret, arr[l]);
            l++;
        }
    }
    return ret;
}

```

5.3.8 Sqrt Decomp

Impl

```

#define OO 1e18

const int sz = 2e5 + 5;
const int sq = 500;

int arr[sz] = {};
int ans[sq] = {};

void pre() {
    fill(ans, ans + sq, OO);
    for(int i = 0; i < sz; i++) {
        ans[i / sq] = min(ans[i / sq], arr[i]);
    }
}

// can be O(1) with inversable operations, else it's sqrt
void update(int k, int x) {
    arr[k] = x;
    int start = k / sq;
    ans[start] = *min_element(arr + (start * sq), arr + (start + 1) * sq);
}

```

5.4 Ordered Set

Ordered Set

```

#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/tree_policy.hpp>

using namespace __gnu_pbds;

template<typename T>
using ordered_set = tree<T, null_type, less<T>, rb_tree_tag,
    tree_order_statistics_node_update>;

template <class T>
using ordered_multiset = tree<T, null_type, CUSTUM_COMPARE, rb_tree_tag,
    tree_order_statistics_node_update>;

void erase_set(ordered_set &os, int v) {
    // Number of elements less than v
    int rank = os.order_of_key(v);

    auto it = os.find_by_order(rank);
    os.erase(it);
}

// Returns iterator to 0-th

```

```
// largest element in the set
cout << *S.find_by_order(0) << " ";
```

```
// Returns iterator to 2-nd
// largest element in the set
cout << *S.find_by_order(2);
```

5.5 Custom Compare Functions

Custom Compare functions

```
template<class T>
struct custom_compare {
    bool operator()(const T& a, const T& b) const {
        if (a == b) return true; // Keep duplicates
        return a > b;
    }
};

//REF: GFG
class CustomComparator {
public:
    CustomComparator(int baseValue) : baseValue_(baseValue) {}

    bool operator()(int a, int b) const {
        // Custom comparison logic involving state
        return (a % baseValue_) < (b % baseValue_);
    }

private:
    int baseValue_;
};

// OR through capture by reference (capture clauses)
auto compare = [&](char a, char b) { return localStructure[a] >
    localStructure[b]; };
```

5.6 Median Finder

Median Finder

```
struct MedianFinder {
    multiset<ll> low, up;
    ll sumLow = 0, sumUp = 0;

    void insert(ll val) {
        if (low.empty() || val <= *low.rbegin()) {
            low.insert(val);
            sumLow += val;
        } else {
            up.insert(val);
            sumUp += val;
        }
        rebalance();
    }

    void erase(ll val) {
        if (low.find(val) != low.end()) {
            low.erase(low.find(val));
            sumLow -= val;
        } else if (up.find(val) != up.end()) {
            up.erase(up.find(val));
            sumUp -= val;
        }
        rebalance();
    }

    void rebalance() {
        // Ensure low has (n+1)/2 elements
        while (low.size() > up.size() + 1) {
            ll val = *low.rbegin();
            low.erase(prev(low.end()));
            sumLow -= val;
            up.insert(val);
            sumUp += val;
        }
        while (low.size() < up.size()) {
            ll val = *up.begin();
            up.erase(up.begin());
            sumUp -= val;
```

```

        low.insert(val);
        sumLow += val;
    }
}

double median() const {
    if (low.size() == up.size()) {
        return (*low.rbegin() + *up.begin()) / 2.0;
    }
    return *low.rbegin();
}

ll balanceCost() {
    return sumUp - sumLow +
        ((low.size() + up.size()) % 2 == 0 ? 0 : this->median());
}
};

```

5.7 Binary Trie

Binary Trie

```

template <typename IntegerType = int, int INT_SIZE = 31, int capacity = 1
e5>
struct BinaryTrie {
    int nxt[capacity][2] {}, freq[capacity] {}, nodesCount;

    BinaryTrie() {
        nodesCount = 0;
    }

    void add(const IntegerType& x) {
        int node = 0;
        for (int i = INT_SIZE; i >= 0; --i) {
            bool bit = (x >> i) & 1;

            if (nxt[node][bit] == 0)
                nxt[node][bit] = ++nodesCount;

            node = nxt[node][bit];
            ++freq[node];
        }
    }
};

```

```

    }
}

void erase(const IntegerType& x) {
    int node = 0;
    for (int i = INT_SIZE; i >= 0; --i) {
        bool bit = (x >> i) & 1;
        node = nxt[node][bit];
        --freq[node];
    }
}

IntegerType getMin(const IntegerType& x) {
    IntegerType res = 0;
    int node = 0;
    for (int i = INT_SIZE; i >= 0; --i) {
        bool bit = (x >> i) & 1;
        if (nxt[node][bit] != 0 && freq[nxt[node][bit]]) {
            node = nxt[node][bit];
        }
        else {
            node = nxt[node][bit ^ 1];
            res |= (1LL << i);
        }
    }

    return res;
}

IntegerType getMax(const IntegerType& x) {
    IntegerType res = 0;
    int node = 0;
    for (int i = INT_SIZE; i >= 0; --i) {
        bool bit = (x >> i) & 1;
        if (nxt[node][bit ^ 1] != 0 && freq[nxt[node][bit ^ 1]]) {
            node = nxt[node][bit ^ 1];
            res |= (1LL << i);
        }
        else {
            node = nxt[node][bit];
        }
    }
}

```

```

    return res;
}
};

```

6 Counting Principles

6.1 nCr

$$C(n, k) = \frac{n!}{(n-k)!k!} = \frac{n * (n-1) * (n-2) * \dots * (n-k+1)}{k!}$$

6.1.1 Fast nCr

$$C(n, k) = \frac{n * (n-1) * (n-2) * \dots * (n-k+1)}{1 * 2 * 3 * \dots * k} = \prod_{i=0}^{k-1} \frac{n-i}{i+1} = \prod_{i=0}^{k-1} (n-i)(i+1)^{-1}$$

Fast nCr

```

int nCr(const int& n, const int& r) {
    double res = 1;
    for (int i = 1; i <= r; ++i)
        res = res * (n - r + i) / i;
    return (int)(res + 0.01);
}

```

6.1.2 Method 1: Pascal's Triangle (Dynamic Programming) - $\mathcal{O}(n^2)$

nCk using dp

// REF: USACO guide

```

/** @return nCk mod p using dynamic programming */
int binomial(int n, int k, int p) {
    // dp[i][j] stores iCj
    vector<vector<int>> dp(n + 1, vector<int>(k + 1, 0));

    // base cases described above

```

```

for (int i = 0; i <= n; i++) {
    /*
     * i choose 0 is always 1 since there is exactly one way
     * to choose 0 elements from a set of i elements
     * (don't choose anything)
     */
    dp[i][0] = 1;
    /*
     * i choose i is always 1 since there is exactly one way
     * to choose i elements from a set of i elements
     * (choose every element in the set)
     */
    if (i <= k) { dp[i][i] = 1; }
}

```

```

for (int i = 0; i <= n; i++) {
    for (int j = 1; j <= min(i, k); j++) {
        if (i != j) { // skips over the base cases
            // uses the recurrence relation above
            dp[i][j] = (dp[i-1][j-1] + dp[i-1][j]) % p;
        }
    }
}

return dp[n][k]; // returns nCk modulo p
}

```

6.1.3 Method 2: Factorial Definition (Modular Inverses) - $\mathcal{O}(n + \log MOD)$

nCk using Modular Inverses

// REF: USACO guide

```
const int MAXN = 1e6;
```

```
long long fac[MAXN + 1];
long long inv[MAXN + 1];
```

```

/** @return x^n modulo m in O(log p) time. */
long long exp(long long x, long long n, long long m) {

```

```

x %= m; // note: m * m must be less than 2^63 to avoid ll overflow
long long res = 1;
while (n > 0) {
    if (n % 2 == 1) { res = res * x % m; }
    x = x * x % m;
    n /= 2;
}
return res;
}

/** Precomputes n! from 0 to MAXN. */
void factorial(long long p) {
    fac[0] = 1;
    for (int i = 1; i <= MAXN; i++) { fac[i] = fac[i - 1] * i % p; }
}

/**
 * Precomputes all modular inverse factorials
 * from 0 to MAXN in O(n + log p) time
 */
void inverses(long long p) {
    inv[MAXN] = exp(fac[MAXN], p - 2, p);
    for (int i = MAXN; i >= 1; i--) { inv[i - 1] = inv[i] * i % p; }
}

/** @return nCr mod p */
long long choose(long long n, long long r, long long p) {
    return fac[n] * inv[r] % p * inv[n - r] % p;
}

int main() {
    factorial();
    inverses();
    int n;
    cin >> n;
    for (int i = 0; i < n; i++) {
        int a, b;
        cin >> a >> b;
        cout << choose(a, b) << '\n';
    }
}

```

7 Graph Theory

7.1 Shortest Path algorithms

7.1.1 Dijkstra Algorithm

Dijkstra Implementation

