

Team notebook

HCMUS-PenguinSpammers

February 2, 2022

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```
/*
https://www.spoj.com/problems/FREQ2/
*/
vector<int> MoQueries(int n, vector<query> Q){

    block_size = sqrt(n);
    sort(Q.begin(), Q.end(), [](const query &A,
        const query &B){
        return (A.l/block_size != B.l/block_size)?
            (A.l/block_size < B.l/block_size) :
            (A.r < B.r);
    });
    vector<int> res;
    res.resize((int)Q.size());

    int L = 1, R = 0;
    for(query q: Q){
        while (L > q.l) add(--L);
        while (R < q.r) add(++R);
```

```

while (L < q.l) del(L++);
while (R > q.r) del(R--);

res[q.pos] = calc(1, R-L+1);
}
return res;
}

```

1.2 Mo's Algorithms on Trees

/*
Given a tree with N nodes and Q queries. Each node has an integer weight.
Each query provides two numbers u and v, ask for how many different integers weight of nodes there are on path from u to v.

Modify DFS:

For each node u, maintain the start and the end DFS time. Let's call them ST(u) and EN(u).
=> For each query, a node is considered if its occurrence count is one.

Query solving:

Let's query be (u, v). Assume that ST(u) <= ST(v). Denotes P as LCA(u, v).

Case 1: P = u
Our query would be in range [ST(u), ST(v)].

Case 2: P != u
Our query would be in range [EN(u), ST(v)] + [ST(p), ST(p)]
*/

```

void update(int &L, int &R, int qL, int qR){
    while (L > qL) add(--L);

```

```

while (R < qR) add(++R);

while (L < qL) del(L++);
while (R > qR) del(R--);
}

vector<int> MoQueries(int n, vector<query> Q){
    block_size = sqrt((int)nodes.size());
    sort(Q.begin(), Q.end(), [](const query &A, const query &B){
        return (ST[A.l]/block_size != ST[B.l]/block_size)?
            (ST[A.l]/block_size < ST[B.l]/block_size) : (ST[A.r] < ST[B.r]);
    });
    vector<int> res;
    res.resize((int)Q.size());

    LCA lca;
    lca.initialize(n);

    int L = 1, R = 0;
    for(query q: Q){
        int u = q.l, v = q.r;
        if(ST[u] > ST[v]) swap(u, v); // assume that S[u] <= S[v]
        int parent = lca.get(u, v);

        if(parent == u){
            int qL = ST[u], qR = ST[v];
            update(L, R, qL, qR);
        }else{
            int qL = EN[u], qR = ST[v];
            update(L, R, qL, qR);
            if(cnt_val[a[parent]] == 0)
                res[q.pos] += 1;
        }

        res[q.pos] += cur_ans;
    }
    return res;
}

```

1.3 Parallel Binary Search

```

int lo[N], mid[N], hi[N];
vector<int> vec[N];

void clear() //Reset
{
    memset(bit, 0, sizeof(bit));
}

void apply(int idx) //Apply ith update/query
{
    if(ql[idx] <= qr[idx])
        update(ql[idx], qa[idx]),
        update(qr[idx]+1, -qa[idx]);
    else
    {
        update(1, qa[idx]);
        update(qr[idx]+1, -qa[idx]);
        update(ql[idx], qa[idx]);
    }
}

bool check(int idx) //Check if the condition is satisfied
{
    int req=reqd[idx];
    for(auto &it:owns[idx])
    {
        req-=pref(it);
        if(req<0)
            break;
    }
    if(req<=0)
        return 1;
    return 0;
}

void work()
{
    for(int i=1;i<=q;i++)
        vec[i].clear();
    for(int i=1;i<=n;i++)

```

```

        if(mid[i]>0)
            vec[mid[i]].push_back(i);
clear();
for(int i=1;i<=q;i++)
{
    apply(i);
    for(auto &it:vec[i]) //Add
        appropriate check conditions
    {
        if(check(it))
            hi[it]=i;
        else
            lo[it]=i+1;
    }
}

void parallel_binary()
{
    for(int i=1;i<=n;i++)
        lo[i]=1, hi[i]=q+1;
    bool changed = 1;
    while(changed)
    {
        changed=0;
        for(int i=1;i<=n;i++)
        {
            if(lo[i]<hi[i])
            {
                changed=1;
                mid[i]=(lo[i] +
                    hi[i])/2;
            }
            else
                mid[i]=-1;
        }
        work();
    }
}

```

2 Combinatorics

2.1 Factorial Approximate

Approximate Factorial:

$$n! = \sqrt{2\pi \cdot n} \cdot \left(\frac{n}{e}\right)^n \quad (1)$$

2.2 Factorial

n	1	2	3	4	5	6	7	8	9	10
$n!$	1	2	6	24	120	720	5040	40320	362880	3628800
n	11	12	13	14	15	16	17			
$n!$	4.0e7	4.8e8	6.2e9	8.7e10	1.3e12	2.1e13	3.6e14			
n	20	25	30	40	50	100	150	171		
$n!$	2e18	2e25	3e32	8e47	3e64	9e157	6e262	>DBL_MAX		

2.3 Fast Fourier Transform

```

/**
 * Fast Fourier Transform.
 * Useful to compute convolutions.
 * computes:
 *   C(f star g)[n] = sum_m(f[m] * g[n - m])
 * for all n.
 * test: icpc live archive, 6886 - Golf Bot
 */

```

```

using namespace std;
#include <bits/stdc++.h>
#define D(x) cout << #x " = " << (x) << endl
#define endl '\n'

```

```

const int MN = 262144 << 1;
int d[MN + 10], d2[MN + 10];

```

```

const double PI = acos(-1.0);

```

```

struct cpx {

```

```

    double real, image;
    cpx(double _real, double _image) {
        real = _real;
        image = _image;
    }
    cpx(){}
};

cpx operator + (const cpx &c1, const cpx &c2) {
    return cpx(c1.real + c2.real, c1.image +
        c2.image);
}

cpx operator - (const cpx &c1, const cpx &c2) {
    return cpx(c1.real - c2.real, c1.image -
        c2.image);
}

cpx operator * (const cpx &c1, const cpx &c2) {
    return cpx(c1.real*c2.real - c1.image*c2.image,
        c1.real*c2.image + c1.image*c2.real);
}

int rev(int id, int len) {
    int ret = 0;
    for (int i = 0; (1 << i) < len; i++) {
        ret <<= 1;
        if (id & (1 << i)) ret |= 1;
    }
    return ret;
}

cpx A[1 << 20];

void FFT(cpx *a, int len, int DFT) {
    for (int i = 0; i < len; i++)
        A[rev(i, len)] = a[i];
    for (int s = 1; (1 << s) <= len; s++) {
        int m = (1 << s);
        cpx wm = cpx(cos( DFT * 2 * PI / m), sin(DFT
            * 2 * PI / m));
        for(int k = 0; k < len; k += m) {
            cpx w = cpx(1, 0);
            for(int j = 0; j < (m >> 1); j++) {

```

```

    cpx t = w * A[k + j + (m >> 1)];
    cpx u = A[k + j];
    A[k + j] = u + t;
    A[k + j + (m >> 1)] = u - t;
    w = w * wm;
}
}
}
if (DFT == -1) for (int i = 0; i < len; i++)
    A[i].real /= len, A[i].image /= len;
for (int i = 0; i < len; i++) a[i] = A[i];
return;
}

```

```
cpx in[1 << 20];
```

```

void solve(int n) {
    memset(d, 0, sizeof d);
    int t;
    for (int i = 0; i < n; ++i) {
        cin >> t;
        d[t] = true;
    }
    int m;
    cin >> m;
    vector<int> q(m);
    for (int i = 0; i < m; ++i)
        cin >> q[i];

    for (int i = 0; i < MN; ++i) {
        if (d[i])
            in[i] = cpx(1, 0);
        else
            in[i] = cpx(0, 0);
    }
}

```

```

FFT(in, MN, 1);
for (int i = 0; i < MN; ++i) {
    in[i] = in[i] * in[i];
}
FFT(in, MN, -1);

```

