

TCR

Il twee = 1; – Utrecht University

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Hash script

```
# Last 6 chars of hash should match; var names
→ matter
gcc -E -P -w -nostdinc file.cpp | tr -d '[:space:]'
→ | md5sum
Test script
g++ -g -Wall -fsanitize=address,undefined
→ -Wfatal-errors -std=c++17 $1.cc || exit
for i in $1/*.in
do
    j="${i/.in/.ans}"
    ./a.out < $i > output
    diff output $j || echo "!!WA on $i!!"
done
template.cc
Hash: b33a1b
#include <bits/stdc++.h>
using namespace std;

typedef long long ll;
typedef long double ld;
typedef pair<ll, ll> ii;
typedef vector<ll> vi;
typedef vector<vi> vvi;
typedef vector<ii> vii;
typedef vector<vii> vvii;
typedef vector<bool> vb;
typedef vector<vb> vvb;
typedef vector<ld> vd;
typedef vector<vd> vvd;
typedef vector<string> vs;

#define x first
#define y second
#define pb push_back
#define eb emplace_back
#define rep(i,a,b) for(auto i=(a); i<(b); ++i)
#define REP(i,n) rep(i,0,n)
#define all(v) begin(v), end(v)
#define sz(v) ((int) (v).size())
#define rs resize

namespace std { template<class T1, class T2>
struct hash<pair<T1,T2>> { public:
    size_t operator()(const pair<T1,T2> &p) const {
        size_t x = hash<T1>()(p.x), y = hash<T2>()(p.y);
        return x ^ (y + 0x9e3779b9 + (x<<6) + (x>>2));
    }
}; }

void run() {
}

signed main() {
```

```
// DON'T MIX "scanf" and "cin"!
ios_base::sync_with_stdio(false);
cin.tie(NULL);
cout << fixed << setprecision(20);
run();
return 0;
}

template.py

# reading input:
from sys import *
n,m = [ int(x) for x in
        stdin.readline().rstrip().split() ]
stdout.write( str(n*m)+"\n" )
# set operations:
from itertools import *
for (x,y) in product(range(3),repeat=2):
    stdout.write( str(3*x+y)+" " )
print()
for L in combinations(range(4),2):
    stdout.write( str(L)+" " )
print()
# fancy lambdas:
from functools import *
y = reduce( lambda x,y: x+y, map( lambda x: x*x,
        range(4) ), -3 )
print(y)
# formatting:
from math import *
stdout.write( "{0:.2f}\n".format(pi) )
```

0.1. De winnende aanpak.

- Slaap goed & heb een vroeg ritme!
- Drink & eet genoeg voor & tijdens de wedstrijd!
- Houd een lijst bij met info over alle problemen.
- Iedereen moet **ALLE** opgaves **goed** lezen!
- Analyseer de voorbeeld test cases.
- Houd na 2 uur een pauze en overleg waar iedereen mee bezig is.
- Maak zelf (zware) test cases.
- Gebruik ll.

0.2. Wrong Answer.

- Print de oplossing om te debuggen!
 - Kijk naar wellicht makkelijkere problemen.
 - Bedenk zelf test cases met **randgevallen!**
 - Controleer de **precisie**.
 - Controleer op **overflow** (gebruik **OVERAL** ll, ld).

Kijk naar overflows in tussenantwoorden bij modulo.
 - Controleer op **typo's**.
 - Loop de voorbeeld test case accuraat langs.
 - Controleer op off-by-one-errors (in indices of lus-grenzen)?
- Basics** Hash: 6b2dcb

```
auto comp = [](T i, T j){return i < j;}; //strictly
// smaller!
sort(v.begin(), v.end(), comp); // Sort vector v
priority_queue<T, vector<T>, decltype(comp)>
// q(comp); // Max heap.
set<T, decltype(comp)> s(comp); // Balanced binary
// search tree.
map<T, S, decltype(comp)> m(comp); // Balanced
// binary search tree map with key T and value S.

random_device rd; mt19937 gen(rd());
uniform_int_distribution<ll> uid(1, 9); // Generate
// integers between 1 and 9 inclusive.
uniform_real_distribution<ld> urd(1.0, 2.0); //
// Generate real numbers between 1 and 2
// left-inclusive.
ll x = uid(gen); ld y = urd(gen);

Detecting overflow: This GNU builtin checks for over-
and underflow. Result is in res if successful: Hash: d5a5b6
bool isOverflow =
// __builtin_[add|mul|sub]_overflow(a, b, &res);
```

