

El Mufoso

UTN FRSF - Champán en Lata

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1 Template

```
1 #include <bits/stdc++.h>
2 #define forr(i, a, b) for (int i = (a); i < (b); i++)
3 #define forn(i, n) forr(i, 0, n)
4 #define dforn(i, n) for (int i = (n) - 1; i >= 0; i--)
5 #define forall(it, v) for (auto it = v.begin(); it != v.end(); it++)
6 #define sz(c) ((int)c.size())
7 #define rsz resize
8 #define pb push_back
9 #define mp make_pair
10 #define lb lower_bound
11 #define ub upper_bound
12 #define fst first
13 #define snd second
14
15 #ifdef ANARAP
16 // local
17 #else
18 // judge
19 #endif
20
21 using namespace std;
22
23 typedef long long ll;
24 typedef pair<int, int> ii;
25
26 int main() {
27 // agregar g++ -DANARAP en compilacion
28 #ifdef ANARAP
29     freopen("input.in", "r", stdin);
30     // freopen("output.out", "w", stdout);
31 #endif
32     ios::sync_with_stdio(false);
33     cin.tie(NULL);
34     cout.tie(NULL);
35     return 0;
36 }
```

2 Math

2.1 Identidades

$$\sum_{i=0}^n \binom{n}{i} = 2^n$$

$$\sum_{i=0}^n i \binom{n}{i} = n * 2^{n-1}$$

$$\sum_{i=m}^n i = \frac{n(n+1)}{2} - \frac{m(m-1)}{2} = \frac{(n+1-m)(n+m)}{2}$$

$$\sum_{i=0}^n i = \sum_{i=1}^n i = \frac{n(n+1)}{2}$$

$$\sum_{i=0}^n i^2 = \frac{n(n+1)(2n+1)}{6} = \frac{n^3}{3} + \frac{n^2}{2} + \frac{n}{6}$$

$$\sum_{i=0}^n i(i-1) = \frac{8}{6} \left(\frac{n}{2}\right) \left(\frac{n}{2} + 1\right) (n+1) \text{ (doubles)} \rightarrow \text{Sino ver caso impar y par}$$

$$\sum_{i=0}^n i^3 = \left(\frac{n(n+1)}{2}\right)^2 = \frac{n^4}{4} + \frac{n^3}{2} + \frac{n^2}{4} = \left[\sum_{i=1}^n i\right]^2$$

$$\sum_{i=0}^n i^4 = \frac{n(n+1)(2n+1)(3n^2+3n-1)}{30} = \frac{n^5}{5} + \frac{n^4}{2} + \frac{n^3}{3} - \frac{n}{30}$$

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

$$r = e - v + k + 1$$

Teorema de Pick: (Area, puntos interiores y puntos en el borde)

$$A = I + \frac{B}{2} - 1$$

2.2 Ec. Característica

$$a_0 T(n) + a_1 T(n-1) + \dots + a_k T(n-k) = 0$$

$$p(x) = a_0 x^k + a_1 x^{k-1} + \dots + a_k$$

Sean r_1, r_2, \dots, r_q las raíces distintas, de mult. m_1, m_2, \dots, m_q

$$T(n) = \sum_{i=1}^q \sum_{j=0}^{m_i-1} c_{ij} n^j r_i^n$$

Las constantes c_{ij} se determinan por los casos base.

2.3 Modular operations

```

1 const ll MOD = 1000000007; // Change according to problem
2 // Only needed for MOD > 2^31
3 // Actually, for 2^31 < MOD < 2^63 it's usually better to use __int128
4 // and normal multiplication (* operator) instead of mulMod
5 // returns (a*b) %c, and minimize overflow
6 ll mulMod(ll a, ll b, ll m = MOD) { // O(log b)
7     ll x = 0, y = a % m;
8     while (b > 0) {
9         if (b % 2 == 1) x = (x + y) % m;
10        y = (y * 2) % m;
11        b /= 2;
12    }
13    return x % m;
14 }
15 ll expMod(ll b, ll e, ll m = MOD) { // O(log e)
16     if (e < 0) return 0;
17     ll ret = 1;
18     while (e) {
19         if (e & 1) ret = ret * b % m; // ret = mulMod(ret,b,m); //if needed
20         b = b * b % m; // b = mulMod(b,b,m);
21         e >>= 1;
22     }
23     return ret;
24 }
25 ll sumMod(ll a, ll b, ll m = MOD) {
26     a %= m;
27     b %= m;
28     if (a < 0) a += m;
29     if (b < 0) b += m;
30     return (a + b) % m;
31 }
32 ll difMod(ll a, ll b, ll m = MOD) {
33     a %= m;
34     b %= m;
35     if (a < 0) a += m;
36     if (b < 0) b += m;
37     ll ret = a - b;
38     if (ret < 0) ret += m;
39     return ret;
40 }
41 ll divMod(ll a, ll b, ll m = MOD) { return mulMod(a, inverso(b), m); }
```

2.4 Chinese remainder theorem, extended euclid and diophantine equations

$$y = \sum_{j=1}^n (x_j * (\prod_{i=1, i \neq j}^n m_i)^{-1}_{m_j} * \prod_{i=1, i \neq j}^n m_i)$$

```

1 // ecuacion diofantica lineal
2 // sea d=gcd(a,b); la ecuacion a * x + b * y = c tiene soluciones enteras si
3 // d|c. La siguiente funcion nos sirve para esto. De forma general sera:
4 // x = x0 + (b/d)n      x0 = xx*c/d
5 // y = y0 - (a/d)n      y0 = yy*c/d
6 // la funcion devuelve d
7 ll euclid(ll a, ll b, ll &xx, ll &yy) {
8     if (!b) return xx = 1, yy = 0, a;
9     ll d = euclid(b, a % b, yy, xx);
10    return yy -= a / b * xx, d;
11 }
12
13 // Chinese remainder theorem (special case): find z such that
14 // z % m = a, z % n = b. Here, z is unique modulo M = lcm(m, n)
15 // Return -1 when there is no solution
16 // CRT is associative and idempotent
17 ll crt(ll a, ll m, ll b, ll n) {
18     if (n > m) swap(a, b), swap(m, n);
19     ll x, y, g = euclid(m, n, x, y);
20     if ((a - b) % g != 0) return -1; // comment to get RTE when there is no
        solution
21     assert((a - b) % g == 0);
22     x = (b - a) % n * x % n / g * m + a;
23     return x < 0 ? x + m * n / g : x;
24 }
25
26 // Chinese remainder theorem: find z such that z % m[i] = r[i] for all i.
27 // Note that the solution is unique modulo M = lcm_i (m[i]).
28 // Return z. On failure, return -1.
29 // Note that we do not require the m[i]'s to be relatively prime.
30 ll crt(const vector<ll>& r, const vector<ll>& m) {
31     assert(sz(r) == sz(m));
32     ll ret = r[0], l = m[0];
33     forr(i, 1, sz(m)) {
34         ret = crt(ret, l, r[i], m[i]);
35         l = lcm(r[i], m[i]);
36         if (ret == -1) break;
37     }
38     return ret;
39 }

```

2.5 Modular inverse

```

1 #define MAXMOD 15485867
2 ll inv[MAXMOD]; // inv[i]*i=1 mod MOD
3 void calc(int p) { // O(p)
4     inv[1] = 1;
5     forr(i, 2, p) inv[i] = p - ((p / i) * inv[p % i]) % p;
6 }
7 int inverso(int x) { // O(log MOD)
8     return expMod(x, eulerPhi(MOD) - 1); // si mod no es primo(sacar a mano)
9     return expMod(x, MOD - 2); // si mod es primo
10 }

```

```

11
12 // fact[i] = i!*MOD and ifact[i] = 1/(i!)%MOD
13 // inv is modular inverse function
14 ll fact[MAXN], ifact[MAXN];
15 void build_facts() { // O(MAXN)
16     fact[0] = 1;
17     forr(i, 1, MAXN) fact[i] = fact[i - 1] * i % MOD;
18     ifact[MAXN - 1] = inverso(fact[MAXN - 1]);
19     dforr(i, MAXN - 1) ifact[i] = ifact[i + 1] * (i + 1) % MOD;
20     return;
21 }
22 // n! / k!(n-k)!
23 // assumes 0 <= n < MAXN
24 ll comb(ll n, ll k) {
25     if (k < 0 || n < k) return 0;
26     return fact[n] * ifact[k] % MOD * ifact[n - k] % MOD;
27 }

```

2.6 Combinatorics

```

1 void cargarComb() { // O(MAXN^2)
2     forr(i, MAXN) { // comb[i][k]=i tomados de a k = i!/(k!(i-k)!)
3         comb[0][i] = 0;
4         comb[i][0] = comb[i][i] = 1;
5         forr(k, 1, i) comb[i][k] = (comb[i - 1][k - 1] + comb[i - 1][k]) % MOD;
6     }
7 }
8 ll lucas(ll n, ll k, int p) { // (n,k)%p, needs comb[p][p] precalculated
9     ll aux = 1;
10    while (n + k) {
11        aux = (aux * comb[n % p][k % p]) % p;
12        n /= p, k /= p;
13    }
14    return aux;
15 }

```

2.7 Discrete Logarithm

```

1 // O(sqrt(m)*log(m))
2 // returns x such that a^x = b (mod m) or -1 if inexistent
3 ll discrete_log(ll a, ll b, ll m) {
4     a %= m, b %= m;
5     if (b == 1) return 0;
6     int cnt = 0;
7     ll tmp = 1;
8     for (ll g = __gcd(a, m); g != 1; g = __gcd(a, m)) {
9         if (b % g) return -1;
10        m /= g, b /= g;
11        tmp = tmp * a / g % m;
12        ++cnt;
13        if (b == tmp) return cnt;

```

```

14 }
15 map<ll, int> w;
16 int s = (int)ceil(sqrt(m));
17 ll base = b;
18 forn(i, s) {
19     w[base] = i;
20     base = base * a % m;
21 }
22 base = expMod(a, s, m);
23 ll key = tmp;
24 forr(i, 1, s + 2) {
25     key = base * key % m;
26     if (w.count(key)) return i * s - w[key] + cnt;
27 }
28 return -1;
29 }

```

2.8 Fractions

```

1 struct frac {
2     int p, q;
3     frac(int p = 0, int q = 1) : p(p), q(q) { norm(); }
4     void norm() {
5         int a = gcd(q, p);
6         if (a) p /= a, q /= a;
7         else q = 1;
8         if (q < 0) q = -q, p = -p;
9     }
10    frac operator+(const frac& o) {
11        int a = gcd(o.q, q);
12        return frac(p * (o.q / a) + o.p * (q / a), q * (o.q / a));
13    }
14    frac operator-(const frac& o) {
15        int a = gcd(o.q, q);
16        return frac(p * (o.q / a) - o.p * (q / a), q * (o.q / a));
17    }
18    frac operator*(frac o) {
19        int a = gcd(o.p, q), b = gcd(p, o.q);
20        return frac((p / b) * (o.p / a), (q / a) * (o.q / b));
21    }
22    frac operator/(frac o) {
23        int a = gcd(o.q, q), b = gcd(p, o.p);
24        return frac((p / b) * (o.q / a), (q / a) * (o.p / b));
25    }
26    bool operator<(const frac& o) const { return p * o.q < o.p * q; }
27    bool operator==(frac o) { return p == o.p && q == o.q; }
28 };

```

2.9 Matrix exponentiation

```

1 typedef ll tipo; // maybe use double or other depending on the problem
2 struct Mat {
3     int N; // square matrix
4     vector<vector<tipo>> m;
5     Mat(int n) : N(n), m(n, vector<tipo>(n, 0)) {}
6     vector<tipo>& operator[](int p) { return m[p]; }
7     Mat operator*(Mat& b) { // O(N^3), multiplication
8         assert(N == b.N);
9         Mat res(N);
10        forn(i, N) forn(j, N) forn(k, N) // remove MOD if not needed
11            res[i][j] = (res[i][j] + m[i][k] * b[k][j]) % MOD;
12        return res;
13    }
14    Mat operator^(int k) { // O(N^3 * logk), exponentiation
15        Mat res(N), aux = *this;
16        forn(i, N) res[i][i] = 1;
17        while (k)
18            if (k & 1) res = res * aux, k--;
19            else aux = aux * aux, k /= 2;
20        return res;

```

2.10 Primes, divisors and Phi

```

21 }
22 };

1 #define MAXP 100000 // no necesariamente primo
2 int criba[MAXP + 1];
3 void crearCriba() {
4     int w[] = {4, 2, 4, 2, 4, 6, 2, 6};
5     for (int p = 25; p <= MAXP; p += 10) criba[p] = 5;
6     for (int p = 9; p <= MAXP; p += 6) criba[p] = 3;
7     for (int p = 4; p <= MAXP; p += 2) criba[p] = 2;
8     for (int p = 7, cur = 0; p * p <= MAXP; p += w[cur++ & 7])
9         if (!criba[p])
10             for (int j = p * p; j <= MAXP; j += (p << 1))
11                 if (!criba[j]) criba[j] = p;
12 }
13 vector<int> primos;
14 void buscarPrimos() {
15     crearCriba();
16     forr(i, 2, MAXP + 1) if (!criba[i]) primos.push_back(i);
17 }
18
19 // factoriza bien numeros hasta MAXP^2, llamar a buscarPrimos antes
20 void fact(ll n, map<ll, ll>& f) { // O (cant primos)
21     forall(p, primos) {
22         while (!(n % *p)) {
23             f[*p]++; // divisor found
24             n /= *p;
25         }
26     }
27     if (n > 1) f[n]++;
28 }
29
30 // factoriza bien numeros hasta MAXP, llamar crearCriba antes
31 void fact2(ll n, map<ll, ll>& f) { // O (lg n)
32     while (criba[n]) {
33         f[criba[n]]++;
34         n /= criba[n];
35     }
36     if (n > 1) f[n]++;
37 }
38
39 // Usar asi: divisores(fac, divs, fac.begin()); NO ESTA ORDENADO
40 void divisores(map<ll, ll>& f, vector<ll>& divs, map<ll, ll>::iterator it,
41               ll n = 1) {
42     if (it == f.begin()) divs.clear();
43     if (it == f.end()) {
44         divs.pb(n);
45         return;
46     }
47     ll p = it->fst, k = it->snd;
48     ++it;
49     forn(_, k + 1) divisores(f, divs, it, n) * p;

```

```

50 }
51 ll cantDivs(map<ll, ll>& f) {
52     ll ret = 1;
53     forall(it, f) ret *= (it->second + 1);
54     return ret;
55 }
56 ll sumDivs(map<ll, ll>& f) {
57     ll ret = 1;
58     forall(it, f) {
59         ll pot = 1, aux = 0;
60         forn(i, it->snd + 1) aux += pot, pot *= it->fst;
61         ret *= aux;
62     }
63     return ret;
64 }
65
66 ll eulerPhi(ll n) { // con criba: O(lg n)
67     map<ll, ll> f;
68     fact(n, f);
69     ll ret = n;
70     forall(it, f) ret -= ret / it->first;
71     return ret;
72 }
73 ll eulerPhi2(ll n) { // O (sqrt n)
74     ll r = n;
75     forr(i, 2, n + 1) {
76         if ((ll)i * i > n) break;
77         if (n % i == 0) {
78             while (n % i == 0) n /= i;
79             r -= r / i;
80         }
81     }
82     if (n != 1) r -= r / n;
83     return r;
84 }

```

2.11 Phollard's Rho

```

1 bool es_primo_prob(ll n, int a) {
2     if (n == a) return true;
3     ll s = 0, d = n - 1;
4     while (d % 2 == 0) s++, d /= 2;
5     ll x = expMod(a, d, n);
6     if ((x == 1) || (x + 1 == n)) return true;
7     forn(i, s - 1) {
8         x = (x * x) % n; // mulMod(x, x, n); In most cases, it is necessary to use
9             mulMod to avoid TLE
10        if (x == 1) return false;
11        if (x + 1 == n) return true;
12    }
13    return false;
14 }
15 bool rabin(ll n) { // devuelve true si n es primo
16     if (n == 1) return false;
17     const int ar[] = {2, 3, 5, 7, 11, 13, 17, 19, 23};
18     forn(j, 9) if (!es_primo_prob(n, ar[j])) return false;
19     return true;
20 }
21 ll rho(ll n) {
22     if ((n & 1) == 0) return 2;
23     ll x = 2, y = 2, d = 1;
24     ll c = rand() % n + 1;
25     while (d == 1) {
26         // may want to avoid mulMod if possible
27         // maybe replace with * operator using __int128?
28         x = (mulMod(x, x, n) + c) % n;
29         y = (mulMod(y, y, n) + c) % n;
30         y = (mulMod(y, y, n) + c) % n;
31         if (x - y >= 0) d = gcd(n, x - y);
32         else d = gcd(n, y - x);
33     }
34     return d == n ? rho(n) : d;
35 }
36 void factRho(ll n, map<ll, ll>& f) { // O ((n ^ 1/4) * logn)
37     if (n == 1) return;
38     if (rabin(n)) {
39         f[n]++;
40         return;
41     }
42     ll factor = rho(n);
43     factRho(factor, f);
44     factRho(n / factor, f);
45 }

```

2.12 Guass-Jordan

```

1 // https://cp-algorithms.com/linear_algebra/linear-system-gauss.html
2 const double EPS = 1e-9;
3 const int INF = 2; // a value to indicate infinite solutions
4
5 int gauss(vector<vector<double>> a, vector<double>& ans) {
6     int n = (int)a.size();
7     int m = (int)a[0].size() - 1;
8
9     vector<int> where(m, -1);
10    for (int col = 0, row = 0; col < m && row < n; ++col) {
11        int sel = row;
12        for (int i = row; i < n; ++i)
13            if (abs(a[i][col]) > abs(a[sel][col])) sel = i;
14        if (abs(a[sel][col]) < EPS) continue;
15        for (int i = col; i <= m; ++i) swap(a[sel][i], a[row][i]);
16        where[col] = row;
17
18        for (int i = 0; i < n; ++i)
19            if (i != row) {
20                double c = a[i][col] / a[row][col];
21                for (int j = col; j <= m; ++j) a[i][j] -= a[row][j] * c;
22            }
23        ++row;
24    }
25
26    ans.assign(m, 0);
27    for (int i = 0; i < m; ++i)
28        if (where[i] != -1) ans[i] = a[where[i]][m] / a[where[i]][i];
29    for (int i = 0; i < n; ++i) {
30        double sum = 0;
31        for (int j = 0; j < m; ++j) sum += ans[j] * a[i][j];
32        if (abs(sum - a[i][m]) > EPS) return 0;
33    }
34
35    for (int i = 0; i < m; ++i)
36        if (where[i] == -1) return INF;
37    return 1;
38 }

```


2.13 Guass-Jordan modular

```

1 // inv -> modular inverse function
2 // disclaimer: not very well tested, but got AC on a problem with this
3 int gauss(vector<vector<int>> > a, vector<int>& ans) {
4     int n = (int)a.size();
5     int m = (int)a[0].size() - 1;
6
7     vector<int> where(m, -1);
8     for (int col = 0, row = 0; col < m && row < n; ++col) {
9         int sel = row;
10        for (int i = row; i < n; ++i)
11            if (a[i][col] > a[sel][col]) sel = i;
12        if (a[sel][col] == 0) continue;
13        for (int i = col; i <= m; ++i) swap(a[sel][i], a[row][i]);
14        where[col] = row;
15
16        for (int i = 0; i < n; ++i)
17            if (i != row) {
18                int c = (a[i][col] * inv(a[row][col])) % MOD;
19                for (int j = col; j <= m; ++j)
20                    a[i][j] = (a[i][j] - a[row][j] * c % MOD + MOD) % MOD;
21            }
22        ++row;
23    }
24    ans.clear();
25    ans.rsz(m, 0);
26    for (int i = 0; i < m; ++i)
27        if (where[i] != -1) ans[i] = (a[where[i]][m] * inv(a[where[i]][i])) % MOD;
28    for (int i = 0; i < n; ++i) {
29        int sum = 0;
30        for (int j = 0; j < m; ++j) sum = (sum + ans[j] * a[i][j]) % MOD;
31        if ((sum - a[i][m] + MOD) % MOD != 0) return 0;
32    }
33
34    for (int i = 0; i < m; ++i)
35        if (where[i] == -1) return INF;
36    return 1;
37 }

```

2.14 Guass-Jordan with bitset

```

1 // https://cp-algorithms.com/linear_algebra/linear-system-gauss.html
2 // special case of gauss_jordan_mod with mod=2, bitset for efficiency
3 // finds lexicographically minimal solution (0 < 1, False < True)
4 // for lexicographically maximal change your solution model accordingly
5 int gauss(vector<bitset<N>> > a, int n, int m, bitset<N>& ans) {
6     vector<int> where(m, -1);
7     for (int col = m - 1, row = 0; col >= 0 && row < n; --col) {
8         for (int i = row; i < n; ++i)
9             if (a[i][col]) {
10                swap(a[i], a[row]);
11                break;
12            }
13        if (!a[row][col]) continue;
14        where[col] = row;
15
16        for (int i = 0; i < n; ++i)
17            if (i != row && a[i][col]) a[i] ^= a[row];
18        ++row;
19    }
20    ans.reset();
21    forn(i, m) if (where[i] != -1) { ans[i] = a[where[i]][m] & a[where[i]][i]; }
22    forn(i, n) if ((ans & a[i]).count() % 2 != a[i][m]) return 0;
23    forn(i, m) if (where[i] == -1) return INF;
24    return 1;
25 }

```

2.15 Simpson

```

1 typedef long double T;
2 // polar coordinates: x=r*cos(theta), y=r*sin(theta), f=(r*r)/2
3 T simpson(std::function<T(T)> f, T a, T b, int n = 10000) { // O(n)
4     T area = 0, h = (b - a) / T(n), fa = f(a), fb;
5     forn(i, n) {
6         fb = f(a + h * T(i + 1));
7         area += fa + T(4) * f(a + h * T(i + 0.5)) + fb;
8         fa = fb;
9     }
10    return area * h / T(6.);
11 }

```

2.16 Fast Fourier Transform (FFT)

```

1 typedef __int128 T;
2 typedef double ld;
3 typedef vector<T> poly;
4 const T MAXN = (1 << 21); // MAXN must be power of 2,
5 // MOD-1 needs to be a multiple of MAXN, big mod and primitive root for NTT
6 const T MOD = 2305843009255636993LL, RT = 5;
7 // const T MOD = 998244353, RT = 3;
8
9 // NTT
10 struct CD {
11     T x;
12     CD(T x_) : x(x_) {}
13     CD() {}
14 };
15 T mulmod(T a, T b) { return a * b % MOD; }
16 T addmod(T a, T b) {
17     T r = a + b;
18     if (r >= MOD) r -= MOD;
19     return r;
20 }
21 T submod(T a, T b) {
22     T r = a - b;
23     if (r < 0) r += MOD;
24     return r;
25 }
26 CD operator*(const CD& a, const CD& b) { return CD(mulmod(a.x, b.x)); }
27 CD operator+(const CD& a, const CD& b) { return CD(addmod(a.x, b.x)); }
28 CD operator-(const CD& a, const CD& b) { return CD(submod(a.x, b.x)); }
29 vector<T> rts(MAXN + 9, -1);
30 CD root(int n, bool inv) {
31     T r = rts[n] < 0 ? rts[n] = expMod(RT, (MOD - 1) / n) : rts[n];
32     return CD(inv ? expMod(r, MOD - 2) : r);
33 }
34
35 // FFT
36 // struct CD {
37 //     ld r, i;
38 //     CD(ld r_ = 0, ld i_ = 0) : r(r_), i(i_) {}
39 //     ld real() const { return r; }
40 //     void operator/=(const int c) { r /= c, i /= c; }
41 // };
42 // CD operator*(const CD& a, const CD& b) {
43 //     return CD(a.r * b.r - a.i * b.i, a.r * b.i + a.i * b.r);
44 // }
45 // CD operator+(const CD& a, const CD& b) { return CD(a.r + b.r, a.i + b.i); }
46 // CD operator-(const CD& a, const CD& b) { return CD(a.r - b.r, a.i - b.i); }
47 // const ld pi = acos(-1.0);
48
49 CD cpl[MAXN + 9], cp2[MAXN + 9];
50 int R[MAXN + 9];
51 void dft(CD* a, int n, bool inv) {
52     forn(i, n) if (R[i] < i) swap(a[R[i]], a[i]);
53     for (int m = 2; m <= n; m *= 2) {
54         // ld z=2*pi/m*(inv?-1:1); // FFT