```

#define INF (1e18) // for int defined as ll

int n, m;
vector<vector<pair<int, int>>> adj;
vector<int> cost;
vector<int> parent;

void dijkstra(int startNode = 1) {
    priority_queue<pair<ll, int>, vector<pair<ll, int>>, greater<>> pq;

    cost[startNode] = 0;
    pq.emplace(0, startNode);

    while (!pq.empty()) {
        int u = pq.top().second;
        ll d = pq.top().first;
        pq.pop();

        if (d > cost[u]) continue;

        for (auto &p: adj[u]) {
            int v = p.first;
            int w = p.second;
            if (cost[v] > cost[u] + w) {
                cost[v] = cost[u] + w;
                parent[v] = u;
                pq.emplace(cost[v], v);
            }
        }
    }
}

void run_test_case(int testNum) {
    cin >> n >> m;
}

```

```

adj.assign(n + 1, {});
cost.assign(n + 1, INF);
parent.assign(n + 1, -1);

while (m--) {
    // Read Edges
}

dijkstra();

if (cost[n] == INF) {
    cout << -1 << endl; // not connected {Depends on you use case}
    return;
}

stack<int> ans;
for (int v = n; v != -1; v = parent[v]) ans.push(v);

while (!ans.empty()) { // printing the path
    cout << ans.top() << ' ';
    ans.pop();
}
cout << endl;
}

```

7.1.2 Floyd Warshal Algorithm

FloydWarshal Implementation

```

int main() {
    int n, m; cin >> n >> m;
    vector<vector<int>> adj(n + 1, vector<int>(n + 1, 2e9));
    for (int i = 0; i < n; i++) adj[i][i] = 0;

    while(m--) {
        int u, v, w;
        cin >> u >> v >> w;
        adj[u][v] = min(adj[u][v], w);
        adj[v][u] = min(adj[v][u], w);
    }
}

```

```

for (int mid = 1; mid <= n; mid++) {
    for (int start = 1; start <= n; start++) {
        for (int end = 1; end <= n; end++) {
            adj[start][end] = min(adj[start][end], adj[start][mid] +
                                   adj[mid][end]);
        }
    }
}

return 0;
}

```

7.1.3 Bellman Ford Algorithm

BellmanFord Implementation

```

vector<vector<pair<int, int>>> &adj

vector<long long> BellmanFord(int src) {
    int n = (int)adj.size();
    vector<long long> dist(n, 2e18);

    dist[src] = 0;
    for (int it = 0; it < n-1; it++) {
        bool in = false;
        for (int i = 0; i < n; i++) { // iterate on the edges
            for (auto &[j, w] : adj[i]) {
                if (dist[j] > dist[i] + w) {
                    in = true;
                    dist[j] = dist[i] + w;
                }
            }
        }
        if (!in) return dist;
    }

    for (int i = 0; i < n; i++) {
        for (auto &[j, w] : adj[i]) {
            if (dist[j] > dist[i] + w) { //negative cycle
                return vector<long long>(n, -1); // or any flag
            }
        }
    }
}

```

```

    }
}

return dist;
}

```

7.2 Cycle Detection

7.2.1 DFS Implementation

DFS Implementation

```

// return true with number of nodes in the cycle, either odd cycle or even
bool cycle_detection(unordered_map<int, vector<int>> &graph, int source,
    int par, unordered_map<int, bool> vis, int c){
    if(vis[source]) return true;

    vis[source] = true;

    for(int v: graph[source]){
        if(v != par){
            c++;
            if(dfs(graph, v, source, vis, c)) return true;
        }
    }
    return false;
}

```

7.2.2 Another way for undirected graphs

Another way for undirected graphs

```

// this is true only for undirected graphs
bool dfs1(int cur, int par) {
    bool ret = false;
    vis[cur] = true;
    for (auto &i : adj[cur]) {

```

```

        if (!vis[i]) ret|=dfs1(i, cur);
        else if (par != i) ret = true;
    }
    return ret;
}

```

7.2.3 General Way

General Way

```

// general algorithm
vector<bool> cyc;
bool dfs(int cur, int par) {
    bool ret = false;
    vis[cur] = cyc[cur] = true;
    for (auto &i : adj[cur]) {
        if (par == i) continue;
        if (!vis[i]) ret|=dfs(i, cur);
        else if (cyc[i]) ret = true;
    }
    cyc[cur] = false;
    return ret;
}

```

7.2.4 DSU Implementation

DSU Implementation

```

#include <iostream>
#include <vector>

class UnionFind {
public:
    UnionFind(int n) {
        parent.resize(n);
        rank.resize(n, 0);
        for (int i = 0; i < n; ++i) {
            parent[i] = i;
        }
    }
}

```

```

int find(int u) {
    if (parent[u] != u) {
        parent[u] = find(parent[u]);
    }
    return parent[u];
}

void unionSets(int u, int v) {
    int rootU = find(u);
    int rootV = find(v);

    if (rootU != rootV) {
        if (rank[rootU] > rank[rootV]) {
            parent[rootV] = rootU;
        } else if (rank[rootU] < rank[rootV]) {
            parent[rootU] = rootV;
        } else {
            parent[rootV] = rootU;
            ++rank[rootU];
        }
    }
}

private:
    std::vector<int> parent;
    std::vector<int> rank;
};

bool detectCycle(const std::vector<std::pair<int, int>>& edges, int n) {
    UnionFind uf(n);

    for (const auto& edge : edges) {
        int u = edge.first;
        int v = edge.second;

        if (uf.find(u) == uf.find(v)) {
            return true;
        }
        uf.unionSets(u, v);
    }

    return false;
}

```

```

}

int main() {
    std::vector<std::pair<int, int>> edges = { {0, 1}, {1, 2}, {2, 3}, {3, 0} };
    int n = 4; // Number of vertices

    if (detectCycle(edges, n)) {
        std::cout << "Cycle detected" << std::endl;
    } else {
        std::cout << "No cycle detected" << std::endl;
    }

    return 0;
}

```

7.3 Algorithms

7.3.1 Heavy Light Decomposition

Basic HLD Impl

```

struct Node {
    int val;
};

const Node nullNode = {0};

const int N = 2e5 + 5, S = 1 << 19;
int n, q;
int val[N];
int sz[N], par[N], dep[N], id[N], top[N];
vector<int> adj[N];

Node st[S];

Node merge(const Node& a, const Node& b) {
    return {a.val + b.val};
}

void update(int idx, Node val) {

```



```

    st[idx += n] = val;
    for (idx /= 2; idx; idx /= 2) st[idx] = merge(st[idx * 2], st[idx * 2
+ 1]);
}

Node query(int lo, int hi) {
    Node ra = nullNode, rb = nullNode;

    for (lo += n, hi += n + 1; lo < hi; lo /= 2, hi /= 2) {
        if (lo & 1) ra = merge(ra, st[lo++]);
        if (hi & 1) rb = merge(st[--hi], rb);
    }

    return merge(ra, rb);
}

int dfs_size(const int& node, const int& parent) {
    sz[node] = 1;
    par[node] = parent;
    for (const int& ch : adj[node]) {
        if (ch == parent) continue;
        dep[ch] = dep[node] + 1;
        par[ch] = node;
        sz[node] += dfs_size(ch, node);
    }
    return sz[node];
}

int curId = 0;

void dfs_hld(const int& cur, const int& parent, const int& curTop) {
    id[cur] = curId++;
    top[cur] = curTop;
    update(id[cur], {val[cur]});
    int heavyChild = -1, heavyMax = -1;
    for (const int& ch : adj[cur]) {
        if (ch == parent) continue;
        if (sz[ch] > heavyMax) {
            heavyMax = sz[ch];
            heavyChild = ch;
        }
    }
}

```

```

    if (heavyChild == -1) return;
    dfs_hld(heavyChild, cur, curTop);
    for (int ch : adj[cur]) {
        if (ch == parent || ch == heavyChild) continue;

        dfs_hld(ch, cur, ch);
    }
}

Node path(int u, int v) {
    Node ans = nullNode;

    while (top[u] != top[v]) {
        if (dep[top[u]] < dep[top[v]]) swap(u, v);
        ans = merge(ans, query(id[top[u]], id[u]));
        u = par[top[u]];
    }

    if (dep[u] > dep[v]) swap(u, v);
    ans = merge(ans, query(id[u], id[v]));
    return ans;
}

void init() {
    for (int i = 0; i < S; i++) st[i] = nullNode;
    dfs_size(1, 1);
    dfs_hld(1, 1, 1);
}

int main() {
    cin >> n >> q;
    for (int i = 1; i <= n; i++) cin >> val[i];

    int a, b;
    for (int i = 2; i <= n; i++) {
        cin >> a >> b;
        adj[a].pb(b);
        adj[b].pb(a);
    }

    init(); // <----- DON'T FORGET TO CALL THIS FUNCTION

    int type;

```

```

while (q--) {
    cin >> type;
    if (type == 1) {
        cin >> a >> b;
        val[a] = b;
        update(id[a], {val[a]});
    }
    else {
        cin >> a;
        cout << path(1, a).val << el;
    }
}

```

7.3.2 Heavy Light Decomposition with lazy SegTree

Basic HLD Impl