```

int ans = 0;
for (int i = 0; i < q.size(); ++i) {

```

```

    if (in[q[i]].real > 0.5 || d[q[i]]) {
        ans++;
    }
}
cout << ans << endl;
}

int main() {
    ios_base::sync_with_stdio(false); cin.tie(NULL);
    int n;
    while (cin >> n)
        solve(n);
    return 0;
}

```

2.4 General purpose numbers

Bernoulli numbers

EGF of Bernoulli numbers is $B(t) = \frac{t}{e^t - 1}$ (FFT-able).

$B[0, \dots] = [1, -\frac{1}{2}, \frac{1}{6}, 0, -\frac{1}{30}, 0, \frac{1}{42}, \dots]$

Sums of powers:

$$\sum_{i=1}^n i^m = \frac{1}{m+1} \sum_{k=0}^m \binom{m+1}{k} B_k \cdot (n+1)^{m+1-k}$$

Euler-Maclaurin formula for infinite sums:

$$\begin{aligned} \sum_{i=m}^{\infty} f(i) &= \int_m^{\infty} f(x) dx - \sum_{k=1}^{\infty} \frac{B_k}{k!} f^{(k-1)}(m) \\ &\approx \int_m^{\infty} f(x) dx + \frac{f(m)}{2} - \frac{f'(m)}{12} + \frac{f'''(m)}{720} + O(f^{(5)}(m)) \end{aligned}$$

Stirling numbers of the first kind

Number of permutations on n items with k cycles.

$$c(n, k) = c(n-1, k-1) + (n-1)c(n-1, k), \quad c(0, 0) = 1$$

$$\sum_{k=0}^n c(n, k) x^k = x(x+1) \dots (x+n-1)$$

$$c(8, k) = 8, 0, 5040, 13068, 13132, 6769, 1960, 322, 28, 1$$

Stirling numbers of the second kind

Partitions of n distinct elements into exactly k groups.

$$S(n, k) = S(n-1, k-1) + kS(n-1, k)$$

$$S(n, 1) = S(n, n) = 1$$

$$S(n, k) = \frac{1}{k!} \sum_{j=0}^k (-1)^{k-j} \binom{k}{j} j^n$$

Eulerian numbers

Number of permutations $\pi \in S_n$ in which exactly k elements are greater than the previous element. k j :s s.t. $\pi(j) > \pi(j+1)$, $k+1$ j :s s.t. $\pi(j) \geq j$, k j :s s.t. $\pi(j) > j$.

$$E(n, k) = (n-k)E(n-1, k-1) + (k+1)E(n-1, k)$$

$$E(n, 0) = E(n, n-1) = 1$$

$$E(n, k) = \sum_{j=0}^k (-1)^j \binom{n+1}{j} (k+1-j)^n$$

Bell numbers

Total number of partitions of n distinct elements. $B(n) = 1, 1, 2, 5, 15, 52, 203, 877, 4140, 21147, \dots$. For p prime,

$$B(p^m + n) \equiv mB(n) + B(n+1) \pmod{p}$$

Labeled unrooted trees

on n vertices: n^{n-2}

on k existing trees of size n_i : $n_1 n_2 \dots n_k n^{k-2}$

with degrees d_i : $(n-2)! / ((d_1-1)! \dots (d_n-1)!)$

Catalan numbers

$$C_n = \frac{1}{n+1} \binom{2n}{n} = \binom{2n}{n} - \binom{2n}{n+1} = \frac{(2n)!}{(n+1)!n!}$$

$$C_0 = 1, \quad C_{n+1} = \frac{2(2n+1)}{n+2} C_n, \quad C_{n+1} = \sum C_i C_{n-i}$$

$$C_n = 1, 1, 2, 5, 14, 42, 132, 429, 1430, 4862, 16796, 58786, \dots$$

[noitemsep]sub-diagonal monotone paths in an $n \times n$ grid. strings with n pairs of parenthesis, correctly nested. binary trees with $n+1$ leaves (0 or 2 children). ordered trees with $n+1$ vertices. ways a convex polygon with $n+2$ sides can be cut into triangles by connecting vertices with straight lines. permutations of $[n]$ with no 3-term increasing subseq.

2.5 Lucas Theorem

For non-negative integers m and n and a prime p , the following congruence relation holds: :

$$\binom{m}{n} \equiv \prod_{i=0}^k \binom{m_i}{n_i} \pmod{p},$$

where :

$$m = m_k p^k + m_{k-1} p^{k-1} + \dots + m_1 p + m_0,$$

and :

$$n = n_k p^k + n_{k-1} p^{k-1} + \dots + n_1 p + n_0$$

are the base p expansions of m and n respectively. This uses the convention that $\binom{m}{n} = 0$ if $m \leq n$.

2.6 Multinomial

```
/**
 * Description: Computes  $\displaystyle \binom{k_1 + \dots + k_n}{k_1, k_2, \dots, k_n} = \frac{(\sum k_i)!}{k_1! k_2! \dots k_n!}$ .
 * Status: Tested on kattis:lexicography
 */
#pragma once

long long multinomial(vector<int>& v) {
    long long c = 1, m = v.empty() ? 1 : v[0];
    for (long long i = 1; i < v.size(); i++) {
        for (long long j = 0; j < v[i]; j++) {
            c = c * ++m / (j + 1);
        }
    }
    return c;
}
```

2.7 Others

Cycles Let $g_S(n)$ be the number of n -permutations whose cycle lengths all belong to the set S . Then

$$\sum_{n=0}^{\infty} g_S(n) \frac{x^n}{n!} = \exp \left(\sum_{n \in S} \frac{x^n}{n} \right)$$

Derangements Permutations of a set such that none of the elements appear in their original position.

$$D(n) = (n-1)(D(n-1)+D(n-2)) = nD(n-1)+(-1)^n = \left\lfloor \frac{n!}{e} \right\rfloor$$

Burnside's lemma Given a group G of symmetries and a set X , the number of elements of X up to symmetry equals

$$\frac{1}{|G|} \sum_{g \in G} |X^g|,$$

where X^g are the elements fixed by g ($g.x = x$).

If $f(n)$ counts "configurations" (of some sort) of length n , we can ignore rotational symmetry using $G = Z_n$ to get

$$g(n) = \frac{1}{n} \sum_{k=0}^{n-1} f(\gcd(n, k)) = \frac{1}{n} \sum_{k|n} f(k) \phi(n/k).$$

2.8 Permutation To Int

```
/**
 * Description: Permutation -> integer
 *              conversion. (Not order preserving.)
 * Integer -> permutation can use a lookup table.
 * Time: O(n)
 */

int permToInt(vector<int>& v) {
    int use = 0, i = 0, r = 0;
    for(int x : v) r = r * ++i +
        __builtin_popcount(use & ~(1<<x)),
```

```
        use |= 1 << x;           //
        (note: minus, not ~!)
    return r;
}
```

2.9 Sigma Function

The Sigma Function is defined as:

$$\sigma_x(n) = \sum_{d|n} d^x$$

when $x = 0$ is called the divisor function, that counts the number of positive divisors of n .

Now, we are interested in find

$$\sum_{d|n} \sigma_0(d)$$

If n is written as prime factorization:

$$n = \prod_{i=1}^k P_i^{e_i}$$

We can demonstrate that:

$$\sum_{d|n} \sigma_0(d) = \prod_{i=1}^k g(e_i + 1)$$

where $g(x)$ is the sum of the first x positive numbers:

$$g(x) = (x * (x + 1)) / 2$$

3 Data Structures

3.1 Binary Index Tree

```

struct BIT {
    int n;
    int t[2 * N];

    void add(int where, long long what) {
        for (where++; where <= n; where += where &
            -where) {
            t[where] += what;
        }
    }

    void add(int from, int to, long long what) {
        add(from, what);
        add(to + 1, -what);
    }

    long long query(int where) {
        long long sum = t[0];

        for (where++; where > 0; where -= where &
            -where) {
            sum += t[where];
        }

        return sum;
    }
};

```

3.2 Disjoint Set Union (DSU)

```

class DSU{
public:
    vector<int> parent;
    void initialize(int n){
        parent.resize(n+1, -1);
    }

    int findSet(int u){
        while(parent[u] > 0)
            u = parent[u];
        return u;
    }
};

```