```

```

55         // CD wi=CD(cos(z),sin(z)); // FFT
56         CD wi = root(m, inv); // NTT
57         for (int j = 0; j < n; j += m) {
58             CD w(1);
59             for (int k = j, k2 = j + m / 2; k2 < j + m; k++, k2++) {
60                 CD u = a[k];
61                 CD v = a[k2] * w;
62                 a[k] = u + v;
63                 a[k2] = u - v;
64                 w = w * wi;
65             }
66         }
67     }
68     // if(inv) forn(i,n) a[i]/=n; // FFT
69     if (inv) { // NTT
70         CD z(expMod(n, MOD - 2));
71         forn(i, n) a[i] = a[i] * z;
72     }
73 }
74 poly multiply(poly& p1, poly& p2) {
75     int n = sz(p1) + sz(p2) + 1;
76     int m = 1, cnt = 0;
77     while (m <= n) m += m, cnt++;
78     forn(i, m) {
79         R[i] = 0;
80         forn(j, cnt) R[i] = (R[i] << 1) | ((i >> j) & 1);
81     }
82     forn(i, m) cpl[i] = 0, cp2[i] = 0;
83     forn(i, sz(p1)) cpl[i] = p1[i];
84     forn(i, sz(p2)) cp2[i] = p2[i];
85     dft(cpl, m, false);
86     dft(cp2, m, false);
87     forn(i, m) cpl[i] = cpl[i] * cp2[i];
88     dft(cpl, m, true);
89     poly res;
90     n -= 2;
91     // forn(i,n) res.pb((T) floor(cpl[i].real()+0.5)); // FFT
92     forn(i, n) res.pb(cpl[i].x); // NTT
93     return res;
94 }

```

2.17 Karatsuba

```

1 template<typename T> void rec_kara(T* a, int one, T* b, int two, T* r) {
2     if (min(one, two) <= 20) { // must be at least "<= 1"
3         forn(i, one) forn(j, two) r[i+j] += a[i] * b[j];
4         return;
5     }
6     const int x = min(one, two);
7     if (one < two) rec_kara(a, x, b + x, two - x, r + x);
8     if (two < one) rec_kara(a + x, one - x, b, x, r + x);
9     const int n = (x + 1) / 2, right = x / 2;
10    vector<T> tu(2 * n);
11    rec_kara(a, n, b, n, tu.data());

```

```

12  forn(i, 2*n-1) {
13      r[i] += tu[i];
14      r[i+n] -= tu[i];
15      tu[i] = 0;
16  }
17  rec_kara(a + n, right, b + n, right, tu.data());
18  forn(i, 2*right-1) r[i+n] -= tu[i], r[i+2*n] += tu[i];
19  tu[n-1] = a[n-1]; tu[2*n-1] = b[n-1];
20  forn(i, right) tu[i] = a[i]+a[i+n], tu[i+n] = b[i]+b[i+n];
21  rec_kara(tu.data(), n, tu.data() + n, n, r + n);
22  }
23  template<typename T> vector<T> multiply(vector<T> a, vector<T> b) {
24      if(a.empty() || b.empty()) return {};
25      vector<T> r(a.size() + b.size() - 1);
26      rec_kara(a.data(), a.size(), b.data(), b.size(), r.data());
27      return r;
28  }

```

2.18 Simplex

```

1  typedef double tipo;
2  typedef vector<tipo> vt;
3  // maximize c^T x s.t. Ax<=b, x>=0, returns pair (max val, solution vector)
4  pair<tipo, vt> simplex(vector<vt> A, vt b, vt c) {
5      int n = sz(b), m = sz(c);
6      tipo z = 0.;
7      vector<int> X(m), Y(n);
8      forn(i, m) X[i] = i;
9      forn(i, n) Y[i] = i + m;
10     auto pivot = [&](int x, int y) {
11         swap(X[y], Y[x]);
12         b[x] /= A[x][y];
13         forn(i, m) if (i != y) A[x][i] /= A[x][y];
14         A[x][y] = 1 / A[x][y];
15         forn(i, n) if (i != x && abs(A[i][y]) > EPS) {
16             b[i] -= A[i][y] * b[x];
17             forn(j, m) if (j != y) A[i][j] -= A[i][y] * A[x][j];
18             A[i][y] *= -A[x][y];
19         }
20         z += c[y] * b[x];
21         forn(i, m) if (i != y) c[i] -= c[y] * A[x][i];
22         c[y] *= -A[x][y];
23     };
24     while (1) {
25         int x = -1, y = -1;
26         tipo mn = -EPS;
27         forn(i, n) if (b[i] < mn) mn = b[i], x = i;
28         if (x < 0) break;
29         forn(i, m) if (A[x][i] < -EPS) {
30             y = i;
31             break;
32         }
33         assert(y >= 0); // no solution to Ax<=b
34         pivot(x, y);
35     }
36     while (1) {
37         tipo mx = EPS;
38         int x = -1, y = -1;
39         forn(i, m) if (c[i] > mx) mx = c[i], y = i;
40         if (y < 0) break;
41         tipo mn = 1e200;
42         forn(i, n) if (A[i][y] > EPS && b[i] / A[i][y] < mn) {
43             mn = b[i] / A[i][y], x = i;
44         }
45         assert(x >= 0); // c^T x is unbounded
46         pivot(x, y);
47     }
48     vt r(m);
49     forn(i, n) if (Y[i] < m) r[Y[i]] = b[i];
50     return {z, r};
51 }

```

2.19 Tablas y cotas (Primos, Divisores, Factoriales, etc)

Factoriales	
0! = 1	11! = 39.916.800
1! = 1	12! = 479.001.600 (∈ int)
2! = 2	13! = 6.227.020.800
3! = 6	14! = 87.178.291.200
4! = 24	15! = 1.307.674.368.000
5! = 120	16! = 20.922.789.888.000
6! = 720	17! = 355.687.428.096.000
7! = 5.040	18! = 6.402.373.705.728.000
8! = 40.320	19! = 121.645.100.408.832.000
9! = 362.880	20! = 2.432.902.008.176.640.000 (∈ tint)
10! = 3.628.800	21! = 51.090.942.171.709.400.000
Primos	
2 3 5 7 11 13 17 19 23 29 31 37 41 43 47 53 59 61 67 71 73 79 83 89 97 101 103 107 109 113 127 131 137 139 149 151 157 163 167 173 179 181 191 193 197 199 211 223 227 229 233 239 241 251 257 263 269 271 277 281 283 293 307 311 313 317 331 337 347 349 353 359 367 373 379 383 389 397 401 409 419 421 431 433 439 443 449 457 461 463 467 479 487 491 499 503 509 521 523 541 547 557 563 569 571 577 587 593 599 601 607 613 617 619 631 641 643 647 653 659 661 673 677 683 691 701 709 719 727 733 739 743 751 757 761 769 773 787 797 809 811 821 823 827 829 839 853 857 859 863 877 881 883 887 907 911 919 929 937 941 947 953 967 971 977 983 991 997 1009 1013 1019 1021 1031 1033 1039 1049 1051 1061 1063 1069 1087 1091 1093 1097 1103 1109 1117 1123 1129 1151 1153 1163 1171 1181 1187 1193 1201 1213 1217 1223 1229 1231 1237 1249 1259 1277 1279 1283 1289 1291 1297 1301 1303 1307 1319 1321 1327 1361 1367 1373 1381 1399 1409 1423 1427 1429 1433 1439 1447 1451 1453 1459 1471 1481 1483 1487 1489 1493 1499 1511 1523 1531 1543 1549 1553 1559 1567 1571 1579 1583 1597 1601 1607 1609 1613 1619 1621 1627 1637 1657 1663 1667 1669 1693 1697 1699 1709 1721 1723 1733 1741 1747 1753 1759 1777 1783 1787 1789 1801 1811 1823 1831 1847 1861 1867 1871 1873 1877 1879 1889 1901 1907 1913 1931 1933 1949 1951 1973 1979 1987 1993 1997 1999 2003 2011 2017 2027 2029 2039 2053 2063 2069 2081	

Primos cercanos a 10 ⁿ											
9941	9949	9967	9973	10007	10009	10037	10039	10061	10067	10069	10079
99961	99971	99989	99991	100003	100019	100043	100049	100057	100069		
	999959	999961	999979	999983	1000003	1000033	1000037	1000039			
9999943	9999971	9999973	9999991	10000019	10000079	10000103	10000121				
99999941	99999959	99999971	99999989	100000007	100000037	100000039					
				100000049							
999999893	999999929	999999937	1000000007	1000000009	1000000021						
				1000000033							

Cantidad de primos menores que 10 ⁿ											
$\pi(10^1) = 4$; $\pi(10^2) = 25$; $\pi(10^3) = 168$; $\pi(10^4) = 1229$; $\pi(10^5) = 9592$ $\pi(10^6) = 78.498$; $\pi(10^7) = 664.579$; $\pi(10^8) = 5.761.455$; $\pi(10^9) = 50.847.534$ $\pi(10^{10}) = 455.052,511$; $\pi(10^{11}) = 4.118.054.813$; $\pi(10^{12}) = 37.607.912.018$											

2.20 Números Catalanés

Utiles para problemas de Combinatoria

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

Con $Cat(0) = 1$.

- Diferentes aplicaciones:
1. Contar la cantidad de diferentes arboles binarios con n nodos que se pueden armar.
 2. Contar las formas en que un polígono convexo de $n + 2$ lados puede ser triangulado.
 3. Contar la cantidad de caminos monotonos a lo largo de los lados de una grilla $n * n$, que no cruzan la diagonal.
 4. Contar el número de expresiones que contienen n pares de paréntesis correctamente colocados

2.20.1 Primeros 25 Catalanés

1	1	2	5	14	42	132	429	1430	4862	16796	58786	208012	742900	2674440	9694845
35357670	129644790	477638700	1767263190	6564120420	24466267020										
91482563640	343059613650	1289904147324	4861946401452												

3 Geometry

3.1 Point

```

1 typedef long double T; // double could be faster but less precise
2 typedef long double ld;
3 const T EPS = 1e-9; // if T is integer, set to 0
4 const T INF = 1e18;
5 struct pto{
6     T x, y;
7     pto() : x(0), y(0) {}
8     pto(T _x, T _y) : x(_x), y(_y) {}
9     pto operator+(pto b) { return pto(x+b.x, y+b.y); }
10    pto operator-(pto b) { return pto(x-b.x, y-b.y); }
11    pto operator+(T k) { return pto(x+k, y+k); }
12    pto operator*(T k) { return pto(x*k, y*k); }
13    pto operator/(T k) { return pto(x/k, y/k); }
14    // dot product
15    T operator*(pto b) { return x*b.x + y*b.y; }
16    // module of cross product, a^b>0 if angle_cw(u,v)<180
17    T operator^(pto b) { return x*b.y - y*b.x; }
18    // vector projection of this above b
19    pto proj(pto b) { return b*((*this)*b) / (b*b); }
20    T norm_sq() { return x*x + y*y; }
21    ld norm() { return sqrtl(x*x + y*y); }
22    ld dist(pto b) { return (b - (*this)).norm(); }
23    //rotate by theta rads CCW w.r.t. origin (0,0)
24    pto rotate(T ang) {
25        return pto(x*cosl(ang) - y*sinl(ang), x*sinl(ang) + y*cosl(ang));
26    }
27    // true if this is at the left side of line ab
28    bool left(pto a, pto b) { return ((a-*this) ^ (b-*this)) > 0; }
29    bool operator<(const pto &b) const {
30        return x < b.x-EPS || (abs(x - b.x) <= EPS && y < b.y-EPS);
31    }
32    bool operator==(pto b) { return abs(x-b.x)<=EPS && abs(y-b.y)<=EPS; }
33 };
34 ld angle(pto a, pto o, pto b) {
35     pto oa = a-o, ob = b-o;
36     return atan2l(oa^ob, oa*ob);
37 }
38 ld angle(pto a, pto b) { // smallest angle bewteen a and b
39     ld cost = (a*b) / a.norm() / b.norm();
40     return acosl(max(ld(-1.), min(ld(1.), cost)));
41 }

```

3.2 Radial order

```

1 // radial sort around point O in CCW direction starting from vector v
2 struct cmp {
3     pto o, v;
4     cmp(pto no, pto nv) : o(no), v(nv) {}
5     bool half(pto p) {

```

```

6         assert(!(p.x == 0 && p.y == 0)); // (0,0) isn't well defined
7         return (v ^ p) < 0 || ((v ^ p) == 0 && (v * p) < 0);
8     }
9     bool operator()(pto& p1, pto& p2) {
10         return mp(half(p1 - o), T(0)) < mp(half(p2 - o), ((p1 - o) ^ (p2 - o)));
11     }
12 };

```

3.3 Line

```

1 int sgn(T x) { return x < 0 ? -1 : !!x; }
2 struct line {
3     T a, b, c; // Ax+By=C
4     line() {}
5     line(T a_, T b_, T c_) : a(a_), b(b_), c(c_) {}
6     // TO DO: check negative C (multiply everything by -1)
7     line(pto u, pto v) : a(v.y - u.y), b(u.x - v.x), c(a * u.x + b * u.y) {}
8     int side(pto v) { return sgn(a * v.x + b * v.y - c); }
9     bool inside(pto v) { return abs(a * v.x + b * v.y - c) <= EPS; }
10    bool parallel(line v) { return abs(a * v.b - v.a * b) <= EPS; }
11    pto inter(line v) {
12        T det = a * v.b - v.a * b;
13        if (abs(det) <= EPS) return pto(INF, INF);
14        return pto(v.b * c - b * v.c, a * v.c - v.a * c) / det;
15    }
16 };

```

3.4 Segment

```

1 struct segm {
2     pto s, e;
3     segm(pto s_, pto e_) : s(s_), e(e_) {}
4     pto closest(pto b) {
5         pto bs = b - s, es = e - s;
6         ld l = es * es;
7         if (abs(l) <= EPS) return s;
8         ld t = (bs * es) / l;
9         if (t < 0.) return s; // comment for lines
10        else if (t > 1.) return e; // comment for lines
11        return s + (es * t);
12    }
13    bool inside(pto b) { return abs(s.dist(b) + e.dist(b) - s.dist(e)) < EPS; }
14    pto inter(segm b) { // if a and b are collinear, returns one point
15        if ((*this).inside(b.s)) return b.s;
16        if ((*this).inside(b.e)) return b.e;
17        pto in = line(s, e).inter(line(b.s, b.e));
18        if ((*this).inside(in) && b.inside(in)) return in;
19        return pto(INF, INF);
20    }
21 };

```

3.5 Circle

```

1 #define sqr(a) ((a)*(a))
2 pto perp(pto a){return pto(-a.y, a.x);}
3 line bisector(pto a, pto b){
4     line l = line(a, b); pto m = (a+b)/2;
5     return line(-l.b, l.a, -l.b*m.x+l.a*m.y);
6 }
7 struct circle{
8     pto o; T r;
9     circle(){}
10    circle(pto a, pto b, pto c) {
11        o = bisector(a, b).inter(bisector(b, c));
12        r = o.dist(a);
13    }
14    bool inside(pto p) { return (o-p).norm_sq() <= r*r+EPS; }
15    bool inside(circle c) { // this inside of c
16        T d = (o - c.o).norm_sq();
17        return d <= (c.r-r) * (c.r-r) + EPS;
18    }
19    // circle containing p1 and p2 with radius r
20    // swap p1, p2 to get snd solution
21    circle* circle2PtoR(pto a, pto b, T r_) {
22        ld d2 = (a-b).norm_sq(), det = r_*r_/d2 - ld(0.25);
23        if(det < 0) return nullptr;
24        circle *ret = new circle();
25        ret->o = (a+b)/ld(2) + perp(b-a)*sqrt(det);
26        ret->r = r_;
27        return ret;
28    }
29    pair<pto, pto> tang(pto p) {
30        pto m = (p+o)/2;
31        ld d = o.dist(m);
32        ld a = r*r/(2*d);
33        ld h = sqrtl(r*r - a*a);
34        pto m2 = o + (m-o)*a/d;
35        pto per = perp(m-o)/d;
36        return make_pair(m2 - per*h, m2 + per*h);
37    }
38    vector<pto> inter(line l) {
39        ld a = l.a, b = l.b, c = l.c - l.a*o.x - l.b*o.y;
40        pto xy0 = pto(a*c/(a*a + b*b), b*c/(a*a + b*b));
41        if(c*c > r*r*(a*a + b*b) + EPS) {
42            return {};
43        }else if(abs(c*c - r*r*(a*a + b*b)) < EPS) {
44            return { xy0 + o };
45        }else{
46            ld m = sqrtl((r*r - c*c/(a*a + b*b))/(a*a + b*b));
47            pto p1 = xy0 + (pto(-b,a)*m);
48            pto p2 = xy0 + (pto(b,-a)*m);
49            return { p1 + o, p2 + o };
50        }
51    }
52    vector<pto> inter(circle c) {
53        line l;
54        l.a = o.x - c.o.x;

```

```

55        l.b = o.y - c.o.y;
56        l.c = (sqr(c.r)-sqr(r)+sqr(o.x)-sqr(c.o.x)+sqr(o.y)-sqr(c.o.y))/2.0;
57        return (*this).inter(l);
58    }
59    ld inter_triangle(pto a, pto b) { // area of intersection with oab
60        if(abs((o-a)^(o-b)) <= EPS) return 0.;
61        vector<pto> q = {a}, w = inter(line(a,b));
62        if(sz(w) == 2) forn(i,sz(w)) if((a-w[i])*(b-w[i]) < -EPS) q.pb(w[i]);
63        q.pb(b);
64        if(sz(q) == 4 && (q[0]-q[1])*(q[2]-q[1]) > EPS) swap(q[1], q[2]);
65        ld s = 0;
66        forn(i, sz(q)-1){
67            if(!inside(q[i]) || !inside(q[i+1])) {
68                s += r*r*angle((q[i]-o),q[i+1]-o)/T(2);
69            }
70            else s += abs((q[i]-o)^(q[i+1]-o)/2);
71        }
72        return s;
73    }
74 };
75 vector<ld> inter_circles(vector<circle> c){
76     vector<ld> r(sz(c)+1); // r[k]: area covered by at least k circles
77     forn(i, sz(c)) { // O(n^2 log n) (high constant)
78         int k = 1;
79         cmp s(c[i].o, pto(1,0));
80         vector<pair<pto,int>> p = {
81             {c[i].o + pto(1,0)*c[i].r, 0},
82             {c[i].o - pto(1,0)*c[i].r, 0}};
83         forn(j, sz(c)) if(j != i) {
84             bool b0 = c[i].inside(c[j]), b1 = c[j].inside(c[i]);
85             if(b0 && (!b1 || i<j)) k++;
86             else if(!b0 && !b1) {
87                 vector<pto> v = c[i].inter(c[j]);
88                 if(sz(v) == 2) {
89                     p.pb({v[0], 1}); p.pb({v[1], -1});
90                     if(s(v[1], v[0])) k++;
91                 }
92             }
93         }
94         sort(p.begin(), p.end(), [&](pair<pto,int> a, pair<pto,int> b) {
95             return s(a.fst,b.fst); });
96         forn(j,sz(p)) {
97             pto p0 = p[j? j-1: sz(p)-1].fst, p1 = p[j].fst;
98             ld a = angle(p0 - c[i].o, p1 - c[i].o);
99             r[k]+=(p0.x-p1.x)*(p0.y+p1.y)/ld(2)+c[i].r*c[i].r*(a-sinl(a))/ld(2);
100            k += p[j].snd;
101        }
102    }
103    return r;
104 }

```

3.6 Polygon

```

1 struct poly{
2     vector<pto> pt;
3     poly(){}
4     poly(vector<pto> pt_) : pt(pt_) {}
5     void delete_collinears() { // delete collinear points
6         deque<pto> nxt; int len = 0;
7         forn(i,sz(pt)) {
8             if(len>1 && abs((pt[i]-nxt[len-2])^(nxt[len-1]-nxt[len-2])) <= EPS)
9                 nxt.pop_back(), len--;
10            nxt.pb(pt[i]); len++;
11        }
12        if(len>2 && abs((nxt[1]-nxt[len-1])^(nxt[0]-nxt[len-1])) <= EPS)
13            nxt.pop_front(), len--;
14        if(len>2 && abs((nxt[len-1]-nxt[len-2])^(nxt[0]-nxt[len-2])) <= EPS)
15            nxt.pop_back(), len--;
16        pt.clear(); forn(i,sz(nxt)) pt.pb(nxt[i]);
17    }
18    void normalize() {
19        delete_collinears();
20        if(pt[2].left(pt[0], pt[1])) reverse(pt.begin(), pt.end()); //make it CW
21        int n = sz(pt), pi = 0;
22        forn(i, n)
23            if(pt[i].x<pt[pi].x || (pt[i].x==pt[pi].x && pt[i].y<pt[pi].y))
24                pi = i;
25        rotate(pt.begin(), pt.begin()+pi, pt.end());
26    }
27    bool is_convex() { // delete collinear points first
28        int N = sz(pt);
29        if(N < 3) return false;
30        bool isLeft = pt[0].left(pt[1], pt[2]);
31        forr(i, 1, sz(pt))
32            if(pt[i].left(pt[(i+1)%N], pt[(i+2)%N]) != isLeft)
33                return false;
34        return true;
35    }
36    // for convex or concave polygons
37    // excludes boundaries, check it manually
38    bool inside(pto p) { // O(n)
39        bool c = false;
40        forn(i, sz(pt)) {
41            int j = (i+1)%sz(pt);
42            if((pt[j].y>p.y) != (pt[i].y > p.y) &&
43                (p.x < (pt[i].x-pt[j].x)*(p.y-pt[j].y)/(pt[i].y-pt[j].y)+pt[j].x))
44                c = !c;
45        }
46        return c;
47    }
48    bool inside_convex(pto p) { // O(lg(n)) normalize first
49        if(p.left(pt[0], pt[1]) || p.left(pt[sz(pt)-1], pt[0])) return false;
50        int a = 1, b = sz(pt)-1;
51        while(b-a > 1){
52            int c = (a+b)/2;
53            if(!p.left(pt[0], pt[c])) a = c;
54            else b = c;

```

```

55        }
56        return !p.left(pt[a], pt[a+1]);
57    }
58    // cuts this along line ab and return the left side
59    // (swap a, b for the right one)
60    poly cut(pto a, pto b) { // O(n)
61        vector<pto> ret;
62        forn(i, sz(pt)) {
63            ld left1 = (b-a)^(pt[i]-a), left2 = (b-a)^(pt[(i+1)%sz(pt)]-a);
64            if(left1 >= 0) ret.pb(pt[i]);
65            if(left1*left2 < 0)
66                ret.pb(line(pt[i], pt[(i+1)%sz(pt)]).inter(line(a, b)));
67        }
68        return poly(ret);
69    }
70    // cuts this with line ab and returns the range [from, to] that is
71    // strictly on the left side (note that indexes are circular)
72    ii cut(pto u, pto v) { // O(log(n)) for convex polygons
73        int n = sz(pt); pto dir = v-u;
74        int L = farthest(pto(dir.y,-dir.x));
75        int R = farthest(pto(-dir.y,dir.x));
76        if(!pt[L].left(u,v)) swap(L,R);
77        if(!pt[L].left(u,v)) return mp(-1,-1); // line doesn't cut the poly
78
79        ii ans;
80        int l = L, r = L > R ? R+n : R;
81        while(l<r) {
82            int med = (l+r+1)/2;
83            if(pt[med] >= n ? med-n : med].left(u,v)) l = med;
84            else r = med-1;
85        }
86        ans.snd = l >= n ? l-n : l;
87
88        l = R, r = L < R ? L+n : L;
89        while(l<r) {
90            int med = (l+r)/2;
91            if(!pt[med] >= n ? med-n : med].left(u,v)) l = med+1;
92            else r = med;
93        }
94        ans.fst = l >= n ? l-n : l;
95
96        return ans;
97    }
98    // addition of convex polygons
99    poly minkowski(poly p) { // O(n+m) n=|this|,m=|p|
100        this->normalize(); p.normalize();
101        vector<pto> a = (*this).pt, b = p.pt;
102        a.pb(a[0]); a.pb(a[1]);
103        b.pb(b[0]); b.pb(b[1]);
104        vector<pto> sum;
105        int i = 0, j = 0;
106        while(i < sz(a)-2 || j < sz(b)-2) {
107            sum.pb(a[i]+b[j]);
108            T cross = (a[i+1]-a[i])^(b[j+1]-b[j]);
109            if(cross <= 0 && i < sz(a)-2) i++;
110            if(cross >= 0 && j < sz(b)-2) j++;