```

struct Node {
    int val;
};

const Node nullNode = {0};

const int N = 2e5 + 5, S = 1 << 19;
int n, q;
int val[N];
int sz[N], par[N], dep[N], id[N], top[N];
vector<int> adj[N];

Node st[S];
int lazy[S];

Node merge(const Node& a, const Node& b) {
    return {a.val + b.val};
}

void push(int idx, int l, int r) {
    if (lazy[idx] != 0) {
        st[idx].val += lazy[idx] * (r - l + 1);
        if (l != r) {

```

```

            lazy[idx * 2] += lazy[idx];
            lazy[idx * 2 + 1] += lazy[idx];
        }
        lazy[idx] = 0;
    }
}

void update_range(int lo, int hi, int l, int r, int idx, int value) {
    push(idx, l, r);
    if (lo > r || hi < l) return;
    if (lo <= l && r <= hi) {
        lazy[idx] += value;
        push(idx, l, r);
        return;
    }
    int mid = (l + r) / 2;
    update_range(lo, hi, l, mid, idx * 2, value);
    update_range(lo, hi, mid + 1, r, idx * 2 + 1, value);
    st[idx] = merge(st[idx * 2], st[idx * 2 + 1]);
}

void update(int idx, Node val) {
    update_range(idx, idx, 0, n - 1, 1, val.val);
}

void update_range(int lo, int hi, int value) {
    update_range(lo, hi, 0, n - 1, 1, value);
}

Node query(int lo, int hi, int l, int r, int idx) {
    push(idx, l, r);
    if (lo > r || hi < l) return nullNode;
    if (lo <= l && r <= hi) return st[idx];
    int mid = (l + r) / 2;
    return merge(query(lo, hi, l, mid, idx * 2), query(lo, hi, mid + 1, r,
        idx * 2 + 1));
}

Node query(int lo, int hi) {
    return query(lo, hi, 0, n - 1, 1);
}

int dfs_size(const int& node, const int& parent) {

```

```

    sz[node] = 1;
    par[node] = parent;
    for (const int& ch : adj[node]) {
        if (ch == parent) continue;
        dep[ch] = dep[node] + 1;
        par[ch] = node;
        sz[node] += dfs_size(ch, node);
    }
    return sz[node];
}

int curId = 0;

void dfs_hld(const int& cur, const int& parent, const int& curTop) {
    id[cur] = curId++;
    top[cur] = curTop;
    update(id[cur], {val[cur]});
    int heavyChild = -1, heavyMax = -1;
    for (const int& ch : adj[cur]) {
        if (ch == parent) continue;
        if (sz[ch] > heavyMax) {
            heavyMax = sz[ch];
            heavyChild = ch;
        }
    }

    if (heavyChild == -1) return;
    dfs_hld(heavyChild, cur, curTop);
    for (int ch : adj[cur]) {
        if (ch == parent || ch == heavyChild) continue;

        dfs_hld(ch, cur, ch);
    }
}

int get(int u) {
    return query(id[u], id[u]).val;
}

void path(int u, int v, int val) {
    // Node ans = nullNode;

    while (top[u] != top[v]) {

```

```

        if (dep[top[u]] < dep[top[v]]) swap(u, v);
        // ans = merge(ans, query(id[top[u]], id[u]));
        update_range(id[top[u]], id[u], val);
        u = par[top[u]];
    }

    if (dep[u] > dep[v]) swap(u, v);
    // ans = merge(ans, query(id[u], id[v]));
    update_range(id[u], id[v], val);
    // return ans;
}

void init() {
    for (int i = 0; i < S; i++) st[i] = nullNode;
    memset(lazy, 0, sizeof(lazy));
    dfs_size(1, 1);
    dfs_hld(1, 1, 1);
}

int main(void) {
    cin >> n >> q;
    for (int i = 1; i <= n; i++) val[i] = 0;
    int a, b;
    for (int i = 2; i <= n; i++) {
        cin >> a >> b;
        adj[a].push_back(b);
        adj[b].push_back(a);
    }

    init(); // <----- DON'T FORGET TO CALL THIS FUNCTION
    int v;
    while (q--) {
        cin >> a >> b >> v;
        path(a, b, v);
    }

    for (int i = 1; i <= n; i++) {
        cout << get(i) << " ";
    }
    cout << el;
}

```

7.3.3 LCA functions using Binary Lifting

LCA functions using Binary Lifting

```

const int N = 2e5 + 15, M = 23;
int ancestors[N][M], depth[N], parent[N], val[N];
vector<vector<int>> adj;
//int tin[N], tout[N], timer;

void dfs_LCA(const int &node, const int &par) {
    //    tin[node] = timer++;
    parent[node] = par;
    ancestors[node][0] = par;
    depth[node] = depth[par] + 1;

    for (int i = 1; i < M; i++) {
        int p = ancestors[node][i - 1];
        ancestors[node][i] = ancestors[p][i - 1];
    }

    for (const int &v: adj[node]) {
        if (v == par) continue;
        dfs_LCA(v, node);
    }
    //    tout[node] = timer++;
}

//bool is_ancestor(int u, int v) {
//    return tin[u] <= tin[v] && tout[u] >= tout[v];
//}

int findKth(int u, int k) {
    if (depth[u] <= k) return -1;
    for (int i = M - 1; i >= 0; i--) {
        if (k & (1 << i)) {
            u = ancestors[u][i];
        }
    }
    return u;
}

int getLCA(int u, int v) {
    if (depth[u] < depth[v])

```

```

        swap(u, v);

    u = findKth(u, depth[u] - depth[v]);
    if (u == v) return u;

    for (int i = M - 1; i >= 0; i--) {
        if (ancestors[u][i] == ancestors[v][i]) continue;
        u = ancestors[u][i];
        v = ancestors[v][i];
    }
    return ancestors[u][0];
}

int getDistance(int u, int v) {
    int lca = getLCA(u, v);
    return (depth[u] + depth[v]) - (2 * depth[lca]);
}

int dfs_accumulate(const int &node, const int &par) {
    for (const int& ch: adj[node]) {
        if (ch == par) continue;
        val[node] += dfs_accumulate(ch, node);
    }
    return val[node];
}

void applyOpOnPath(const int a, const int b, const int w) {
    // adding w to each node on the path a to b
    val[a] += w;
    val[b] += w;
    int lca = getLCA(a, b);
    val[lca] -= w;
    val[parent[lca]] -= w;
}

int main(void) {
    int n, q;
    cin >> n >> q;
    adj.resize(n + 1);

    int u, v;
    for (int i = 2; i <= n; ++i) {

```

```

        cin >> u >> v;
        adj[u].push_back(v);
        adj[v].push_back(u);
    }

    dfs_LCA(1, 1);
    parent[1] = -1;

    int w;
    for (int i = 0; i < q; ++i) {
        cin >> u >> v;
        cout << getDistance(u, v) << el;
    }

    // dfs_accumulate(1, 0);
    //
    // for (int i = 1; i <= n; i++) {
    //     cout << val[i] << " ";
    // }
    // cout << el;
    //

```

7.3.4 Topological Sort

Topological Sort Using DFS

```

//REF: USACO Guide
vector<int> top_sort;
vector<vector<int>> graph;
vector<bool> visited;

void dfs(int node) {
    for (int next : graph[node]) {
        if (!visited[next]) {
            visited[next] = true;
            dfs(next);
        }
    }
    top_sort.push_back(node);
}

```

```

int main() {
    int n, m; // The number of nodes and edges respectively
    std::cin >> n >> m;

    graph = vector<vector<int>>(n);
    for (int i = 0; i < m; i++) {
        int a, b;
        std::cin >> a >> b;
        graph[a - 1].push_back(b - 1);
    }

    visited = vector<bool>(n);
    for (int i = 0; i < n; i++) {
        if (!visited[i]) {
            visited[i] = true;
            dfs(i);
        }
    }
    std::reverse(top_sort.begin(), top_sort.end());

    vector<int> ind(n);
    for (int i = 0; i < n; i++) { ind[top_sort[i]] = i; }

    // Check if the topological sort is valid
    bool valid = true;
    for (int i = 0; i < n; i++) {
        for (int j : graph[i]) {
            if (ind[j] <= ind[i]) {
                valid = false;
                goto answer;
            }
        }
    }
    answer::;

    if (valid) {
        for (int i = 0; i < n - 1; i++) { cout << top_sort[i] + 1 << ' '; }
        cout << top_sort.back() + 1 << endl;
    } else {
        cout << "IMPOSSIBLE" << endl;
    }
}

```

7.3.5 Tarjan Strongly Connected Components

Tarjan SCC