```

    }

    void Union(int u, int v){
        int x = parent[u] + parent[v];
        if(parent[u] > parent[v]){
            parent[v] = x;
            parent[u] = v;
        }else{
            parent[u] = x;
            parent[v] = u;
        }
    }
};

```

3.3 Fake Update

```

vector<int> fake_bit[MAXN];

void fake_update(int x, int y, int limit_x){
    for(int i = x; i < limit_x; i += i&(-i))
        fake_bit[i].pb(y);
}

void fake_get(int x, int y){
    for(int i = x; i >= 1; i -= i&(-i))
        fake_bit[i].pb(y);
}

vector<int> bit[MAXN];

void update(int x, int y, int limit_x, int val){
    for(int i = x; i < limit_x; i += i&(-i)){
        for(int j =
            lower_bound(fake_bit[i].begin(),
                fake_bit[i].end(), y) -
                fake_bit[i].begin(); j <
                fake_bit[i].size(); j += j&(-j))
            bit[i][j] = max(bit[i][j], val);
        }
    }

    int get(int x, int y){

```

```

        int ans = 0;
        for(int i = x; i >= 1; i -= i&(-i)){
            for(int j =
                lower_bound(fake_bit[i].begin(),
                    fake_bit[i].end(), y) -
                    fake_bit[i].begin(); j >= 1; j -=
                    j&(-j))
                ans = max(ans, bit[i][j]);
            }
        }
        return ans;
    }

    int main(){
        _io
        int n; cin >> n;
        vector<int> Sx, Sy;
        for(int i = 1; i <= n; i++){
            cin >> a[i].fi >> a[i].se;
            Sx.pb(a[i].fi);
            Sy.pb(a[i].se);
        }
        unique_arr(Sx);
        unique_arr(Sy);
        // unique all value
        for(int i = 1; i <= n; i++){
            a[i].fi = lower_bound(Sx.begin(),
                Sx.end(), a[i].fi) - Sx.begin();
            a[i].se = lower_bound(Sy.begin(),
                Sy.end(), a[i].se) - Sy.begin();
        }

        // do fake BIT update and get operator
        for(int i = 1; i <= n; i++){
            fake_get(a[i].fi-1, a[i].se-1);
            fake_update(a[i].fi, a[i].se,
                (int)Sx.size());
        }

        for(int i = 0; i < Sx.size(); i++){
            fake_bit[i].pb(INT_MIN); // avoid zero
            sort(fake_bit[i].begin(),
                fake_bit[i].end());
            fake_bit[i].resize(unique(fake_bit[i].begin(),
                fake_bit[i].end()) -

```

```

        fake_bit[i].begin());
    bit[i].resize((int)fake_bit[i].size(), 0);
}

// real update, get operator
int res = 0;
for(int i = 1; i <= n; i++){
    int maxCurLen = get(a[i].fi-1, a[i].se-1)
        + 1;
    res = max(res, maxCurLen);
    update(a[i].fi, a[i].se, (int)Sx.size(),
        maxCurLen);
}
}

```

3.4 Fenwick Tree

```

template <typename T>
class FenwickTree{
    vector <T> fenw;
    int n;
public:
    void initialize(int _n){
        this->n = _n;
        fenw.resize(n+1);
    }

    void update(int id, T val) {
        while (id <= n) {
            fenw[id] += val;
            id += id&(-id);
        }
    }

    T get(int id){
        T ans{};
        while(id >= 1){
            ans += fenw[id];
            id -= id&(-id);
        }
        return ans;
    }
}

```

```
};
```

3.5 Hash Table

```

/*
 * Micro hash table, can be used as a set.
 * Very efficient vs std::set
 */

const int MN = 1001;
struct ht {
    int _s[(MN + 10) >> 5];
    int len;
    void set(int id) {
        len++;
        _s[id >> 5] |= (1LL << (id & 31));
    }
    bool is_set(int id) {
        return _s[id >> 5] & (1LL << (id & 31));
    }
};

```

3.6 Range Minimum Query

```

/*
    return min(v[a], v[a + 1], ..., v[b - 1]) in
    constant time
*/

template<class T>
struct RMQ {
    vector<vector<T>> jmp;
    RMQ(const vector<T>& V) : jmp(1, V) {
        for (int pw = 1, k = 1; pw * 2 <=
            sz(V); pw *= 2, ++k) {
            jmp.emplace_back(sz(V) - pw
                * 2 + 1);
            rep(j, 0, sz(jmp[k]))

```

```

                jmp[k][j] =
                    min(jmp[k -
                        1][j], jmp[k -
                            1][j + pw]);
            }
        }
        T query(int a, int b) {
            assert(a < b); // or return inf if
                a == b
            int dep = 31 - __builtin_clz(b - a);
            return min(jmp[dep][a], jmp[dep][b
                - (1 << dep)]);
        }
    };
};

```

3.7 STL Treap

```

struct Node {
    Node *l = 0, *r = 0;
    int val, y, c = 1;
    Node(int val) : val(val), y(rand()) {}
    void recalc();
};

int cnt(Node* n) { return n ? n->c : 0; }
void Node::recalc() { c = cnt(l) + cnt(r) + 1; }

template<class F> void each(Node* n, F f) {
    if (n) { each(n->l, f); f(n->val);
        each(n->r, f); }
}

pair<Node*, Node*> split(Node* n, int k) {
    if (!n) return {};
    if (cnt(n->l) >= k) { // "n->val >= k" for
        lower_bound(k)
        auto pa = split(n->l, k);
        n->l = pa.second;
        n->recalc();
        return {pa.first, n};
    } else {

```

```

        auto pa = split(n->r, k - cnt(n->l)
            - 1); // and just "k"
        n->r = pa.first;
        n->recalc();
        return {n, pa.second};
    }
}

Node* merge(Node* l, Node* r) {
    if (!l) return r;
    if (!r) return l;
    if (l->y > r->y) {
        l->r = merge(l->r, r);
        l->recalc();
        return l;
    } else {
        r->l = merge(l, r->l);
        r->recalc();
        return r;
    }
}

Node* ins(Node* t, Node* n, int pos) {
    auto pa = split(t, pos);
    return merge(merge(pa.first, n),
        pa.second);
}

// Example application: move the range [l, r) to
// index k
void move(Node*& t, int l, int r, int k) {
    Node *a, *b, *c;
    tie(a,b) = split(t, l); tie(b,c) =
        split(b, r - l);
    if (k <= l) t = merge(ins(a, b, k), c);
    else t = merge(a, ins(c, b, k - r));
}

```

3.8 Segment Tree

```

#include <bits/stdc++.h>
using namespace std;

```

```

const int N = 1e5 + 10;

int node[4*N];

void modify(int seg, int l, int r, int p, int
    val){
    if(l == r){
        node[seg] += val;
        return;
    }
    int mid = (l + r)/2;
    if(p <= mid){
        modify(2*seg + 1, l, mid, p, val);
    }else{
        modify(2*seg + 2, mid + 1, r, p, val);
    }
    node[seg] = node[2*seg + 1] + node[2*seg + 2];
}

int sum(int seg, int l, int r, int a, int b){
    if(l > b || r < a) return 0;
    if(l >= a && r <= b) return node[seg];
    int mid = (l + r)/2;
    return sum(2*seg + 1, l, mid, a, b) +
        sum(2*seg + 2, mid + 1, r, a, b);
}

```

3.9 Sparse Table

```

template <typename T, typename func =
    function<T(const T, const T)>>
struct SparseTable {
    func calc;
    int n;
    vector<vector<T>> ans;

    SparseTable() {}

    SparseTable(const vector<T>& a, const func&
        f) : n(a.size()), calc(f) {

```

```

        int last = trunc(log2(n)) + 1;
        ans.resize(n);
        for (int i = 0; i < n; i++){
            ans[i].resize(last);
        }
        for (int i = 0; i < n; i++){
            ans[i][0] = a[i];
        }
        for (int j = 1; j < last; j++){
            for (int i = 0; i <= n - (1 << j);
                i++){
                ans[i][j] = calc(ans[i][j - 1],
                    ans[i + (1 << (j - 1))][j -
                        1]);
            }
        }
    }