```

```

111     }
112     return poly(sum);
113 }
114 pto farthest(pto v) { // O(log(n)) for convex polygons
115     if(sz(pt)<10) {
116         int k=0;
117         forr(i,1,sz(pt)) if(v * (pt[i] - pt[k]) > EPS) k = i;
118         return pt[k];
119     }
120     pt.pb(pt[0]);
121     pto a=pt[1] - pt[0];
122     int s = 0, e = sz(pt)-1, ua = v*a > EPS;
123     if(!ua && v*(pt[sz(pt)-2]-pt[0]) <= EPS){ pt.pop_back(); return pt[0];}
124     while(1) {
125         int m = (s+e)/2; pto c = pt[m+1]-pt[m];
126         int uc = v*c > EPS;
127         if(!uc && v*(pt[m+1]-pt[m]) <= EPS){ pt.pop_back(); return pt[m];}
128         if(ua && (!uc || v*(pt[s]-pt[m]) > EPS)) e = m;
129         else if(ua || uc || v*(pt[s]-pt[m]) >= -EPS) s = m, a = c, ua = uc;
130         else e = m;
131         assert(e > s+1);
132     }
133 }
134 ld inter_circle(circle c){ // area of intersection with circle
135     ld r = 0.;
136     forn(i,sz(pt)) {
137         int j = (i+1)%sz(pt); ld w = c.inter_triangle(pt[i], pt[j]);
138         if(((pt[j]-c.o)^(pt[i]-c.o)) > 0) r += w;
139         else r -= w;
140     }
141     return abs(r);
142 }
143 // area ellipse = M_PI*a*b where a and b are the semi axis lengths
144 // area triangle = sqrt(s*(s-a)(s-b)(s-c)) where s=(a+b+c)/2
145 ld area(){ // O(n)
146     ld area = 0;
147     forn(i, sz(pt)) area += pt[i]^pt[(i+1)%sz(pt)];
148     return abs(area)/ld(2);
149 }
150 // returns one pair of most distant points
151 pair<pto,pto> callipers() { // O(n), for convex poly, normalize first
152     int n = sz(pt);
153     if(n <= 2) return {pt[0], pt[1%n]};
154     pair<pto,pto> ret = {pt[0], pt[1]};
155     T maxi = 0; int j = 1;
156     forn(i,sz(pt)) {
157         while(((pt[(i+1)%n]-pt[i])^(pt[(j+1)%n]-pt[j]))<-EPS) j=(j+1)%sz(pt);
158         if(pt[i].dist(pt[j]) > maxi+EPS)
159             ret = {pt[i], pt[j]}, maxi = pt[i].dist(pt[j]);
160     }
161     return ret;
162 }
163 pto centroid(){ // (barycenter, mass center, needs float points)
164     int n = sz(pt);
165     pto r(0,0); ld t=0;
166     forn(i,n) {

```

```

167         r = r + (pt[i] + pt[(i+1)%n]) * (pt[i] ^ pt[(i+1)%n]);
168         t += pt[i] ^ pt[(i+1)%n];
169     }
170     return r/t/3;
171 }
172 };
173 // Dynamic convex hull trick (based on poly struct)
174 vector<poly> w;
175 void add(pto q) { // add(q), O(log^2(n))
176     vector<pto> p = {q};
177     while(!w.empty() && sz(w.back().pt) < 2*sz(p)){
178         for(pto v : w.back().pt) p.pb(v);
179         w.pop_back();
180     }
181     w.pb(poly(CH(p))); // CH = convex hull, must delete collinears
182 }
183 T query(pto v) { // max(q*v:q in w), O(log^2(n))
184     T r = -INF;
185     for(auto& p : w) r = max(r, p.farthest(v)*v);
186     return r;
187 }

```


3.7 Halfplane

```

1 struct halfplane { // left half plane
2     pto u, uv;
3     int id;
4     ld angle;
5     halfplane() {}
6     halfplane(pto u_, pto v_) : u(u_), uv(v_ - u_), angle(atan2l(uv.y, uv.x)) {}
7     bool operator<(halfplane h) const { return angle < h.angle; }
8     bool out(pto p) { return (uv ^ (p - u)) < -EPS; }
9     pto inter(halfplane& h) {
10         T alpha = ((h.u - u) ^ h.uv) / (uv ^ h.uv);
11         return u + (uv * alpha);
12     }
13 };
14 vector<pto> intersect(vector<halfplane> h) {
15     pto box[4] = {{INF, INF}, {-INF, INF}, {-INF, -INF}, {INF, -INF}};
16     forn(i, 4) h.pb(halfplane(box[i], box[(i + 1) % 4]));
17     sort(h.begin(), h.end());
18     deque<halfplane> dq;
19     int len = 0;
20     forn(i, sz(h)) {
21         while (len > 1 && h[i].out(dq[len - 1].inter(dq[len - 2]))) {
22             dq.pop_back(), len--;
23         }
24         while (len > 1 && h[i].out(dq[0].inter(dq[1]))) { dq.pop_front(), len--; }
25         if (len > 0 && abs(h[i].uv ^ dq[len - 1].uv) <= EPS) {
26             if (h[i].uv * dq[len - 1].uv < 0.) { return vector<pto>(); }
27             if (h[i].out(dq[len - 1].u)) {
28                 dq.pop_back(), len--;
29             } else continue;
30         }
31         dq.pb(h[i]);
32         len++;
33     }
34     while (len > 2 && dq[0].out(dq[len - 1].inter(dq[len - 2]))) {
35         dq.pop_back(), len--;
36     }
37     while (len > 2 && dq[len - 1].out(dq[0].inter(dq[1]))) {
38         dq.pop_front(), len--;
39     }
40     if (len < 3) return vector<pto>();
41     vector<pto> inter;
42     forn(i, len) inter.pb(dq[i].inter(dq[(i + 1) % len]));
43     return inter;
44 }

```

3.8 Convex Hull

```

1 // returns convex hull of p in CCW order
2 // left must return >=0 to delete collinear points
3 vector<pto> CH(vector<pto>& p) {
4     if (sz(p) < 3) return p; // edge case, keep line or point
5     vector<pto> ch;
6     sort(p.begin(), p.end());
7     forn(i, sz(p)) { // lower hull
8         while (sz(ch) >= 2 && ch[sz(ch) - 1].left(ch[sz(ch) - 2], p[i]))
9             ch.pop_back();
10        ch.pb(p[i]);
11    }
12    ch.pop_back();
13    int k = sz(ch);
14    dforn(i, sz(p)) { // upper hull
15        while (sz(ch) >= k + 2 && ch[sz(ch) - 1].left(ch[sz(ch) - 2], p[i]))
16            ch.pop_back();
17        ch.pb(p[i]);
18    }
19    ch.pop_back();
20    return ch;
21 }

```

3.9 Dynamic Convex Hull

```

1 struct semi_chull {
2     set<pto> pt; // maintains semi chull without collinears points
3     // in case we want them on the set, make the changes commented below
4     bool check(pto p) {
5         if (pt.empty()) return false;
6         if (*pt.rbegin() < p) return false;
7         if (p < *pt.begin()) return false;
8         auto it = pt.lower_bound(p);
9         if (it->x == p.x) return p.y <= it->y; // change? for collinears
10        pto b = *it;
11        pto a = *prev(it);
12        return ((b - p) ^ (a - p)) + EPS >= 0; // change? for collinears
13    }
14    void add(pto p) {
15        if (check(p)) return;
16        pt.erase(p);
17        pt.insert(p);
18        auto it = pt.find(p);
19        while (true) {
20            if (next(it) == pt.end() || next(next(it)) == pt.end()) break;
21            pto a = *next(it), b = *next(next(it));
22            if (((b - a) ^ (p - a)) + EPS >= 0) { // change? for collinears
23                pt.erase(next(it));
24            } else break;
25        }
26        it = pt.find(p);
27        while (true) {

```

```

28     if (it == pt.begin() || prev(it) == pt.begin()) break;
29     pto a = *prev(it), b = *prev(prev(it));
30     if ((b - a) ^ (p - a)) - EPS <= 0) { // change? for collinears
31         pt.erase(prev(it));
32     } else break;
33 }
34 }
35 };
36 struct CHD {
37     semi_chull sup, inf;
38     void add(pto p) { sup.add(p), inf.add(p * (-1)); }
39     bool check(pto p) { return sup.check(p) && inf.check(p * (-1)); }
40 };

```

3.10 Convex Hull Trick

```

1 struct CHT {
2     deque<pto> h;
3     T f = 1, pos;
4     CHT(bool min_ = 0) : f(min_ ? 1 : -1), pos(0) {} // min_=1 for min queries
5     void add(pto p) { // O(1), pto(m,b) <=> y = mx + b
6         p = p * f;
7         if (h.empty()) {
8             h.pb(p);
9             return;
10        }
11        // p.x should be the lower/greater hull x
12        assert(p.x <= h[0].x || p.x >= h.back().x);
13        if (p.x <= h[0].x) {
14            while (sz(h) > 1 && h[0].left(p, h[1])) h.pop_front(), pos--;
15            h.push_front(p), pos++;
16        } else {
17            while (sz(h) > 1 && h[sz(h) - 1].left(h[sz(h) - 2], p)) h.pop_back();
18            h.pb(p);
19        }
20        pos = min(max(T(0), pos), T(sz(h) - 1));
21    }
22    T get(T x) {
23        pto q = {x, 1};
24        // O(log) query for unordered x
25        int L = 0, R = sz(h) - 1, M;
26        while (L < R) {
27            M = (L + R) / 2;
28            if (h[M + 1] * q <= h[M] * q) L = M + 1;
29            else R = M;
30        }
31        return h[L] * q * f;
32        // O(1) query for ordered x
33        while (pos > 0 && h[pos - 1] * q < h[pos] * q) pos--;
34        while (pos < sz(h) - 1 && h[pos + 1] * q < h[pos] * q) pos++;
35        return h[pos] * q * f;
36    }
37 };

```

3.11 Li-Chao tree

```

1 typedef long long T;
2 const T INF = 1e18;
3 // Li-Chao works for any function such that any pair of the functions
4 // inserted intersect at most once with each other. Most problems are
5 // about lines, but you may want to adapt this struct to your function
6 struct line {
7     T m, b;
8     line() {}
9     line(T m_, T b_) {
10         m = m_;
11         b = b_;
12     }
13     T f(T x) { return m * x + b; }
14     line operator+(line l) { return line(m + l.m, b + l.b); }
15     line operator*(T k) { return line(m * k, b * k); }
16 };
17 struct li_chao {
18     vector<line> cur, add;
19     vector<int> L, R;
20     T f, minx, maxx;
21     line identity;
22     int cnt;
23     void new_node(line cur_, int l = -1, int r = -1) {
24         cur.pb(cur_);
25         add.pb(line(0, 0));
26         L.pb(l);
27         R.pb(r);
28         cnt++;
29     }
30     li_chao(bool min_, T minx_, T maxx_) { // for min: min_=1, for max: min_=0
31         f = min_ ? 1 : -1;
32         identity = line(0, INF);
33         minx = minx_;
34         maxx = maxx_;
35         cnt = 0;
36         new_node(identity); // root id is 0
37     }
38     // only needed when "adding" lines lazily
39     void apply(int id, line to_add_) {
40         add[id] = add[id] + to_add_;
41         cur[id] = cur[id] + to_add_;
42     }
43     // this method is needed even when no lazy is used, to avoid
44     // null pointers and other problems in the code
45     void push_lazy(int id) {
46         if (L[id] == -1) {
47             new_node(identity);
48             L[id] = cnt - 1;
49         }
50         if (R[id] == -1) {
51             new_node(identity);
52             R[id] = cnt - 1;
53         }
54         // code below only needed when lazy ops are needed

```

```

55     apply(L[id], add[id]);
56     apply(R[id], add[id]);
57     add[id] = line(0, 0);
58 }
59 // only needed when "adding" lines lazily
60 void push_line(int id, T tl, T tr) {
61     T m = (tl + tr) / 2;
62     insert_line(L[id], cur[id], tl, m);
63     insert_line(R[id], cur[id], m, tr);
64     cur[id] = identity;
65 }
66 // O(log), or persistent return int instead of void
67 void insert_line(int id, line new_line, T l, T r) {
68     T m = (l + r) / 2;
69     bool lef = new_line.f(l) < cur[id].f(l);
70     bool mid = new_line.f(m) < cur[id].f(m);
71     // uncomment for persistent
72     // line to_push = new_line, to_keep = cur[id];
73     // if(mid) swap(to_push, to_keep);
74     if (mid) swap(new_line, cur[id]);
75
76     if (r - l == 1) {
77         // uncomment for persistent
78         // new_node(to_keep);
79         // return cnt-1;
80         return;
81     }
82     push_lazy(id);
83     if (lef != mid) {
84         // uncomment for persistent
85         // int lid = insert_line(L[id], to_push, l, m);
86         // new_node(to_keep, lid, R[id]);
87         // return cnt-1;
88         insert_line(L[id], new_line, l, m);
89     } else {
90         // uncomment for persistent
91         // int rid = insert_line(R[id], to_push, m, r);
92         // new_node(to_keep, L[id], rid);
93         // return cnt-1;
94         insert_line(R[id], new_line, m, r);
95     }
96 }
97 // for persistent, return int instead of void
98 void insert_line(int id, line new_line) {
99     insert_line(id, new_line * f, minx, maxx);
100 }
101 // O(log^2) doesn't support persistence
102 void insert_segm(int id, line new_line, T l, T r, T tl, T tr) {
103     if (tr <= l || tl >= r || tl >= tr || l >= r) return;
104     if (tl >= l && tr <= r) {
105         insert_line(id, new_line, tl, tr);
106         return;
107     }
108     push_lazy(id);
109     T m = (tl + tr) / 2;
110     insert_segm(L[id], new_line, l, r, tl, m);

```

```

111     insert_segm(R[id], new_line, l, r, m, tr);
112 }
113 // [l,r)
114 void insert_segm(int id, line new_line, T l, T r) {
115     insert_segm(id, new_line * f, l, r, minx, maxx);
116 }
117 // O(log^2) doesn't support persistence
118 void add_line(int id, line to_add_, T l, T r, T tl, T tr) {
119     if (tr <= l || tl >= r || tl >= tr || l >= r) return;
120     if (tl >= l && tr <= r) {
121         apply(id, to_add_);
122         return;
123     }
124     push_lazy(id);
125     push_line(id, tl, tr); // comment if insert isn't used
126     T m = (tl + tr) / 2;
127     add_line(L[id], to_add_, l, r, tl, m);
128     add_line(R[id], to_add_, l, r, m, tr);
129 }
130 void add_line(int id, line to_add_, T l, T r) {
131     add_line(id, to_add_ * f, l, r, minx, maxx);
132 }
133 // O(log)
134 T get(int id, T x, T tl, T tr) {
135     if (tl + 1 == tr) return cur[id].f(x);
136     push_lazy(id);
137     T m = (tl + tr) / 2;
138     if (x < m) return min(cur[id].f(x), get(L[id], x, tl, m));
139     else return min(cur[id].f(x), get(R[id], x, m, tr));
140 }
141 T get(int id, T x) { return get(id, x, minx, maxx) * f; }
142 };

```

3.12 KD tree

```

1 bool cmpx(pto a, pto b) { return a.x + EPS < b.x; }
2 bool cmpy(pto a, pto b) { return a.y + EPS < b.y; }
3 struct kd_tree {
4     pto p;
5     T x0 = INF, x1 = -INF, y0 = INF, y1 = -INF;
6     kd_tree *l, *r;
7     T distance(pto q) {
8         T x = min(max(x0, q.x), x1);
9         T y = min(max(y0, q.y), y1);
10        return (pto(x, y) - q).norm_sq();
11    }
12    kd_tree(vector<pto>&& pts) : p(pts[0]) {
13        l = nullptr, r = nullptr;
14        forn(i, sz(pts)) {
15            x0 = min(x0, pts[i].x), x1 = max(x1, pts[i].x);
16            y0 = min(y0, pts[i].y), y1 = max(y1, pts[i].y);
17        }
18        if (sz(pts) > 1) {
19            sort(pts.begin(), pts.end(), x1 - x0 >= y1 - y0 ? cmpx : cmpy);
20            int m = sz(pts) / 2;
21            l = new kd_tree({pts.begin(), pts.begin() + m});
22            r = new kd_tree({pts.begin() + m, pts.end()});
23        }
24    }
25    void nearest(pto q, int k, priority_queue<pair<T, pto>>& ret) {
26        if (l == nullptr) {
27            // avoid query point as answer
28            // if(p == q) return;
29            ret.push({(q - p).norm_sq(), p});
30            while (sz(ret) > k) ret.pop();
31            return;
32        }
33        kd_tree *al = l, *ar = r;
34        T bl = l->distance(q), br = r->distance(q);
35        if (bl > br) swap(al, ar), swap(bl, br);
36        al->nearest(q, k, ret);
37        if (br < ret.top().fst) ar->nearest(q, k, ret);
38        while (sz(ret) > k) ret.pop();
39    }
40    priority_queue<pair<T, pto>> nearest(pto q, int k) {
41        priority_queue<pair<T, pto>> ret;
42        forn(i, k) ret.push({INF * INF, pto(INF, INF)});
43        nearest(q, k, ret);
44        return ret;
45    }
46 };

```

3.13 Voronoi

```

1 // Returns planar graph representing Delaunay's triangulation.
2 // Edges for each vertex are in ccw order.
3 // To use doubles replace __int128 for long double in line 51
4 pto pinf = pto(INF, INF);
5 typedef struct QuadEdge* Q;
6 struct QuadEdge {
7     int id, used;
8     pto o;
9     Q rot, nxt;
10    QuadEdge(int id_ = -1, pto o_ = pinf)
11        : id(id_), used(0), o(o_), rot(0), nxt(0) {}
12    Q rev() { return rot->rot; }
13    Q next() { return nxt; }
14    Q prev() { return rot->next()->rot; }
15    pto dest() { return rev()->o; }
16 };
17
18 Q edge(pto a, pto b, int ida, int idb) {
19     Q e1 = new QuadEdge(ida, a);
20     Q e2 = new QuadEdge(idb, b);
21     Q e3 = new QuadEdge;
22     Q e4 = new QuadEdge;
23     tie(e1->rot, e2->rot, e3->rot, e4->rot) = {e3, e4, e2, e1};
24     tie(e1->nxt, e2->nxt, e3->nxt, e4->nxt) = {e1, e2, e4, e3};
25     return e1;
26 }
27
28 void splice(Q a, Q b) {
29     swap(a->nxt->rot->nxt, b->nxt->rot->nxt);
30     swap(a->nxt, b->nxt);
31 }
32
33 void del_edge(Q& e, Q ne) {
34     splice(e, e->prev());
35     splice(e->rev(), e->rev()->prev());
36     delete e->rev()->rot;
37     delete e->rev();
38     delete e->rot;
39     delete e;
40     e = ne;
41 }
42
43 Q conn(Q a, Q b) {
44     Q e = edge(a->dest(), b->o, a->rev()->id, b->id);
45     splice(e, a->rev()->prev());
46     splice(e->rev(), b);
47     return e;
48 }
49
50 auto area(pto p, pto q, pto r) { return (q - p) ^ (r - q); }
51
52 // is p in circunference formed by (a,b,c)?
53 bool in_c(pto a, pto b, pto c, pto p) {
54     // Warning: this number is O(max_coord^4).

```

```

55 // Consider using doubles or an alternative method for this function
56 __int128 p2 = p * p, A = a * a - p2, B = b * b - p2, C = c * c - p2;
57 return area(p, a, b) * C + area(p, b, c) * A + area(p, c, a) * B > EPS;
58 }
59
60 pair<Q, Q> build_tr(vector<pto>& p, int l, int r) {
61     if (r - l + 1 <= 3) {
62         Q a = edge(p[l], p[l + 1], l, l + 1), b = edge(p[l + 1], p[r], l + 1, r);
63         if (r - l + 1 == 2) return {a, a->rev()};
64         splice(a->rev(), b);
65         auto ar = area(p[l], p[l + 1], p[r]);
66         Q c = abs(ar) > EPS ? conn(b, a) : 0;
67         if (ar >= -EPS) return {a, b->rev()};
68         return {c->rev(), c};
69     }
70     int m = (l + r) / 2;
71     Q la, ra, lb, rb;
72     tie(la, ra) = build_tr(p, l, m);
73     tie(lb, rb) = build_tr(p, m + 1, r);
74     while (1) {
75         if (ra->dest().left(lb->o, ra->o)) ra = ra->rev()->prev();
76         else if (lb->dest().left(lb->o, ra->o)) lb = lb->rev()->next();
77         else break;
78     }
79     Q b = conn(lb->rev(), ra);
80     auto valid = [&](Q e) { return b->o.left(e->dest(), b->dest()); };
81     if (ra->o == la->o) la = b->rev();
82     if (lb->o == rb->o) rb = b;
83     while (1) {
84         Q L = b->rev()->next();
85         if (valid(L))
86             while (in_c(b->dest(), b->o, L->dest(), L->next()->dest()))
87                 del_edge(L, L->next());
88         Q R = b->prev();
89         if (valid(R))
90             while (in_c(b->dest(), b->o, R->dest(), R->prev()->dest()))
91                 del_edge(R, R->prev());
92         if (!valid(L) && !valid(R)) break;
93         if (!valid(L) || (valid(R) && in_c(L->dest(), L->o, R->o, R->dest())))
94             b = conn(R, b->rev());
95         else b = conn(b->rev(), L->rev());
96     }
97     return {la, rb};
98 }
99
100 vector<vector<int>> delaunay(vector<pto> v) {
101     int n = sz(v);
102     auto tmp = v;
103     vector<int> id(n);
104     iota(id.begin(), id.end(), 0);
105     sort(id.begin(), id.end(), [&](int l, int r) { return v[l] < v[r]; });
106     forn(i, n) v[i] = tmp[id[i]];
107     assert(unique(v.begin(), v.end()) == v.end());
108     vector<vector<int>> g(n);
109     int col = 1;
110     forr(i, 2, n) col &= abs(area(v[i], v[i - 1], v[i - 2])) <= EPS;

```

```

111 if (col) {
112     forr(i, 1, n) g[id[i - 1]].pb(id[i]), g[id[i]].pb(id[i - 1]);
113 } else {
114     Q e = build_tr(v, 0, n - 1).fst;
115     vector<Q> edg = {e};
116     for (int i = 0; i < sz(edg); e = edg[i++]) {
117         for (Q at = e; !at->used; at = at->next()) {
118             at->used = 1;
119             g[id[at->id]].pb(id[at->rev()->id]);
120             edg.pb(at->rev());
121         }
122     }
123 }
124 return g;
125 }

```

3.14 All point pairs

```

1 // after each step() execution pt is sorted by dot product of the event
2 struct all_point_pairs { // O(n*n*log(n*n)), must add id, u, v to pto
3     vector<pto> pt, ev;
4     vector<int> idx;
5     int cur_step;
6     all_point_pairs(vector<pto> pt_) : pt(pt_) {
7         idx = vector<int>(sz(pt));
8         forn(i, sz(pt)) forn(j, sz(pt)) if (i != j) {
9             pto p = pt[j] - pt[i];
10             p.u = pt[i].id, p.v = pt[j].id;
11             ev.pb(p);
12         }
13         sort(ev.begin(), ev.end(), cmp(pto(0, 0), pto(1, 0)));
14         pto start(ev[0].y, -ev[0].x);
15         sort(pt.begin(), pt.end(),
16             [&](pto& u, pto& v) { return u * start < v * start; });
17         forn(i, sz(idx)) idx[pt[i].id] = i;
18         cur_step = 0;
19     }
20     bool step() {
21         if (cur_step >= sz(ev)) return false;
22         int u = ev[cur_step].u, v = ev[cur_step].v;
23         swap(pt[idx[u]], pt[idx[v]]);
24         swap(idx[u], idx[v]);
25         cur_step++;
26         return true;
27     }
28 };