```

struct TarjanSCC {
    vector<vector<int>> adj;
    vector<int> idx, lowLink;
    vector<bool> onStack;
    stack<int> st;
    int _size, components, timer;
    vector<vector<int>> sccs;

    explicit TarjanSCC(const int& n, const vector<vector<int>>& graph) :
        adj(graph), _size(n) {
        components = 0;
        timer = 0;

        onStack.assign(n + 1, false);
        idx.assign(n + 1, -1);
        lowLink.assign(n + 1, -1);

        for (int node = 1; node <= n; ++node) if (idx[node] == -1) dfs(node);

        ranges::sort(all(sccs), [](const vector<int>& a, const vector<int>& b) {
            return a.size() > b.size();
        });
    }

    void dfs(const int& node) {
        idx[node] = timer;
        lowLink[node] = timer++;
        onStack[node] = true;
        st.push(node);

        for (const int& ch : adj[node]) {
            if (idx[ch] == -1) {
                dfs(ch);
                lowLink[node] = min(lowLink[node], lowLink[ch]);
            } else if (onStack[ch]) {

```

```

                lowLink[node] = min(lowLink[node], lowLink[ch]);
            }
        }

        if (idx[node] == lowLink[node]) {
            vector<int> scc;
            int cur = -1;
            while (cur != node) {
                cur = st.top();
                st.pop();
                onStack[cur] = false;
                scc.push_back(cur);
            }

            sccs.push_back(scc);
            components++;
        }
    }

    int getLargestCompSize() const {
        return sccs.front().size();
    }

    vector<int> getLargestComp() const {
        return sccs.front();
    }

    vector<vector<int>> getAllComp() const {
        return this->sccs;
    }
};

void run_test_case(int testNum) {
    int n, m;
    cin >> n >> m;
    vector<vector<int>> adj(n + 1);
    int a, b;
    while (m--) {
        cin >> a >> b;
        adj[a].push_back(b);
    }

    const TarjanSCC tar(n, adj);

```

```

    cout << tar.components << el;
    for (const int &i : tar.getLargestComp()) {
        cout << i << " ";
    }
}

```

8 Techniques

8.1 Coordinate Compression

```

void coordinate_compress(vector<int> &x, int start=0, int
    step=1) {
    set unique(x.begin(), x.end());
    map<int, int> valPos;

    int idx=0;
    for (auto i: unique) {
        valPos[i] = start + idx * step;
        ++idx;
    }
    for(auto &i: x) i = valPos[i];
}

```

Coordinate Compression

8.2 Binary to decimal

Binary to decimal

```

// Function to convert binary to decimal
// O(32)
int binaryToDecimal(string str)
{
    int dec_num = 0;
    int power = 0 ;

```

```

    int n = str.length() ;

    for(int i = n-1 ; i>=0 ; i--){
        if(str[i] == '1'){
            dec_num += (1<<power) ;
        }
        power++ ;
    }

    return dec_num;
}

```

8.3 Decimal to binary

Decimal to binary

```

// Function that convert Decimal to binary
// O(32)
void decToBinary(int n)
{
    // Size of an integer is assumed to be 32 bits
    for (int i = 31; i >= 0; i--) {
        int k = n >> i;
        if (k & 1)
            cout << "1";
        else
            cout << "0";
    }
}

// O(logn)
string DecimalToBinary(int num)
{
    string str;
    while(num){
        if(num & 1) // 1
            str+='1';
        else // 0
            str+='0';
        num>>=1; // Right Shift by 1
    }
}

```

```
    return str;
}
```

9 Number Theory

9.1 Divisors

9.1.1 formulas

number of divisors

```
int d(int n){
    unordered_map<int, int> factors = pf(n);
    int c = 1;
    for(const auto& factor: factors){
        c *= (factor.second+1);
    }
    return c;
}
```

```
// range Count Divisors backward thinking MAXN = 2e6
for(int i=1; i <= n; ++i) {
    for(int j = i; j <= n; j += i) {
        numFactors[j]++;
    }
}
```

```
int countDivisors(int n) {
    int count = 0;
    for (int i = 1; i * i <= n; ++i) {
        if (n % i == 0) {
            if (i == n / i) {
                count++; // Perfect square
            } else {
                count += 2; // Pair of divisors
            }
        }
    }
    return count;
}
```

```
}
```

sum of divisors

```
int s(int n){
    unordered_map<int, int> factors = pf(n);
    int sum = 1;
    for(const auto& factor: factors){
        int p = factor.first;
        int exp = factor.second;
        sum *= (pow(p,exp+1)-1)/p-1;
    }
    return sum;
}
```

9.2 Primes

prime factorization

```
void factorize(int x, unordered_map<int, int>& factors) {
    while (x % 2 == 0) {
        factors[2]++;
        x /= 2;
    }
    for (int i = 3; i * i <= x; i += 2) {
        while (x % i == 0) {
            factors[i]++;
            x /= i;
        }
    }
    if (x > 2) factors[x]++;
}
```

number of co-primes with n

```
int eulerTotient(int n){
    int result = n;
```



```

for(int i = 2; SQ(i) <= n; i++){
    if(n%i == 0){
        while(n%i == 0){
            n/=i;
        }
        result -= result/i;
    }
}

if(n > 1) result -= result/n;
return result;
}

//Phi(n) = n * (1 - 1/P1) * (1 - 1/P2) * ...

//NOTE: summation of Euler function over divisors of n is equal to n

// using seive
void phi_generator() {
    const int MAX = 1000000;
    char primes[MAX];
    int phi[MAX];

    memset(primes, 1, sizeof(primes));

    for (int k = 0; k < MAX; ++k)
        phi[k] = 1;

    for (int i = 2; i <= MAX; ++i) {
        if (primes[i]) {
            phi[i] = i - 1; // phi(prime) = p-1

            for (int j = i * 2; j <= MAX; j += i) {
                primes[j] = 0;
                int n = j, pow = 1;
                while (n % i == 0) {
                    pow *= i;
                    n /= i;
                }
                phi[j] *= (pow / i) * (i - 1);
            }
        }
    }
}

```

```

    }
}

// phi(N!) = (N is prime ? N-1 : N) * phi((N-1)!)
ll phi_factn(int n) {
    ll ret = 1;
    for (int i = 2; i <= n; ++i)
        ret = ret * (isprime(i) ? i - 1 : i);
    return ret;
}

```

Prime Check

```

vector<bool> isPrime(MAXN, true);

void sieve() {
    isPrime[0] = isPrime[1] = false;

    for (int i=2; i * i <= isPrime.size(); ++i) {
        if(isPrime[i]) {
            for (int j = 2 * i; j <= isPrime.size(); j += i)
                prime[j] = false;
        }
    }
}

bool Prime(int n) {
    if(n == 2) return true;
    if(n < 2 || n % 2 == 0) return false;

    for(int i=3; i * i <= n; i += 2) {
        if(n % i == 0) return false;
    }
    return true;
}

// Generate Primes
const int sz = sqrt(MAXN);
vector<int> prime;
vector<bool> vis(sz);

```

```

void pre() {
    prime.push_back(2);
    for (int j = 4; j < sz; j += 2) vis[j] = true;
    for (int i = 3; i < sz; i += 2) {
        if (vis[i]) continue;
        prime.push_back(i);
        for (int j = i * i; j < sz; j += i) vis[j] = true;
    }
}