    T query(int l, int r){
        assert(0 <= l && l <= r && r < n);
        int k = trunc(log2(r - l + 1));
        return calc(ans[l][k], ans[r - (1 << k) +
            1][k]);
    }
};

```

3.10 Trie

```

const int MN = 26; // size of alphabet
const int MS = 100010; // Number of states.

```

```

struct trie{
    struct node{
        int c;
        int a[MN];
    };

    node tree[MS];
    int nodes;

    void clear(){
        tree[nodes].c = 0;

```



```

memset(tree[nodes].a, -1, sizeof
       tree[nodes].a);
nodes++;
}

void init(){
    nodes = 0;
    clear();
}

int add(const string &s, bool query = 0){
    int cur_node = 0;
    for(int i = 0; i < s.size(); ++i){
        int id = gid(s[i]);
        if(tree[cur_node].a[id] == -1){
            if(query) return 0;
            tree[cur_node].a[id] = nodes;
            clear();
        }
        cur_node = tree[cur_node].a[id];
    }
    if(!query) tree[cur_node].c++;
    return tree[cur_node].c;
}
};

```

4 Dynamic Programming Optimization

4.1 Convex Hull Trick

```

#define long long long
#define pll pair<long, long>
#define all(c) c.begin(), c.end()
#define fastio ios_base::sync_with_stdio(false);
cin.tie(0)

struct line{
    long a, b;

```

```

    line() {}
    line(long a, long b) : a(a), b(b) {}
    bool operator < (const line &A) const {
        return pll(a,b) < pll(A.a,A.b);
    }
};

bool bad(line A, line B, line C){
    return (C.b - B.b) * (A.a - B.a) <= (B.b -
        A.b) * (B.a - C.a);
}

void addLine(vector<line> &memo, line cur){
    int k = memo.size();
    while (k >= 2 && bad(memo[k - 2], memo[k -
        1], cur)){
        memo.pop_back();
        k--;
    }
    memo.push_back(cur);
}

long Fn(line A, long x){
    return A.a * x + A.b;
}

long query(vector<line> &memo, long x){
    int lo = 0, hi = memo.size() - 1;
    while (lo != hi){
        int mi = (lo + hi) / 2;
        if (Fn(memo[mi], x) > Fn(memo[mi + 1], x)){
            lo = mi + 1;
        }
        else hi = mi;
    }
    return Fn(memo[lo], x);
}

const int N = 1e6 + 1;
long dp[N];

int main()
{
    fastio;

```

```

    int n, c; cin >> n >> c;
    vector<line> memo;
    for (int i = 1; i <= n; i++){
        long val; cin >> val;
        addLine(memo, {-2 * val, val * val + dp[i
            - 1]});
        dp[i] = query(memo, val) + val * val + c;
    }
    cout << dp[n] << '\n';
    return 0;
}

```

4.2 Divide and Conquer

```

/**
 * recurrence:
 *   dp[k][i] = min dp[k-1][j] + c[i][j - 1], for
 *   all j > i;
 *
 * "comp" computes dp[k][i] for all i in O(n log
 *   n) (k is fixed)
 *
 * Problems:
 *   https://icpc.kattis.com/problems/branch
 *   http://codeforces.com/contest/321/problem/E
 * */

void comp(int l, int r, int le, int re) {
    if (l > r) return;

    int mid = (l + r) >> 1;

    int best = max(mid + 1, le);
    dp[cur][mid] = dp[cur ^ 1][best] + cost(mid,
        best - 1);
    for (int i = best; i <= re; i++) {
        if (dp[cur][mid] > dp[cur ^ 1][i] + cost(mid,
            i - 1)) {
            best = i;
            dp[cur][mid] = dp[cur ^ 1][i] + cost(mid, i
                - 1);
        }
    }
}

```

```

}

comp(l, mid - 1, le, best);
comp(mid + 1, r, best, re);
}

```

5 Geometry

5.1 Closest Pair Problem

```

struct point {
    double x, y;
    int id;
    point() {}
    point (double a, double b) : x(a), y(b) {}
};

double dist(const point &o, const point &p) {
    double a = p.x - o.x, b = p.y - o.y;
    return sqrt(a * a + b * b);
}

double cp(vector<point> &p, vector<point> &x,
    vector<point> &y) {
    if (p.size() < 4) {
        double best = 1e100;
        for (int i = 0; i < p.size(); ++i)
            for (int j = i + 1; j < p.size(); ++j)
                best = min(best, dist(p[i], p[j]));
        return best;
    }

    int ls = (p.size() + 1) >> 1;
    double l = (p[ls - 1].x + p[ls].x) * 0.5;
    vector<point> xl(ls), xr(p.size() - ls);
    unordered_set<int> left;
    for (int i = 0; i < ls; ++i) {
        xl[i] = x[i];
        left.insert(x[i].id);
    }
    for (int i = ls; i < p.size(); ++i) {

```

```

        xr[i - ls] = x[i];
    }

    vector<point> yl, yr;
    vector<point> pl, pr;
    yl.reserve(ls); yr.reserve(p.size() - ls);
    pl.reserve(ls); pr.reserve(p.size() - ls);
    for (int i = 0; i < p.size(); ++i) {
        if (left.count(y[i].id))
            yl.push_back(y[i]);
        else
            yr.push_back(y[i]);

        if (left.count(p[i].id))
            pl.push_back(p[i]);
        else
            pr.push_back(p[i]);
    }

    double dl = cp(pl, xl, yl);
    double dr = cp(pr, xr, yr);
    double d = min(dl, dr);
    vector<point> yp; yp.reserve(p.size());
    for (int i = 0; i < p.size(); ++i) {
        if (fabs(y[i].x - l) < d)
            yp.push_back(y[i]);
    }
    for (int i = 0; i < yp.size(); ++i) {
        for (int j = i + 1; j < yp.size() && j < i + 7; ++j) {
            d = min(d, dist(yp[i], yp[j]));
        }
    }
    return d;
}

double closest_pair(vector<point> &p) {
    vector<point> x(p.begin(), p.end());
    sort(x.begin(), x.end(), [](const point &a,
        const point &b) {
        return a.x < b.x;
    });
    vector<point> y(p.begin(), p.end());

```

```

    sort(y.begin(), y.end(), [](const point &a,
        const point &b) {
        return a.y < b.y;
    });
    return cp(p, x, y);
}

```

5.2 Convex Diameter

```

struct point{
    int x, y;
};

struct vec{
    int x, y;
};

vec operator - (const point &A, const point &B){
    return vec{A.x - B.x, A.y - B.y};
}

int cross(vec A, vec B){
    return A.x*B.y - A.y*B.x;
}

int cross(point A, point B, point C){
    int val = A.x*(B.y - C.y) + B.x*(C.y - A.y) +
        C.x*(A.y - B.y);
    if(val == 0)
        return 0; // coline
    if(val < 0)
        return 1; // clockwise
    return -1; //counter clockwise
}

vector<point> findConvexHull(vector<point>
    points){
    vector<point> convex;
    sort(points.begin(), points.end(), [](const
        point &A, const point &B){
        return (A.x == B.x)? (A.y < B.y): (A.x <
            B.x);
    });

```

```

});
vector<point> Up, Down;
point A = points[0], B = points.back();
Up.push_back(A);
Down.push_back(A);

for(int i = 0; i < points.size(); i++){
    if(i == points.size()-1 || cross(A,
        points[i], B) > 0){
        while(Up.size() > 2 &&
            cross(Up[Up.size()-2],
                Up[Up.size()-1], points[i]) <= 0)
            Up.pop_back();
        Up.push_back(points[i]);
    }
    if(i == points.size()-1 || cross(A,
        points[i], B) < 0){
        while(Down.size() > 2 &&
            cross(Down[Down.size()-2],
                Down[Down.size()-1], points[i]) >= 0)
            Down.pop_back();
        Down.push_back(points[i]);
    }
}

for(int i = 0; i < Up.size(); i++)
    convex.push_back(Up[i]);
for(int i = Down.size()-2; i > 0; i--)
    convex.push_back(Down[i]);
return convex;
}

int dist(point A, point B){
    return (A.x - B.x)*(A.x - B.x) + (A.y -
        B.y)*(A.y - B.y);
}

double findConvexDiameter(vector<point>
    convexHull){
    int n = convexHull.size();

    int is = 0, js = 0;
    for(int i = 1; i < n; i++){
        if(convexHull[i].y > convexHull[is].y)

```