```

4 Data structures

4.1 Indexed set

```

1 #include <ext/pb_ds/assoc_container.hpp>
2 #include <ext/pb_ds/tree_policy.hpp>
3 using namespace __gnu_pbds;
4 //<key,mapped type,comparator,...>
5 typedef tree<int,null_type,less<int>,rb_tree_tag,
6   tree_order_statistics_node_update> indexed_set;
7 // find_by_order(i) returns iterator to the i-th elemnt
8 // order_of_key(k): returns position of the lower bound of k (0-indexed)
9 // Ej: 12, 100, 505, 1000, 10000.
10 // order_of_key(10) == 0, order_of_key(100) == 1,
11 // order_of_key(707) == 3, order_of_key(9999999) == 5

```

4.2 Hash Table

```

1 struct Hash { // similar logic for any other data type
2   size_t operator()(const vector<int>& v) const {
3     size_t s = 0;
4     for (auto& e : v) s ^= hash<int>()(e) + 0x9e3779b9 + (s << 6) + (s >> 2);
5     return s;
6   }
7 };
8 unordered_set<vector<int>, Hash> s; // unordered_map<key, value, hasher>

```

4.3 Union find

4.3.1 Classic DSU

```

1 struct UnionFind {
2   int nsets;
3   vector<int> f, setsz; // f[i] = parent of node i
4   UnionFind(int n) : nsets(n), f(n, -1), setsz(n, 1) {}
5   int comp(int x) { return (f[x] == -1 ? x : f[x] = comp(f[x])); } // O(1)
6   bool join(int i, int j) { // returns true if already in the same set
7     int a = comp(i), b = comp(j);
8     if (a != b) {
9       if (setsz[a] > setsz[b]) swap(a, b);
10      f[a] = b; // the bigger group (b) now represents the smaller (a)
11      nsets--, setsz[b] += setsz[a];
12    }
13    return a == b;
14  }
15 };

```

4.3.2 DSU with rollbacks

```

1 struct dsu_save {
2   int v, rnk, u, rnku;
3   dsu_save() {}
4   dsu_save(int _v, int _rnk, int _u, int _rnku)
5     : v(_v), rnk(_rnk), u(_u), rnku(_rnku) {}
6 };
7 struct dsu_with_rollback {
8   vector<int> p, rnk;
9   int comps;
10  stack<dsu_save> op;
11  dsu_with_rollback() {}
12  dsu_with_rollback(int n) {
13    p.resize(n), rnk.resize(n);
14    for (i, n) { p[i] = i, rnk[i] = 0; }
15    comps = n;
16  }
17  int find_set(int v) { return (v == p[v]) ? v : find_set(p[v]); }
18  bool unite(int v, int u) {
19    v = find_set(v), u = find_set(u);
20    if (v == u) return false;
21    comps--;
22    if (rnk[v] > rnk[u]) swap(v, u);
23    op.push(dsu_save(v, rnk[v], u, rnk[u]));
24    p[v] = u;
25    if (rnk[u] == rnk[v]) rnk[u]++;
26    return true;
27  }
28  void rollback() {
29    if (op.empty()) return;
30    dsu_save x = op.top();
31    op.pop(), comps++;
32    p[x.v] = x.v, rnk[x.v] = x.rnk;
33    p[x.u] = x.u, rnk[x.u] = x.rnk;
34  }
35 };

```

4.4 Segment tree

4.4.1 ST static

```

1 // Solo para funciones idempotentes (como min y max, pero no sum)
2 // Usar la version dynamic si la funcion no es idempotente
3 struct RMQ {
4 #define LVL 10 // LVL such that 2^LVL>n
5     tipo vec[LVL][1 << (LVL + 1)];
6     tipo& operator[](int p) { return vec[0][p]; }
7     tipo get(int i, int j) { // intervalo [i,j] - O(1)
8         int p = 31 - __builtin_clz(j - i);
9         return min(vec[p][i], vec[p][j - (1 << p)]);
10    }
11 void build(int n) { // O(nlogn)
12     int mp = 31 - __builtin_clz(n);
13     forn(p, mp) forn(x, n - (1 << p)) vec[p + 1][x] =
14         min(vec[p][x], vec[p][x + (1 << p)]);
15 }
16 }; // Use: define LVL y tipo; insert data with []; call build; answer queries

```

4.4.2 ST dynamic

```

1 typedef ll tipo;
2 const tipo neutro = 0;
3 tipo oper(const tipo& a, const tipo& b) { return a + b; }
4 struct ST {
5     int sz;
6     vector<tipo> t;
7     ST(int n) {
8         sz = 1 << (32 - __builtin_clz(n));
9         t = vector<tipo>(2 * sz, neutro);
10    }
11 tipo& operator[](int p) { return t[sz + p]; }
12 void updall() { dforn(i, sz) t[i] = oper(t[2 * i], t[2 * i + 1]); }
13 tipo get(int i, int j) { return get(i, j, 1, 0, sz); }
14 tipo get(int i, int j, int n, int a, int b) { // O(log n), [i, j]
15     if (j <= a || b <= i) return neutro;
16     if (i <= a && b <= j) return t[n]; // n = node of range [a,b]
17     int c = (a + b) / 2;
18     return oper(get(i, j, 2 * n, a, c), get(i, j, 2 * n + 1, c, b));
19 }
20 void set(int p, tipo val) { // O(log n)
21     p += sz;
22     while (p > 0 && t[p] != val) {
23         t[p] = val;
24         p /= 2;
25         val = oper(t[p * 2], t[p * 2 + 1]);
26     }
27 }
28 }; // Use: definir oper tipo neutro,
29 // cin >> n; ST st(n); forn(i, n) cin >> st[i]; st.updall();

```

4.4.3 ST lazy

```

1 typedef ll Elem;
2 typedef ll Alt;
3 const Elem neutro = 0;
4 const Alt neutro2 = 0;
5 Elem oper(const Elem& a, const Elem& b) { return a + b; }
6 struct ST {
7     int sz;
8     vector<Elem> t;
9     vector<Alt> dirty; // Alt and Elem could be different types
10    ST(int n) {
11        sz = 1 << (32 - __builtin_clz(n));
12        t = vector<Elem>(2 * sz, neutro);
13        dirty = vector<Alt>(2 * sz, neutro2);
14    }
15 Elem& operator[](int p) { return t[sz + p]; }
16 void updall() { dforn(i, sz) t[i] = oper(t[2 * i], t[2 * i + 1]); }
17 void push(int n, int a, int b) { // push dirt to n's child nodes
18     if (dirty[n] != neutro2) { // n = node of range [a,b]
19         t[n] += dirty[n] * (b - a); // CHANGE for your problem
20         if (n < sz) {
21             dirty[2 * n] += dirty[n]; // CHANGE for your problem
22             dirty[2 * n + 1] += dirty[n]; // CHANGE for your problem
23         }
24         dirty[n] = neutro2;
25     }
26 }
27 Elem get(int i, int j, int n, int a, int b) { // O(lgn)
28     if (j <= a || b <= i) return neutro;
29     push(n, a, b); // adjust value before using it
30     if (i <= a && b <= j) return t[n]; // n = node of range [a,b]
31     int c = (a + b) / 2;
32     return oper(get(i, j, 2 * n, a, c), get(i, j, 2 * n + 1, c, b));
33 }
34 Elem get(int i, int j) { return get(i, j, 1, 0, sz); }
35 // altera los valores en [i, j] con una alteracion de val
36 void update(Alt val, int i, int j, int n, int a, int b) { // O(lgn)
37     push(n, a, b);
38     if (j <= a || b <= i) return;
39     if (i <= a && b <= j) {
40         dirty[n] += val; // CHANGE for your problem
41         push(n, a, b);
42         return;
43     }
44     int c = (a + b) / 2;
45     update(val, i, j, 2 * n, a, c), update(val, i, j, 2 * n + 1, c, b);
46     t[n] = oper(t[2 * n], t[2 * n + 1]);
47 }
48 void update(Alt val, int i, int j) { update(val, i, j, 1, 0, sz); }
49 }; // Use: definir operacion, neutros, Alt, Elem, uso de dirty
50 // cin >> n; ST st(n); forn(i,n) cin >> st[i]; st.updall()

```

4.4.4 ST persistente

```

1 typedef int tipo;
2 const tipo neutro = 0;
3 tipo oper(const tipo& a, const tipo& b) { return a + b; }
4 struct ST {
5     int n;
6     vector<tipo> st;
7     vector<int> L, R;
8     ST(int nn) : n(nn), st(1, neutro), L(1, 0), R(1, 0) {}
9     int new_node(tipo v, int l = 0, int r = 0) {
10         int id = sz(st);
11         st.pb(v), L.pb(l), R.pb(r);
12         return id;
13     }
14     int init(vector<tipo>& v, int l, int r) {
15         if (l + 1 == r) return new_node(v[l]);
16         int m = (l + r) / 2, a = init(v, l, m), b = init(v, m, r);
17         return new_node(oper(st[a], st[b]), a, b);
18     }
19     int update(int cur, int pos, tipo val, int l, int r) {
20         int id = new_node(st[cur], L[cur], R[cur]);
21         if (l + 1 == r) {
22             st[id] = val;
23             return id;
24         }
25         int m = (l + r) / 2, ASD; // MUST USE THE ASD!!!
26         if (pos < m) ASD = update(L[id], pos, val, l, m), L[id] = ASD;
27         else ASD = update(R[id], pos, val, m, r), R[id] = ASD;
28         st[id] = oper(st[L[id]], st[R[id]]);
29         return id;
30     }
31     tipo get(int cur, int from, int to, int l, int r) {
32         if (to <= l || r <= from) return neutro;
33         if (from <= l && r <= to) return st[cur];
34         int m = (l + r) / 2;
35         return oper(get(L[cur], from, to, l, m), get(R[cur], from, to, m, r));
36     }
37     int init(vector<tipo>& v) { return init(v, 0, n); }
38     int update(int root, int pos, tipo val) {
39         return update(root, pos, val, 0, n);
40     }
41     tipo get(int root, int from, int to) { return get(root, from, to, 0, n); }
42 }; // usage: ST st(n); root = st.init(v) (or root = 0);
43 // new_root = st.update(root,i,x); st.get(root,l,r);

```

4.4.5 ST implicit

```

1 typedef int tipo;
2 const tipo neutro = 0;
3 tipo oper(const tipo& a, const tipo& b) { return a + b; }
4 // Compressed segtree, it works for any range (even negative indexes)
5 struct ST {
6     ST *lc, *rc;
7     tipo val;
8     int L, R;
9     ST(int l, int r, tipo x = neutro) {
10         lc = rc = nullptr;
11         L = l, R = r, val = x;
12     }
13     ST(int l, int r, ST* lp, ST* rp) {
14         if (lp != nullptr && rp != nullptr && lp->L > rp->L) swap(lp, rp);
15         lc = lp, rc = rp;
16         L = l, R = r;
17         val = oper(lp == nullptr ? neutro : lp->val,
18                   rp == nullptr ? neutro : rp->val);
19     }
20     // O(log(R-L)), parameter 'isnew' only needed when persistent
21     // This operation inserts at most 2 nodes to the tree, i.e. the
22     // total memory used by the tree is O(N), where N is the number
23     // of times this 'set' function is called. (2*log nodes when persistent)
24     void set(int p, tipo x, bool isnew = false) { // return ST* for persistent
25         // uncomment for persistent
26         // if(!isnew) {
27             // ST* newnode = new ST(L, R, lc, rc);
28             // return newnode->set(p, x, true);
29         // }
30         if (L + 1 == R) {
31             val = x;
32             return; // 'return this;' for persistent
33         }
34         int m = (L + R) / 2;
35         ST** c = p < m ? &lc : &rc;
36         if (!*c) *c = new ST(p, p + 1, x);
37         else if ((*c)->L <= p && p < (*c)->R) {
38             // replace by comment for persistent
39             (*c)->set(p, x);
40             // *c = (*c)->set(p,x);
41         } else {
42             int l = L, r = R;
43             while ((p < m) == ((*c)->L < m)) {
44                 if (p < m) r = m;
45                 else l = m;
46                 m = (l + r) / 2;
47             }
48             *c = new ST(l, r, *c, new ST(p, p + 1, x));
49             // The code above, inside this else block, could be
50             // replaced by the following 2 lines when the complete
51             // range has the form [0, 2^k)
52             // int rm = (1<<(32-__builtin_clz(p^(*c)->L)))-1;
53             // *c = new ST(p & ~rm, (p | rm)+1, *c, new ST(p, p+1, x));
54         }

```



```

55     val = oper(lc ? lc->val : neutro, rc ? rc->val : neutro);
56     // return this; // uncomment for persistent
57 }
58 tipo get(int ql, int qr) { // O(log(R-L))
59     if (qr <= L || R <= ql) return neutro;
60     if (ql <= L && R <= qr) return val;
61     return oper(lc ? lc->get(ql, qr) : neutro, rc ? rc->get(ql, qr) : neutro);
62 }
63 }; // Usage: 1- RMQ st(MIN_INDEX, MAX_INDEX) 2- normally use set/get

```

4.4.6 ST 2d

```

1 #define operacion(x, y) max(x, y)
2 int n, m;
3 int a[MAXN][MAXN], st[2 * MAXN][2 * MAXN];
4 void build() { // O(n*m)
5     forn(i, n) forn(j, m) st[i + n][j + m] = a[i][j];
6     forn(i, n) dform(j, m) // build st of row i+n (each row independently)
7         st[i + n][j] = operacion(st[i + n][j << 1], st[i + n][j << 1 | 1]);
8     dform(i, n) forn(j, 2 * m) // build st of ranges of rows
9         st[i][j] = operacion(st[i << 1][j], st[i << 1 | 1][j]);
10 }
11 void upd(int x, int y, int v) { // O(logn * logm)
12     st[x + n][y + m] = v;
13     for (int j = y + m; j > 1; j >>= 1) // update ranges containing y+m
14         st[x + n][j >> 1] = operacion(st[x + n][j], st[x + n][j ^ 1]);
15     for (int i = x + n; i > 1; i >>= 1) // in each range that contains row x+n
16         for (int j = y + m; j > 1; j >>= 1) // update the ranges that contains y+m
17             st[i >> 1][j] = operacion(st[i][j], st[i ^ 1][j]);
18 }
19 int query(int x0, int x1, int y0, int y1) { // O(logn * logm)
20     int r = NEUT;
21     // start at the bottom and move up each time
22     for (int i0 = x0 + n, i1 = x1 + n; i0 < i1; i0 >>= 1, i1 >>= 1) {
23         int t[4], q = 0;
24         // if the whole segment of row node i0 is included, then move right
25         if (i0 & 1) t[q++] = i0++;
26         // if the whole segment of row node i1-1 is included, then move left
27         if (i1 & 1) t[q++] = --i1;
28         forn(k, q) for (int j0 = y0 + m, j1 = y1 + m; j0 < j1; j0 >>= 1, j1 >>= 1)
29             {
30                 if (j0 & 1) r = operacion(r, st[t[k]][j0++]);
31                 if (j1 & 1) r = operacion(r, st[t[k]][--j1]);
32             }
33     }
34     return r;
35 }

```

4.5 Merge sort tree

```

1 typedef ii datain; // data that goes into the DS
2 typedef int query; // info related to a query
3 typedef bool dataout; // data that results from a query
4 struct DS {
5     set<datain> s; // replace set with what's needed for the problem
6     void insert(const datain& x) {
7         // modify this method according to problem
8         // the example below is "disjoint intervals" (i.e. union of ranges)
9         datain xx = x; // copy to avoid changing original
10        if (xx.fst >= xx.snd) return;
11        auto at = s.lower_bound(xx);
12        auto it = at;
13        if (at != s.begin() && (--at)->snd >= xx.fst) xx.fst = at->fst, --it;
14        for (; it != s.end() && it->fst <= xx.snd; s.erase(it++))
15            xx.snd = max(xx.snd, it->snd);
16        s.insert(xx);
17    }
18    void get(const query& q, dataout& ans) {
19        // modify this method according to problem
20        // the example below is "is there any range covering q?"
21        set<datain>::iterator ite = s.sub(mp(q + 1, 0));
22        if (ite != s.begin() && prev(ite)->snd > q) ans = true;
23    }
24 };
25 struct MST {
26     int sz;
27     vector<DS> t;
28     MST(int n) {
29         sz = 1 << (32 - __builtin_clz(n));
30         t = vector<DS>(2 * sz);
31     }
32     void insert(int i, int j, datain& x) { insert(i, j, x, 1, 0, sz); }
33     void insert(int i, int j, datain& x, int n, int a, int b) {
34         if (j <= a || b <= i) return;
35         if (i <= a && b <= j) {
36             t[n].insert(x);
37             return;
38         }
39         // needed when want to update ranges that intersec with [i,j]
40         // usually only needed on range-query + point-update problem
41         // t[n].insert(x);
42         int c = (a + b) / 2;
43         insert(i, j, x, 2 * n, a, c);
44         insert(i, j, x, 2 * n + 1, c, b);
45     }
46     void get(int i, int j, query& q, dataout& ans) {
47         return get(i, j, q, ans, 1, 0, sz);
48     }
49     void get(int i, int j, query& q, dataout& ans, int n, int a, int b) {
50         if (j <= a || b <= i) return;
51         if (i <= a && b <= j) {
52             t[n].get(q, ans);
53             return;
54         }
55     }
56 }

```

```

55 // needed when want to get from ranges that intersec with [i,j)
56 // usually only needed on point-query + range-update problem
57 // t[n].get(q, ans);
58 int c = (a + b) / 2;
59 get(i, j, q, ans, 2 * n, a, c);
60 get(i, j, q, ans, 2 * n + 1, c, b);
61 }
62 }; // Use: 1- definir todo lo necesario en DS, 2- usar

```

4.6 Fenwick tree

```

1 struct FenwickTree {
2     int N; // maybe replace vector with unordered_map when "many 0s"
3     vector<tipo> ft; // for more dimensions, make ft multi-dimensional
4     FenwickTree(int n) : N(n), ft(n + 1) {}
5     void upd(int i0, tipo v) { // add v to i0th element (0-based)
6         // add extra fors for more dimensions
7         for (int i = i0 + 1; i <= N; i += i & -i) ft[i] += v;
8     }
9     tipo get(int i0) { // get sum of range [0,i0)
10        tipo r = 0; // add extra fors for more dimensions
11        for (int i = i0; i; i -= i & -i) r += ft[i];
12        return r;
13    }
14    tipo get_sum(int i0, int i1) { // get sum of range [i0,i1) (0-based)
15        return get(i1) - get(i0);
16    }
17 };

```

4.7 Link-cut tree

```

1 const int N_DEL = 0, N_VAL = 0; // neutral elements for delta & values
2 inline int u_oper(int x, int y){ return x + y; } // update operation
3 inline int q_oper(int lval, int rval){ return lval + rval; } // query
  operation
4 inline int u_segmn(int d, int len){return d==N_DEL?N_DEL:d*len;} // upd segment
5 inline int u_delta(int d1, int d2){ // update delta
6     if(d1==N_DEL) return d2;
7     if(d2==N_DEL) return d1;
8     return u_oper(d1, d2);
9 }
10 inline int a_delta(int v, int d){ // apply delta
11     return d==N_DEL ? v : u_oper(d, v);
12 }
13
14 // Splay tree
15 struct node_t{
16     int szi, n_val, t_val, d;
17     bool rev;
18     node_t *c[2], *p;
19     node_t(int v) : szi(1), n_val(v), t_val(v), d(N_DEL), rev(0), p(0){

```

```

20         c[0]=c[1]=0;
21     }
22     bool is_root(){return !p || (p->c[0] != this && p->c[1] != this);}
23     void push(){
24         if(rev){
25             rev=0; swap(c[0], c[1]);
26             forr(x,0,2) if(c[x]) c[x]->rev^=1;
27         }
28         n_val = a_delta(n_val, d); t_val=a_delta(t_val, u_segmn(d, szi));
29         forr(x,0,2) if(c[x])
30             c[x]->d = u_delta(d, c[x]->d);
31         d=N_DEL;
32     }
33     void upd();
34 };
35 typedef node_t* node;
36 int get_sz(node r){return r ? r->szi : 0;}
37 int get_tree_val(node r){
38     return r ? a_delta(r->t_val, u_segmn(r->d,r->szi)) : N_VAL;
39 }
40 void node_t::upd() {
41     t_val=q_oper(q_oper(get_tree_val(c[0]),a_delta(n_val,d)),get_tree_val(c[1]))
42     ;
43     szi = 1 + get_sz(c[0]) + get_sz(c[1]);
44 }
45 void conn(node c, node p, int is_left){
46     if(c) c->p = p;
47     if(is_left>=0) p->c[!is_left] = c;
48 }
49 void rotate(node x){
50     node p = x->p, g = p->p;
51     bool gCh=p->is_root(), is_left = x==p->c[0];
52     conn(x->c[is_left],p,is_left);
53     conn(p,x,!is_left);
54     conn(x,g,gCh?-1:(p==g->c[0]));
55     p->upd();
56 }
57 void splay(node x){
58     while(!x->is_root()){
59         node p = x->p, g = p->p;
60         if(!p->is_root()) g->push();
61         p->push(); x->push();
62         if(!p->is_root()) rotate((x==p->c[0])==(p==g->c[0])? p : x);
63         rotate(x);
64     }
65     x->push(); x->upd();
66 }
67 // Link-cut Tree
68 // Keep information of a tree (or forest) and allow to make many types of
69 // operations (see them below) in an efficient way. Internally, each node of
70 // the tree will have at most 1 "preferred" child, and as a consequence, the
71 // tree can be seen as a set of independent "preferred" paths. Each of this
72 // paths is basically a list, represented with a splay tree, where the
73 // "implicit key" (for the BST) of each element is the depth of the
74 // corresponding node in the original tree (or forest). Also, each of these

```

```

75 // preferred paths (except one of them), will know who its "father path" is,
76 // i.e. will know the preferred path of the father of the top-most node.
77
78 // Make the path from the root to 'x' to be a "preferred path", and also make
79 // 'x' to be the root of its splay tree (not the root of the original tree).
80 node expose(node x){
81     node last = 0;
82     for(node y=x; y; y=y->p)
83         splay(y), y->c[0] = last, y->upd(), last = y;
84     splay(x);
85     return last;
86 }
87 void make_root(node x){expose(x);x->rev^=1;}
88 node get_root(node x){
89     expose(x);
90     while(x->c[1]) x = x->c[1];
91     splay(x);
92     return x;
93 }
94 node lca(node x, node y){expose(x); return expose(y);}
95 bool connected(node x, node y){
96     expose(x); expose(y);
97     return x==y ? 1 : x->p!=0;
98 }
99 // makes x son of y
100 void link(node x, node y){ make_root(x); x->p=y; }
101 void cut(node x, node y){ make_root(x); expose(y); y->c[1]->p=0; y->c[1]=0; }
102 node father(node x){
103     expose(x);
104     node r = x->c[1];
105     if(!r) return 0;
106     while(r->c[0]) r = r->c[0];
107     return r;
108 }
109 // cuts x from its father keeping tree root
110 void cut(node x){ expose(father(x)); x->p = 0; }
111 int query(node x, node y){
112     make_root(x); expose(y);
113     return get_tree_val(y);
114 }
115 void update(node x, node y, int d){
116     make_root(x); expose(y); y->d=u_delta(y->d,d);
117 }
118 node lift_rec(node x, int k){
119     if(!x) return 0;
120     if(k == get_sz(x->c[0])){ splay(x); return x; }
121     if(k < get_sz(x->c[0])) return lift_rec(x->c[0],k);
122     return lift_rec(x->c[1], k-get_sz(x->c[0])-1);
123 }
124 // k-th ancestor of x (lift(x,1) is x's father)
125 node lift(node x, int k){ expose(x);return lift_rec(x,k); }
126 // distance from x to its tree root
127 int depth(node x){ expose(x);return get_sz(x)-1; }