1. MATHEMATICS

```
XOR sum:  $\bigoplus_{x=0}^{a-1} x = \{0, a-1, 1, a\}[a \bmod 4]$ .
Hash: d7a1d4
int sign(ll x) { return (x > 0) - (x < 0); }

ll lcm(ll a, ll b) { return a/gcd(a, b)*b; }
ll mod(ll a, ll b) { return (a % b + b) % b; }

// ab % m for m <= 4e18 in O(log b)
ll mod_mul(ll a, ll b, ll m) {
    ll r = 0;
    while(b) {
        if (b & 1) r = mod(r+a, m);
        a = mod(a+a, m); b >= 1;
    }
    return r;
}

// a^b % m for m <= 2e9 in O(log b)
ll mod_pow(ll a, ll b, ll m) {
    ll r = 1;
    while(b) {
        if (b & 1) r = (r * a) % m; // mod_mul
        a = (a * a) % m; // mod_mul
        b >= 1;
    }
    return mod(r, m);
}

// returns x, y such that ax + by = gcd(a, b)
ll egcd(ll a, ll b, ll &x, ll &y) {
    ll xx = y = 0, yy = x = 1;
    if(a < 0) a *= -1, x = -1;
    if(b < 0) b *= -1, yy = -1;
```

```
while (b) {
    x -= a / b * xx; swap(x, xx);
    y -= a / b * yy; swap(y, yy);
    a %= b; swap(a, b);
}
return a;
}

// Chinese Remainder Theorem: returns (u, v) s.t.
// x=u (mod v) <=> x=a (mod n) and x=b (mod m)
pair<ll, ll> crt(ll a, ll n, ll b, ll m) {
    ll s, t, d = egcd(n, m, s, t); //n,m<=1e9
    if (mod(a - b, d)) return { 0, -1 };
    return { mod(s*b%m*n + t*a%n*m, n*m)/d, n*m/d };
}

// phi[i] = # { 0 < j <= i | gcd(i, j) = 1 } sieve
vi totient(int N) {
    vi phi(N);
    REP(i, N) phi[i] = i;
    rep(i, 2, N) if (phi[i] == i)
        for (int j = i; j < N; j+=i) phi[j] -= phi[j]/i;
    return phi;
}

//Calculate (nCK % m) in O(k)
//Assert gcd(i, m) = 1 for i <= k
ll binom(ll n, ll k, ll m) {
    ll ans = 1, inv, y;
    REP(i, k) {
        ans = mod(ans * (n - i), m);
        egcd(i + 1, m, inv, y);
        ans = mod(ans * inv, m);
    }
    return ans;
}

// calculate nCk % p (p prime!) O(p log_p(n))
ll lucas(ll n, ll k, ll p) {
    ll ans = 1;
    while (n) {
        ll np = n % p, kp = k % p;
        if (np < kp) return 0;
        ans = mod(ans * binom(np, kp, p), p);
        n /= p; k /= p;
    }
    return ans;
}

// returns if n is prime for n < 3e24 (>2^64)
// but use mul_mod for n > 2e9.
bool millerRabin(ll n) {
    if (n < 2 || n % 2 == 0) return n == 2;
    ll d = n - 1, ad, s = 0, r;
    for (; d % 2 == 0; d /= 2) s++;
    for (int a : { 2, 3, 5, 7, 11, 13,
        17, 19, 23, 29, 31, 37, 41 }) {
        if (n == a) return true;
        if ((ad = mod_pow(a, d, n)) == 1) continue;
        for (r = 0; r < s && ad + 1 != n; r++)
```

```

    ad = (ad * ad) % n;
    if (r == s) return false;
}
return true;
}

```

1.1. Primitive Root $O(\sqrt{m})$. Returns a generator of \mathbb{F}_m^* . If m not prime, replace $m - 1$ by totient of m . Hash: 370e04

```

ll primitive_root(ll m) {
    vi div; ll phi = m - 1;
    for (ll i = 2; i*i <= phi; i++)
        if (phi % i == 0) {
            div.pb(i);
            div.pb(phi/i);
        }
    rep(x, 2, m) { //skip if gcd(x, m) != 1
        bool ok = true;
        for (ll d : div) if (mod_pow(x, d, m) == 1)
            { ok = false; break; }
        if (ok) return x;
    }
    return -1;
}

```

1.2. Tonelli-Shanks algorithm. Given prime p and integer $1 \leq n < p$, returns the square root r of n modulo p . There is also another solution given by $-r$ modulo p . Hash: 248c3b

```

ll legendre(ll a, ll p) {
    if (a % p == 0) return 0;
    return p == 2 || mod_pow(a, (p-1)/2, p) == 1 ? 1 :
        -1;
}
ll tonelli_shanks(ll n, ll p) {
    //assert(legendre(n,p) == 1);
    if (p == 2) return 1;
    ll s = 0, q = p-1, z = 2;
    while (~q & 1) s++, q >= 1;
    if (s == 1) return mod_pow(n, (p+1)/4, p);
    while (legendre(z, p) != -1) z++;
    ll c = mod_pow(z, q, p),
        r = mod_pow(n, (q+1)/2, p),
        t = mod_pow(n, q, p),
        m = s;
    while (t != 1) {
        ll i = 1, ts = (ll)t*t % p;
        while (ts != 1) i++, ts = ((ll)ts * ts) % p;
        ll b = mod_pow(c, 1LL<<(m-i-1), p);
        r = (ll)r * b % p;
        t = (ll)t * b % p * b % p;
        c = (ll)b * b % p;
        m = i;
    }
    return r;
}

```

1.3. Numeric Integration. Numeric integration using Simpson's rule (with $O(EPS^4)$ error). Hash: f08ec9

```

ld numint(ld (*f)(ld), ld a, ld b, ld EPS = 1e-6) {
    ld ba = b - a, m=(a+b)/2;
    return abs(ba) < EPS
        ? ba*8*(f(a)+f(b)+f(a+ba/3)*3+f(b-ba/3)*3)
        : numint(f,a,m,EPS) + numint(f,m,b,EPS);
}

```

1.4. Fast Hadamard Transform. Computes XOR-convolutions in $O(k2^k)$ on k bits.

For AND-convolution, use $(x+y, y), (x-y, y)$.
 For OR-convolution, use $(x, x+y), (x, -x+y)$.
Note: The array size must be a power of 2. Hash: 60e7b5

```

void fht(vi &A, bool inv, int l, int r) {
    if (l+1 == r) return;
    int k = (r-l)/2;
    if (!inv) fht(A, inv, l, l+k), fht(A, inv, l+k,
        r);
    rep(i, l, l+k) {
        ll x = A[i], y = A[i+k];
        if (!inv) A[i] = x-y, A[i+k] = x+y;
        else A[i] = (x+y)/2, A[i+k] = (-x+y)/2;
    }
    if (inv) fht(A, inv, l, l+k), fht(A, inv, l+k, r);
}

```

```

vi conv(vi A, vi B) {
    int n = sz(A);
    fht(A, false, 0, n); fht(B, false, 0, n);
    vi res = vi(n); REP(i, n) res[i] = A[i] * B[i];
    fht(res, true, 0, n);
    return res;
}