```

        is = i;
        if(convexHull[js].y > convexHull[i].y)
            js = i;
    }

    int maxd = dist(convexHull[is],
        convexHull[js]);
    int i, maxi, j, maxj;
    i = maxi = is;
    j = maxj = js;
    do{
        int ni = (i+1)%n, nj = (j+1)%n;
        if(cross(convexHull[ni] - convexHull[i],
            convexHull[nj] - convexHull[j]) <= 0){
            j = nj;
        }else{
            i = ni;
        }
    }while(i != is || j != js);
    return sqrt(maxd);
}

```

5.3 Pick Theorem

```

struct point{
    ll x, y;
};

//Pick:  $S = I + B/2 - 1$ 

ld polygonArea(vector<point> &points){
    int n = (int)points.size();
    ld area = 0.0;
    int j = n-1;
    for(int i = 0; i < n; i++){

```

```

        area += (points[j].x + points[i].x) *
            (points[j].y - points[i].y);
        j = i;
    }

    return abs(area/2.0);
}

ll boundary(vector<point> points){
    int n = (int)points.size();
    ll num_bound = 0;
    for(int i = 0; i < n; i++){
        ll dx = (points[i].x - points[(i+1)%n].x);
        ll dy = (points[i].y - points[(i+1)%n].y);
        num_bound += abs(__gcd(dx, dy)) - 1;
    }
    return num_bound;
}

```

5.4 Square

```

typedef long double ld;

const ld eps = 1e-12;
int cmp(ld x, ld y = 0, ld tol = eps) {
    return (x <= y + tol) ? (x + tol < y) ? -1 :
        0 : 1;
}

struct point{
    ld x, y;
    point(ld a, ld b) : x(a), y(b) {}
    point() {}
};

struct square{
    ld x1, x2, y1, y2,
        a, b, c;
    point edges[4];
    square(ld _a, ld _b, ld _c) {
        a = _a, b = _b, c = _c;

```

```

    x1 = a - c * 0.5;
    x2 = a + c * 0.5;
    y1 = b - c * 0.5;
    y2 = b + c * 0.5;
    edges[0] = point(x1, y1);
    edges[1] = point(x2, y1);
    edges[2] = point(x2, y2);
    edges[3] = point(x1, y2);
}
};

ld min_dist(point &a, point &b) {
    ld x = a.x - b.x,
        y = a.y - b.y;
    return sqrt(x * x + y * y);
}

bool point_in_box(square s1, point p) {
    if (cmp(s1.x1, p.x) != 1 && cmp(s1.x2, p.x) !=
        -1 &&
        cmp(s1.y1, p.y) != 1 && cmp(s1.y2, p.y) !=
        -1)
        return true;
    return false;
}

bool inside(square &s1, square &s2) {
    for (int i = 0; i < 4; ++i)
        if (point_in_box(s2, s1.edges[i]))
            return true;

    return false;
}

bool inside_vert(square &s1, square &s2) {
    if ((cmp(s1.y1, s2.y1) != -1 && cmp(s1.y1,
        s2.y2) != 1) ||
        (cmp(s1.y2, s2.y1) != -1 && cmp(s1.y2,
        s2.y2) != 1))
        return true;
    return false;
}

bool inside_hori(square &s1, square &s2) {

```

```

    if ((cmp(s1.x1, s2.x1) != -1 && cmp(s1.x1,
        s2.x2) != 1) ||
        (cmp(s1.x2, s2.x1) != -1 && cmp(s1.x2,
        s2.x2) != 1))
        return true;
    return false;
}

ld min_dist(square &s1, square &s2) {
    if (inside(s1, s2) || inside(s2, s1))
        return 0;

    ld ans = 1e100;
    for (int i = 0; i < 4; ++i)
        for (int j = 0; j < 4; ++j)
            ans = min(ans, min_dist(s1.edges[i],
                s2.edges[j]));

    if (inside_hori(s1, s2) || inside_hori(s2, s1))
        {
            if (cmp(s1.y1, s2.y2) != -1)
                ans = min(ans, s1.y1 - s2.y2);
            else
                if (cmp(s2.y1, s1.y2) != -1)
                    ans = min(ans, s2.y1 - s1.y2);
        }

    if (inside_vert(s1, s2) || inside_vert(s2, s1))
        {
            if (cmp(s1.x1, s2.x2) != -1)
                ans = min(ans, s1.x1 - s2.x2);
            else
                if (cmp(s2.x1, s1.x2) != -1)
                    ans = min(ans, s2.x1 - s1.x2);
        }

    return ans;
}

```

5.5 Triangle

Let a, b, c be length of the three sides of a triangle.

$$p = (a + b + c) * 0.5$$

The inradius is defined by:

$$iR = \sqrt{\frac{(p-a)(p-b)(p-c)}{p}}$$

The radius of its circumcircle is given by the formula:

$$cR = \frac{abc}{\sqrt{(a+b+c)(a+b-c)(a+c-b)(b+c-a)}}$$

6 Graphs

6.1 Bridges

```

struct Graph {
    vector<vector<Edge>> g;
    vector<int> vi, low, d, pi, is_b; // vi =
        visited
    int bridges_computed;
    int ticks, edges;

    Graph(int n, int m) {
        g.assign(n, vector<Edge>());
        id_b.assign(m, 0);
        vi.resize(n);
        low.resize(n);
        d.resize(n);
        pi.resize(n);
        edges = 0;
        bridges_computed = 0;
    }

    void addEdge(int u, int v) {
        g[u].push_back(Edge(v, edges));
        g[v].push_back(Edge(u, edges));
    }
}

```

```

    edges++;
}

void dfs(int u) {
    vi[u] = true;
    d[u] = low[u] = ticks++;
    for (int i = 0; i < g[u].size(); i++) {
        int v = g[u][i].to;
        if (v == pi[u]) continue;
        if (!vi[v]) {
            pi[v] = u;
            dfs(v);
            if (d[u] < low[v]) is_b[g[u][i].id]
                = true;
            low[u] = min(low[u], low[v]);
        } else {
            low[u] = min(low[u], low[v]);
        }
    }
}

// multiple edges from a to b are not
// allowed.
// (they could be detected as a bridge).
// if we need to handle this, just count how
// many edges there are from a to b.
void compBridges() {
    fill(pi.begin(), pi.end(), -1);
    fill(vi.begin(), vi.end(), false);
    fill(d.begin(), d.end(), 0);
    fill(low.begin(), low.end(), 0);
    ticks = 0;
    for (int i = 0; i < g.size(); i++)
        if (!vi[i]) dfs(i);
    bridges_computed = 1;
}

map<int, vector<Edge>> bridgesTree() {
    if (!bridges_computed) compBridges();
    int n = g.size();
    Dsu dsu(n);
    for (int i = 0; i < n; i++)
        for (auto e : g[i])
            if (!is_b[e.id]) dsu.Join(i, e.to);
}

```

```

    map<int, vector<Edge>> tree;
    for (int i = 0; i < n; i++)
        for (auto e : g[i])
            if (is_b[e.id])
                tree[dsu.Find(i)].emplace_back(dsu.Find(e.to),
                    e.id);
    return tree;
}
};

```

6.2 Dijkstra

```

struct edge {
    int to;
    long long w;
    edge() {}
    edge(int a, long long b) : to(a), w(b) {}
    bool operator<(const edge &e) const {
        return w > e.w;
    }
};

typedef <vector<vector<edge>> graph;
const long long inf = 1000000LL * 100000000LL;
pair<vector<int>, vector<long long>>
dijkstra(graph& g, int start) {
    int n = g.size();
    vector<long long> d(n, inf);
    vector<int> p(n, -1);
    d[start] = 0;
    priority_queue<edge> q;
    q.push(edge(start, 0));
    while (!q.empty()) {
        int node = q.top().to;
        long long dist = q.top().w;
        q.pop();
        if (dist > d[node]) continue;
        for (int i = 0; i < g[node].size(); i++) {
            int to = g[node][i].to;
            long long w_extra = g[node][i].w;
            if (dist + w_extra < d[to]) {
                p[to] = node;

```