// Preprocessing Prime Factorization of range numbers
constexpr int N = 5e6+1;
int a[N];

for(int i=2; i < N; ++i) {
    if(!a[i]) {
        for(int j=1; i*j < N; ++j) {
            for(int k=i*j; k%i==0; k/=i) a[i*j]++;
        }
    }
    a[i] += a[i-1];
}

```

9.3 Math

9.3.1 Vieta's Formula for a Polynomial of Degree n

Problem: Given a polynomial of degree n :

$$P(x) = a_n x^n + a_{n-1} x^{n-1} + \cdots + a_1 x + a_0$$

with roots r_1, r_2, \dots, r_n , express the sums and products of its roots using Vieta's formulas.

Solution: Using Vieta's formulas, we can relate the coefficients of the polynomial to sums and products of its roots:

- Sum of the roots taken one at a time:

$$r_1 + r_2 + \cdots + r_n = -\frac{a_{n-1}}{a_n}$$

- Sum of the products of the roots taken two at a time:

$$r_1 r_2 + r_1 r_3 + \cdots + r_{n-1} r_n = \frac{a_{n-2}}{a_n}$$

- Sum of the products of the roots taken three at a time:

$$r_1 r_2 r_3 + r_1 r_2 r_4 + \cdots + r_{n-2} r_{n-1} r_n = -\frac{a_{n-3}}{a_n}$$

- Continue this pattern until:

- Product of the roots (for even n):

$$r_1 r_2 \cdots r_n = (-1)^n \frac{a_0}{a_n}$$

Example Problem Using Vieta's Formula

Problem: Given a quadratic equation $x^2 + bx + c = 0$ with roots r_1 and r_2 , find $r_1 + r_2$ and $r_1 r_2$.

Solution: Using Vieta's formulas for a quadratic equation $ax^2 + bx + c = 0$:

- Sum of the roots:

$$r_1 + r_2 = -\frac{b}{a}$$

- Product of the roots:

$$r_1 r_2 = \frac{c}{a}$$

For the given quadratic $x^2 + bx + c = 0$ (where $a = 1$):

Also: To find the roots of the quadratic equation, we can use the discriminant formula, $D = b^2 - 4ac$. The roots will then be $x_1 = \frac{b-\sqrt{D}}{2}$ and $x_2 = \frac{b+\sqrt{D}}{2}$.

- $r_1 + r_2 = -b$

- $r_1 r_2 = c$

Example Vieta's Formula for Cubic Equation

When considering a cubic equation in the form of $f(x) = ax^3 + bx^2 + cx + d$, Vieta's formula states that if the equation $f(x) = 0$ has roots r_1, r_2 , and r_3 , then:

- $r_1 + r_2 + r_3 = -\frac{b}{a}$
- $r_1r_2 + r_2r_3 + r_3r_1 = \frac{c}{a}$
- $r_1r_2r_3 = -\frac{d}{a}$

9.4 Phi Function

- Count integers $i < n$ such that $\gcd(i, n) = 1$
- $\gcd(a, b) = 1 \Rightarrow$ then coprimes: $\gcd(5, 7), \gcd(4, 9)$
- $\gcd(\text{prime}, i) = 1$ for $i < \text{prime}$
- $\varphi(10) = 4 \Rightarrow 1, 3, 7, 9$
- $\varphi(5) = 4 \Rightarrow 1, 2, 3, 4 \dots \varphi(\text{prime}) = \text{prime} - 1$
- If a, b, c are pairwise coprimes, then

$$\varphi(a \cdot b \cdot c) = \varphi(a) \cdot \varphi(b) \cdot \varphi(c)$$

- If $k \geq 1$

$$\varphi(p^k) = p^k - p^{k-1} = p^{k-1}(p - 1) = p^k \left(1 - \frac{1}{p}\right)$$

9.5 Euler's Totient Numbers

Online Sequence

$\varphi(n) = 1, 1, 2, 2, 4, 2, 6, 4, 6, 4, 10, 4, 12, 6, 8, 8, 16, 6, 18, 8, 12, 10, 22, 8, 20, 12, 18, 12, 28, 16, 24, 12, 30, 16, 24, 12, 36, 18, 24, 16, 40, 12, 42, 20, 48, 24, 40, 24, 48, 24, 56, 28, 60, 24, 64, 32, 72, 40, 80, 40, 84, 48, 96, 48, 100, 48, 112, 56, 120, 60, 128, 64, 136, 64, 144, 72, 156, 72, 160, 80, 176, 80, 180, 84, 192, 96, 200, 100, 216, 108, 224, 112, 240, 120, 252, 126, 264, 128, 280, 140, 288, 144, 300, 144, 320, 160, 336, 168, 360, 180, 384, 192, 400, 200, 420, 210, 448, 224, 464, 224, 480, 240, 504, 252, 528, 256, 560, 280, 576, 288, 600, 300, 640, 320, 672, 336, 700, 350, 720, 360, 768, 384, 800, 400, 840, 420, 864, 432, 896, 448, 900, 450, 960, 480, 1008, 504, 1024, 512, 1056, 528, 1080, 540, 1120, 560, 1152, 576, 1176, 588, 1200, 600, 1248, 624, 1260, 630, 1280, 640, 1344, 672, 1360, 680, 1400, 700, 1440, 720, 1472, 736, 1500, 750, 1536, 768, 1560, 780, 1600, 800, 1664, 832, 1680, 840, 1728, 864, 1760, 880, 1800, 900, 1856, 928, 1872, 936, 1900, 950, 1920, 960, 1980, 1008, 2000, 1024, 2040, 1056, 2080, 1080, 2112, 1104, 2160, 1120, 2200, 1152, 2240, 1176, 2280, 1200, 2304, 1216, 2340, 1224, 2368, 1232, 2400, 1240, 2448, 1260, 2464, 1272, 2500, 1280, 2520, 1296, 2560, 1312, 2600, 1320, 2640, 1344, 2688, 1360, 2700, 1380, 2736, 1400, 2760, 1440, 2800, 1472, 2840, 1488, 2880, 1500, 2912, 1536, 2940, 1560, 3000, 1536, 3024, 1560, 3072, 1584, 3120, 1600, 3168, 1620, 3200, 1640, 3248, 1664, 3280, 1680, 3328, 1700, 3360, 1728, 3400, 1744, 3440, 1760, 3488, 1792, 3520, 1800, 3568, 1824, 3600, 1840, 3648, 1872, 3680, 1896, 3720, 1920, 3760, 1944, 3780, 1960, 3840, 1980, 3888, 2000, 3920, 2016, 3960, 2040, 4000, 2064, 4040, 2080, 4080, 2100, 4128, 2144, 4160, 2160, 4200, 2200, 4240, 2240, 4280, 2280, 4320, 2304, 4360, 2384, 4400, 2400, 4440, 2440, 4480, 2464, 4500, 2480, 4560, 2520, 4600, 2560, 4640, 2600, 4680, 2640, 4720, 2688, 4760, 2800, 4800, 2840, 4840, 2880, 4880, 2912, 4900, 2928, 4960, 2980, 5000, 3000, 5040, 3024, 5080, 3040, 5120, 3072, 5160, 3104, 5200, 3120, 5240, 3160, 5280, 3200, 5320, 3240, 5360, 3280, 5400, 3400, 5440, 3480, 5480, 3520, 5520, 3560, 5560, 3600, 5600, 3640, 5640, 3680, 5680, 3720, 5720, 3760, 5760, 3800, 5800, 3840, 5840, 3880, 5880, 3920, 5920, 3960, 5960, 4000, 6000, 4040, 6040, 4080, 6080, 4120, 6120, 4160, 6160, 4200, 6200, 4240, 6240, 4280, 6280, 4320, 6320, 4360, 6360, 4400, 6400, 4440, 6440, 4480, 6480, 4520, 6520, 4560, 6560, 4600, 6600, 4640, 6640, 4680, 6680, 4720, 6720, 4760, 6760, 4800, 6800, 4840, 6840, 4880, 6880, 4920, 6920, 4960, 6960, 5000, 7000, 5040, 7040, 5080, 7080, 5120, 7120, 5160, 7160, 5200, 7200, 5240, 7240, 5280, 7280, 5320, 7320, 5360, 7360, 5400, 7400, 5440, 7440, 5480, 7480, 5520, 7520, 5560, 7560, 5600, 7600, 5640, 7640, 5680, 7680, 5720, 7720, 5760, 7760, 5800, 7800, 5840, 7840, 5880, 7880, 5920, 7920, 5960, 7960, 6000, 8000, 6040, 8040, 6080, 8080, 6120, 8120, 6160, 8160, 6200, 8200, 6240, 8240, 6280, 8280, 6320, 8320, 6360, 8360, 6400, 8400, 6440, 8440, 6480, 8480, 6520, 8520, 6560, 8560, 6600, 8600, 6640, 8640, 6680, 8680, 6720, 8720, 6760, 8760, 6800, 8800, 6840, 8840, 6880, 8880, 6920, 8920, 6960, 8960, 7000, 9000, 7040, 9040, 7080, 9080, 7120, 9120, 7160, 9160, 7200, 9200, 7240, 9240, 7280, 9280, 7320, 9320, 7360, 9360, 7400, 9400, 7440, 9440, 7480, 9480, 7520, 9520, 7560, 9560, 7600, 9600, 7640, 9640, 7680, 9680, 7720, 9720, 7760, 9760, 7800, 9800, 7840, 9840, 7880, 9880, 7920, 9920, 7960, 9960, 8000, 10000, 8040, 10040, 8080, 10080, 8120, 10120, 8160, 10160, 8200, 10200, 8240, 10240, 8280, 10280, 8320, 10320, 8360, 10360, 8400, 10400, 8440, 10440, 8480, 10480, 8520, 10520, 8560, 10560, 8600, 10600, 8640, 10640, 8680, 10680, 8720, 10720, 8760, 10760, 8800, 10800, 8840, 10840, 8880, 10880, 8920, 10920, 8960, 10960, 9000, 11000, 9040, 11040, 9080, 11080, 9120, 11120, 9160, 11160, 9200, 11200, 9240, 11240, 9280, 11280, 9320, 11320, 9360, 11360, 9400, 11400, 9440, 11440, 9480, 11480, 9520, 11520, 9560, 11560, 9600, 11600, 9640, 11640, 9680, 11680, 9720, 11720, 9760, 11760, 9800, 11800, 9840, 11840, 9880, 11920, 9960, 12000, 12040, 12080, 12120, 12160, 12200, 12240, 12280, 12320, 12360, 12400, 12440, 12480, 12520, 12560, 12600, 12640, 12680, 12720, 12760, 12800, 12840, 12880, 12920, 12960, 13000, 13040, 13080, 13120, 13160, 13200, 13240, 13280, 13320, 13360, 13400, 13440, 13480, 