```

1.5. Tridiagonal Matrix Algorithm. Solves a tridiagonal system of linear equations

$$a_i x_{i-1} + b_i x_i + c_i x_{i+1} = d_i$$

where $a_1 = c_n = 0$. Beware of numerical instability. Hash: c97ec8

```

void solve(int n, vd& a, vd& b, vd& c, vd& d, vd& x)
{
    c[0] /= b[0]; d[0] /= b[0];
    rep(i, 1, n-1) c[i] /= b[i] - a[i]*c[i-1];
    rep(i, 1, n) d[i] =
        (d[i] - a[i]*d[i-1]) / (b[i] - a[i]*c[i-1]);
    x[n-1] = d[n-1];
    for (int i = n-1; i--;) x[i] = d[i] - c[i]*x[i+1];
}

```

1.6. Number of Integer Points under Line. Count the number of integer solutions to $Ax + By \leq C$, $0 \leq x \leq n$, $0 \leq y$. In other words, evaluate the sum $\sum_{x=0}^n \max(0, \lfloor \frac{C-Ax}{B} + 1 \rfloor)$. Be very careful about overflows. Hash: 9111c1

```

ll floor_sum(ll n, ll a, ll b, ll c) {
    if (a < 0) c -= n * a, a *= -1;
    if (c == 0) return 1;
}

```

```

if (c < 0) return 0;
n = min(n, c / a);
if (a % b == 0) return
    → (n+1)*(c/b+1)-n*(n+1)/2*a/b;
if (a >= b) return
    → floor_sum(n, a%b, b, c)-a/b*n*(n+1)/2;
ll t = (c-a*n+b)/b;
return floor_sum((c-b*t)/b, b, a, c-b*t)+t*(n+1); }

```

1.7. Solving linear recurrences. Given some brute-forced sequence $s[0], s[1], \dots, s[2n-1]$, Berlekamp-Massey finds the shortest possible recurrence relation in $\mathcal{O}(n^2)$. After that, lin_rec finds $s[k]$ in $\mathcal{O}(n^2 \log k)$. Hash: abc4ad

```

// Given a sequence s[0], ..., s[2n-1] finds the
// smallest linear recurrence
// of size <= n compatible with s.
vi BerlekampMassey(const vi &s, ll mod) {
    int n = sz(s), L = 0, m = 0;
    vi C(n), B(n), T;
    C[0] = B[0] = 1;
    ll b = 1;
    REP(i, n) {
        ++m;
        ll d = s[i] % mod;
        rep(j, 1, L+1) d = (d + C[j] * s[i-j]) % mod;
        if (!d) continue;
        T = C;
        ll coef = d * modpow(b, mod-2, mod) % mod;
        rep(j, m, n) C[j] = (C[j] - coef * B[j-m]) % mod;
        if (2 * L > i) continue;
        L = i + 1 - L;
        B = T; b = d; m = 0;
    }
    C.rs(L + 1);
    C.erase(C.begin());
    for (auto &x : C) x = (mod - x) % mod;
    return C;
}

```

```

// Input: A[0,...,n-1], C[0,...,n-1] satisfying
// A[i] = \sum_{j=1}^i C[j-1] A[i-j],
// Outputs A[k]
ll lin_rec(const vi &A, const vi &C, ll k, ll mod) {
    int n = sz(A);
    auto combine = [&](vi a, vi b) {
        vi res(sz(a) + sz(b) - 1, 0);
        REP(i, sz(a)) REP(j, sz(b))
            res[i+j] = (res[i+j] + a[i]*b[j]) % mod;
        for (int i = 2*n; i > n; --i) REP(j, n)
            res[i-1-j] = (res[i-1-j] + res[i]*C[j]) % mod;
        res.rs(n + 1);
        return res;
    };
    vi pol(n + 1), e(pol);
    pol[0] = e[1] = 1;
    for (++k; k; k /= 2) {
        if (k % 2) pol = combine(pol, e);
        e = combine(e, e);
    }
}

```

```

    }
    ll res = 0;
    REP(i, n) res = (res + pol[i + 1] * A[i]) % mod;
    return res;
}

```

1.8. Misc.

1.8.1. Josephus problem. Last man standing out of n if every k th is killed. Zero-based, and does not kill 0 on first pass.
Hash: 42afc7

```

int J(int n, int k) {
    if (n == 1 || k == 1) return n-1;
    if (n < k) return (J(n-1, k)+k)%n;
    int np = n - n/k;
    return k*((J(np,k)+np-n%k%np)%np) / (k-1);
}

```

- **Prime numbers:** 1031, 32771, 1048583, 33554467, 998244353, 9982451653, 1073741827, 34359738421, 1099511627791, 35184372088891, 1125899906842679, 36028797018963971, $10^{18} + 7$.

$$10^3 + \{-9, -3, 9, 13\}, \quad 10^6 + \{-17, 3, 33\}, \quad 10^9 + \{7, 9, 21, 33, 87\}.$$

- **Generating functions:** Ordinary (ogf): $A(x) := \sum_{n=0}^{\infty} a_n x^n$.

Calculate product $c_n = \sum_{k=0}^n a_k b_{n-k}$ with FFT.

Exponential (e.g.f.): $A(x) := \sum_{n=0}^{\infty} a_n x^n / n!$,

$$c_n = \sum_{k=0}^n \binom{n}{k} a_k b_{n-k} = n! \sum_{k=0}^n \frac{a_k}{k!} \frac{b_{n-k}}{(n-k)!}$$
 (use FFT).

- **General linear recurrences:** If $a_n = \sum_{k=0}^{n-1} a_k b_{n-k}$, then $A(x) = \frac{a_0}{1-B(x)}$.

- **Inverse polynomial modulo x^l :** Given $A(x)$, find $B(x)$ such that $A(x)B(x) = 1 + x^l Q(x)$ for some $Q(x)$.