```

4.8 Implicit treap

```

1 // An array represented as a treap, where the "key" is the index.
2 // However, the key is not stored explicitly, but can be calculated as
3 // the sum of the sizes of the left child of the ancestors where the node
4 // is in the right subtree of it.
5 // (commented parts are specific to range sum queries and other problems)
6 // rng = random number generator, works better than rand in some cases
7 mt19937 rng(chrono::steady_clock::now().time_since_epoch().count());
8 typedef struct item* pitem;
9 struct item {
10     int pr, cnt, val;
11     bool rev; // for reverse operation
12     int sum; // for range query
13     int add; // for lazy prop
14     pitem l, r;
15     pitem p; // ptr to parent, for getRoot
16     item(int val) : pr(rng()), cnt(1), val(val), rev(false), sum(val), add(0) {
17         l = r = p = NULL;
18     }
19 };
20 void push(pitem node) {
21     if (node) {
22         // for reverse operation
23         if (node->rev) {
24             swap(node->l, node->r);
25             if (node->l) node->l->rev ^= true;
26             if (node->r) node->r->rev ^= true;
27             node->rev = false;
28         }
29         // for lazy prop
30         node->val += node->add, node->sum += node->cnt * node->add;
31         if (node->l) node->l->add += node->add;
32         if (node->r) node->r->add += node->add;
33         node->add = 0;
34     }
35 }
36 int cnt(pitem t) { return t ? t->cnt : 0; }
37 int sum(pitem t) { return t ? push(t), t->sum : 0; } // for range query
38 void upd_cnt(pitem t) {
39     if (t) {
40         t->cnt = cnt(t->l) + cnt(t->r) + 1;
41         t->sum = t->val + sum(t->l) + sum(t->r); // for range sum
42         if (t->l) t->l->p = t; // for getRoot
43         if (t->r) t->r->p = t; // for getRoot
44         t->p = NULL; // for getRoot
45     }
46 }
47 void split(pitem node, pitem& L, pitem& R, int sz) { // sz: wanted size for L
48     if (!node) {
49         L = R = 0;
50         return;
51     }
52     push(node);
53     // If node's left child has at least sz nodes, go left
54     if (sz <= cnt(node->l)) split(node->l, L, node->l, sz), R = node;

```

```

55 // Else, go right changing wanted sz
56 else split(node->r, node->r, R, sz - 1 - cnt(node->l)), L = node;
57 upd_cnt(node);
58 }
59 void merge(pitem& result, pitem L, pitem R) { // O(log)
60     push(L), push(R);
61     if (!L || !R) result = L ? L : R;
62     else if (L->pr > R->pr) merge(L->r, L->r, R), result = L;
63     else merge(R->l, L, R->l), result = R;
64     upd_cnt(result);
65 }
66 void insert(pitem& node, pitem x, int pos) { // 0-index O(log)
67     pitem l, r;
68     split(node, l, r, pos);
69     merge(l, l, x);
70     merge(node, l, r);
71 }
72 void erase(pitem& node, int pos) { // 0-index O(log)
73     if (!node) return;
74     push(node);
75     if (pos == cnt(node->l)) merge(node, node->l, node->r);
76     else if (pos < cnt(node->l)) erase(node->l, pos);
77     else erase(node->r, pos - 1 - cnt(node->l));
78     upd_cnt(node);
79 }
80 // reverse operation
81 void reverse(pitem& node, int L, int R) { //[L, R) O(log)
82     pitem t1, t2, t3;
83     split(node, t1, t2, L);
84     split(t2, t2, t3, R - L);
85     t2->rev ^= true;
86     merge(node, t1, t2);
87     merge(node, node, t3);
88 }
89 // lazy add
90 void add(pitem& node, int L, int R, int x) { //[L, R) O(log)
91     pitem t1, t2, t3;
92     split(node, t1, t2, L);
93     split(t2, t2, t3, R - L);
94     t2->add += x;
95     merge(node, t1, t2);
96     merge(node, node, t3);
97 }
98 // range query get
99 int get(pitem& node, int L, int R) { //[L, R) O(log)
100     pitem t1, t2, t3;
101     split(node, t1, t2, L);
102     split(t2, t2, t3, R - L);
103     push(t2);
104     int ret = t2->sum;
105     merge(node, t1, t2);
106     merge(node, node, t3);
107     return ret;
108 }
109 void push_all(pitem t) { // for getRoot
110     if (t->p) push_all(t->p);

```

```

111     push(t);
112 }
113 pitem getRoot(pitem t, int& pos) { // get root and position for node t
114     push_all(t);
115     pos = cnt(t->l);
116     while (t->p) {
117         pitem p = t->p;
118         if (t == p->r) pos += cnt(p->l) + 1;
119         t = p;
120     }
121     return t;
122 }
123 void output(pitem t) { // useful for debugging
124     if (!t) return;
125     push(t);
126     output(t->l);
127     cout << ' ' << t->val;
128     output(t->r);
129 }

```

4.9 Treap (not implicit)

```

1 typedef struct item* pitem;
2 struct item {
3     // pr = randomized priority, key = BST value, cnt = size of subtree
4     int pr, key, cnt;
5     pitem l, r;
6     item(int key) : key(key), pr(rand()), cnt(1), l(NULL), r(NULL) {}
7 };
8 int cnt(pitem node) { return node ? node->cnt : 0; }
9 void upd_cnt(pitem node) {
10     if (node) node->cnt = cnt(node->l) + cnt(node->r) + 1;
11 }
12 // splits t in l and r - l: <= key, r: > key
13 void split(pitem node, int key, pitem& L, pitem& R) { // O(log)
14     if (!node) L = R = 0;
15     // if cur > key, go left to split and cur is part of R
16     else if (key < node->key) split(node->l, key, L, node->l), R = node;
17     // if cur <= key, go right to split and cur is part of L
18     else split(node->r, key, node->r, R), L = node;
19     upd_cnt(node);
20 }
21 // 1) go down the BST following the key of the new node (x), until
22 // you reach NULL or a node with lower pr than the new one.
23 // 2.1) if you reach NULL, put the new node there
24 // 2.2) if you reach a node with lower pr, split the subtree rooted at that
25 // node, put the new one there and put the split result as children of it
26 void insert(pitem& node, pitem x) { // O(log)
27     if (!node) node = x;
28     else if (x->pr > node->pr) split(node, x->key, x->l, x->r), node = x;
29     else insert(x->key <= node->key ? node->l : node->r, x);
30     upd_cnt(node);
31 }
32 // Assumes that the key of every element in L <= to the keys in R

```

```

33 void merge(pitem& result, pitem L, pitem R) { // O(log)
34     // If one of the nodes is NULL, the merge result is the other node
35     if (!L || !R) result = L ? L : R;
36     // if L has higher priority than R, put L and update it's right child
37     // with the merge result of L->r and R
38     else if (L->pr > R->pr) merge(L->r, L->r, R), result = L;
39     // if R has higher priority than L, put R and update it's left child
40     // with the merge result of L and R->l
41     else merge(R->l, L, R->l), result = R;
42     upd_cnt(result);
43 }
44 // go down the BST following the key to erase. When the key is found,
45 // replace that node with the result of merging it children
46 void erase(pitem& node, int key) { // O(log), (erases only 1 repetition)
47     if (node->key == key) merge(node, node->l, node->r);
48     else erase(key < node->key ? node->l : node->r, key);
49     upd_cnt(node);
50 }
51 // union of two treaps
52 void unite(pitem& t, pitem L, pitem R) { // O(M*log(N/M))
53     if (!L || !R) {
54         t = L ? L : R;
55         return;
56     }
57     if (L->pr < R->pr) swap(L, R);
58     pitem p1, p2;
59     split(R, L->key, p1, p2);
60     unite(L->l, L->l, p1);
61     unite(L->r, L->r, p2);
62     t = L;
63     upd_cnt(t);
64 }
65 pitem kth(pitem t, int k) { // element at "position" k
66     if (!t) return 0;
67     if (k == cnt(t->l)) return t;
68     return k < cnt(t->l) ? kth(t->l, k) : kth(t->r, k - cnt(t->l) - 1);
69 }
70 pair<int, int> lb(pitem t, int key) { // position and value of lower_bound
71     if (!t) return {0, 1 << 30}; // (special value)
72     if (key > t->key) {
73         auto w = lb(t->r, key);
74         w.fst += cnt(t->l) + 1;
75         return w;
76     }
77     auto w = lb(t->l, key);
78     if (w.fst == cnt(t->l)) w.snd = t->key;
79     return w;
80 }

```

4.10 STL rope

```

1 #include <ext/rope>
2 using namespace __gnu_cxx;
3 rope<int> s;
4 // Sequence with O(log(n)) random access, insert, erase at any position
5 // s.push_back(x)
6 // s.append(other_rope)
7 // s.insert(i,x)
8 // s.insert(i,other_rope) // insert rope r at position i
9 // s.erase(i,k) // erase subsequence [i,i+k)
10 // s.substr(i,k) // return new rope corresponding to subsequence [i,i+k)
11 // s[i] // access ith element (cannot modify)
12 // s.mutable_reference_at(i) // acces ith element (allows modification)
13 // s.begin() and s.end() are const iterators (use mutable_begin(), mutable_end
14 // to allow modification)

```

4.11 BIGInt

```

1 #define BASEEXP 6
2 #define BASE 1000000
3 #define LMAX 1000
4 struct bint {
5     int l;
6     ll n[LMAX];
7     bint(ll x = 0) {
8         l = 1;
9         forn(i, LMAX) {
10             if (x) l = i + 1;
11             n[i] = x % BASE;
12             x /= BASE;
13         }
14     }
15     bint(string x) {
16         l = (x.size() - 1) / BASEEXP + 1;
17         fill(n, n + LMAX, 0);
18         ll r = 1;
19         forn(i, sz(x)) {
20             n[i / BASEEXP] += r * (x[x.size() - 1 - i] - '0');
21             r *= 10;
22             if (r == BASE) r = 1;
23         }
24     }
25     void out() {
26         cout << n[l - 1];
27         dforn(i, l - 1) printf("%6.6llu", n[i]); // 6=BASEEXP!
28     }
29     void invar() {
30         fill(n + 1, n + LMAX, 0);
31         while (l > 1 && !n[l - 1]) l--;
32     }
33 };

```

```

34 bint operator+(const bint& a, const bint& b) {
35     bint c;
36     c.l = max(a.l, b.l);
37     ll q = 0;
38     forn(i, c.l) q += a.n[i] + b.n[i], c.n[i] = q % BASE, q /= BASE;
39     if (q) c.n[c.l++] = q;
40     c.invar();
41     return c;
42 }
43 pair<bint, bool> lresta(const bint& a, const bint& b) // c = a - b
44 {
45     bint c;
46     c.l = max(a.l, b.l);
47     ll q = 0;
48     forn(i, c.l) q += a.n[i] - b.n[i], c.n[i] = (q + BASE) % BASE,
49                                     q = (q + BASE) / BASE - 1;
50     c.invar();
51     return make_pair(c, !q);
52 }
53 bint& operator--(bint& a, const bint& b) { return a = lresta(a, b).first; }
54 bint& operator-(const bint& a, const bint& b) { return lresta(a, b).first; }
55 bool operator<(const bint& a, const bint& b) { return !lresta(a, b).second; }
56 bool operator<=(const bint& a, const bint& b) { return lresta(b, a).second; }
57 bool operator==(const bint& a, const bint& b) { return a <= b && b <= a; }
58 bint operator*(const bint& a, ll b) {
59     bint c;
60     ll q = 0;
61     forn(i, a.l) q += a.n[i] * b, c.n[i] = q % BASE, q /= BASE;
62     c.l = a.l;
63     while (q) c.n[c.l++] = q % BASE, q /= BASE;
64     c.invar();
65     return c;
66 }
67 bint operator*(const bint& a, const bint& b) {
68     bint c;
69     c.l = a.l + b.l;
70     fill(c.n, c.n + b.l, 0);
71     forn(i, a.l) {
72         ll q = 0;
73         forn(j, b.l) q += a.n[i] * b.n[j] + c.n[i + j], c.n[i + j] = q % BASE,
74                                     q /= BASE;
75         c.n[i + b.l] = q;
76     }
77     c.invar();
78     return c;
79 }
80 pair<bint, ll> ldiv(const bint& a, ll b) { // c = a / b ; rm = a % b
81     bint c;
82     ll rm = 0;
83     dforn(i, a.l) {
84         rm = rm * BASE + a.n[i];
85         c.n[i] = rm / b;
86         rm %= b;
87     }
88     c.l = a.l;
89     c.invar();

```

```

90     return make_pair(c, rm);
91 }
92 bint operator/(const bint& a, ll b) { return ldiv(a, b).first; }
93 ll operator%(const bint& a, ll b) { return ldiv(a, b).second; }
94 pair<bint, bint> ldiv(const bint& a, const bint& b) {
95     bint c;
96     bint rm = 0;
97     dforn(i, a.l) {
98         if (rm.l == 1 && !rm.n[0]) rm.n[0] = a.n[i];
99         else {
100             dforn(j, rm.l) rm.n[j + 1] = rm.n[j];
101             rm.n[0] = a.n[i];
102             rm.l++;
103         }
104         ll q = rm.n[b.l] * BASE + rm.n[b.l - 1];
105         ll u = q / (b.n[b.l - 1] + 1);
106         ll v = q / b.n[b.l - 1] + 1;
107         while (u < v - 1) {
108             ll m = (u + v) / 2;
109             if (b * m <= rm) u = m;
110             else v = m;
111         }
112         c.n[i] = u;
113         rm -= b * u;
114     }
115     c.l = a.l;
116     c.invar();
117     return make_pair(c, rm);
118 }
119 bint operator/(const bint& a, const bint& b) { return ldiv(a, b).first; }
120 bint operator%(const bint& a, const bint& b) { return ldiv(a, b).second; }

```

4.12 Gain cost set

```

1 // stores pairs (benefit,cost) (erases non-optimal pairs)
2 // Note that these pairs will be increasing by g and increasing by c
3 // If we insert a pair that is included in other, the big one will be deleted
4 // For lis 2d, create a GCS por each possible length, use as (-g, c) and
5 // binary search looking for the longest length where (-g, c) could be added
6 struct GCS {
7     set<ii> s;
8     void add(int g, int c) {
9         ii x = {g, c};
10        auto p = s.lower_bound(x);
11        if (p != s.end() && p->snd <= x.snd) return;
12        if (p != s.begin()) { // erase pairs with less or eq benefit and more
13                                cost
14            --p;
15            while (p->snd >= x.snd) {
16                if (p == s.begin()) {
17                    s.erase(p);
18                    break;
19                }
20                s.erase(p--);

```

```

20     }
21     }
22     s.insert(x);
23 }
24 int get(int gain) { // min cost for the benefit greater or equal to gain
25     auto p = s.lower_bound(ii){gain, -INF});
26     int r = p == s.end() ? INF : p->snd;
27     return r;
28 }
29 };

```

5 Strings

5.1 Z function

```

1 // z[i] = length of longest substring starting from s[i] that is prefix of s
2 // z[i] = max k: s[0,k) == s[i,i+k)
3 vector<int> zFunction(string& s) {
4     int l = 0, r = 0, n = sz(s);
5     vector<int> z(n, 0);
6     forr(i, 1, n) {
7         if (i <= r) z[i] = min(r - i + 1, z[i - l]);
8         while (i + z[i] < n && s[z[i]] == s[i + z[i]]) z[i]++;
9         if (i + z[i] - 1 > r) l = i, r = i + z[i] - 1;
10    }
11    return z;
12 }
13 void match(string& T, string& P) { // Text, Pattern -- O(|T|+|P|)
14     string s = P + '$' + T; //' '$' should be a character that is not present in
15         T
16     vector<int> z = zFunction(s);
17     forr(i, sz(P) + 1, sz(s)) if (z[i] == sz(P)); // match found, idx = i-sz(P)
18         -1
19 }

```

5.2 KMP

```

1 // b[i] = longest border of t[0,i) = length of the longest prefix of
2 // the substring P[0..i-1) that is also suffix of the substring P[0..i)
3 // For "AABAACAABAA", b[i] = {-1, 0, 1, 0, 1, 2, 0, 1, 2, 3, 4, 5}
4 vector<int> kmppre(string& P) { //
5     vector<int> b(sz(P) + 1);
6     b[0] = -1;
7     int j = -1;
8     forn(i, sz(P)) {
9         while (j >= 0 && P[i] != P[j]) j = b[j];
10        b[i + 1] = ++j;
11    }
12    return b;
13 }
14 void kmp(string& T, string& P) { // Text, Pattern -- O(|T|+|P|)
15     int j = 0;
16     vector<int> b = kmppre(P);
17     forn(i, sz(T)) {
18         while (j >= 0 && T[i] != P[j]) j = b[j];
19         if (++j == sz(P)) {
20             // Match at i-j+1, do something
21             j = b[j];
22         }
23     }
24 }

```

5.3 Manacher

```

1 int d1[MAXN]; // d1[i] = max odd palindrome centered on i
2 int d2[MAXN]; // d2[i] = max even palindrome centered on i
3 // s aabbaacaabbaa
4 // d1 111117111111
5 // d2 0103010010301
6 void manacher(string& s) { // O(|S|) - find longest palindromic substring
7     int l = 0, r = -1, n = s.size();
8     forn(i, n) { // build d1
9         int k = i > r ? 1 : min(d1[l + r - i], r - i);
10        while (i + k < n && i - k >= 0 && s[i + k] == s[i - k]) k++;
11        d1[i] = k--;
12        if (i + k > r) l = i - k, r = i + k;
13    }
14    l = 0, r = -1;
15    forn(i, n) { // build d2
16        int k = (i > r ? 0 : min(d2[l + r - i + 1], r - i + 1)) + 1;
17        while (i + k <= n && i - k >= 0 && s[i + k - 1] == s[i - k]) k++;
18        d2[i] = --k;
19        if (i + k - 1 > r) l = i - k, r = i + k - 1;
20    }
21 }

```

5.4 Booth's algorithm

```

1 // Booth's algorithm
2 // Find lexicographically minimal string rotation in O(|S|)
3 int booth(string S) {
4     S += S; // Concatenate string to it self to avoid modular arithmetic
5     int n = sz(S);
6     vector<int> f(n, -1);
7     int k = 0; // Least rotation of string found so far
8     forn(j, 1, n) {
9         char sj = S[j];
10        int i = f[j - k - 1];
11        while (i != -1 and sj != S[k + i + 1]) {
12            if (sj < S[k + i + 1]) k = j - i - 1;
13            i = f[i];
14        }
15        if (sj != S[k + i + 1]) {
16            if (sj < S[k]) k = j;
17            f[j - k] = -1;
18        } else {
19            f[j - k] = i + 1;
20        }
21    }
22    return k; // Lexicographically minimal string rotation's position
23 }

```

5.5 Hashing

5.5.1 Classic hashing (with substring hash)

```

1 // P should be a prime number, could be randomly generated,
2 // sometimes is good to make it close to alphabet size
3 // MOD[i] must be a prime of this order, could be randomly generated
4 const int P = 1777771, MOD[2] = {999727999, 1070777777};
5 const int PI[2] = {325255434, 10018302}; // PI[i] = P^-1 % MOD[i]
6 struct Hash {
7     vector<int> h[2], pi[2];
8     vector<ll> vp[2]; // Only used if getChanged is used (delete it if not)
9     Hash(string& s) {
10         forn(k, 2) h[k].rsz(s.size() + 1), pi[k].rsz(s.size() + 1),
11             vp[k].rsz(s.size() + 1);
12         forn(k, 2) {
13             h[k][0] = 0;
14             vp[k][0] = pi[k][0] = 1;
15             ll p = 1;
16             forr(i, 1, sz(s) + 1) {
17                 h[k][i] = (h[k][i - 1] + p * s[i - 1]) % MOD[k];
18                 pi[k][i] = (1LL * pi[k][i - 1] * PI[k]) % MOD[k];
19                 vp[k][i] = p = (p * P) % MOD[k];
20             }
21         }
22     }
23     ll get(int s, int e) { // get hash value of the substring [s, e)
24         ll H[2];
25         forn(i, 2) {
26             H[i] = (h[i][e] - h[i][s] + MOD[i]) % MOD[i];
27             H[i] = (1LL * H[i] * pi[i][s]) % MOD[i];
28         }
29         return (H[0] << 32) | H[1];
30     }
31     // get hash value of [s, e) if origVal in pos is changed to val
32     // Assumes s <= pos < e. If multiple changes are needed,
33     // do what is done in the for loop for every change
34     ll getChanged(int s, int e, int pos, int val, int origVal) {
35         ll hv = get(s, e), hh[2];
36         hh[1] = hv & ((1LL << 32) - 1);
37         hh[0] = hv >> 32;
38         forn(i, 2) hh[i] = (hh[i] + vp[i][pos] * (val - origVal + MOD[i])) % MOD[i];
39         return (hh[0] << 32) | hh[1];
40     }
41 };

```


5.5.2 Simple hashing (no substring hash)

```

1 // P should be a prime number, could be randomly generated,
2 // sometimes is good to make it close to alphabet size
3 // MOD[i] must be a prime of this order, could be randomly generated
4 const int P = 1777771, MOD[2] = {999727999, 1070777777};
5 const int PI[2] = {325255434, 10018302}; // PI[i] = P^-1 % MOD[i]
6 struct Hash {
7     ll h[2];
8     vector<ll> vp[2];
9     deque<int> x;
10    Hash(vector<int>& s) {
11        forn(i, sz(s)) x.pb(s[i]);
12        forn(k, 2) vp[k].rsz(s.size() + 1);
13        forn(k, 2) {
14            h[k] = 0;
15            vp[k][0] = 1;
16            ll p = 1;
17            forr(i, 1, sz(s) + 1) {
18                h[k] = (h[k] + p * s[i - 1]) % MOD[k];
19                vp[k][i] = p = (p * P) % MOD[k];
20            }
21        }
22    }
23    // Put the value val in position pos and update the hash value
24    void change(int pos, int val) {
25        forn(i, 2) h[i] = (h[i] + vp[i][pos] * (val - x[pos] + MOD[i])) % MOD[i];
26        x[pos] = val;
27    }
28    // Add val to the end of the current string
29    void push_back(int val) {
30        int pos = sz(x);
31        x.pb(val);
32        forn(k, 2) {
33            assert(pos <= sz(vp[k]));
34            if (pos == sz(vp[k])) vp[k].pb(vp[k].back() * P % MOD[k]);
35            ll p = vp[k][pos];
36            h[k] = (h[k] + p * val) % MOD[k];
37        }
38    }
39    // Delete the first element of the current string
40    void pop_front() {
41        assert(sz(x) > 0);
42        forn(k, 2) {
43            h[k] = (h[k] - x[0] + MOD[k]) % MOD[k];
44            h[k] = h[k] * PI[k] % MOD[k];
45        }
46        x.pop_front();
47    }
48    ll getHashVal() { return (h[0] << 32) | h[1]; }
49 };

```

5.5.3 Hashing 128 bits

```

1 typedef __int128 bint; // needs gcc compiler?
2 const bint MOD = 212345678987654321LL, P = 1777771, PI = 106955741089659571LL;
3 struct Hash {
4     vector<bint> h, pi;
5     Hash(string& s) {
6         assert((P * PI) % MOD == 1);
7         h.resize(s.size() + 1), pi.resize(s.size() + 1);
8         h[0] = 0, pi[0] = 1;
9         bint p = 1;
10        forr(i, 1, sz(s) + 1) {
11            h[i] = (h[i - 1] + p * s[i - 1]) % MOD;
12            pi[i] = (pi[i - 1] * PI) % MOD;
13            p = (p * P) % MOD;
14        }
15    }
16    ll get(int s, int e) { // get hash value of the substring [s, e)
17        return (((h[e] - h[s] + MOD) % MOD) * pi[s]) % MOD;
18    }
19 };

```

5.6 Trie

```

1 struct Trie {
2     map<char, Trie> m; // Trie* when using persistence
3     // For persistent trie only. Call "clone" probably from
4     // "add" and/or other methods, to implement persistence.
5     void clone(int pos) {
6         Trie* prev = NULL;
7         if (m.count(pos)) prev = m[pos];
8         m[pos] = new Trie();
9         if (prev != NULL) {
10             m[pos]->m = prev->m;
11             // copy other relevant data
12         }
13     }
14     void add(const string& s, int p = 0) {
15         if (s[p]) m[s[p]].add(s, p + 1);
16     }
17     void dfs() {
18         // Do stuff
19         forall(it, m) it->second.dfs();
20     }
21 };