13520, 13560, 13600, 13640, 13680, 13720, 13760, 13800, 13840, 13880, 13920, 13960, 14000, 14040, 14080, 14120, 14160, 14200, 14240, 14280, 14320, 14360, 14400, 14440, 14480, 14520, 14560, 14600, 14640, 14680, 14720, 14760, 14800, 14840, 14880, 14920, 14960, 15000, 15040, 15080, 15120, 15160, 15200, 15240, 15280, 15320, 15360, 15400, 15440, 15480, 15520, 15560, 15600, 15640, 15680, 15720, 15760, 15800, 15840, 15880, 15920, 15960, 16000, 16040, 16080, 16120, 16160, 16200, 16240, 16280, 16320, 16360, 16400, 16440, 16480, 16520, 16560, 16600, 16640, 16680, 16720, 16760, 16800, 16840, 16880, 16920, 16960, 17000, 17040, 17080, 17120, 17160, 17200, 17240, 17280, 17320, 17360, 17400, 17440, 17480, 17520, 17560, 17600, 17640, 17680, 17720, 17760, 17800, 17840, 17880, 17920, 17960, 18000, 18040, 18080, 18120, 18160, 18200, 18240, 18280, 18320, 18360, 18400, 18440, 18480, 18520, 18560, 18600, 18640, 18680, 18720, 18760, 18800, 18840, 18880, 18920, 18960, 19000, 19040, 19080, 19120, 19160, 19200, 19240, 19280, 19320, 19360, 19400, 19440, 19480, 19520, 19560, 19600, 19640, 19680, 19720, 19760, 19800, 19840, 19880, 19920, 19960, 20000, 20040, 20080, 20120, 20160, 20200, 20240, 20280, 20320, 20360, 20400, 20440, 20480, 20520, 20560, 20600, 20640, 20680, 20720, 20760, 20800, 20840, 20880, 20920, 20960, 21000, 21040, 21080, 21120, 21160, 21200, 21240, 21280, 21320, 21360, 21400, 21440, 21480, 21520, 21560, 21600, 21640, 21680, 21720, 21760, 21800, 21840, 21880, 21920, 21960, 22000, 22040, 22080, 22120, 22160, 22200, 22240, 22280, 22320, 22360, 22400, 22440, 22480, 22520, 22560, 22600, 22640, 22680, 22720, 22760, 22800, 22840, 22880, 22920, 22960, 23000, 23040, 23080, 23120, 23160, 23200, 23240, 23280, 23320, 23360, 23400, 23440, 23480, 23520, 23560, 23600, 23640, 23680, 23720, 23760, 23800, 23840, 23880, 23920, 23960, 24000, 24040, 24080, 24120, 24160, 24200, 24240, 24280, 24320, 24360, 24400, 24440, 24480, 24520, 24560, 24600, 24640, 24680, 24720, 24760, 24800, 24840, 24880, 24920, 24960, 25000, 25040, 25080, 25120, 25160, 25200, 25240, 25280, 25320, 25360, 25400, 25440, 25480, 25520, 25560, 25600, 25640, 25680, 25720, 25760, 25800, 25840, 25880, 25920, 25960, 26000, 26040, 26080, 26120, 26160, 26200, 26240, 26280, 26320, 26360, 26400, 26440, 26480, 26520, 26560, 26600, 26640, 26680, 26720, 26760, 26800, 26840, 26880, 26920, 26960, 27000, 27040, 27080, 27120, 27160, 27200, 27240, 27280, 27320, 27360, 27400, 27440, 27480, 27520, 27560, 27600, 27640, 27680, 27720, 27760, 27800, 27840, 27880, 27920, 27960, 28000, 28040, 28080, 28120, 28160, 28200, 28240, 28280, 28320, 28360, 28400, 28440, 28480, 28520, 28560, 28600, 28640, 28680, 28720, 28760, 28800, 28840, 28880, 28920, 28960, 29000, 29040, 29080, 29120, 29160, 29200, 29240, 29280, 29320, 29360, 29400, 29440, 29480, 29520, 29560, 29600, 29640, 29680, 29720, 29760, 29800, 29840, 29880, 29920, 29960, 30000, 30040, 30080, 30120, 30160, 30200, 30240, 30280, 30320, 30360, 30400, 30440, 30480, 30520, 30560, 30600, 30640, 30680, 30720, 30760, 30800, 30840, 30880, 30920, 30960, 31000, 31040, 31080, 31120, 31160, 31200, 31240, 31280, 31320, 31360, 31400, 31440, 31480, 31520, 31560, 31600, 31640, 31680, 31720, 31760, 31800, 31840, 31880, 31920, 31960, 32000, 32040, 32080, 32120, 32160, 32200, 32240, 32280, 32320, 32360, 32400, 32440, 32480, 32520, 32560, 32600, 32640, 32680, 32720, 32760, 32800, 32840, 32880, 32920, 32960, 33000, 33040, 33080, 33120, 33160, 33200, 33240, 33280, 33320, 33360, 33400, 33440, 33480, 33520, 33560, 33600, 33640, 33680, 33720, 33760, 33800, 33840, 33880, 33920, 33960, 34000, 34040, 34080, 34120, 34160, 34200, 34240, 34280, 34320, 34360, 34400, 34440, 34480, 34520, 34560, 34600, 34640, 34680, 34720, 34760, 34800, 34840, 34880, 34920, 34960, 35000, 35040, 35080, 35120, 35160, 35200, 35240, 35280, 35320, 35360, 35400, 35440, 35480, 35520, 35560, 35600, 35640, 35680, 35720, 35760, 35800, 35840, 35880, 35920, 35960, 36000, 36040, 36080, 36120, 36160, 36200, 36240, 36280, 36320, 36360, 36400, 36440, 36480, 36520, 36560, 36600, 36640, 36680, 36720, 36760, 36800, 36840, 36880, 36920, 36960, 37000, 37040, 37080, 37120, 37160, 37200, 37240, 37280, 37320, 37360, 37400, 37440, 37480, 37520, 37560, 37600, 37640, 37680, 37720, 37760, 37800, 37840, 37880, 37920, 37960, 38000, 38040, 38080, 38120, 38160, 38200, 38240, 38280, 38320, 38360, 38400, 38440, 38480, 38520, 38560, 38600, 38640, 38680, 38720, 38760, 38800, 38840, 38880, 38920, 38960, 39000, 39040, 39080, 39120, 39160, 39200, 39240, 39280, 39320, 39360, 39400, 39440, 39480, 39520, 39560, 39600, 39640, 39680, 39720, 39760, 39800, 39840, 39880, 39920, 39960, 40000, 40040, 40080, 40120, 40160, 40200, 40240, 40280, 40320, 40360, 40400, 40440, 40480, 40520, 40560, 40600, 40640, 40680, 40720, 40760, 40800, 40840, 40880, 40920, 40960, 41000, 41040, 41080, 41120, 41160, 41200, 41240, 41280, 41320, 41360, 41400, 41440, 41480, 41520, 41560, 41600, 41640, 41680, 41720, 41760, 41800, 41840, 41880, 41920, 41960, 42000, 42040, 42080, 42120, 42160, 42200, 42240, 42280, 42320, 42360, 42400, 42440, 42480, 42520, 42560, 42600, 42640, 42680, 42720, 42760, 42800, 42840, 42880, 42920, 42960, 43000, 43040, 43080, 43120, 43160, 43200, 43240, 43280, 43320, 43360, 43400, 43440, 43480, 43520, 43560, 43600, 43640, 43680, 43720, 43760, 43800, 43840, 43880, 43920, 43960, 44000, 44040, 44080, 44120, 44160, 44200, 44240, 44280, 44320, 44360, 44400, 44440, 44480, 44520, 44560, 44600, 44640, 44680, 44720, 44760, 44800, 44840, 44880, 44920, 44960, 45000, 45040, 45080, 45120, 45160, 45200, 45240, 45280, 45320, 45360, 45400, 45440, 45480, 45520, 45560, 45600, 45640, 45680, 45720, 45760, 45800, 45840, 45880, 45920, 45960, 46000, 46040, 46080, 46120, 46160, 46200, 46240, 46280, 46320, 46360, 46400, 46440, 46480, 46520, 46560, 46600, 46640, 46680, 46720, 46760, 46800, 46840, 46880, 46920, 46960, 47000, 47040, 47080, 47120, 47160, 47200, 47240, 47280, 47320, 47360, 47400, 47440, 47480, 47520, 47560, 47600, 47640, 47680, 47720, 47760, 47800, 47840, 47880, 47920, 47960, 48000, 48040, 48080, 48120, 48160, 48200, 48240, 48280, 48320, 48360, 48400, 48440, 48480, 48520, 48560, 48600, 48640, 48680, 48720, 48760, 48800, 48840, 48880, 48920, 48960, 49000, 49040, 49080, 49120, 49160, 49200, 49240, 49280, 49320, 49360, 49400, 49440, 49480, 49520, 49560, 49600, 49640, 49680, 49720, 49760, 49800, 49840, 49880, 49920, 49960, 50000, 50040, 50080, 50120, 50160, 50200, 50240, 50280, 50320, 50360, 50400, 50440, 50480, 50520, 50560, 50600, 50640, 50680, 50720, 50760, 50800, 50840, 50880, 50920, 50960, 51000, 51040, 51080, 51120, 51160, 51200, 51240, 51280, 51320, 51360, 51400, 51440, 51480, 51520, 51560, 51600, 51640, 51680, 51720, 51760, 51800, 51840, 51880, 51920, 51960, 52000, 52040, 52080, 52120, 52160, 52200, 52240, 52280, 52320, 52360, 52400, 52440, 52480, 52520, 52560, 52600, 52640, 52680, 52720, 52760, 52800, 52840, 52880, 52920, 52960, 53000, 53040, 53080, 53120, 53160, 53200, 53240, 53280, 53320, 53360, 53400, 53440, 53480, 53520, 53560, 53600, 53640, 5368$