Step 1: Start with $B_0(x) = 1/a_0$

Step 2: $B_{k+1}(x) = (-B_k(x)^2 A(x) + 2B_k(x)) \bmod x^{2^{k+1}}$.

- **Fast subset convolution:** Given array a_i of size 2^k calculate $b_i = \sum_{j \& i=j} a_j$. Hash: 33fc1b

```

for (int b = 1; b < (1 << k); b <= 1)
    for (int i = 0; i < (1<<k); i++)
        if (!(i & b)) a[i | b] += a[i];
    // inv: if (!(i & b)) a[i | b] -= a[i];
}

```

- **Primitive Roots:** It only exists when n is $2, 4, p^k, 2p^k$, where p odd prime. If g is a primitive root, all primitive roots are of the form g^k where $k, \phi(p)$ are coprime (hence there are $\phi(\phi(p))$ primitive roots). Examples:

$$998244352 = 2^{23} \cdot 7 \cdot 17 + 1 : 2, 2013 \cdot 265 \cdot 921 = 2^{27} \cdot 3 \cdot 5 + 1 : 31, \\ 10^9 + 7 : 5, 10^9 + 9 : 13, 10^9 + 21 : 2, 10^9 + 33 : 5, 10^9 + 87 : 3, \\ 36028797018963971 : 2, 10^{18} + 7 : 5, (10^9 + 7)^2 : 5$$

- **Maximum number of divisors:**

$\leq N$	10^3	10^6	10^9	10^{12}	10^{18}
m	840	720720	735134400	963761198400	
$\sigma_0(m)$	32	240	1344	6270	103680

For $n = 10^{18}$, $m = 897612484786617600$.

2. DATASTRUCTURES

2.1. Order tree. Hash: 36a167

```

#include <bits/extc++.h>
using namespace __gnu_pbds;
template<class TK, class TM> using order_tree =
    tree<TK,TM,less<TK>,rb_tree_tag,
    tree_order_statistics_node_update>;
template<class TK> using order_set =
    order_tree<TK,null_type>;
order_set<ll> s;
s.insert(5);
s.insert(2);
s.insert(3);
s.find_by_order(2); // 5
s.order_of_key(3); // 1
s.order_of_key(4); // 2

```

2.2. Segment tree $\mathcal{O}(\log n)$. All intervals are right closed $[\ell, r]$.

2.2.1. Lazy segment tree. Allows for efficient range updates.

Hash: c39abc

```

struct node {
    int k, r, x, lazy;
    node() {}
    node(int _l, int _r) : k(_l), r(_r), x(INT_MAX),
    ↪ lazy(0){}
    node(int _l, int _r, int _x) : node(_l,_r){x=_x;}
    node(node a, node b):node(a.k,b.r){x=min(a.x,b.x);}
    void update(int v) { x = v; }
    void range_update(int v) { lazy = v; }
    void apply() { x += lazy; lazy = 0; }
    void push(node &u) { u.lazy += lazy; }
};

```

```

struct segment_tree {
    int n;
    vector<node> arr;
    segment_tree() {}
    segment_tree(const vi &a) : n(sz(a)), arr(4*n) {
        mk(a,0,0,n-1);
    }
    node mk(const vi &a, int i, int k, int r) {
        int m = (k+r)/2;
        return arr[i] = k > r ? node(k,r) :
            k == r ? node(k,r,a[k]) :
            node(mk(a,2*i+1,k,m),mk(a,2*i+2,m+1,r));
    }
    node update(int at, ll v, int i=0) {
        propagate(i);
        int hl = arr[i].k, hr = arr[i].r;
        if (at < hl || hr < at) return arr[i];
    }
}

```

```

if (hl == at && at == hr) {
    arr[i].update(v); return arr[i];
}
return arr[i] =
    node(update(at,v,2*i+1),update(at,v,2*i+2));
}

```

```

node query(int k, int r, int i=0) {
    propagate(i);
    int hl = arr[i].k, hr = arr[i].r;
    if (r < hl || hr < k) return arr[i];
    if (k <= hl && hr <= r) return arr[i];
    return node(query(k,r,2*i+1),query(k,r,2*i+2));
}

```

```

node range_update(int k, int r, ll v, int i=0) {
    propagate(i);
    int hl = arr[i].k, hr = arr[i].r;
    if (r < hl || hr < k) return arr[i];
    if (k <= hl && hr <= r) {
        arr[i].range_update(v);
        propagate(i);
        return arr[i];
    }
    return arr[i] = node(range_update(k,r,v,2*i+1),
    range_update(k,r,v,2*i+2));
}

```

```

void propagate(int i) {
    if (arr[i].k < arr[i].r) {
        arr[i].push(arr[2*i+1]);
        arr[i].push(arr[2*i+2]);
    }
    arr[i].apply();
}
;
```

2.2.2. Persistent segment tree. Keeps track of older versions of segment tree by id.

Hash: 885699

```

typedef ll T;
T combine(T k, T r) { return k + r; }

```

```

struct segment {
    int k, r, lid, rid;
    T val;
    segment(int _l, int _r) : k(_l), r(_r), val(0){}
};
vector<segment> S;

```

```

int build(int k, int r) {
    if (k > r) return -1;
    int id = sz(S);
    S.pb(segment(k,r));
    if(k != r) {
        int m = (k + r) / 2;
        S[id].lid = build(k, m);
        S[id].rid = build(m + 1, r);
    }
    return id;
}
int update(int idx, T v, int id) { // Make a[idx] = v
    if (id == -1) return -1;
}