```

                d[to] = dist + w_extra;
                q.push(edge(to, d[to]));
            }
        }
    }
    return {p, d};
}

```

6.3 Directed MST

```

struct Edge { int a, b; ll w; };
struct Node { /// lazy skew heap node
    Edge key;
    Node *l, *r;
    ll delta;
    void prop() {
        key.w += delta;
        if (l) l->delta += delta;
        if (r) r->delta += delta;
        delta = 0;
    }
    Edge top() { prop(); return key; }
};

Node *merge(Node *a, Node *b) {
    if (!a || !b) return a ? b;
    a->prop(), b->prop();
    if (a->key.w > b->key.w) swap(a, b);
    swap(a->l, (a->r = merge(b, a->r)));
    return a;
}

void pop(Node*& a) { a->prop(); a = merge(a->l, a->r); }

pair<ll, vi> dmst(int n, int r, vector<Edge>& g) {
    RollbackUF uf(n);
    vector<Node*> heap(n);
    for (Edge e : g) heap[e.b] =
        merge(heap[e.b], new Node{e});
    ll res = 0;
    vi seen(n, -1), path(n), par(n);
    seen[r] = r;
    vector<Edge> Q(n), in(n, {-1, -1}), comp;

```

```

deque<tuple<int, int, vector<Edge>>> cys;
rep(s,0,n) {
    int u = s, qi = 0, w;
    while (seen[u] < 0) {
        if (!heap[u]) return
            {-1, {}};
        Edge e = heap[u]->top();
        heap[u]->delta -= e.w,
            pop(heap[u]);
        Q[qi] = e, path[qi++] = u,
            seen[u] = s;
        res += e.w, u =
            uf.find(e.a);
        if (seen[u] == s) { ///
            found cycle, contract
            Node* cyc = 0;
            int end = qi, time =
                uf.time();
            do cyc = merge(cyc,
                heap[w =
                    path[--qi]]);
            while (uf.join(u,
                w));
            u = uf.find(u),
                heap[u] = cyc,
                seen[u] = -1;
            cys.push_front({u,
                time, {&Q[qi],
                    &Q[end]}});
        }
    }
    rep(i,0,qi) in[uf.find(Q[i].b)] =
        Q[i];
}

for (auto& [u,t,comp] : cys) { // restore
    sol (optional)
    uf.rollback(t);
    Edge inEdge = in[u];
    for (auto& e : comp)
        in[uf.find(e.b)] = e;
    in[uf.find(inEdge.b)] = inEdge;
}
rep(i,0,n) par[i] = in[i].a;

```

```

        return {res, par};
    }

```

6.4 Edge Coloring

```

vi edgeColoring(int N, vector<pii> eds) {
    vi cc(N + 1), ret(sz(eds)), fan(N),
        free(N), loc;
    for (pii e : eds) ++cc[e.first],
        ++cc[e.second];
    int u, v, ncols = *max_element(all(cc)) +
        1;
    vector<vi> adj(N, vi(ncols, -1));
    for (pii e : eds) {
        tie(u, v) = e;
        fan[0] = v;
        loc.assign(ncols, 0);
        int at = u, end = u, d, c =
            free[u], ind = 0, i = 0;
        while (d = free[v], !loc[d] && (v =
            adj[u][d]) != -1)
            loc[d] = ++ind, cc[ind] =
                d, fan[ind] = v;
        cc[loc[d]] = c;
        for (int cd = d; at != -1; cd ^= c
            ^ d, at = adj[at][cd])
            swap(adj[at][cd], adj[end =
                at][cd ^ c ^ d]);
        while (adj[fan[i]][d] != -1) {
            int left = fan[i], right =
                fan[++i], e = cc[i];
            adj[u][e] = left;
            adj[left][e] = u;
            adj[right][e] = -1;
            free[right] = e;
        }
        adj[u][d] = fan[i];
        adj[fan[i]][d] = u;
        for (int y : {fan[0], u, end})
            for (int& z = free[y] = 0;
                adj[y][z] != -1; z++);
    }
}

```

```

rep(i,0,sz(eds))
    for (tie(u, v) = eds[i];
        adj[u][ret[i]] != v;) ++ret[i];
return ret;
}

```

6.5 Eulerian Path

```

struct DirectedEulerPath
{
    int n;
    vector<vector<int>> > g;
    vector<int> path;

    void init(int _n){
        n = _n;
        g = vector<vector<int>> > (n + 1,
            vector<int> ());
        path.clear();
    }

    void add_edge(int u, int v){
        g[u].push_back(v);
    }

    void dfs(int u)
    {
        while(g[u].size())
        {
            int v = g[u].back();
            g[u].pop_back();
            dfs(v);
        }
        path.push_back(u);
    }

    bool getPath(){
        int ctEdges = 0;
        vector<int> outDeg, inDeg;
        outDeg = inDeg = vector<int> (n +
            1, 0);
        for(int i = 1; i <= n; i++)

```

```

{
    ctEdges += g[i].size();
    outDeg[i] += g[i].size();
    for(auto &u:g[i])
        inDeg[u]++;
}
int ctMiddle = 0, src = 1;
for(int i = 1; i <= n; i++)
{
    if(abs(inDeg[i] -
        outDeg[i]) > 1)
        return 0;
    if(inDeg[i] == outDeg[i])
        ctMiddle++;
    if(outDeg[i] > inDeg[i])
        src = i;
}
if(ctMiddle != n && ctMiddle + 2 !=
    n)
    return 0;
dfs(src);
reverse(path.begin(), path.end());
return (path.size() == ctEdges + 1);
}
};

```

6.6 Floyd - Warshall

```

const ll inf = 1LL << 62;
void floydWarshall(vector<vector<ll>>& m) {
    int n = sz(m);
    rep(i,0,n) m[i][i] = min(m[i][i], 0LL);
    rep(k,0,n) rep(i,0,n) rep(j,0,n)
        if (m[i][k] != inf && m[k][j] !=
            inf) {
            auto newDist = max(m[i][k]
                + m[k][j], -inf);
            m[i][j] = min(m[i][j],
                newDist);
        }
    rep(k,0,n) if (m[k][k] < 0) rep(i,0,n)
        rep(j,0,n)

```

```

        if (m[i][k] != inf && m[k][j] !=
            inf) m[i][j] = -inf;
}

```

6.7 Ford - Bellman

```

const ll inf = LLONG_MAX;
struct Ed { int a, b, w, s() { return a < b ? a :
    -a; } };
struct Node { ll dist = inf; int prev = -1; };

void bellmanFord(vector<Node>& nodes, vector<Ed>&
    eds, int s) {
    nodes[s].dist = 0;
    sort(all(eds), [](Ed a, Ed b) { return
        a.s() < b.s(); });

    int lim = sz(nodes) / 2 + 2; // /3+100
    with shuffled vertices
    rep(i,0,lim) for (Ed ed : eds) {
        Node cur = nodes[ed.a], &dest =
            nodes[ed.b];
        if (abs(cur.dist) == inf) continue;
        ll d = cur.dist + ed.w;
        if (d < dest.dist) {
            dest.prev = ed.a;
            dest.dist = (i < lim-1 ? d
                : -inf);
        }
    }
    rep(i,0,lim) for (Ed e : eds) {
        if (nodes[e.a].dist == -inf)
            nodes[e.b].dist = -inf;
    }
}

```

6.8 Gomory Hu

```

#include "PushRelabel.cpp"

```

```

typedef array<ll, 3> Edge;
vector<Edge> gomoryHu(int N, vector<Edge> ed) {
    vector<Edge> tree;
    vi par(N);
    rep(i,1,N) {
        PushRelabel D(N); // Dinic also
        works
        for (Edge t : ed) D.addEdge(t[0],
            t[1], t[2], t[2]);
        tree.push_back({i, par[i],
            D.calc(i, par[i])});
        rep(j,i+1,N)
            if (par[j] == par[i] &&
                D.leftOfMinCut(j))
                par[j] = i;
    }
    return tree;
}

```

6.9 Karp Min Mean Cycle