```

5.7 Aho Corasick

```

1 struct Node {
2     map<char, int> next, go;
3     int p, link, leafLink;
4     char pch;
5     vector<int> leaf;
6     Node(int pp, char c) : p(pp), link(-1), leafLink(-1), pch(c) {}
7 };
8 struct AhoCorasick {
9     vector<Node> t = {Node(-1, -1)};
10    void add_string(string s, int id) {
11        int v = 0;
12        for (char c : s) {
13            if (!t[v].next.count(c)) {
14                t[v].next[c] = sz(t);
15                t.pb(Node(v, c));
16            }
17            v = t[v].next[c];
18        }
19        t[v].leaf.pb(id);
20    }
21    int go(int v, char c) {
22        if (!t[v].go.count(c)) {
23            if (t[v].next.count(c)) t[v].go[c] = t[v].next[c];
24            else t[v].go[c] = v == 0 ? 0 : go(get_link(v), c);
25        }
26        return t[v].go[c];
27    }
28    int get_link(int v) { // suffix link
29        if (t[v].link < 0) {
30            if (!v || !t[v].p) t[v].link = 0;
31            else t[v].link = go(get_link(t[v].p), t[v].pch);
32        }
33        return t[v].link;
34    }
35    // like suffix link, but only going to the root or to a node with
36    // a non-empty "leaf" list. Copy only if needed
37    int get_leaf_link(int v) {
38        if (t[v].leafLink < 0) {
39            if (!v || !t[v].p) t[v].leafLink = 0;
40            else if (!t[get_link(v)].leaf.empty()) t[v].leafLink = t[v].link;
41            else t[v].leafLink = get_leaf_link(t[v].link);
42        }
43        return t[v].leafLink;
44    }
45 };

```

5.8 Suffix array

5.8.1 Slow version $O(n \cdot \log n \cdot \log n)$

```

1 pair<int, int> sf[MAXN];
2 bool sacomp(int lhs, int rhs) { return sf[lhs] < sf[rhs]; }
3 vector<int> constructSA(string& s) { //  $O(n \log^2 n)$ 
4     int n = s.size(); // (sometimes fast enough)
5     vector<int> sa(n), r(n);
6     forn(i, n) r[i] = s[i]; // r[i]: equivalence class of s[i..i+m)
7     for (int m = 1; m < n; m *= 2) {
8         // sf[i] = {r[i], r[i+m]}, used to sort for next equivalence classes
9         forn(i, n) sa[i] = i, sf[i] = {r[i], i + m < n ? r[i + m] : -1};
10        stable_sort(sa.begin(), sa.end(), sacomp); //  $O(n \log n)$ 
11        r[sa[0]] = 0;
12        // if sf[sa[i]] == sf[sa[i-1]] then same equivalence class
13        forr(i, 1, n) r[sa[i]] = sf[sa[i]] != sf[sa[i - 1]] ? i : r[sa[i - 1]];
14    }
15    return sa;
16 }

```

5.8.2 Fast version $O(n \cdot \log n)$

```

1 #define RB(x) (x < n ? r[x] : 0)
2 void csort(vector<int>& sa, vector<int>& r, int k) { // counting sort  $O(n)$ 
3     int n = sa.size();
4     vector<int> f(max(255, n), 0), t(n);
5     forn(i, n) f[RB(i + k)]++;
6     int sum = 0;
7     forn(i, max(255, n)) f[i] = (sum += f[i]) - f[i];
8     forn(i, n) t[f[RB(sa[i] + k)]++] = sa[i];
9     sa = t;
10 }
11 vector<int> constructSA(string& s) { //  $O(n \log n)$ 
12     int n = s.size(), rank;
13     vector<int> sa(n), r(n), t(n);
14     forn(i, n) sa[i] = i, r[i] = s[i]; // r[i]: equivalence class of s[i..i+k)
15     for (int k = 1; k < n; k *= 2) {
16         csort(sa, r, k);
17         csort(sa, r, 0); // counting sort,  $O(n)$ 
18         t[sa[0]] = rank = 0; // t : equivalence classes array for next size
19         forr(i, 1, n) {
20             // check if sa[i] and sa[i-1] are in the same equivalence class
21             if (r[sa[i]] != r[sa[i - 1]] || RB(sa[i] + k) != RB(sa[i - 1] + k))
22                 rank++;
23             t[sa[i]] = rank;
24         }
25         r = t;
26         if (r[sa[n - 1]] == n - 1) break;
27     }
28     return sa;
29 }

```

5.8.3 Longest common prefix (LCP)

```

1 // LCP(sa[i], sa[j]) = min(lcp[i+1], lcp[i+2], ..., lcp[j])
2 // example: "banana", sa = {5,3,1,0,4,2}, lcp = {0,1,3,0,0,2}
3 // Num of dif substrings: (n*n+n)/2 - (sum over lcp array)
4 // Build suffix array (sa) before calling
5 vector<int> computeLCP(string& s, vector<int>& sa) {
6     int n = s.size(), L = 0;
7     vector<int> lcp(n), plcp(n), phi(n);
8     phi[sa[0]] = -1;
9     forr(i, 1, n) phi[sa[i]] = sa[i - 1];
10    forn(i, n) {
11        if (phi[i] < 0) {
12            plcp[i] = 0;
13            continue;
14        }
15        while (s[i + L] == s[phi[i] + L]) L++;
16        plcp[i] = L;
17        L = max(L - 1, 0);
18    }
19    forn(i, n) lcp[i] = plcp[sa[i]];
20    return lcp; // lcp[i]=LCP(sa[i-1],sa[i])
21 }

```

5.9 Suffix automaton

```

1 // The substrings of S can be decomposed into equivalence classes
2 // 2 substr are of the same class if they have the same set of endpos
3 // Example: endpos("bc") = {2, 4, 6} in "abcbcbc"
4 // Each class is a node of the automaton.
5 // Len is the longest substring of each class
6 // Link in state X is the state where the longest suffix of the longest
7 // substring in X, with a different endpos set, belongs
8 // The links form a tree rooted at 0
9 // last is the state of the whole string after each extention
10 struct state {
11     int len, link;
12     map<char, int> next;
13 }; // clear next!!
14 state st[MAXN];
15 int sz, last;
16 void sa_init() {
17     last = st[0].len = 0;
18     sz = 1;
19     st[0].link = -1;
20 }
21 void sa_extend(char c) {
22     int k = sz++, p; // k = new state
23     st[k].len = st[last].len + 1;
24     // while c is not present in p assign it as edge to the new state and
25     // move through link (note that p always corresponds to a suffix state)
26     for (p = last; p != -1 && !st[p].next.count(c); p = st[p].link)
27         st[p].next[c] = k;

```

```

28     if (p == -1) st[k].link = 0;
29     else {
30         // state p already goes to state q through char c. Then, link of k
31         // should go to a state with len = st[p].len + 1 (because of c)
32         int q = st[p].next[c];
33         if (st[p].len + 1 == st[q].len) st[k].link = q;
34         else {
35             // q is not the state we are looking for. Then, we
36             // create a clone of q (w) with the desired length
37             int w = sz++;
38             st[w].len = st[p].len + 1;
39             st[w].next = st[q].next;
40             st[w].link = st[q].link;
41             // go through links from p and while next[c] is q, change it to w
42             for (; p != -1 && st[p].next[c] == q; p = st[p].link) st[p].next[c] = w;
43             // change link of q from p to w, and finally set link of k to w
44             st[q].link = st[k].link = w;
45         }
46     }
47     last = k;
48 }
49 // input: abcbcbc
50 // i,link,len,next
51 // 0 -1 0 (a,1) (b,5) (c,7)
52 // 1 0 1 (b,2)
53 // 2 5 2 (c,3)
54 // 3 7 3 (b,4)
55 // 4 9 4 (c,6)
56 // 5 0 1 (c,7)
57 // 6 11 5 (b,8)
58 // 7 0 2 (b,9)
59 // 8 9 6 (c,10)
60 // 9 5 3 (c,11)
61 // 10 11 7
62 // 11 7 4 (b,8)

```

5.10 Suffix tree

```

1 const int INF = 1e6 + 10; // INF > n
2 const int MAXLOG = 20; // 2^MAXLOG > 2*n
3 // The SuffixTree of S is the compressed trie that would result after
4 // inserting every suffix of S.
5 // As it is a COMPRESSED trie, some edges may correspond to strings,
6 // instead of chars, and the compression is done in a way that every
7 // vertex that doesn't correspond to a suffix and has only one
8 // descendent, is omitted.
9 struct SuffixTree {
10     vector<char> s;
11     vector<map<int, int>> to; // fst char of substring on edge -> node
12     // s[fpos[i], fpos[i]+len[i]] is the substring on the edge between
13     // i's father and i.
14     // link[i] goes to the node that corresponds to the substring that
15     // result after "removing" the first character of the substring that
16     // i represents. Only defined for internal (non-leaf) nodes.
17     vector<int> len, fpos, link;
18     SuffixTree(int nn = 0) { // O(nn). nn should be the expected size
19         s.reserve(nn), to.reserve(2 * nn), len.reserve(2 * nn);
20         fpos.reserve(2 * nn), link.reserve(2 * nn);
21         make_node(0, INF);
22     }
23     int node = 0, pos = 0, n = 0;
24     int make_node(int p, int l) {
25         fpos.pb(p), len.pb(l), to.pb({}), link.pb(0);
26         return sz(to) - 1;
27     }
28     void go_edge() {
29         while (pos > len[to[node][s[n - pos]]]) {
30             node = to[node][s[n - pos]];
31             pos -= len[node];
32         }
33     }
34     void add(char c) {
35         s.pb(c), n++, pos++;
36         int last = 0;
37         while (pos > 0) {
38             go_edge();
39             int edge = s[n - pos];
40             int& v = to[node][edge];
41             int t = s[fpos[v] + pos - 1];
42             if (v == 0) {
43                 v = make_node(n - pos, INF);
44                 link[last] = node;
45                 last = 0;
46             } else if (t == c) {
47                 link[last] = node;
48                 return;
49             } else {
50                 int u = make_node(fpos[v], pos - 1);
51                 to[u][c] = make_node(n - 1, INF);
52                 to[u][t] = v;
53                 fpos[v] += pos - 1, len[v] -= pos - 1;
54                 v = u, link[last] = u, last = u;

```

```

55     }
56     if (node == 0) pos--;
57     else node = link[node];
58 }
59 }
60 // Call this after you finished building the SuffixTree to correctly
61 // set some values of the vector 'len' that currently have a big
62 // value (because of INF usage). Note that you shouldn't call 'add'
63 // anymore after calling this method.
64 void finishedAdding() {
65     forn(i, sz(len)) if (len[i] + fpos[i] > n) len[i] = n - fpos[i];
66 }
67 // From here, copy only if needed!!
68 // Map each suffix with it corresponding leaf node
69 // vleaf[i] = node id of leaf of suffix s[i..n)
70 // Note that the last character of the string must be unique
71 // Use 'buildLeaf' not 'dfs' directly. Also 'finishedAdding' must
72 // be called before calling 'buildLeaf'.
73 // When this is needed, usually binary lifting (vp) and depths are
74 // also needed.
75 // Usually you also need to compute extra information in the dfs.
76 vector<int> vleaf, vdepth;
77 vector<vector<int>> vp;
78 void dfs(int cur, int p, int curlen) {
79     if (cur > 0) curlen += len[cur];
80     vdepth[cur] = curlen;
81     vp[cur][0] = p;
82     if (to[cur].empty()) {
83         assert(0 < curlen && curlen <= n);
84         assert(vleaf[n - curlen] == -1);
85         vleaf[n - curlen] = cur;
86         // here maybe compute some extra info
87     } else forall(it, to[cur]) {
88         dfs(it->snd, cur, curlen);
89         // maybe change return type and here compute extra info
90     }
91     // maybe return something here related to extra info
92 }
93 void buildLeaf() {
94     vdepth.rsz(sz(to), 0); // tree size
95     vleaf.rsz(n, -1); // string size
96     vp.rsz(sz(to), vector<int>(MAXLOG)); // tree size * log
97     dfs(0, 0, 0);
98     forr(k, 1, MAXLOG) forn(i, sz(to)) vp[i][k] = vp[vp[i][k - 1]][k - 1];
99     forn(i, n) assert(vleaf[i] != -1);
100 }
101 };

```

6 Grafos

6.1 Dijkstra

```

1 struct Dijkstra {          // WARNING: ii usually needs to be pair<ll, int>
2     vector<vector<ii>> G;    // ady. list with pairs (weight, dst)
3     vector<ll> dist;
4     // vector<int> vp; // for path reconstruction (parent of each node)
5     int N;
6     Dijkstra(int n) : G(n), N(n) {}
7     void addEdge(int a, int b, ll w) { G[a].pb(mp(w, b)); }
8     void run(int src) {     // O(|E| log |V|)
9         dist = vector<ll>(N, INF);
10        // vp = vector<int>(N, -1);
11        priority_queue<ii, vector<ii>, greater<ii>> Q;
12        Q.push(make_pair(0, src)); dist[src] = 0;
13        while (sz(Q)) {
14            int node = Q.top().snd;
15            ll d = Q.top().fst;
16            Q.pop();
17            if (d > dist[node]) continue;
18            forall(it, G[node]) if (d + it->fst < dist[it->snd]) {
19                dist[it->snd] = d + it->fst;
20                // vp[it->snd] = node;
21                Q.push(mp(dist[it->snd], it->snd));
22            }
23        }
24    }
25 };

```

6.2 Floyd-Warshall

```

1 // Min path between every pair of nodes in directed graph
2 // G[i][j] initially needs weight of edge (i, j) or INF
3 // be careful with multiedges and loops when assigning to G
4 int G[MAX_N][MAX_N];
5 void floyd() { // O(N^3)
6     forn(k, N) forn(i, N) if (G[i][k] != INF) forn(j, N) if (G[k][j] != INF)
7         G[i][j] = min(G[i][j], G[i][k] + G[k][j]);
8 }
9 bool inNegCycle(int v) { return G[v][v] < 0; }
10 // checks if there's a neg. cycle in path from a to b
11 bool hasNegCycle(int a, int b) {
12     forn(i, N) if (G[a][i] != INF && G[i][i] < 0 && G[i][b] != INF) return true;
13     return false;
14 }

```

6.3 Bellman-Ford

```

1 // Mas lento que Dijsktra, pero maneja arcos con peso negativo
2 //
3 // Can solve systems of "difference inequalities":
4 // 1. for each inequality  $x_i - x_j \leq k$  add an edge  $j \rightarrow i$  with weight  $k$ 
5 // 2. create an extra node  $Z$  and add an edge  $Z \rightarrow i$  with weight 0 for
6 //     each variable  $x_i$  in the inequalities
7 // 3. run( $Z$ ): if negcycle, no solution, otherwise "dist" is a solution
8 //
9 // Can transform a graph to get all edges of positive weight
10 // ("Johnson algorithmt"):
11 // 1. Create an extra node  $Z$  and add edge  $Z \rightarrow i$  with weight 0 for all
12 //     nodes  $i$ 
13 // 2. Run bellman ford from  $Z$ 
14 // 3. For each original edge  $a \rightarrow b$  (with weight  $w$ ), change its weight to
15 //     be  $w + \text{dist}[a] - \text{dist}[b]$  (where  $\text{dist}$  is the result of step 2)
16 // 4. The shortest paths in the old and new graph are the same (their
17 //     weight result may differ, but the paths are the same)
18 // Note that this doesn't work well with negative cycles, but you can
19 // identify them before step 3 and then ignore all new weights that
20 // result in a negative value when executing step 3.
21 struct BellmanFord {
22     vector<vector<ii>> G;    // ady. list with pairs (weight, dst)
23     vector<ll> dist;
24     int N;
25     BellmanFord(int n) : G(n), N(n) {}
26     void addEdge(int a, int b, ll w) { G[a].pb(mp(w, b)); }
27     void run(int src) {    // O(VE)
28         dist = vector<ll>(N, INF);
29         dist[src] = 0;
30         forn(i, N - 1) forn(j, N) if (dist[j] != INF) forall(it, G[j])
31             dist[it->snd] = min(dist[it->snd], dist[j] + it->fst);
32     }
33
34     bool hasNegCycle() {
35         forn(j, N) if (dist[j] != INF)
36             forall(it, G[j]) if (dist[it->snd] > dist[j] + it->fst) return true;
37         // inside if: all points reachable from it->snd will have -INF
38         // distance. However this is not enough to identify which exact
39         // nodes belong to a neg cycle, nor even which can reach a neg
40         // cycle. To do so, you need to run SCC (kosaraju) and check
41         // whether each SCC hasNegCycle independently. For those that
42         // do hasNegCycle, then all of its nodes are part of a (not
43         // necessarily simple) neg cycle.
44         return false;
45     }
46 };

```

6.4 Kruskal

```

1 struct Edge {
2     int a, b, w;
3 };
4 bool operator<(const Edge& a, const Edge& b) { return a.w < b.w; }
5 // Minimun Spanning Tree in O(E log E)
6 ll kruskal(vector<Edge> &E, int n) {
7     ll cost = 0; sort(E.begin(), E.end());
8     UnionFind uf(n);
9     forall(it, E) if(!uf.join(it->a, it->b))
10         cost += it->w;
11     return cost;
12 }

```

6.5 Prim

```

1 vector<ii> G[MAXN];
2 bool taken[MAXN];
3 priority_queue<ii, vector<ii>, greater<ii> > pq; // min heap
4 void process(int v) {
5     taken[v] = true;
6     forall(e, G[v]) if (!taken[e->second]) pq.push(*e);
7 }
8 // Minimun Spanning Tree in O(n^2)
9 ll prim() {
10     zero(taken);
11     process(0);
12     ll cost = 0;
13     while (sz(pq)) {
14         ii e = pq.top();
15         pq.pop();
16         if (!taken[e.second]) cost += e.first, process(e.second);
17     }
18     return cost;
19 }

```

6.6 Kosaraju SCC

```

1 struct Kosaraju {
2     vector<vector<int>> G, gt;
3     // nodos 0...N-1 ; componentes 0...cantcomp-1
4     int N, cantcomp;
5     vector<int> comp, used;
6     stack<int> pila;
7     Kosaraju(int n) : G(n), gt(n), N(n), comp(n) {}
8     void addEdge(int a, int b) { G[a].pb(b), gt[b].pb(a); }
9     void dfs1(int nodo) {
10         used[nodo] = 1;
11         forall(it, G[nodo]) if (!used[*it]) dfs1(*it);
12         pila.push(nodo);

```

```

13     }
14     void dfs2(int nodo) {
15         used[nodo] = 2;
16         comp[nodo] = cantcomp - 1;
17         forall(it, gt[nodo]) if (used[*it] != 2) dfs2(*it);
18     }
19     void run() {
20         cantcomp = 0;
21         used = vector<int>(N, 0);
22         forn(i, N) if (!used[i]) dfs1(i);
23         while (!pila.empty()) {
24             if (used[pila.top()] != 2) {
25                 cantcomp++;
26                 dfs2(pila.top());
27             }
28             pila.pop();
29         }
30     }
31 };

```

6.7 2-SAT + Tarjan SCC

```

1 // Usage:
2 // 1. Create with n = number of variables (0-indexed)
3 // 2. Add restrictions through the existing methods, using ~X for
4 //    negating variable X for example.
5 // 3. Call satisf() to check whether there is a solution or not.
6 // 4. Find a valid assignment by looking at verdad[cmp[2*X]] for each
7 //    variable X
8 struct Sat2 {
9     // We have a vertex representing a variable and other for its
10    // negation. Every edge stored in G represents an implication.
11    vector<vector<int>> G;
12    // idx[i]=index assigned in the dfs
13    // lw[i]=lowest index (closer from the root) reachable from i
14    // verdad[cmp[2*i]]=valor de la variable i
15    int N, qidx, qcmp;
16    vector<int> lw, idx, cmp, verdad;
17    stack<int> q;
18    Sat2(int n) : G(2 * n), N(n) {}
19    void tjn(int v) {
20        lw[v] = idx[v] = ++qidx;
21        q.push(v), cmp[v] = -2;
22        forall(it, G[v]) if (!idx[*it] || cmp[*it] == -2) {
23            if (!idx[*it]) tjn(*it);
24            lw[v] = min(lw[v], lw[*it]);
25        }
26        if (lw[v] == idx[v]) {
27            int x;
28            do { x = q.top(), q.pop(), cmp[x] = qcmp; } while (x != v);
29            verdad[qcmp] = (cmp[v ^ 1] < 0);
30            qcmp++;
31        }
32    }

```

```

33 bool satisf() { // O(N)
34     idx = lw = verdad = vector<int>(2 * N, 0);
35     cmp = vector<int>(2 * N, -1);
36     qidx = qcmp = 0;
37     forn(i, N) {
38         if (!idx[2 * i]) tjn(2 * i);
39         if (!idx[2 * i + 1]) tjn(2 * i + 1);
40     }
41     forn(i, N) if (cmp[2 * i] == cmp[2 * i + 1]) return false;
42     return true;
43 }
44 // a -> b, here ids are transformed to avoid negative numbers
45 void addimpl(int a, int b) {
46     a = a >= 0 ? 2 * a : 2 * (~a) + 1;
47     b = b >= 0 ? 2 * b : 2 * (~b) + 1;
48     G[a].pb(b), G[b ^ 1].pb(a ^ 1);
49 }
50 void addor(int a, int b) { addimpl(~a, b); } // a | b = ~a -> b
51 void addeq(int a, int b) { // a = b, a <-> b (iff)
52     addimpl(a, b);
53     addimpl(b, a);
54 }
55 void addxor(int a, int b) { addeq(a, ~b); } // a xor b
56 void force(int x, bool val) { // force x to take val
57     if (val) addimpl(~x, x);
58     else addimpl(x, ~x);
59 }
60 // At most 1 true in all v
61 void atmost1(vector<int> v) {
62     int auxid = N;
63     N += sz(v);
64     G.rsz(2 * N);
65     forn(i, sz(v)) {
66         addimpl(auxid, ~v[i]);
67         if (i) {
68             addimpl(auxid, auxid - 1);
69             addimpl(v[i], auxid - 1);
70         }
71         auxid++;
72     }
73     assert(auxid == N);
74 }
75 };

```

6.8 Articulation points

```

1 int N;
2 vector<int> G[1000000];
3 // V[i]=node number(if visited), L[i]= lowest V[i] reachable from i
4 int qV, V[1000000], L[1000000], P[1000000];
5 void dfs(int v, int f) {
6     L[v] = V[v] = ++qV;
7     forall(it, G[v]) if (!V[*it]) {
8         dfs(*it, v);

```

```

9     L[v] = min(L[v], L[*it]);
10    P[v] += L[*it] >= V[v];
11 }
12 else if (*it != f) L[v] = min(L[v], V[*it]); }
13 int cantart() { // O(n)
14     qV = 0;
15     zero(V), zero(P);
16     dfs(1, 0);
17     P[1]--;
18     int q = 0;
19     forn(i, N) if (P[i]) q++;
20     return q;
21 }

```

6.9 Biconnected components and bridges

```

1 struct Bicon {
2     vector<vector<int>> G;
3     struct edge {
4         int u, v, comp;
5         bool bridge;
6     };
7     vector<edge> ve;
8     void addEdge(int u, int v) {
9         G[u].pb(sz(ve)), G[v].pb(sz(ve));
10        ve.pb({u, v, -1, false});
11    }
12    // d[i] = dfs id
13    // b[i] = lowest id reachable from i
14    // art[i]>0 iff i is an articulation point
15    // nbc = total # of biconnected comps
16    // nart = total # of articulation points
17    vector<int> d, b, art;
18    int n, t, nbc, nart;
19    Bicon(int nn) {
20        n = nn;
21        t = nbc = nart = 0;
22        b = d = vector<int>(n, -1);
23        art = vector<int>(n, 0);
24        G = vector<vector<int>>(n);
25        ve.clear();
26    }
27    stack<int> st;
28    void dfs(int u, int pe) { // O(n + m)
29        b[u] = d[u] = t++;
30        forall(eid, G[u]) if (*eid != pe) {
31            int v = ve[*eid].u ^ ve[*eid].v ^ u;
32            if (d[v] == -1) {
33                st.push(*eid);
34                dfs(v, *eid);
35                if (b[v] > d[u]) ve[*eid].bridge = true; // bridge
36                if (b[v] >= d[u]) { // art
37                    if (art[u]++ == 0) nart++;
38                    int last; // start biconnected