```

```

if (idx < S[id].k || idx > S[id].r) return id;
int nid = sz(S);
S.pb(segment(S[id].k, S[id].r));
if (S[nid].k == S[nid].r)
    S[nid].val = v;
else{
    int k = S[nid].lid = update(idx, v, S[id].lid);
    int r = S[nid].rid = update(idx, v, S[id].rid);
    S[nid].val = combine(S[k].val, S[r].val);
}
return nid;
}

T query(int id, int k, int r) {
    if (r < S[id].k || S[id].r < k) return 0;
    if (k<=S[id].k && S[id].r<=r) return S[id].val;
    return
        → combine(query(S[id].lid,k,r),query(S[id].rid,k,r));
}

2.3. Binary Indexed Tree  $\mathcal{O}(\log n)$ . Use one-based indices ( $i > 0$ )! Stores and updates prefix sums efficiently. Hash: ad0ad1

struct BIT {
    int n; vi A;
    BIT(int _n) : n(_n), A(_n+1, 0) {}
    BIT(vi &v) : n(sz(v)), A(1) {
        for (ll x:v) A.pb(x);
        for (int i=1, j; j=i&~i, i<=n; i++)
            if (i+j <= n) A[i+j] += A[i];
    }
    void update(int i, ll v) { // a[i] += v
        while (i <= n) A[i] += v, i += i&~i;
    }
    ll query(int i) { // sum_{j<=i} a[j]
        ll v = 0;
        while (i) v += A[i], i -= i&~i;
        return v;
    }
}

struct rangeBIT {
    int n; BIT b1, b2;
    rangeBIT(int _n) : n(_n), b1(_n), b2(_n+1) {}
    rangeBIT(vi &v) : n(sz(v)), b1(v), b2(sz(v)+1) {}
    void pupdate(int i, ll v) { b1.update(i, v); }
    void rupdate(int i, int j, ll v) { // a[i...j] += v
        b2.update(i, v);
        b2.update(j+1, -v);
        b1.update(j+1, v*j);
        b1.update(i, (1-i)*v);
    }
    ll query(int i){return b1.query(i)+b2.query(i)*i;}
}

```

2.4. Disjoint-Set / Union-Find $\mathcal{O}(\alpha(n))$. Hash: 216404

```

struct dsu { vi p; dsu(int n) : p(n, -1) {}
    int find(int i) {
        return p[i] < 0 ? i : p[i] = find(p[i]); }
    void unite(int a, int b) {

```

```

        if ((a = find(a)) == (b = find(b))) return;
        if (p[a] > p[b]) swap(a, b);
        p[a] += p[b]; p[b] = a;
    }
}

2.5. Cartesian tree/Treap. Binary tree derived from a sequence of points. The root is the point with smallest  $y$ -coordinate and contains the points with smaller  $x$  in its left subtree (and larger  $x$  in right subtree). Can be used as treap (= BST on  $x$ ), by adding random  $y$  to each point. Additional information can be updated in augment. Can be made persistent by changing the update instructions in split, merge and erase to creating new nodes (use keyword new). Hash: 732435

struct node {
    ll x, y, size;
    node *l, *r;
    node(ll _x = 0, ll _y = 0)
        : x(_x), y(_y), size(1), l(NULL), r(NULL) { }
        → {};
    ll tsize(node* t) { return t ? t->size : 0; }
    ll tsum(node* t) { return t ? t->sum : 0; }
    void augment(node *t) { //update all information
        → here
        t->size = 1 + tsize(t->l) + tsize(t->r);
    }
    pair<node*,node*> split(node *t, ll x) {
        if (!t) return {NULL,NULL};
        if (t->x < x) {
            pair<node*,node*> res = split(t->r, x);
            t->r = res.x; augment(t);
            return make_pair(t, res.y);
        }
        pair<node*,node*> res = split(t->l, x);
        t->l = res.y; augment(t);
        return make_pair(res.x, t);
    }
    node* merge(node *l, node *r) {
        if (!l) return r; if (!r) return l;
        if (l->y < r->y) {
            l->r = merge(l->r, r); augment(l); return l;
            → }
            r->l = merge(l, r->l); augment(r); return r;
        }
        node* find(node *t, ll x) {
            while (t) {
                if (x < t->x) t = t->l;
                else if (t->x < x) t = t->r;
                else return t;
            }
            return NULL;
        }
        node* insert(node *t, ll x, ll y) {
            pair<node*,node*> res = split(t, x);
            return merge(res.x, merge(new node(x, y),
            → res.y));
        }
        node* erase(node *t, ll x) {
            if (!t) return NULL;
            if (t->x < x) t->r = erase(t->r, x);
            else if (x < t->x) t->l = erase(t->l, x);

```

```

        else{node *old=t; t=merge(t->l,t->r); delete
            → old;}
            if (t) augment(t); return t;
        }
        ll kth(node *t, ll k) {
            if (k < tsize(t->l)) return kth(t->l, k);
            if (k == tsize(t->l)) return t->x;
            return kth(t->r, k - tsize(t->l) - 1);
        }
    }

```

Construction based on arrays $\mathcal{O}(n)$. Hash: 6d6756

```

//if points, sort(vii a) and compare .y in walk
vi a, l, r; ll root;
vi walk(vi& a, bool eq) {
    vi stack, res;
    REP(i, sz(a)) {
        ll b = -1;
        while (sz(stack) > 0) {
            if (a[i] > a[stack.back()] ||
                (eq && a[i] == a[stack.back()]))
                → break;
            b = stack.back(); stack.pop_back();
            stack.pb(b); res.pb(b);
        }
        return res;
    }
    void constructtree() {
        l = walk(a, true);
        reverse(all(a));
        r = walk(a, false);
        reverse(all(r)); reverse(all(a));
        REP(i, sz(r)) if (r[i] != -1)
            r[i] = sz(a) - 1 - r[i];
        root = 0;
        REP(i,sz(a)) if (a[i] < a[root]) root = i;
    }
}