```

/**
 * Finds the min mean cycle, if you need the max
 * mean cycle
 * just add all the edges with negative cost and
 * print
 * ans * -1
 *
 * test: uva, 11090 - Going in Cycle!!
 */

const int MN = 1000;
struct edge{
    int v;
    long long w;
    edge(){} edge(int v, int w) : v(v), w(w) {}
};

long long d[MN][MN];
// This is a copy of g because increments the size
// pass as reference if this does not matter.
int karp(vector<vector<edge> > g) {

```

```

int n = g.size();

g.resize(n + 1); // this is important

for (int i = 0; i < n; ++i)
    if (!g[i].empty())
        g[n].push_back(edge(i,0));
++n;

for(int i = 0;i<n;++i)
    fill(d[i],d[i]+(n+1),INT_MAX);

d[n - 1][0] = 0;

for (int k = 1; k <= n; ++k) for (int u = 0; u
    < n; ++u) {
    if (d[u][k - 1] == INT_MAX) continue;
    for (int i = g[u].size() - 1; i >= 0; --i)
        d[g[u][i].v][k] = min(d[g[u][i].v][k],
            d[u][k - 1] + g[u][i].w);
}

bool flag = true;

for (int i = 0; i < n && flag; ++i)
    if (d[i][n] != INT_MAX)
        flag = false;

if (flag) {
    return true; // return true if there is no a
                cycle.
}

double ans = 1e15;

for (int u = 0; u + 1 < n; ++u) {
    if (d[u][n] == INT_MAX) continue;
    double W = -1e15;

    for (int k = 0; k < n; ++k)
        if (d[u][k] != INT_MAX)
            W = max(W, (double)(d[u][n] - d[u][k]) /
                (n - k));

```

```

    ans = min(ans, W);
}

// printf("%.2lf\n", ans);
cout << fixed << setprecision(2) << ans << endl;

return false;
}

```

6.10 Konig's Theorem

In any bipartite graph, the number of edges in a maximum matching equals the number of vertices in a minimum vertex cover

6.11 LCA

```

#include "../Data Structures/RMQ.h"

struct LCA {
    int T = 0;
    vi time, path, ret;
    RMQ<int> rmq;

    LCA(vector<vi>& C) : time(sz(C)),
        rmq((dfs(C,0,-1), ret)) {}
    void dfs(vector<vi>& C, int v, int par) {
        time[v] = T++;
        for (int y : C[v]) if (y != par) {
            path.push_back(v),
                ret.push_back(time[v]);
            dfs(C, y, v);
        }
    }

    int lca(int a, int b) {
        if (a == b) return a;
        tie(a, b) = minmax(time[a],
            time[b]);
        return path[rmq.query(a, b)];
    }
}

```

```

//dist(a,b){return depth[a] + depth[b] -
    2*depth[lca(a,b)];}

};

```

6.12 Math

Number of Spanning Trees

Create an $N \times N$ matrix mat , and for each edge $a \rightarrow b \in G$, do $\text{mat}[a][b]--$, $\text{mat}[b][b]++$ (and $\text{mat}[b][a]--$, $\text{mat}[a][a]++$ if G is undirected). Remove the i th row and column and take the determinant; this yields the number of directed spanning trees rooted at i (if G is undirected, remove any row/column).

Erdős–Gallai theorem

A simple graph with node degrees $d_1 \geq \dots \geq d_n$ exists iff $d_1 + \dots + d_n$ is even and for every $k = 1 \dots n$,

$$\sum_{i=1}^k d_i \leq k(k-1) + \sum_{i=k+1}^n \min(d_i, k).$$

6.13 Push Relabel

```

struct PushRelabel {
    struct Edge {
        int dest, back;
        ll f, c;
    };
    vector<vector<Edge>> g;
    vector<ll> ec;
    vector<Edge*> cur;
    vector<vi> hs; vi H;
    PushRelabel(int n) : g(n), ec(n), cur(n),
        hs(2*n), H(n) {}

    void addEdge(int s, int t, ll cap, ll
        rcap=0) {
        if (s == t) return;
        g[s].push_back({t, sz(g[t]), 0,
            cap});

```



```

        g[t].push_back({s, sz(g[s])-1, 0,
            rcap});
    }

    void addFlow(Edge& e, ll f) {
        Edge &back = g[e.dest][e.back];
        if (!ec[e.dest] && f)
            hs[H[e.dest]].push_back(e.dest);
        e.f += f; e.c -= f; ec[e.dest] += f;
        back.f -= f; back.c += f;
        ec[back.dest] -= f;
    }

    ll calc(int s, int t) {
        int v = sz(g); H[s] = v; ec[t] = 1;
        vi co(2*v); co[0] = v-1;
        rep(i,0,v) cur[i] = g[i].data();
        for (Edge& e : g[s]) addFlow(e,
            e.c);

        for (int hi = 0;;) {
            while (hs[hi].empty()) if
                (!hi--) return -ec[s];
            int u = hs[hi].back();
            hs[hi].pop_back();
            while (ec[u] > 0) //
                discharge u
                if (cur[u] ==
                    g[u].data() +
                    sz(g[u])) {
                    H[u] = 1e9;
                    for (Edge& e
                        : g[u])
                        if (e.c
                            && H[u] >
                                H[e.dest]+1)
                            H[u] =
                                H[e.dest]+1,
                                cur[u]
                                =
                                &e;
                    if
                        (++co[H[u]],
                            !--co[hi]
                                && hi < v)

```

```

        rep(i,0,v)
            if
                (hi
                    <
                        H[i]
                            &&
                                H[i]
                                    <
                                        v)
                    --co[H[i]],
                    H[i]
                    =
                    v
                    +
                    1;

            hi = H[u];
        } else if (cur[u]->c
            && H[u] ==
                H[cur[u]->dest]+1)
            addFlow(*cur[u],
                min(ec[u],
                    cur[u]->c));
        else ++cur[u];
    }

    }

    bool leftOfMinCut(int a) { return H[a] >=
        sz(g); }

};

```

6.14 SCC Kosaraju

// SCC = Strongly Connected Components

```

struct SCC {
    vector<vector<int>> g, gr;
    vector<bool> used;
    vector<int> order, component;
    int total_components;

    SCC(vector<vector<int>>& adj) {
        g = adj;
        int n = g.size();
    }

```

```

        gr.resize(n);
        for (int i = 0; i < n; i++)
            for (auto to : g[i])
                gr[to].push_back(i);

        used.assign(n, false);
        for (int i = 0; i < n; i++)
            if (!used[i])
                GenTime(i);

        used.assign(n, false);
        component.assign(n, -1);
        total_components = 0;
        for (int i = n - 1; i >= 0; i--) {
            int v = order[i];
            if (!used[v]) {
                vector<int> cur_component;
                Dfs(cur_component, v);
                for (auto node : cur_component)
                    component[node] =
                        total_components;
            }
        }

        void GenTime(int node) {
            used[node] = true;
            for (auto to : g[node])
                if (!used[to])
                    GenTime(to);
            order.push_back(node);
        }

        void Dfs(vector<int>& cur, int node) {
            used[node] = true;
            cur.push_back(node);
            if (!used[to])
                Dfs(cur, to);
        }

        vector<vector<int>> CondensedGraph() {
            vector<vector<int>> ans(total_components);
            for (int i = 0; i < int(g.size()); i++) {
                for (int to : g[i]) {

```

```

        int u = component[i], v =
            component[to];
        if (u != v)
            ans[u].push_back(v);
    }
}
return ans;
}
};

```

6.15 Topological Sort

```

vi topoSort(const vector<vi>& gr) {
    vi indeg(sz(gr)), ret;
    for (auto& li : gr) for (int x : li)
        indeg[x]++;
    queue<int> q; // use priority_queue for
        lexic. largest ans.
    rep(i,0,sz(gr)) if (indeg[i] == 0)
        q.push(i);
    while (!q.empty()) {
        int i = q.front(); // top() for
            priority queue
        ret.push_back(i);
        q.pop();
        for (int x : gr[i])
            if (--indeg[x] == 0)
                q.push(x);
    }
    return ret;
}

```

7 Misc

7.1 Dates