```

```

39     do {
40         last = st.top();
41         st.pop();
42         ve[last].comp = nbc;
43     } while (last != *eid);
44     nbc++; // end biconnected
45 }
46 b[u] = min(b[u], b[v]);
47 } else if (d[v] < d[u]) { // back edge
48     st.push(*eid);
49     b[u] = min(b[u], d[v]);
50 }
51 }
52 }
53 void run() { forn(i, n) if (d[i] == -1) art[i]--, dfs(i, -1); }
54 // block-cut tree (copy only if needed)
55 vector<set<int>> bctree; // set to dedup
56 vector<int> artid; // art nodes to tree node (-1 for !arts)
57 void buildBlockCutTree() { // call run first!!
58     // node id: [0, nbc) -> bc, [nbc, nbc+nart) -> art
59     int ntrees = nbc + nart, auxid = nbc;
60     bctree = vector<set<int>>(ntrees);
61     artid = vector<int>(n, -1);
62     forn(i, n) if (art[i] > 0) {
63         forall(eid, G[i]) { // edges always bc <-> art
64             // depending on the problem, may want
65             // to add more data on bctree edges
66             bctree[auxid].insert(ve[*eid].comp);
67             bctree[ve[*eid].comp].insert(auxid);
68         }
69         artid[i] = auxid++;
70     }
71 }
72 int getTreeIdForGraphNode(int u) {
73     if (artid[u] != -1) return artid[u];
74     if (!G[u].empty()) return ve[G[u][0]].comp;
75     return -1; // for nodes with no neighbours in G
76 }
77 };

```

```

13 }
14 void addEdge(int a, int b) { G[a].pb(b), G[b].pb(a); }
15 void dfs(int node, int p, int lvl) {
16     vp[0][node] = p, L[node] = lvl;
17     forall(it, G[node]) if (*it != p) dfs(*it, node, lvl + 1);
18 }
19 void build() {
20     // Here you may also want to change the 2nd param to -1
21     dfs(ROOT, ROOT, 0);
22     forn(k, LOGN - 1) forn(i, N) vp[k + 1][i] = vp[k][vp[k][i]];
23 }
24 int climb(int a, int d) { // O(lgn)
25     if (!d) return a;
26     dform(i, lg(L[a]) + 1) if (1 <= i <= d) a = vp[i][a], d -= 1 < i;
27     return a;
28 }
29 int lca(int a, int b) { // O(lgn)
30     if (L[a] < L[b]) swap(a, b);
31     a = climb(a, L[a] - L[b]);
32     if (a == b) return a;
33     dform(i, lg(L[a]) + 1) if (vp[i][a] != vp[i][b]) a = vp[i][a], b = vp[i][b];
34     return vp[0][a];
35 }
36 int dist(int a, int b) { // returns distance between nodes
37     return L[a] + L[b] - 2 * L[lca(a, b)];
38 }
39 };

```

6.10 LCA + Climb

```

1 #define lg(x) (31 - __builtin_clz(x)) //floor(log2(x))
2 // Usage: 1) Create 2) Add edges 3) Call build 4) Use
3 struct LCA {
4     int N, LOGN, ROOT;
5     // vp[k][node] holds the 2^k ancestor of node
6     // L[v] holds the level of v
7     vector<int> L;
8     vector<vector<int>> vp, G;
9     LCA(int n, int root) : N(n), LOGN(lg(n) + 1), ROOT(root), L(n), G(n) {
10         // Here you may want to replace the default from root to other
11         // value, like maybe -1.
12         vp = vector<vector<int>>(LOGN, vector<int>(n, root));

```


6.11 Virtual tree

```

1 // Usage: (VT = VirtualTree)
2 // 1- Build the LCA and use it for creating 1 VT instance
3 // 2- Call updateVT every time you want
4 // 3- Between calls of updateVT you probably want to use the tree, imp
5 // and VTroot variables from this struct to solve your problem
6 struct VirtualTree {
7     // n = #nodes full tree
8     // curt used for computing tin and tout
9     int n, curt;
10    LCA* lca;
11    vector<int> tin, tout;
12    vector<vector<ii>> tree; // {node, dist}, only parent -> child dire
13    // imp[i] = true iff i was part of 'newv' from last time that
14    // updateVT was called (note that LCAs are not imp)
15    vector<bool> imp;
16    void dfs(int node, int p) {
17        tin[node] = curt++;
18        forall(it, lca->G[node]) if (*it != p) dfs(*it, node);
19        tout[node] = curt++;
20    }
21    VirtualTree(LCA* l) { // must call l.build() before
22        lca = l, n = sz(l->G), lca = l, curt = 0;
23        tin.rsz(n), tout.rsz(n), tree.rsz(n), imp.rsz(n);
24        dfs(l->ROOT, l->ROOT);
25    }
26    bool isAncestor(int a, int b) { return tin[a] < tin[b] && tout[a] > tout[b];
27    }
28    int VTroot = -1; // root of the current VT
29    vector<int> v; // list of nodes of current VT (includes LCAs)
30    void updateVT(vector<int>& newv) { // O(sz(newv)*log)
31        assert(!newv.empty()); // this method assumes non-empty
32        auto cmp = [this](int a, int b) { return tin[a] < tin[b]; };
33        forn(i, sz(v)) tree[v[i]].clear(), imp[v[i]] = false;
34        v = newv;
35        sort(v.begin(), v.end(), cmp);
36        set<int> s;
37        forn(i, sz(v)) s.insert(v[i]), imp[v[i]] = true;
38        forn(i, sz(v) - 1) s.insert(lca->lca(v[i], v[i + 1]));
39        v.clear();
40        forall(it, s) v.pb(*it);
41        sort(v.begin(), v.end(), cmp);
42        stack<int> st;
43        forn(i, sz(v)) {
44            while (!st.empty() && !isAncestor(st.top(), v[i])) st.pop();
45            assert(i == 0 || !st.empty());
46            if (!st.empty()) tree[st.top()].pb(mp(v[i], lca->dist(st.top(), v[i])));
47            st.push(v[i]);
48        }
49        VTroot = v[0];
50    };

```

6.12 Heavy Light Decomposition

```

1 // Usage: 1. HLD(# nodes) 2. add tree edges 3. build() 4. use it
2 struct HLD {
3     vector<int> w, p, dep; // weight, father, depth
4     vector<vector<int>> g;
5     HLD(int n) : w(n), p(n), dep(n), g(n), pos(n), head(n) {}
6     void addEdge(int a, int b) { g[a].pb(b), g[b].pb(a); }
7     void build() { p[0] = -1, dep[0] = 0, dfs1(0), curpos = 0, hld(0, -1); }
8     void dfs1(int x) {
9         w[x] = 1;
10        for (int y : g[x]) if (y != p[x]) {
11            p[y] = x, dep[y] = dep[x] + 1, dfs1(y);
12            w[x] += w[y];
13        }
14    }
15    int curpos;
16    vector<int> pos, head;
17    void hld(int x, int c) {
18        if (c < 0) c = x;
19        pos[x] = curpos++, head[x] = c;
20        int mx = -1;
21        for (int y : g[x]) if (y != p[x] && (mx < 0 || w[mx] < w[y])) mx = y;
22        if (mx >= 0) hld(mx, c);
23        for (int y : g[x]) if (y != mx && y != p[x]) hld(y, -1);
24    }
25    // Here ST is segtree static/dynamic/lazy or other DS according to problem
26    tipo query(int x, int y, ST& st) { // ST tipo
27        tipo r = neutro;
28        while (head[x] != head[y]) {
29            if (dep[head[x]] > dep[head[y]]) swap(x, y);
30            r = oper(r, st.get(pos[head[y]], pos[y] + 1)); // ST oper
31            y = p[head[y]];
32        }
33        if (dep[x] > dep[y]) swap(x, y); // now x is lca
34        r = oper(r, st.get(pos[x], pos[y] + 1)); // ST oper
35        return r;
36    }
37 };
38 // for point updates: st.set(pos[x], v) (x = node, v = new value)
39 // for lazy range updates: something similar to the query method
40 // for queries on edges: - assign values of edges to "child" node
41 // - change pos[x] to pos[x]+1 in query (line 34)

```

6.13 Centroid Decomposition

```

1 // Usage: 1. Centroid(# nodes), 2. add tree edges, 3. build(), 4. use it
2 struct Centroid {
3     vector<vector<int>> g;
4     vector<int> vp, vsz;
5     vector<bool> taken;
6     Centroid(int n) : g(n), vp(n), vsz(n), taken(n) {}
7     void addEdge(int a, int b) { g[a].pb(b), g[b].pb(a); }
8     void build() { centroid(0, -1, -1); } // O(nlogn)
9     int dfs(int node, int p) {
10         vsz[node] = 1;
11         forall(it, g[node]) if (*it != p && !taken[*it])
12             vsz[node] += dfs(*it, node);
13         return vsz[node];
14     }
15     void centroid(int node, int p, int cursz) {
16         if (cursz == -1) cursz = dfs(node, -1);
17         forall(it, g[node]) if (!taken[*it] && vsz[*it] > cursz / 2) {
18             vsz[node] = 0, centroid(*it, p, cursz);
19             return;
20         }
21         taken[node] = true, vp[node] = p;
22         // do something using node as centroid
23         forall(it, g[node]) if (!taken[*it]) centroid(*it, node, -1);
24     }
25 };

```

6.14 Tree Reroot

```

1 struct Edge {
2     int u, v; // maybe add more data, depending on the problem
3 };
4 // USAGE:
5 // 1- define all the logic in SubtreeData
6 // 2- create a reroot and add all the edges
7 // 3- call Reroot.run()
8 struct SubtreeData {
9     // Define here what data you need for each subtree
10    SubtreeData() {} // just empty
11    SubtreeData(int node) {
12        // Initialize the data here as if this new subtree
13        // has size 1, and its only node is 'node'
14    }
15    void merge(Edge* e, SubtreeData& s) {
16        // Modify this subtree's data to reflect that 's' is being
17        // merged into 'this' through the edge 'e'.
18        // When e == NULL, then no edge is present, but then, 'this'
19        // and 's' have THE SAME ROOT (be CAREFUL with this).
20        // These 2 subtrees don't have any other shared nodes nor edges.
21    }
22 };
23 struct Reroot {

```

```

24 int N; // # of nodes
25 // vresult[i] = SubtreeData for the tree where i is the root
26 // this should be what you need as result
27 vector<SubtreeData> vresult, vs;
28 vector<Edge> ve;
29 vector<vector<int>> g; // the tree as a bidirectional graph
30 Reroot(int n) : N(n), vresult(n), vs(n), ve(0), g(n) {}
31 void addEdge(Edge e) { // will be added in both ways
32     g[e.u].pb(sz(ve));
33     g[e.v].pb(sz(ve));
34     ve.pb(e);
35 }
36 void dfs1(int node, int p) {
37     vs[node] = SubtreeData(node);
38     forall(e, g[node]) {
39         int nxt = node ^ ve[*e].u ^ ve[*e].v;
40         if (nxt == p) continue;
41         dfs1(nxt, node);
42         vs[node].merge(&ve[*e], vs[nxt]);
43     }
44 }
45 void dfs2(int node, int p, SubtreeData fromp) {
46     vector<SubtreeData> vsuf(sz(g[node]) + 1);
47     int pos = sz(g[node]);
48     SubtreeData pref = vsuf[pos] = SubtreeData(node);
49     vresult[node] = vs[node];
50     dforall(e, g[node]) { // dforall = forall in reverse
51         pos--;
52         vsuf[pos] = vsuf[pos + 1];
53         int nxt = node ^ ve[*e].u ^ ve[*e].v;
54         if (nxt == p) {
55             pref.merge(&ve[*e], fromp);
56             vresult[node].merge(&ve[*e], fromp);
57             continue;
58         }
59         vsuf[pos].merge(&ve[*e], vs[nxt]);
60     }
61     assert(pos == 0);
62     forall(e, g[node]) {
63         pos++;
64         int nxt = node ^ ve[*e].u ^ ve[*e].v;
65         if (nxt == p) continue;
66         SubtreeData aux = pref;
67         aux.merge(NULL, vsuf[pos]);
68         dfs2(nxt, node, aux);
69         pref.merge(&ve[*e], vs[nxt]);
70     }
71 }
72 void run() {
73     dfs1(0, 0);
74     dfs2(0, 0, SubtreeData());
75 }
76 };

```

6.15 Diameter of a tree

```

1 vector<int> G[MAXN];
2 int n, m, p[MAXN], d[MAXN], d2[MAXN];
3 int bfs(int r, int* d) {
4     queue<int> q;
5     d[r] = 0, q.push(r);
6     int v;
7     while (sz(q)) {
8         v = q.front();
9         q.pop();
10        forall(it, G[v]) if (d[*it] == -1) {
11            d[*it] = d[v] + 1, p[*it] = v, q.push(*it);
12        }
13    }
14    return v; // ultimo nodo visitado
15 }
16 vector<int> diams;
17 vector<ii> centros;
18 void diametros() {
19     memset(d, -1, sizeof(d));
20     memset(d2, -1, sizeof(d2));
21     diams.clear(), centros.clear();
22     forn(i, n) if (d[i] == -1) {
23         int v, c;
24         c = v = bfs(bfs(i, d2), d);
25         forn(_, d[v] / 2) c = p[c];
26         diams.pb(d[v]);
27         if (d[v] & 1) centros.pb(ii(c, p[c]));
28         else centros.pb(ii(c, c));
29     }
30 }

```

6.16 Euler path or cycle

```

1 // Be careful with nodes with degree 0 when solving your problem, the
2 // comments below assume that there are no nodes with degree 0.
3 //
4 // Euler [path/cycle] exists in a bidirectional graph iff the graph is
5 // connected and at most [2/0] nodes have odd degree. The path must
6 // start from an odd degree vertex when there are 2.
7 //
8 // Euler [path/cycle] exists in a directed graph iff the graph is
9 // [connected when making edges bidirectional / a single SCC], and
10 // at most [1/0] node have indg - outdg = 1, at most [1/0] node have
11 // outdg - indg = 1, all the other nodes have indg = outdg. The path
12 // must start from the node with outdg - indg = 1, when there is one.
13 //
14 // Directed version (uncomment commented code for undirected)
15 struct edge {
16     int y;
17     // list<edge>::iterator rev;
18     edge(int yy) : y(yy) {}

```

```

19 };
20 struct EulerPath {
21     vector<list<edge>> g;
22     EulerPath(int n) : g(n) {}
23     void addEdge(int a, int b) {
24         g[a].push_front(edge(b));
25         // auto ia = g[a].begin();
26         // g[b].push_front(edge(a));
27         // auto ib = g[b].begin();
28         // ia->rev=ib, ib->rev=ia;
29     }
30     vector<int> p;
31     void go(int x) {
32         while (sz(g[x])) {
33             int y = g[x].front().y;
34             // g[y].erase(g[x].front().rev);
35             g[x].pop_front();
36             go(y);
37         }
38         p.push_back(x);
39     }
40     vector<int> getPath(int x) { // get a path that starts from x
41         // you must check that a path exists from x before calling get_path!
42         p.clear(), go(x);
43         reverse(p.begin(), p.end());
44         return p;
45     }
46 };

```

6.17 Dynamic Connectivity

```

1 struct UnionFind {
2     int n, comp;
3     vector<int> pre, si, c;
4     UnionFind(int n = 0) : n(n), comp(n), pre(n), si(n, 1) {
5         forn(i, n) pre[i] = i;
6     }
7     int find(int u) { return u == pre[u] ? u : find(pre[u]); }
8     bool merge(int u, int v) {
9         if ((u = find(u)) == (v = find(v))) return false;
10        if (si[u] < si[v]) swap(u, v);
11        si[u] += si[v], pre[v] = u, comp--, c.pb(v);
12        return true;
13    }
14    int snap() { return sz(c); }
15    void rollback(int snap) {
16        while (sz(c) > snap) {
17            int v = c.back();
18            c.pop_back();
19            si[pre[v]] -= si[v], pre[v] = v, comp++;
20        }
21    }
22 };
23 enum { ADD, DEL, QUERY };

```

```

24 struct Query {
25     int type, u, v;
26 };
27 struct DynCon { // bidirectional graphs; create vble as DynCon name(
    cant_nodos)
28     vector<Query> q;
29     UnionFind dsu;
30     vector<int> match, res;
31     // se puede no usar cuando hay identificador para cada arista (mejora poco)
32     map<ii, int> last;
33     DynCon(int n = 0) : dsu(n) {}
34     void add(int u, int v) // to add an edge
35     {
36         if (u > v) swap(u, v);
37         q.pb((Query){ADD, u, v}), match.pb(-1);
38         last[ii(u, v)] = sz(q) - 1;
39     }
40     void remove(int u, int v) // to remove an edge
41     {
42         if (u > v) swap(u, v);
43         q.pb((Query){DEL, u, v});
44         int prev = last[ii(u, v)];
45         match[prev] = sz(q) - 1;
46         match.pb(prev);
47     }
48     void query() // to add a question (query) type of query
49     {
50         q.pb((Query){QUERY, -1, -1}), match.pb(-1);
51     }
52     void process() // call this to process queries in the order of q
53     {
54         forn(i, sz(q)) if (q[i].type == ADD && match[i] == -1) match[i] = sz(q);
55         go(0, sz(q));
56     }
57     void go(int l, int r) {
58         if (l + 1 == r) {
59             if (q[l].type == QUERY) // Aqui responder la query usando el dsu!
60                 res.pb(dsu.comp()); // aqui query=cantidad de componentes conexas
61             return;
62         }
63         int s = dsu.snap(), m = (l + r) / 2;
64         forr(i, m, r) if (match[i] != -1 && match[i] < l) dsu.merge(q[i].u, q[i].v);
65         go(l, m);
66         dsu.rollback(s);
67         s = dsu.snap();
68         forr(i, l, m) if (match[i] != -1 && match[i] >= r)
69             dsu.merge(q[i].u, q[i].v);
70         go(m, r);
71         dsu.rollback(s);
72     }
73 };

```

7 Flow

7.1 Dinic

```

1 struct Edge {
2     int u, v;
3     ll cap, flow;
4     Edge() {}
5     Edge(int uu, int vv, ll c) : u(uu), v(vv), cap(c), flow(0) {}
6 };
7 struct Dinic {
8     int N;
9     vector<Edge> E;
10    vector<vector<int>>> g;
11    vector<int> d, pt;
12    Dinic(int n) : N(n), g(n), d(n), pt(n) {} // clear and init
13    void addEdge(int u, int v, ll cap) {
14        if (u != v) {
15            g[u].pb(sz(E));
16            E.pb({u, v, cap});
17            g[v].pb(sz(E));
18            E.pb({v, u, 0});
19        }
20    }
21    bool BFS(int S, int T) {
22        queue<int> q({S});
23        fill(d.begin(), d.end(), N + 1);
24        d[S] = 0;
25        while (!q.empty()) {
26            int u = q.front();
27            q.pop();
28            if (u == T) break;
29            for (int k : g[u]) {
30                Edge& e = E[k];
31                if (e.flow < e.cap && d[e.v] > d[e.u] + 1) {
32                    d[e.v] = d[e.u] + 1;
33                    q.push(e.v);
34                }
35            }
36        }
37        return d[T] != N + 1;
38    }
39    ll DFS(int u, int T, ll flow = -1) {
40        if (u == T || flow == 0) return flow;
41        for (int& i = pt[u]; i < sz(g[u]); ++i) {
42            Edge& e = E[g[u][i]];
43            Edge& oe = E[g[u][i] ^ 1];
44            if (d[e.v] == d[e.u] + 1) {
45                ll amt = e.cap - e.flow;
46                if (flow != -1 && amt > flow) amt = flow;
47                if (ll pushed = DFS(e.v, T, amt)) {
48                    e.flow += pushed;
49                    oe.flow -= pushed;
50                    return pushed;
51                }

```

```

52     }
53 }
54 return 0;
55 }
56 ll maxFlow(int S, int T) { // O(V^2*E), unit nets: O(sqrt(V)*E)
57     ll total = 0;
58     while (BFS(S, T)) {
59         fill(pt.begin(), pt.end(), 0);
60         while (ll flow = DFS(S, T)) total += flow;
61     }
62     return total;
63 }
64 };
65 // Dinic wrapper to allow setting demands of min flow on edges
66 // If an edge with a min flow demand is part of a cycle, then the result
67 // is not guaranteed to be correct, it could result in false positives
68 struct DinicWithDemands {
69     int N;
70     vector<pair<Edge, ll>> E; // (normal dinic edge, min flow)
71     Dinic dinic;
72     DinicWithDemands(int n) : N(n), E(0), dinic(n + 2) {}
73     void addEdge(int u, int v, ll cap, ll minFlow) {
74         assert(minFlow <= cap);
75         if (u != v) E.pb(mp(Edge(u, v, cap), minFlow));
76     }
77     ll maxFlow(int S, int T) { // Same complexity as normal Dinic
78         int SRC = N, SNK = N + 1;
79         ll minFlowSum = 0;
80         forall(e, E) { // force the min flow
81             minFlowSum += e->snd;
82             dinic.addEdge(SRC, e->fst.v, e->snd);
83             dinic.addEdge(e->fst.u, SNK, e->snd);
84             dinic.addEdge(e->fst.u, e->fst.v, e->fst.cap - e->snd);
85         }
86         dinic.addEdge(T, S, INF); // INF >= max possible flow
87         ll flow = dinic.maxFlow(SRC, SNK);
88         if (flow < minFlowSum) return -1; // no valid flow exists
89         assert(flow == minFlowSum);
90         // Now go back to the original network, to a valid
91         // state where all min flow values are satisfied.
92         forn(i, sz(E)) {
93             forn(j, 4) {
94                 assert(j % 2 || dinic.E[6 * i + j].flow == E[i].snd);
95                 dinic.E[6 * i + j].cap = dinic.E[6 * i + j].flow = 0;
96             }
97             dinic.E[6 * i + 4].cap += E[i].snd;
98             dinic.E[6 * i + 4].flow += E[i].snd;
99             // don't change edge [6*i+5] to keep forcing the mins
100         }
101         forn(i, 2) dinic.E[6 * sz(E) + i].cap = dinic.E[6 * sz(E) + i].flow = 0;
102         // Just finish the maxFlow now
103         dinic.maxFlow(S, T);
104         flow = 0; // get the result manually
105         forall(e, dinic.g[S]) flow += dinic.E[*e].flow;
106         return flow;
107     }

```

```

108 };

```

7.2 Min cost - Max flow

```

1 typedef ll tf;
2 typedef ll tc;
3 const tf INF_FLOW = 1e14;
4 const tc INF_COST = 1e14;
5 struct edge {
6     int u, v;
7     tf cap, flow;
8     tc cost;
9     tf rem() { return cap - flow; }
10 };
11 struct MCMF {
12     vector<edge> e;
13     vector<vector<int>>> g;
14     vector<tf> vcap;
15     vector<tc> dist;
16     vector<int> pre;
17     tc minCost;
18     tf maxFlow;
19     // tf wantedFlow; // Use it for fixed flow instead of max flow
20     MCMF(int n) : g(n), vcap(n), dist(n), pre(n) {}
21     void addEdge(int u, int v, tf cap, tc cost) {
22         g[u].pb(sz(e)), e.pb({u, v, cap, 0, cost});
23         g[v].pb(sz(e)), e.pb({v, u, 0, 0, -cost});
24     }
25     // O(n*m * min(flow, n*m)), sometimes faster in practice
26     void run(int s, int t) {
27         vector<bool> inq(sz(g));
28         maxFlow = minCost = 0; // result will be in these variables
29         while (1) {
30             fill(vcap.begin(), vcap.end(), 0), vcap[s] = INF_FLOW;
31             fill(dist.begin(), dist.end(), INF_COST), dist[s] = 0;
32             fill(pre.begin(), pre.end(), -1), pre[s] = 0;
33             queue<int> q;
34             q.push(s), inq[s] = true;
35             while (sz(q)) { // Fast bellman-ford
36                 int u = q.front();
37                 q.pop(), inq[u] = false;
38                 for (auto eid : g[u]) {
39                     edge& E = e[eid];
40                     if (E.rem() && dist[E.v] > dist[u] + E.cost) {
41                         dist[E.v] = dist[u] + E.cost;
42                         pre[E.v] = eid;
43                         vcap[E.v] = min(vcap[u], E.rem());
44                         if (!inq[E.v]) q.push(E.v), inq[E.v] = true;
45                     }
46                 }
47             }
48             if (pre[t] == -1) break;
49             tf flow = vcap[t];
50             // flow = min(flow, wantedFlow); //For fixed flow

```

```

51     maxFlow += flow;
52     minCost += flow * dist[t];
53     for (int v = t; v != s; v = e[pre[v]].u) {
54         e[pre[v]].flow += flow;
55         e[pre[v] ^ 1].flow -= flow;
56     }
57     // if(maxFlow == wantedFlow) break; //For fixed flow
58 }
59 }
60 };