```

2.6. Heap. An implementation of a binary heap. Hash: a583e0

```

//heap stores keys, not values
//Use values in compare function
struct heap {
    vi q, loc;
    bool (*less) (ll, ll);
    heap(bool (*_less) (ll, ll)) : less(_less) {}
    bool cmp(int i, int j) { return less(q[i],q[j]); }
    void swp(int i, int j) {
        swap(q[i], q[j]), swap(loc[q[i]], loc[q[j]]);
    }
    void swim(int i) {
        for (int p; i; swp(i, p), i = p)
            if (!cmp(i, p=(i-1)/2)) break;
    }
    void sink(int i) {
        for (int j; (j=2*i+1)<sz(q); swp(j, i), i=j)
            if (j+1 < sz(q) && cmp(j+1, j)) ++j;
            if (!cmp(j, i)) break;
        }
    void push(int n) {

```

```

while (n >= sz(loc)) loc.pb(-1);
loc[n] = sz(q), q.pb(n);
swim(sz(q) - 1);
}
int top() { return q[0]; }
int pop() {
    int res = top();
    q[0] = q.back(), q.pop_back();
    loc[q[0]] = 0, loc[res] = -1;
    sink(0); return res;
}
void heapify() {
    for (int i=sz(q); --i; )
        if (cmp(i, (i-1)/2)) swap(i, (i-1)/2);
}
void update_key(int n) {
    swim(loc[n]), sink(loc[n]);
}
int size() { return sz(q); }
bool empty() { return !size(); }
void clear() { q.clear(), loc.clear(); }
};

```

2.7. Misof Tree. A simple tree data structure for inserting, erasing, and querying the n th largest element. Hash: 1d305e

```

struct misof_tree {
    vvi cnt;
    int bits;
    misof_tree(int _bits) : bits(_bits) {
        cnt = vvi(bits, vi(1 << bits, 0));
    }
    void change(int x, int d) {
        for (int i=0; i<bits; cnt[i++][x] += d, x >>=
            1);
    }
    void insert(int x) { change(x, 1); }
    void erase(int x) { change(x, -1); }
    int nth(int n) {
        int res = 0;
        for (int i = bits-1; i >= 0; i--)
            if (cnt[i][res <<= 1] <= n)
                n -= cnt[i][res], res++;
        return res;
    };
}

```

2.8. k-d Tree. A k -dimensional tree supporting fast construction, adding points, and nearest neighbor queries. NOTE: Not completely stable, occasionally segfaults. Hash: 955938

```

#define INC(c) ((c) == K - 1 ? 0 : (c) + 1)
const ld EPS = 1e-9;
template <int K> struct kd_tree {
    struct pt {
        double coord[K];
        pt() {}
        pt(double c[K]) { REP(i,K) coord[i] = c[i]; }
        double dist(const pt &other) const {
            double sum = 0.0;
            REP(i,K) sum +=
                pow(coord[i]-other.coord[i],2);
            return sqrt(sum); } };
    struct cmp {

```

```

        int c;
        cmp(int _c) : c(_c) {}
        bool operator ()(const pt &a, const pt &b) {
            for (int i = 0, cc; i <= K; i++) {
                cc = i == 0 ? c : i - 1;
                if (abs(a.coord[cc] - b.coord[cc]) > EPS)
                    return a.coord[cc] < b.coord[cc];
            }
            return false; } };
        struct bb {
            pt from, to;
            bb(pt _from, pt _to) : from(_from), to(_to) {}
            double dist(const pt &p) {
                double sum = 0.0;
                REP(i,K) {
                    if (p.coord[i] < from.coord[i])
                        sum += pow(from.coord[i] - p.coord[i],
                            2.0);
                    else if (p.coord[i] > to.coord[i])
                        sum += pow(p.coord[i] - to.coord[i], 2.0);
                }
                return sqrt(sum); }
            bb bound(double l, int c, bool left) {
                pt nf(from.coord), nt(to.coord);
                if (left) nt.coord[c] = min(nt.coord[c], l);
                else nf.coord[c] = max(nf.coord[c], l);
                return bb(nf, nt); } };
        struct node {
            pt p; node *l, *r;
            node(pt _p, node *_l, node *_r)
                : p(_p), l(_l), r(_r) { } };
        node *root;
        kd_tree() : root(NULL) { }
        kd_tree(vector<pt> pts) {
            root = construct(pts, 0, sz(pts) - 1, 0);
            node* construct(vector<pt> &pts, int fr, int to,
                int c) {
                if (fr > to) return NULL;
                int mid = fr + (to-fr) / 2;
                nth_element(pts.begin() + fr, pts.begin() + mid,
                    pts.begin() + to + 1, cmp(c));
                return new node(pts[mid],
                    construct(pts, fr, mid - 1, INC(c)),
                    construct(pts, mid + 1, to, INC(c)));
            }
            bool contains(const pt &p) { return
                _con(p, root, 0); }
            bool _con(const pt &p, node *n, int c) {
                if (!n) return false;
                if (cmp(c)(p, n->p)) return _con(p, n->l, INC(c));
                if (cmp(c)(n->p, p)) return _con(p, n->r, INC(c));
                return true; }
            void insert(const pt &p) { _ins(p, root, 0); }
            void _ins(const pt &p, node* &n, int c) {
                if (!n) n = new node(p, NULL, NULL);
                else if (cmp(c)(p, n->p)) _ins(p, n->l, INC(c));
                else if (cmp(c)(n->p, p)) _ins(p, n->r, INC(c));
            }
            void clear() { _clr(root); root = NULL; }