```

//
// Time - Leap years
//

```

```

// A[i] has the accumulated number of days from
// months previous to i
const int A[13] = { 0, 0, 31, 59, 90, 120, 151,
    181, 212, 243, 273, 304, 334 };
// same as A, but for a leap year
const int B[13] = { 0, 0, 31, 60, 91, 121, 152,
    182, 213, 244, 274, 305, 335 };
// returns number of leap years up to, and
// including, y
int leap_years(int y) { return y / 4 - y / 100 +
    y / 400; }
bool is_leap(int y) { return y % 400 == 0 || (y %
    4 == 0 && y % 100 != 0); }
// number of days in blocks of years
const int p400 = 400*365 + leap_years(400);
const int p100 = 100*365 + leap_years(100);
const int p4 = 4*365 + 1;
const int p1 = 365;
int date_to_days(int d, int m, int y)
{
    return (y - 1) * 365 + leap_years(y - 1) +
        (is_leap(y) ? B[m] : A[m]) + d;
}
void days_to_date(int days, int &d, int &m, int
    &y)
{
    bool top100; // are we in the top 100 years of
        a 400 block?
    bool top4; // are we in the top 4 years of a
        100 block?
    bool top1; // are we in the top year of a 4
        block?

    y = 1;
    top100 = top4 = top1 = false;

    y += ((days-1) / p400) * 400;
    d = (days-1) % p400 + 1;

    if (d > p100*3) top100 = true, d -= 3*p100, y
        += 300;
    else y += ((d-1) / p100) * 100, d = (d-1) %
        p100 + 1;
}

```

```

if (d > p4*24) top4 = true, d -= 24*p4, y +=
    24*4;
else y += ((d-1) / p4) * 4, d = (d-1) % p4 + 1;

if (d > p1*3) top1 = true, d -= p1*3, y += 3;
else y += (d-1) / p1, d = (d-1) % p1 + 1;

const int *ac = top1 && (!top4 || top100) ? B :
    A;
for (m = 1; m < 12; ++m) if (d <= ac[m + 1])
    break;
d -= ac[m];
}

```

8 Number Theory

8.1 Chinese Remainder Theorem

```

/**
 * Chinese remainder theorem.
 * Find z such that z % x[i] = a[i] for all i.
 * */
long long crt(vector<long long> &a, vector<long
    long> &x) {
    long long z = 0;
    long long n = 1;
    for (int i = 0; i < x.size(); ++i)
        n *= x[i];

    for (int i = 0; i < a.size(); ++i) {
        long long tmp = (a[i] * (n / x[i])) % n;
        tmp = (tmp * mod_inv(n / x[i], x[i])) % n;
        z = (z + tmp) % n;
    }

    return (z + n) % n;
}

```

8.2 Convolution

```
typedef long long int LL;
typedef pair<LL, LL> PLL;

inline bool is_pow2(LL x) {
    return (x & (x-1)) == 0;
}

inline int ceil_log2(LL x) {
    int ans = 0;
    --x;
    while (x != 0) {
        x >>= 1;
        ans++;
    }
    return ans;
}

/* Returns the convolution of the two given
   vectors in time proportional to n*log(n).
   * The number of roots of unity to use
     nroots_unity must be set so that the product
     of the first
   * nroots_unity primes of the vector
     nth_roots_unity is greater than the maximum
     value of the
   * convolution. Never use sizes of vectors bigger
     than 2^24, if you need to change the values
     of
   * the nth roots of unity to appropriate primes
     for those sizes.
   */
vector<LL> convolve(const vector<LL> &a, const
    vector<LL> &b, int nroots_unity = 2) {
    int N = 1 << ceil_log2(a.size() + b.size());
    vector<LL> ans(N,0), fA(N), fB(N), fC(N);
    LL modulo = 1;
    for (int times = 0; times < nroots_unity;
        times++) {
        fill(fA.begin(), fA.end(), 0);
        fill(fB.begin(), fB.end(), 0);
```

```
        for (int i = 0; i < a.size(); i++) fA[i] =
            a[i];
        for (int i = 0; i < b.size(); i++) fB[i] =
            b[i];
        LL prime = nth_roots_unity[times].first;
        LL inv_modulo = mod_inv(modulo % prime,
            prime);
        LL normalize = mod_inv(N, prime);
        ntfft(fA, 1, nth_roots_unity[times]);
        ntfft(fB, 1, nth_roots_unity[times]);
        for (int i = 0; i < N; i++) fC[i] = (fA[i] *
            fB[i]) % prime;
        ntfft(fC, -1, nth_roots_unity[times]);
        for (int i = 0; i < N; i++) {
            LL curr = (fC[i] * normalize) % prime;
            LL k = (curr - (ans[i] % prime) + prime) %
                prime;
            k = (k * inv_modulo) % prime;
            ans[i] += modulo * k;
        }
        modulo *= prime;
    }
    return ans;
}
```

8.3 Diophantine Equations

```
long long gcd(long long a, long long b, long long
    &x, long long &y) {
    if (a == 0) {
        x = 0;
        y = 1;
        return b;
    }
    long long x1, y1;
    long long d = gcd(b % a, a, x1, y1);
    x = y1 - (b / a) * x1;
    y = x1;
    return d;
}
```

```
bool find_any_solution(long long a, long long b,
    long long c, long long &x0,
    long long &y0, long long &g) {
    g = gcd(abs(a), abs(b), x0, y0);
    if (c % g) {
        return false;
    }

    x0 *= c / g;
    y0 *= c / g;
    if (a < 0) x0 = -x0;
    if (b < 0) y0 = -y0;
    return true;
}

void shift_solution(long long &x, long long &y,
    long long a, long long b,
    long long cnt) {
    x += cnt * b;
    y -= cnt * a;
}

long long find_all_solutions(long long a, long
    long b, long long c,
    long long minx, long long maxx, long long
    miny,
    long long maxy) {
    long long x, y, g;
    if (!find_any_solution(a, b, c, x, y, g))
        return 0;
    a /= g;
    b /= g;

    long long sign_a = a > 0 ? +1 : -1;
    long long sign_b = b > 0 ? +1 : -1;

    shift_solution(x, y, a, b, (minx - x) / b);
    if (x < minx) shift_solution(x, y, a, b,
        sign_b);
    if (x > maxx) return 0;
    long long lx1 = x;

    shift_solution(x, y, a, b, (maxx - x) / b);
```

```

if (x > maxx) shift_solution(x, y, a, b,
    -sign_b);
long long rx1 = x;

shift_solution(x, y, a, b, -(miny - y) / a);
if (y < miny) shift_solution(x, y, a, b,
    -sign_a);
if (y > maxy) return 0;
long long lx2 = x;

shift_solution(x, y, a, b, -(maxy - y) / a);
if (y > maxy) shift_solution(x, y, a, b,
    sign_a);
long long rx2 = x;

if (lx2 > rx2) swap(lx2, rx2);
long long lx = max(lx1, lx2);
long long rx = min(rx1, rx2);

if (lx > rx) return 0;
return (rx - lx) / abs(b) + 1;
}

```

8.4 Discrete Logarithm

```

// Computes x which  $a^x = b \pmod n$ .

long long d_log(long long a, long long b, long
    long n) {
    long long m = ceil(sqrt(n));
    long long aj = 1;
    map<long long, long long> M;
    for (int i = 0; i < m; ++i) {
        if (!M.count(aj))
            M[aj] = i;
        aj = (aj * a) % n;
    }

    long long coef = mod_pow(a, n - 2, n);
    coef = mod_pow(coef, m, n);
    // coef =  $a^{(-m)}$ 
    long long gamma = b;
    for (int i = 0; i < m; ++i) {
        if (M.count(gamma)) {
            return i * m + M[gamma];
        }
    }
}

```

```

    } else {
        gamma = (gamma * coef) % n;
    }
}
return -1;
}

```

8.5 Ext Euclidean

```

void ext_euclid(long long a, long long b, long
    long &x, long long &y, long long &g) {
    x = 0, y = 1, g = b;
    long long m, n, q, r;
    for (long long u = 1, v = 0; a != 0; g = a, a =
        r) {
        q = g / a, r = g % a;
        m = x - u * q, n = y - v * q;
        x = u, y = v, u = m, v = n;
    }
}

```