```

for (ll i = 2; i <= MAX; i++)
    moebius[i] = -1, prime[i] = 1;

for (ll i = 2; i <= MAX; ++i)
    if (prime[i]) {
        moebius[i] = 1;

        for (ll j = 2 * i; j <= MAX; j += i)
            prime[j] = 0, moebius[j] = j % (i * i) == 0 ? -moebius[j] : 1;
    }
}

// Mobius Inclusion Exclusion
// Count triples gcd(a, b, c) = 1
int n = 4;
ll sum = n * n * n;
for (ll i = 2; i <= n; ++i)
    sum -= moebius[i] * (n / i) * (n / i) * (n / i);

```

9.7 Möbius and Inclusion Exclusion

Count the triples (a, b, c) such that $a, b, c \leq n$, and $\gcd(a, b, c) = 1$

- Reverse thinking, total - (# triples $\gcd > 1$)
- How many triples with \gcd multiple of 2: $(n/2)^3$
- How many triples with \gcd multiple of 3: $(n/3)^3$
- and 4? Ignore any numbers of internal duplicate primes
- and 6? already computed in 2, 3. Remove it: $-(n/6)^3$

9.8 Totient and Möbius Connection

Sum over divisors d of n

$$\sum_d d\mu\left(\frac{n}{d}\right) = \varphi(n)$$

9.9 Lagrange's four-square theorem

Lagrange's four-square theorem states that, every positive integer can be expressed as the sum of the squares of four integers.

Lagrange's four-square theorem

```

#include <cmath>

bool isPerfectSquare(int n) {
    int rt = sqrt(n);
    return rt * rt == n;
}

// Function to compute the minimum number of perfect squares
int numSquares(int n) {
    // Case 1:
    if (isPerfectSquare(n)) return 1;

    // Case 2: Check if n can be expressed as the sum of two perfect
    // squares
    for (int i = 1; i * i <= n; i++) {
        int d = n - i * i;
        if (isPerfectSquare(d)) return 2;
    }

    // Case 3:
    // If n can be reduced to the form 4^a * (8b + 7), then it requires 4
    // squares
    int m = n;
    while (m % 4 == 0) m /= 4;
    if (m % 8 == 7) return 4;

    // Case 4:
    return 3;
}

```

10 Geometry

10.1 Linearity

10.1.1 co-linear points

check if two points are co-linear

```
bool co_linear(int x1, int y1, int x2, int y2, int x3, int y3){
    int area = x1*(y2-y3) + x2*(y3-y1) + x3*(y1-y2);
    return area == 0;
}
```

10.2 Polygons

10.2.1 Polygon formation

check if can form polygon with given angle

```
bool possible(double angle){
    if(angle <= 0 || angle >= 180) return false;

    double sides = 360.0/(180.0-angle);

    return (sides == static_cast<int>(sides) && sides >= 3);
}
```

10.2.2 Polygon Area

area of any polygon with x vertices

```
double shoelace(vector<pair<double, double>> points) {
    double leftSum = 0.0;
    double rightSum = 0.0;

    for (int i = 0; i < points.size(); ++i) {
        int j = (i + 1) % points.size();
        leftSum += points[i].first * points[j].second;
        rightSum += points[j].first * points[i].second;
    }
}
```

```
}

return 0.5 * abs(leftSum - rightSum);
}
```

10.3 Intersections

10.3.1 Rectangle

intersection area between 2 rectangles

```
struct Rectangle {
    int x1, y1; // Bottom-left corner
    int x2, y2; // Top-right corner
};

int intersectionArea(const Rectangle& rect1, const Rectangle& rect2){

    int x_left = max(rect1.x1, rect2.x1);
    int y_bottom = max(rect1.y1, rect2.y1);
    int x_right = min(rect1.x2, rect2.x2);
    int y_top = min(rect1.y2, rect2.y2);

    int intersection_width = x_right - x_left;
    int intersection_height = y_top - y_bottom;

    if (intersection_width > 0 && intersection_height > 0) {
        return intersection_width * intersection_height;
    }

    return 0;
}
```

10.3.2 Circle

intersection area between 2 circles

```
double area(int x0, int y0, int r0, int x1, int y1, int r1){
    const double PI = 3.14159265358979323846;
```

```

double rr0 = r0 * r0;
double rr1 = r1 * r1;
double d = sqrt((x1 - x0) * (x1 - x0) + (y1 - y0) * (y1 - y0));
if(d >= r0 + r1){
    return 0;
}
double phiAngle = (rr0 + (d * d) - rr1) / (2 * r0 * d);
double phi = acos(phiAngle) * 2;
double thetaAngle = (rr1 + (d * d) - rr0) / (2 * r1 * d);
double theta = acos(thetaAngle) * 2;
double area1 = 0.5 * theta * rr1 - 0.5 * rr1 * sin(theta);
double area2 = 0.5 * phi * rr0 - 0.5 * rr0 * sin(phi);
return area1+area2;
}

```

10.3.3 Triangle

intersection area between 2 triangles

```

struct Point {
    double x, y;
};

typedef vector<Point> Polygon;

bool inside(const Point &p, const pair<Point, Point> &edge) {
    Point a = edge.first, b = edge.second;
    return (b.x - a.x) * (p.y - a.y) - (b.y - a.y) * (p.x - a.x) >= 0;
}

Point compute_intersection(const Point &p1, const Point &p2, const pair<
    Point, Point> &edge) {
    Point a = edge.first, b = edge.second;
    double A1 = b.y - a.y, B1 = a.x - b.x, C1 = b.x * a.y - a.x * b.y;
    double A2 = p2.y - p1.y, B2 = p1.x - p2.x, C2 = p2.x * p1.y - p1.x *
        p2.y;
    double det = A1 * B2 - A2 * B1;
    if (det == 0) return {numeric_limits<double>::quiet_NaN(),
        numeric_limits<double>::quiet_NaN()}; // parallel
    double x = (B1 * C2 - B2 * C1) / det;
    double y = (A2 * C1 - A1 * C2) / det;
    return {x, y};
}

```

```

}

Polygon HodgmanClip(const Polygon &subjectPolygon, const Polygon &
    clipPolygon) {
    Polygon outputList = subjectPolygon;
    for (size_t i = 0; i < clipPolygon.size(); ++i) {
        Point a = clipPolygon[i];
        Point b = clipPolygon[(i + 1) % clipPolygon.size()];
        Polygon inputList = outputList;
        outputList.clear();
        if (inputList.empty()) break;
        Point s = inputList.back();
        for (const auto &e : inputList) {
            if (inside(e, {a, b})) {
                if (!inside(s, {a, b})) {
                    Point intersection = compute_intersection(s, e, {a, b});
                    if (!std::isnan(intersection.x)) {
                        outputList.push_back(intersection);
                    }
                }
                outputList.push_back(e);
            } else if (inside(s, {a, b})) {
                Point intersection = compute_intersection(s, e, {a, b});
                if (!std::isnan(intersection.x)) {
                    outputList.push_back(intersection);
                }
            }
            s = e;
        }
    }
    return outputList;
}