```

```

        void _clr(node *n) {
            if (n) _clr(n->l), _clr(n->r), delete n; }
        pt nearest_neighbour(const pt &p, bool same=true)
        → {
            double mn = INFINITY, cs[K];
            REP(i,K) cs[i] = -INFINITY;
            pt from(cs);
            REP(i,K) cs[i] = INFINITY;
            pt to(cs);
            return _nn(p, root, bb(from, to), mn, 0,
                → same).x;
        }
        pair<pt, boolconst pt &p, node *n, bb b,
            double &mn, int c, bool same) {
            if (!n || b.dist(p) > mn)
                return make_pair(pt(), false);
            bool found = same || p.dist(n->p) > EPS,
                11 = true, 12 = false;
            pt resp = n->p;
            if (found) mn = min(mn, p.dist(resp));
            node *n1 = n->l, *n2 = n->r;
            REP(i,2) {
                if (i == 1 || cmp(c)(n->p, p))
                    swap(n1, n2), swap(11, 12);
                auto res = _nn(p, n1, b.bound(n->p.coord[c],
                    → c, 11), mn, INC(c), same);
                if (res.y && (!found || p.dist(res.x) <
                    → p.dist(resp)))
                    resp = res.x, found = true;
            }
            return make_pair(resp, found); } };

```

2.9. Range Tree. A 2-dimensional range tree supporting range queries in $O(\log(n))$ time. Hash: bf0fb1

```

struct rangetree {
    vi xtop, ytop;
    vi l, r; vvi lind, rind;
    ll base;
    rangetree(vii p) {
        sort(all(p));
        for(base = 1; base < sz(p); base *= 2);
        l = r = vi(2 * base - 1);
        lind = rind = vvi(2 * base - 1);
        ytop = build(p, 0, sz(p) - 1, 0);
        for(ii pt : p) xtop.pb(pt.x);
    }
    vi build(vii p, ll _l, ll _r, ll i) {
        l[i] = _l, r[i] = _r;
        if (_l == _r) { return {p[_l].y}; }
        ll m = (_l + _r) / 2;
        vi left = build(p, _l, m, 2 * i + 1), right
        → = build(p, m + 1, _r, 2 * i + 2);
        ll il = 0, ir = 0; vi res;
        while(il < sz(left) || ir < sz(right)) {
            lind[i].pb(il); rind[i].pb(ir);
            if(il < sz(left) && (ir == sz(right) ||
                → left[il] <= right[ir])) {
                res.pb(left[il]);
            }
            il++;
        }
    }
}

```

```

        else {
            res.pb(right[ir]);
            ir++; } }
    lind[i].pb(il); rind[i].pb(ir); return res;
     $\leftarrow$  }

ll nexti(vi& a, ll v) {//first i with a[i] >= v
    ll k = -1, r = sz(a), m;
    while(r - k > 1) {
        m = (k + r) / 2;
        if(a[m] < v) k = m;
        else r = m; }
    return r; }

ll q(ll iy, ll _l, ll _r, ll i) {
    if(l[i] > _r || r[i] < _l) return 0;
    if(l[i] >= _l && r[i] <= _r) return iy;
    return q(lind[i][iy], _l, _r, 2 * i + 1) +
     $\leftarrow$  q(rind[i][iy], _l, _r, 2 * i + 2); }

//query #points in [xl, xr] x [yl, yr]
ll query(ll xl, ll xr, ll yl, ll yr) {
    ll k = nexti(xtop, xl), r = nexti(xtop, xr +
     $\leftarrow$  1) - 1;
    ll y1 = nexti(ytop, yl), y2 = nexti(ytop, yr
     $\leftarrow$  + 1);
    return q(y2, k, r, 0) - q(y1, k, r, 0); }
};
```

2.10. Monotonic Queue. A queue that supports querying for the minimum element. Useful for sliding window algorithms.
Hash: 112812

```

struct min_stack {
    stack<int> S, M;
    void push(int x) {
        S.push(x);
        M.push(M.empty() ? x : min(M.top(), x)); }
    int top() { return S.top(); }
    int mn() { return M.top(); }
    void pop() { S.pop(); M.pop(); }
    bool empty() { return S.empty(); } };

struct min_queue {
    min_stack inp, outp;
    void push(int x) { inp.push(x); }
    void fix() {
        if (outp.empty()) while (!inp.empty())
            outp.push(inp.top()), inp.pop();
        int top() { fix(); return outp.top(); }
        int mn() {
            if (inp.empty()) return outp.mn();
            if (outp.empty()) return inp.mn();
            return min(inp.mn(), outp.mn()); }
        void pop() { fix(); outp.pop(); }
        bool empty() { return inp.empty() && outp.empty();
         $\leftarrow$  } };
};
```

2.11. Line container à la ‘Convex Hull Trick’ $\mathcal{O}(n \log n)$.
Container where you can add lines of the form $y_i(x) = k_i x + m_i$ and query $\max_i y_i(x)$. Hash: 819ac5

```
bool Q;
```

```

struct Line {
    mutable ll k, m, p;
    bool operator<(const Line& o) const {
        return Q ? p < o.p : k < o.k;
    }
};

struct LineContainer : multiset<Line> {
    // (for doubles, use inf = 1/.0, div(a,b) = a/b)
    const ll inf = LLONG_MAX;
    ll div(ll a, ll b) { // floored division
        return a / b - ((a ^ b) < 0 && a % b); }
    bool isect(iterator x, iterator y) {
        if (y == end()) { x->p = inf; return false; }
        if (x->k == y->k)
            x->p = x->m > y->m ? inf : -inf;
        else
            x->p = div(y->m - x->m, x->k - y->k);
        return x->p >= y->p;
    }
    void add(ll k, ll m) {
        auto z = insert({k, m, 0}), y = z++, x = y;
        while (isect(y, z)) z = erase(z);
        if (x != begin() && isect(--x, y))
            isect(x, y = erase(y));
        while ((y = x) != begin() && (--x)->p >= y->p)
            isect(x, erase(y));
    }
    ll query(ll x) {
        Q=1; auto l = *lower_bound({0, 0, x}); Q=0;
        return l.k * x + l.m;
    }
};
```

