

Team notebook

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Contents		
1 Algorithms	1	
1.1 Mo's Algorithm	1	
1.2 Mo's Algorithms on Trees	1	
1.3 Parallel Binary Search	1	
2 Combinatorics	2	
2.1 Factorial Approximate	2	
2.2 Factorial	2	
2.3 Fast Fourier Transform	2	
2.4 General purpose numbers	3	
2.5 Lucas Theorem	3	
2.6 Multinomial	4	
2.7 Others	4	
2.8 Permutation To Int	4	
2.9 Sigma Function	4	
3 Data Structures	4	
3.1 Binary Index Tree	4	
3.2 Disjoint Set Union (DSU)	5	
3.3 Fake Update	5	
3.4 Fenwick Tree	5	
3.5 Hash Table	5	
3.6 Range Minimum Query	6	
3.7 STL Treap	6	
3.8 Segment Tree	6	
3.9 Sparse Table	6	
3.10 Trie	7	
4 Dynamic Programming Optimization	7	
4.1 Convex Hull Trick	7	
4.2 Divide and Conquer	7	
5 Geometry	8	
5.1 Closest Pair Problem	8	
5.2 Convex Diameter	8	
5.3 Pick Theorem	9	
5.4 Square	9	
5.5 Triangle	10	
6 Graphs	10	
6.1 Bridges	10	
6.2 Dijkstra	10	
6.3 Directed MST	11	
6.4 Edge Coloring	11	
6.5 Eulerian Path	11	
6.6 Floyd - Warshall	12	
6.7 Ford - Bellman	12	
6.8 Gomory Hu	12	
6.9 Karp Min Mean Cycle	12	
6.10 Konig's Theorem	13	
6.11 LCA	13	
6.12 Math	13	
6.13 Push Relabel	13	
6.14 SCC Kosaraju	14	
6.15 Topological Sort	14	
7 Misc	14	
7.1 Dates	14	
8 Number Theory	14	
8.1 Chinese Remainder Theorem	14	
8.2 Convolution	15	
8.3 Diophantine Equations	15	
8.4 Discrete Logarithm	16	
8.5 Ext Euclidean	16	
8.6 Highest Exponent Factorial	16	
8.7 Miller - Rabin	16	
8.8 Mod Integer	16	
8.9 Mod Inv	16	
8.10 Mod Mul	16	
8.11 Mod Pow	17	
8.12 Number Theoretic Transform	17	
8.13 Pollard Rho Factorize	17	
8.14 Primes	17	
8.15 Totient Sieve	18	

1 Algorithms

1.1 Mo's Algorithm

```
/*
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]--;
    }
    work();
}

```

2 Combinatorics

2.1 Factorial Approximate

Approximate Factorial:

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

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:

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

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:

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

We can demonstrate that:

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

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 - 1);
    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;
    }
    int d = dist(convexHull[i], convexHull[j]);
    if(d > maxd){
        maxd = d;
        maxi = i;
        maxj = j;
    }
}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 * 1000000LL;
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>>> cycs;
    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[u]
                    = path[--qi]);
                while (uf.join(u, w));
                u = uf.find(u), heap[u] =
                    cyc, seen[u] = -1;
                cycs.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] : cycs) { /// 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 (Edge 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 $mat[a][b]--$, $mat[b][b]++$ (and $mat[b][a]--$,

`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 mod 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;
    }
}

```

8.6 Highest Exponent Factorial

```

int highest_exponent(int p, const int &n){
    int ans = 0;
    int t = p;
    while(t <= n){
        ans += n/t;
        t*=p;
    }
    return ans;
}

```

8.7 Miller - Rabin

```

const int rounds = 20;

// checks whether a is a witness that n is not prime, 1
// < a < n
bool witness(long long a, long long n) {

```



```

        a[j] = (a[j] + a[k]) % prime;
        a[k] = (w * x) % prime;
    }
    w = (w * basew) % prime;
}
basew = (basew * basew) % prime;
}
int i = 0;
for (int j = 1; j < n - 1; j++) {
    for (int k = n >> 1; k > (i ^= k); k >>= 1);
    if (j < i) swap(a[i], a[j]);
}
}

```

8.13 Pollard Rho Factorize

```

long long pollard_rho(long long n) {
    long long x, y, i = 1, k = 2, d;
    x = y = rand() % n;
    while (1) {
        ++i;
        x = mod_mul(x, x, n);
        x += 2;
        if (x >= n) x -= n;
        if (x == y) return 1;
        d = __gcd(abs(x - y), n);
        if (d != 1) return d;
        if (i == k) {
            y = x;
            k *= 2;
        }
    }
    return 1;
}

// Returns a list with the prime divisors of n
vector<long long> factorize(long long n) {
    vector<long long> ans;
    if (n == 1)
        return ans;
    if (miller_rabin(n)) {
        ans.push_back(n);
    } else {
        long long d = 1;

```

```

        while (d == 1)
            d = pollard_rho(n);
        vector<long long> dd = factorize(d);
        ans = factorize(n / d);
        for (int i = 0; i < dd.size(); ++i)
            ans.push_back(dd[i]);
    }
    return ans;
}

```

8.14 Primes

```

namespace primes {
    const int MP = 100001;
    bool sieve[MP];
    long long primes[MP];
    int num_p;
    void fill_sieve() {
        num_p = 0;
        sieve[0] = sieve[1] = true;
        for (long long i = 2; i < MP; ++i) {
            if (!sieve[i]) {
                primes[num_p++] = i;
                for (long long j = i * i; j < MP; j += i)
                    sieve[j] = true;
            }
        }
    }

    // Finds prime numbers between a and b, using basic
    // primes up to sqrt(b)
    // a must be greater than 1.
    vector<long long> seg_sieve(long long a, long long b)
    {
        long long ant = a;
        a = max(a, 3LL);
        vector<bool> pmap(b - a + 1);
        long long sqrt_b = sqrt(b);
        for (int i = 0; i < num_p; ++i) {
            long long p = primes[i];
            if (p > sqrt_b) break;
            long long j = (a + p - 1) / p;
            for (long long v = (j == 1) ? p + p : j * p; v <=
                b; v += p) {
                pmap[v - a] = true;
            }
        }
    }
}

```

```

    }
}
vector<long long> ans;
if (ant == 2) ans.push_back(2);
int start = a % 2 ? 0 : 1;
for (int i = start, I = b - a + 1; i < I; i += 2)
    if (pmap[i] == false)
        ans.push_back(a + i);
return ans;
}

vector<pair<int, int>> factor(int n) {
    vector<pair<int, int>> ans;
    if (n == 0) return ans;
    for (int i = 0; primes[i] * primes[i] <= n; ++i) {
        if ((n % primes[i]) == 0) {
            int expo = 0;
            while ((n % primes[i]) == 0) {
                expo++;
                n /= primes[i];
            }
            ans.emplace_back(primes[i], expo);
        }
    }

    if (n > 1) {
        ans.emplace_back(n, 1);
    }
    return ans;
}
}

```

8.15 Totient Sieve

```

for (int i = 1; i < MN; i++)
    phi[i] = i;

for (int i = 1; i < MN; i++)
    if (!sieve[i]) // is prime
        for (int j = i; j < MN; j += i)
            phi[j] -= phi[j] / i;

```