```

7.3 Matching - Hopcroft Karp

```

1 struct HopcroftKarp { // [0,n)->[0,m) (ids independent in each side)
2     int n, m;
3     vector<vector<int>>> g;
4     vector<int> mt, mt2, ds;
5     HopcroftKarp(int nn, int mm) : n(nn), m(mm), g(n) {}
6     void add(int a, int b) { g[a].pb(b); }
7     bool bfs() {
8         queue<int> q;
9         ds = vector<int>(n, -1);
10        forn(i, n) if (mt2[i] < 0) ds[i] = 0, q.push(i);
11        bool r = false;
12        while (!q.empty()) {
13            int x = q.front();
14            q.pop();
15            for (int y : g[x]) {
16                if (mt[y] >= 0 && ds[mt[y]] < 0) {
17                    ds[mt[y]] = ds[x] + 1, q.push(mt[y]);
18                } else if (mt[y] < 0) r = true;
19            }
20        }
21        return r;
22    }
23    bool dfs(int x) {
24        for (int y : g[x]) {
25            if (mt[y] < 0 || ds[mt[y]] == ds[x] + 1 && dfs(mt[y])) {
26                mt[y] = x, mt2[x] = y;
27                return true;
28            }
29        }
30        ds[x] = 1 << 30;
31        return false;
32    }
33    int mm() { // O(sqrt(V)*E)
34        int r = 0;
35        mt = vector<int>(m, -1);
36        mt2 = vector<int>(n, -1);
37        while (bfs()) forn(i, n) if (mt2[i] < 0) r += dfs(i);
38        return r;
39    }
40 };

```

7.4 Hungarian

```

1 typedef long double td;
2 typedef vector<int> vi;
3 typedef vector<td> vd;
4 const td INF = 1e100; // for maximum set INF to 0, and negate costs
5 bool zz(td x) { return abs(x) < 1e-9; } // change to x==0, for ints/ll
6 struct Hungarian {
7     int n;
8     vector<vd> cs;
9     vi L, R;
10    Hungarian(int N, int M) : n(max(N, M)), cs(n, vd(n)), L(n), R(n) {
11        forn(x, N) forn(y, M) cs[x][y] = INF;
12    }
13    void set(int x, int y, td c) { cs[x][y] = c; }
14    td assign() { // O(n^3)
15        int mat = 0;
16        vd ds(n), u(n), v(n);
17        vi dad(n), sn(n);
18        forn(i, n) u[i] = *min_element(cs[i].begin(), cs[i].end());
19        forn(j, n) {
20            v[j] = cs[0][j] - u[0];
21            forr(i, 1, n) v[j] = min(v[j], cs[i][j] - u[i]);
22        }
23        L = R = vi(n, -1);
24        forn(i, n) forn(j, n) if (R[j] == -1 && zz(cs[i][j] - u[i] - v[j])) {
25            L[i] = j, R[j] = i, mat++;
26            break;
27        }
28        for (; mat < n; mat++) {
29            int s = 0, j = 0, i;
30            while (L[s] != -1) s++;
31            fill(dad.begin(), dad.end(), -1);
32            fill(sn.begin(), sn.end(), 0);
33            forn(k, n) ds[k] = cs[s][k] - u[s] - v[k];
34            while (1) {
35                j = -1;
36                forn(k, n) if (!sn[k] && (j == -1 || ds[k] < ds[j])) j = k;
37                sn[j] = 1, i = R[j];
38                if (i == -1) break;
39                forn(k, n) if (!sn[k]) {
40                    td new_ds = ds[j] + cs[i][k] - u[i] - v[k];
41                    if (ds[k] > new_ds) ds[k] = new_ds, dad[k] = j;
42                }
43            }
44            forn(k, n) if (k != j && sn[k]) {
45                td w = ds[k] - ds[j];
46                v[k] += w, u[R[k]] -= w;
47            }
48            u[s] += ds[j];
49            while (dad[j] >= 0) {
50                int d = dad[j];
51                R[j] = R[d], L[R[j]] = j, j = d;
52            }
53            R[j] = s, L[s] = j;
54        }
55    }

```

```

55     td ret = 0;
56     forn(i, n) ret += cs[i][L[i]];
57     return ret;
58 }
59 };

```

7.5 Edmond's Karp

```

1 struct EdmondsKarp {
2     int N;
3     vector<unordered_map<int, ll>> g;
4     vector<int> p;
5     ll f;
6     EdmondsKarp(int n) : N(n), g(n), p(n) {}
7     void addEdge(int a, int b, int w) { g[a][b] = w; }
8     void augment(int v, int SRC, ll minE) {
9         if (v == SRC) f = minE;
10        else if (p[v] != -1) {
11            augment(p[v], SRC, min(minE, g[p[v]][v]));
12            g[p[v]][v] -= f, g[v][p[v]] += f;
13        }
14    }
15    ll maxflow(int SRC, int SNK) { // O(min(VE^2, Mf * E))
16        ll ret = 0;
17        do {
18            queue<int> q;
19            q.push(SRC);
20            fill(p.begin(), p.end(), -1);
21            f = 0;
22            while (sz(q)) {
23                int node = q.front();
24                q.pop();
25                if (node == SNK) break;
26                forall(it, g[node]) if (it->snd > 0 && p[it->fst] == -1) {
27                    q.push(it->fst), p[it->fst] = node;
28                }
29            }
30            augment(SNK, SRC, INF); // INF > max possible flow
31            ret += f;
32        } while (f);
33        return ret;
34    }
35 };

```

7.6 Matching

```

1 vector<int> g[MAXN]; // [0,n)->[0,m)
2 int n, m;
3 int mat[MAXM];
4 bool vis[MAXN];
5 int match(int x) {
6     if (vis[x]) return 0;
7     vis[x] = true;
8     for (int y : g[x])
9         if (mat[y] < 0 || match(mat[y])) {
10             mat[y] = x;
11             return 1;
12         }
13     return 0;
14 }
15 vector<pair<int, int>> max_matching() { // O(V^2 * E)
16     vector<pair<int, int>> r;
17     memset(mat, -1, sizeof(mat));
18     forn(i, n) memset(vis, false, sizeof(vis)), match(i);
19     forn(i, m) if (mat[i] >= 0) r.pb({mat[i], i});
20     return r;
21 }

```

7.7 Min Cut

```

1 // Suponemos un grafo con el formato definido en Push relabel
2 bitset<MAX_V> type, used; // reset this
3 void dfs1(int nodo) {
4     type.set(nodo);
5     forall(it, G[nodo]) if (!type[it->fst] && it->snd > 0) dfs1(it->fst);
6 }
7 void dfs2(int nodo) {
8     used.set(nodo);
9     forall(it, G[nodo]) {
10         if (!type[it->fst]) {
11             // edge nodo -> (it->fst) pertenece al min_cut
12             // y su peso original era: it->snd + G[it->fst][nodo]
13             // si no existia arista original al reves
14         } else if (!used[it->fst]) dfs2(it->fst);
15     }
16 }
17 void minCut() // antes correr algun maxflow()
18 {
19     dfs1(SRC);
20     dfs2(SRC);
21     return;
22 }

```

7.8 Push Relabel

```

1 #define MAX_V 1000
2 int N; // valid nodes are [0...N-1]
3 #define INF 1e9
4 // special nodes
5 #define SRC 0
6 #define SNK 1
7 map<int, int> G[MAX_V]; // limpiar esto -- unordered_map mejora
8 // To add an edge use
9 #define add(a, b, w) G[a][b] = w
10 ll excess[MAX_V];
11 int height[MAX_V], active[MAX_V], cuenta[2 * MAX_V + 1];
12 queue<int> Q;
13
14 void enqueue(int v) {
15     if (!active[v] && excess[v] > 0) active[v] = true, Q.push(v);
16 }
17 void push(int a, int b) {
18     int amt = min(excess[a], ll(G[a][b]));
19     if (height[a] <= height[b] || amt == 0) return;
20     G[a][b] -= amt, G[b][a] += amt;
21     excess[b] += amt, excess[a] -= amt;
22     enqueue(b);
23 }
24 void gap(int k) {
25     forn(v, N) {
26         if (height[v] < k) continue;
27         cuenta[height[v]]--;
28         height[v] = max(height[v], N + 1);
29         cuenta[height[v]]++;
30         enqueue(v);
31     }
32 }
33 void relabel(int v) {
34     cuenta[height[v]]--;
35     height[v] = 2 * N;
36     forall(it, G[v]) if (it->snd) height[v] = min(height[v], height[it->fst] +
37         1);
38     cuenta[height[v]]++;
39     enqueue(v);
40 }
41 ll maxflow() // O(V^3)
42 {
43     zero(height), zero(active), zero(cuenta), zero(excess);
44     cuenta[0] = N - 1;
45     cuenta[N] = 1;
46     height[SRC] = N;
47     active[SRC] = active[SNK] = true;
48     forall(it, G[SRC]) {
49         excess[SRC] += it->snd;
50         push(SRC, it->fst);
51     }
52     while (sz(Q)) {
53         int v = Q.front();
54         Q.pop();

```

```

54     active[v] = false;
55     forall(it, G[v]) push(v, it->fst);
56     if (excess[v] > 0) cuenta[height[v]] == 1 ? gap(height[v]) : relabel(v);
57 }
58 ll mf = 0;
59 forall(it, G[SNK]) mf += G[it->fst][SNK];
60 return mf;
61 }

```


8 Other algorithms

8.1 Longest Increasing Subsequence

```

1 // Change comparisons and binary search for non-increasing
2 // Given an array, paint it in the least number of colors so that each
3 // color turns to a non-increasing subsequence. Solution: Min number of
4 // colors=Length of the longest increasing subsequence
5 struct lis {
6     T INF;
7     int n; vector<T> a; // secuencia y su longitud
8     vector<pair<T,int>> d; // d[i]=ultimo valor de la subsecuencia de tamaño i
9     vector<int> p; // padres
10    vector<T> ret; // respuesta
11
12    lis(T INF_, vector<T> &a_) {
13        n = sz(a_);
14        INF = INF_;
15        a = a_;
16        d.resize(n+1);
17        p.resize(n+1);
18    }
19    void rec(int i) {
20        if(i == -1) return;
21        ret.push_back(a[i]);
22        rec(p[i]);
23    }
24    int run() {
25        d[0] = {-INF, -1};
26        forn(i,n) d[i+1] = {INF, -1};
27        forn(i,n) {
28            int j = int(upper_bound(d.begin(), d.end(), mp(a[i], n))-d.begin());
29            if(d[j-1].fst<a[i] && a[i]<d[j].fst) {
30                p[i] = d[j-1].snd;
31                d[j] = {a[i], i};
32            }
33        }
34        ret.clear();
35        dfor(i, n+1) if(d[i].fst!=INF) {
36            rec(d[i].snd); // reconstruir
37            reverse(ret.begin(), ret.end());
38            return i; // longitud
39        }
40        return 0;
41    }
42 };

```

8.2 Mo's

```

1 // Commented code should be used if updates are needed
2 int n, sq, nq; // array size, sqrt(array size), #queries
3 struct Qu { // [l, r)
4     int l, r, id;

```

```

5     // int upds; // # of updates before this query
6 };
7 Qu qs[MAXN];
8 ll ans[MAXN]; // ans[i] = answer to ith query
9 // struct Upd{
10 //     int p, v, prev; // pos, new_val, prev_val
11 // };
12 // Upd vupd[MAXN];
13
14 // Without updates
15 bool qcomp(const Qu& a, const Qu& b) {
16     if (a.l / sq != b.l / sq) return a.l < b.l;
17     return (a.l / sq) & 1 ? a.r < b.r : a.r > b.r;
18 }
19
20 // With updates
21 // bool qcomp(const Qu &a, const Qu &b){
22 //     if(a.l/sq != b.l/sq) return a.l<b.l;
23 //     if(a.r/sq != b.r/sq) return a.r<b.r;
24 //     return a.upds < b.upds;
25 // }
26
27 // Without updates: O(n^2/sq + q*sq)
28 // with sq = sqrt(n): O(n*sqrt(n) + q*sqrt(n))
29 // with sq = n/sqrt(q): O(n*sqrt(q))
30 //
31 // With updates: O(sq*q + q*n^2/sq^2)
32 // with sq = n^(2/3): O(q*n^(2/3))
33 // with sq = (2*n^2)^(1/3) may improve a bit
34 void mos() {
35     forn(i, nq) qs[i].id = i;
36     sq = sqrt(n) + .5; // without updates
37     // sq=pow(n, 2/3.0)+.5; // with updates
38     sort(qs, qs + nq, qcomp);
39     int l = 0, r = 0;
40     init();
41     forn(i, nq) {
42         Qu q = qs[i];
43         while (l > q.l) add(--l);
44         while (r < q.r) add(++r);
45         while (l < q.l) remove(l--);
46         while (r > q.r) remove(++r);
47         // while(upds<q.upds){
48         //     if(vupd[upds].p >= 1 && vupd[upds].p < r) remove(vupd[upds].p);
49         //     v[vupd[upds].p] = vupd[upds].v; // do update
50         //     if(vupd[upds].p >= 1 && vupd[upds].p < r) add(vupd[upds].p);
51         //     upds++;
52         // }
53         // while(upds>q.upds){
54         //     upds--;
55         //     if(vupd[upds].p >= 1 && vupd[upds].p < r) remove(vupd[upds].p);
56         //     v[vupd[upds].p] = vupd[upds].prev; // undo update
57         //     if(vupd[upds].p >= 1 && vupd[upds].p < r) add(vupd[upds].p);
58         // }
59         ans[q.id] = get_ans();
60     }

```

61

}

9Juegos

9.1Nim Game

Juego en el que hay N pilas, con objetos. Cada jugador debe sacar al menos un objeto de una pila. GANA el jugador que saca el último objeto.

$$P_0\oplus P_1\oplus...\oplus P_n=R$$

Si $R\neq 0$ gana el jugador 1.

9.1.1Misere Game

Es un juego con las mismas reglas que Nim, pero PIERDE el que saca el último objeto. Entonces teniendo el resultado de la suma R , y si todas las pilas tienen 1 solo objeto $todos1=true$, podemos decir que el jugador2 GANA si:

$$(R=0)\&\neg todos1\| (R\neq 0)\&todos1$$

9.2Ajedrez

9.2.1Non-Attacking N Queen

Utiliza: <algorithm>

Notas: todo es $O(!N\cdot N^2)$.

```
1 #define NQUEEN 8
2 #define abs(x) ((x)<0?(-(x)):(x))
3
4 int board[NQUEEN];
5 void inline init(){for(int i=0;i<NQUEEN;++i)board[i]=i;}
6 bool check(){
7     for(int i=0;i<NQUEEN;++i)
8         for(int j=i+1;j<NQUEEN;++j)
9             if(abs(i-j)==abs(board[i]-board[j]))
10                 return false;
11     return true;
12 }
13 //en main
14 init();
15 do{
16     if(check()){
17         //process solution
18     }
19 }while(next_permutation(board,board+NQUEEN));
```

9.3 Green Hackenbush

```

1 // A two-player game played on an undirected graph where some nodes
2 // are connected to the ground. On each turn, a player removes an edge.
3 // If this removal splits the graph into two components, any component
4 // that is not connected to the ground is removed. A player loses the game
5 // if it's impossible to make a move.
6 struct green_hackenbush {
7     vector<vector<int>>> g;
8     vector<int> tin, low, gr;
9     int t, root, ans;
10    green_hackenbush(int n) {
11        t = 0, root = -1, ans = 0;
12        g.resize(n); gr.resize(n);
13        tin.resize(n); low.resize(n);
14    }
15    // make u a node in the ground
16    void ground(int u) {
17        gr[u] = 1; if(root == -1) root = u;
18    }
19    // call first ground() if u or v are in the ground
20    void add_edge(int u, int v) {
21        if(gr[u]) u = root;
22        if(gr[v]) v = root;
23        if(u == v) { ans ^= 1; return; }
24        g[u].pb(v); g[v].pb(u);
25    }
26    int solve(int u, int d) {
27        tin[u] = low[u] = ++t;
28        int ret = 0;
29        forn(i,sz(g[u])) {
30            int v = g[u][i];
31            if(v == d) continue;
32            if(tin[v] == 0) {
33                int retv = solve(v,u);
34                low[u] = min(low[u],low[v]);
35                if(low[v] > tin[u]) ret ^= (1+retv)^1;
36                else ret ^= retv;
37            }else low[u] = min(low[u], tin[v]);
38        }
39        forn(i,sz(g[u])) {
40            int v = g[u][i];
41            if(v != d && tin[u] <= tin[v]) ret ^= 1;
42        }
43        return ret;
44    }
45    int solve() {
46        return root == -1? 0 : ans^solve(root,-1);
47    }
48 };

```

10 Utils

10.1 Compile C++20 with g++

```

1 g++ -std=c++20 {file} -o {filename}
2 Para Geany:
3 compile: g++ -DANARAP -std=c++20 -g -O2 -Wconversion -Wshadow -Wall -Wextra -c
4          "%f"
5 build:    g++ -DANARAP -std=c++20 -g -O2 -Wconversion -Wshadow -Wall -Wextra -o
6          "%e" "%f"

```

10.2 C++ utils mix

```

1 // 1- Random number generator (mt19937_64 for 64-bits version)
2 mt19937 rng(chrono::steady_clock::now().time_since_epoch().count());
3 // usage
4 rng()%k // random value [0,k)
5 shuffle(v.begin(), v.end(), rng); // vector random shuffle
6
7 // 2- Pragma
8 #pragma GCC optimize("O3,unroll-loops")
9 #pragma GCC target("avx2,bmi,bmi2,lzcnt,popcnt")
10
11 // 3- Custom comparator for set/map
12 struct comp {
13     bool operator()(const double& a, const double& b) const {
14         return a+EPS<b;
15     };
16 }set<double,comp> w; // or map<double,int,comp>
17
18 // 4- Iterate over non empty subsets of bitmask
19 for(int s=m;s=s(s-1)&m) // Decreasing order
20 for (int s=0;s=s-m&m;) // Increasing order
21
22 // 5- Other bits operations
23 // Return the numbers the numbers of 1-bit in x
24 int __builtin_popcount (unsigned int x)
25 // Returns the number of trailing 0-bits in x. x=0 is undefined.
26 int __builtin_ctz (unsigned int x)
27 // Returns the number of leading 0-bits in x. x=0 is undefined.
28 int __builtin_clz (unsigned int x)
29 // x of type long long just add 'll' at the end of the function.
30 int __builtin_popcountll (unsigned long long x)
31 // Get the value of the least significant bit that is one.
32 v=(x&(-x))
33
34 // 6- Comparing floats
35 const double EPS = 1e-9 // usually correct, but not always
36 abs(x-y) < EPS // use this instead of x == y
37 x > y + EPS // use this instead of x > y (EPS "against" comparison)
38 x > y - EPS // use this instead of x >= y (EPS "in favor" of comparison)
39
40 // 7- string stream, convert types easily

```

```

41 string int_to_str(int x) {
42     stringstream ss;
43     ss << x;
44     string ret;
45     ss >> ret;
46     return ret;
47 }
48
49 // 8- Output
50 cout << setprecision(2) << fixed; // print floats with 2 decimal digits
51 cout << setfill(' ') << setw(3) << 2 << endl; // add spaces to the left
52
53 // 9- Input
54 string line;
55 getline(cin, line); // read whole line
56
57 cin >> noskipws; // make cin stop skipping white spaces
58 cin >> skipws; // make cin start skipping white spaces (on by default)
59
60 inline void Scanf(int& a) { // sometimes faster, only for positive integers
61     char c = 0;
62     while(c<33) c = getc(stdin);
63     a = 0;
64     while(c>33) a = a*10 + c - '0', c = getc(stdin);
65 }
66
67 // 10- Type limits
68 #include <limits>
69 numeric_limits<T>
70     ::max()
71     ::min()
72     ::epsilon()
73 // double inf
74 const double DINF=numeric_limits<double>::infinity();
75
76 // 11- Bitset trick
77 bs._Find_next(idx) // This function returns first set bit after index idx. Ex:
78     bitset<10> bs, bs[1] = 1, bs[3] = 1; bs.Find_next(0) => 1, bs._Find_next
79     (1) => 3

```

10.3 Python example

```

1 import sys, math
2 input = sys.stdin.readline
3
4 ##### ----- Input Functions ----- #####
5 def inp():
6     return(int(input()))
7 def inlt():
8     return(list(map(int,input().split())))
9 def insr():
10    s = input()
11    return(list(s[:len(s) - 1]))
12 def invr():
13    return(map(float,input().split()))
14
15
16 n, k = inlt()
17 intpart = 0
18 while intpart*intpart <= n:
19     intpart += 1
20 intpart -= 1
21
22 if(k == 0):
23     print(intpart)
24 else:
25     L = 0
26     R = 10**k-1
27     aux = 10**k
28
29     while(L < R):
30         M = (L+R+1)//2
31         if intpart**2 * aux**2 + M**2 + 2*intpart*M*aux <= n * aux**2:
32             L = M
33         else:
34             R = M-1
35
36 decpart = str(L)
37 while(len(decpart) < k):
38     decpart = '0'+decpart
39 print(f"{intpart}.{decpart}")

```

10.4 Test generator

```
1 # usage: (note that test_generator.py refers to this file)
2 # 1. Modify the code below to generate the tests you want to use
3 # 2. Compile the 2 solutions to compare (e.g. A.cpp B.cpp into A B)
4 # 3. run: python3 test_generator.py A B
5 # Note that 'test_generator.py', 'A' and 'B' must be in the SAME FOLDER
6 # Note that A and B must READ FROM STANDARD INPUT, not from file,
7 # be careful with the usual freopen("input.in", "r", stdin) in them
8 import sys, subprocess
9 from datetime import datetime
10 from random import randint, seed
11
12 def buildTestCase(): # example of trivial "a+b" problem
13     a = randint(1,100)
14     b = randint(1,100)
15     return f"{a} {b}\n"
16
17 seed(datetime.now().timestamp())
18 ntests = 100 # change as wanted
19 sol1 = sys.argv[1]
20 sol2 = sys.argv[2]
21 # Sometimes it's a good idea to use extra arguments that could then be
22 # passed to 'buildTestCase' and help you "shape" your tests
23 for curtest in range(ntests):
24     test_case = buildTestCase()
25     # Here the test is executed and outputs are compared
26     print("running... ", end='')
27     ans1 = subprocess.check_output(f"./{sol1}",
28                                     input=test_case.encode('utf-8')).decode('utf-8')
29     ans2 = subprocess.check_output(f"./{sol2}",
30                                     input=test_case.encode('utf-8')).decode('utf-8')
31     if ans1 == ans2:
32         assert ans1 != "", 'ERROR?? ans1 = ans2 = empty string ("")'
33         print("OK")
34     else:
35         print("FAILED!")
36         print(test_case)
37         print(f"ans from {sol1}:\n{ans1}")
38         print(f"ans from {sol2}:\n{ans2}")
39         break
```

10.5 Funciones Utiles

Algo	Params	Función
fill, fill_n	f, l / n, elem	void llena [f, l) o [f,f+n) con elem
lower_bound, upper_bound	f, l, elem	it al primer ultimo donde se puede insertar elem para que quede ordenada
copy	f, l, resul	hace resul+i=f+i $\forall i$
find, find_if, find_first_of	f, l, elem / pred / f2, l2	it encuentra i $\in [f,l)$ tq. i==elem, pred(i), $i \in [f2,l2)$
count, count_if	f, l, elem/pred	cuenta elem, pred(i)
search	f, l, f2, l2	busca $[f2,l2) \in [f,l)$
replace, replace_if	f, l, old / pred, new	cambia old / pred(i) por new
lexicographical_compare	f1, l1, f2, l2	bool con $[f1,l1) i [f2,l2)$
accumulate	f, l, i, [op]	$T = \sum / \text{oper de } [f,l)$
inner_product	f1, l1, f2, i	$T = i + [f1, l1) \cdot [f2, \dots)$
partial_sum	f, l, r, [op]	$r+i = \sum / \text{oper de } [f,f+i] \forall i \in [f,l)$
__builtin_ffs	unsigned int	Pos. del primer 1 desde la derecha
__builtin_clz	unsigned int	Cant. de ceros desde la izquierda.
__builtin_ctz	unsigned int	Cant. de ceros desde la derecha.
__builtin_popcount	unsigned int	Cant. de 1's en x.
__builtin_parity	unsigned int	1 si x es par, 0 si es impar.
__builtin_XXXXXXll	unsigned ll	= pero para long long's.