// area of polygon
double shoelace(const Polygon &vertices) {
    double area = 0;
    for (size_t i = 0; i < vertices.size(); ++i) {
        Point p1 = vertices[i];
        Point p2 = vertices[(i + 1) % vertices.size()];
        area += p1.x * p2.y - p2.x * p1.y;
    }
    return fabs(area) / 2.0;
}

```

10.3.4 Rectangle & Circle

intersection area between Rectangle and Circle

```

struct Point {
    double x, y;
};

struct Circle {
    Point center;
    double radius;
};

struct Rectangle {
    Point bottomLeft, topRight;
};

const double PI = acos(-1.0);

bool point_inside_circle(const Point &p, const Circle &c) {
    double dx = p.x - c.center.x;
    double dy = p.y - c.center.y;
    return (dx * dx + dy * dy) <= (c.radius * c.radius);
}

double rect_area(const Rectangle &rect) {
    return (rect.topRight.x - rect.bottomLeft.x) * (rect.topRight.y - rect
        .bottomLeft.y);
}

bool rect_in_circle(const Circle &circle, const Rectangle &rect) {
    vector<Point> corners = {
        rect.bottomLeft,
        {rect.topRight.x, rect.bottomLeft.y},
        rect.topRight,
        {rect.bottomLeft.x, rect.topRight.y}
    };
    for (const auto &corner : corners) {
        if (!isPointInsideCircle(corner, circle)) {

```

```

            return false;
        }
    }
    return true;
}

bool circle_in_rect(const Circle &circle, const Rectangle &rect) {
    return circle.center.x - circle.radius >= rect.bottomLeft.x &&
        circle.center.x + circle.radius <= rect.topRight.x &&
        circle.center.y - circle.radius >= rect.bottomLeft.y &&
        circle.center.y + circle.radius <= rect.topRight.y;
}

double intersection(const Circle &circle, const Rectangle &rect) {
    if (rect_in_circle(circle, rect)) {
        return rect_area(rect);
    }

    if (circle_in_rect(circle, rect)) {
        return PI * circle.radius * circle.radius;
    }

    double intersectionArea = 0.0;
    double dx1 = max(rect.bottomLeft.x, circle.center.x - circle.radius);
    double dx2 = min(rect.topRight.x, circle.center.x + circle.radius);
    double dy1 = max(rect.bottomLeft.y, circle.center.y - circle.radius);
    double dy2 = min(rect.topRight.y, circle.center.y + circle.radius);

    for (double x = dx1; x < dx2; x += 0.001) {
        for (double y = dy1; y < dy2; y += 0.001) {
            Point p = {x, y};
            if (point_inside_circle(p, circle)) {
                intersectionArea += 0.001 * 0.001;
            }
        }
    }

    return intersectionArea;
}

```

10.3.5 Line & Circle

intersection points between Line and Circle

```
struct Point {
    double x, y;
};

struct Circle {
    Point center;
    double radius;
};

struct Line {
    double slope;
    double intercept;
};

vector<Point> intersect_points(const Circle &circle, const Line &line) {
    vector<Point> intersections;

    // solve  $y = mx + b$  with  $(x - h)^2 + (y - k)^2 = r^2$ 
    double h = circle.center.x;
    double k = circle.center.y;
    double r = circle.radius;
    double m = line.slope;
    double b = line.intercept;

    // Quadratic coefficients
    double A = 1 + m * m;
    double B = 2 * (m * b - m * k - h);
    double C = k * k - r * r + h * h - 2 * b * k + b * b;

    // Discriminant
    double discriminant = B * B - 4 * A * C;

    if (discriminant < 0) {
        // No intersection
        return intersections;
    } else if (discriminant == 0) {
        // One intersection (tangent line)
        double x = -B / (2 * A);
        double y = m * x + b;
    }
}
```

```
        intersections.push_back({x, y});
    } else {
        // Two intersections
        double sqrtDiscriminant = sqrt(discriminant);
        double x1 = (-B + sqrtDiscriminant) / (2 * A);
        double y1 = m * x1 + b;
        double x2 = (-B - sqrtDiscriminant) / (2 * A);
        double y2 = m * x2 + b;
        intersections.push_back({x1, y1});
        intersections.push_back({x2, y2});
    }

    return intersections;
}
```

10.4 Linear Operations

10.5 2D Points

Basic Operations

```
#include<bits/stdc++.h>

using namespace std;

#define ftype double

struct Point2D {
    ftype x, y;
    Point2D() {}
    Point2D(ftype x, ftype y): x(x), y(y) {}
    Point2D& operator+=(const Point2D &p2) {
        x += p2.x;
        y += p2.y;
        return *this;
    }
    Point2D& operator-=(const Point2D &p2) {
        x -= p2.x;
        y -= p2.y;
        return *this;
    }
}
```



```

Point2D& operator*=(const Point2D p2) {
    x *= p2.x;
    y *= p2.y;
    return *this;
}
Point2D& operator/=(const Point2D p2) {
    x /= p2.x;
    y /= p2.y;
    return *this;
}

Point2D& operator+(const Point2D p2) {
    return Point2D(*this) += p2;
}
Point2D& operator-(const Point2D p2) {
    return Point2D(*this) -= p2;
}
Point2D& operator/(const Point2D p2) {
    return Point2D(*this) /= p2;
}
Point2D& operator*(const Point2D p2) {
    return Point2D(*this) *= p2;
}

};

Point2D operator*(ftype a, Point2D b) {
    return a * b;
}

int main() {
    Point2D p1(1, 2);
    Point2D p2(3, 4);

    Point2D p3 = p1 * p2;
}

```

10.6 3D Points

Basic Operations

```

#include<bits/stdc++.h>

#define ftype double

struct Point3D {
    ftype x, y, z;
    Point3D() {}
    Point3D(ftype x, ftype y, ftype z): x(x), y(y), z(z) {}
    Point3D& operator+=(const Point3D &p2) {
        x += p2.x;
        y += p2.y;
        z += p2.z;
        return *this;
    }
    Point3D& operator-=(const Point3D &p2) {
        x -= p2.x;
        y -= p2.y;
        z -= p2.z;
        return *this;
    }

    Point3D& operator*=(const Point3D p2) {
        x *= p2.x;
        y *= p2.y;
        z *= p2.z;
        return *this;
    }
    Point3D& operator/=(const Point3D p2) {
        x /= p2.x;
        y /= p2.y;
        z /= p2.z;
        return *this;
    }

    Point3D& operator+(const Point3D p2) {
        return Point3D(*this) += p2;
    }
    Point3D& operator-(const Point3D p2) {
        return Point3D(*this) -= p2;
    }
}

```

```

    }
    Point3D& operator/(const Point3D p2) {
        return Point3D(*this) /= p2;
    }
    Point3D& operator*(const Point3D p2) {
        return Point3D(*this) *= p2;
    }
}

};

Point3D operator*(ftype a, Point3D b) {
    return a * b;
}

int main() {
    Point3D p1(1, 2);
    Point3D p2(3, 4);

    Point3D p3 = p1 * p2;
}

```

11 Miscellaneous

11.1 Faster implementations

11.1.1 hashes

custom hash

```

#define safe hash unordered_map<type, type, custom_hash> // same for
gp_hash_table
struct custom_hash {
    static uint64_t splitmix64(uint64_t x) {
        // http://xorshift.di.unimi.it/splitmix64.c
        x += 0x9e3779b97f4a7c15;
        x = (x ^ (x >> 30)) * 0xbf58476d1ce4e5b9;
        x = (x ^ (x >> 27)) * 0x94d049bb133111eb;
        return x ^ (x >> 31);
    }
}

```

```

size_t operator()(uint64_t x) const {
    static const uint64_t FIXED_RANDOM = chrono::steady_clock::now().
        time_since_epoch().count();
    return splitmix64(x + FIXED_RANDOM);
}
};

```

gb hash table

```

//policy based ds (faster hash table)
#include <ext/pb_ds/assoc_container.hpp>
using namespace __gnu_pbds;
gp_hash_table<int, int> table;

```

11.1.2 Binary Search the value

nearest sqrt

```

long long my_sqrt(long long a)
{
    long long l=0,r=5000000001;
    while(r-l>1)
    {
        long long mid=(l+r)/2;
        if(1ll*mid*mid<=a)l=mid;
        else r=mid;
    }
    return l;
}

```