2.12. Li-Chao tree. Tree where you can add pseudolines in $\mathcal{O}(\log(n))$ and query the maximum line for values $a_1 < a_2 < \dots < a_n$ in $\mathcal{O}(\log(n))$. 2 pseudolines can intersect at most once.
Hash: 5b862b

```

struct line { //Can be any pseudoline
    ll a, b;
    line(): a(0), b(0) {}
    line(ll _a, ll _b): a(_a), b(_b) {}
    bool overtakes(line l) { return a > l.a; }
    ll value(ll i) { return a * i + b; }
};

struct LiChaoTree {
    ll width;
    vector<line> tree; vi v;
    LiChaoTree(vi a) { //any increasing sequence
        for(width = 1; width < sz(a); width *= 2) ;
        v = vi(2 * width - 1);
        tree = vector<line>(2 * width - 1);
        REP(i, width)
            v[i + width - 1] = a[min(i, sz(a) - 1)];
        for(ll i = width - 2; i >= 0; i--)
            v[i] = v[2 * i + 2];
        for(ll i = 0; i < width - 1; i++)
            v[i] = v[2 * i + 1];
        void insert(line& l, ll i = 0) {
```

```

        if(i >= 2 * width - 1) return;
        line cur = tree[i];
        if(l.value(v[i]) > cur.value(v[i])) {
            tree[i] = l;
            swap(l, cur); }
        if(l.overtakes(cur)) insert(l, 2 * i + 2);
        else insert(l, 2 * i + 1); }
    ll query(ll i) { //query maximum value at a[i]
        ll k = (i + width - 1);
        ll res = tree[k].value(i);
        while(k > 0) {
            k = (k - 1) / 2;
            res = max(res, tree[k].value(i)); }
        return res; }
```

2.13. Sparse Table $\mathcal{O}(\log n)$ per query. Static range queries.
Hash: 5284dd

```

struct sparse_table {
    vvi m;
    sparse_table(vi arr) {
        m.pb(arr);
        for (int b=0; (1<<(++b)) <= sz(arr); ) {
            int w = (1<<b), hw = w/2;
            m.pb(vi(sz(arr) - w + 1));
            for (int i = 0; i+w <= sz(arr); i++) {
                m[b][i] = min(m[b-1][i], m[b-1][i+hw]);
            }
        }
        int query(int k, int r) { // query min in [l,r]
            int b = 31 - __builtin_clz(r-k);
            // for (b = 0; 1<<(b+1) <= r-k+1; b++);
            return min(m[b][k], m[b][r-(1<<b)+1]);
        }
};
```

3. GRAPH ALGORITHMS

3.1. Shortest path.

3.1.1. Dijkstra $\mathcal{O}(E \log |V|)$.

3.1.2. Floyd-Warshall $\mathcal{O}(V^3)$ all pairs. Be careful with negative edges! Note: $|d[i][j]|$ can grow exponentially, and INFTY + negative < INFTY. Hash: dc6ed3

```

const ll INF = 1LL << 61;
void floyd_marshall( vvi& d ) {
    ll n = sz(d);
    REP(i, n) REP(j, n) REP(k, n)
        if(d[j][i] < INF && d[i][k] < INF) // neg edges!
            d[j][k] = max(-INF,
                           min(d[j][k], d[j][i] + d[i][k]));
}
```

3.1.3. Bellman Ford $\mathcal{O}(VE)$. This is only useful if there are edges with weight $w_{ij} < 0$ in the graph.

3.2. Maximum Matching.

Matching: A set of edges without common vertices (*Maximum is the largest such set, maximal is a set which you cannot add more edges to without breaking the property*).

Minimum Vertex Cover: A set of vertices such that each edge in the graph is incident to at least one vertex of the set.

Minimum Edge Cover: A set of edges such that every vertex is incident to at least one edge of the set.

Maximum Independent Set: A set of vertices in a graph such that no two of them are adjacent.

Minimum edge cover \iff Maximum independent set.

König's theorem: In any bipartite graph $G = (L \cup R, E)$, the number of edges in a maximum matching equals the number of vertices in a minimum vertex cover. Let U be the set of unmatched vertices in L , and Z be the set of vertices that are either in U or are connected to U by an alternating path. Then $K = (L \setminus Z) \cup (R \cap Z)$ is the minimum vertex cover.

In any bipartite graph,

$$\text{maxmatch} = \text{MVC} = V - \text{MIS}.$$

See 3.2.2.

3.2.1. Standard bipartite matching $\mathcal{O}(|L| \cdot |R|)$. Hash: 9687e2

```
vb vis; vi L, R; vvi G; // L->{R, ...}
void addedge(int a, int b) { G[a].pb(b); }
bool match(int u) {
    for (int v : G[u]) {
        if (vis[v]) continue;
        vis[v] = true;
        if (R[v] == -1 || match(R[v]))
            { R[v] = u, L[u] = v; return true; }
    }
    return false;
}
// perfect matching iff ret == n == m
int maxmatch(int n, int m) {
    L.assign(n, -1);
    R.assign(m, -1);
    int ret = 0;
    REP(i, n) vis.assign(m, false), ret += match(i);
    return ret;
}
```

3.2.2. Hopcroft-Karp bipartite matching $\mathcal{O}(E\sqrt{V})$. Hash: 2ad7e5

```
struct bigraph {
    int n, m, s; vvi G; vi L, R, d;
    bigraph(int _n, int _m) : n(_n), m(_m), s(0),
        G(n), L(n,-1), R(m,n), d(n+1) {}
    void addedge(int a, int b) { G[a].pb(b); }
    bool bfs() {
        queue<int> q; d[n] = LLONG_MAX;
```

```
REP(v, n)
    if (L[v] < 0) d[v] = 0, q.push(v);
    else d[v] = LLONG_MAX;
while (!q.empty()) {
    int v = q.front(); q.pop();
    if (d[v] >= d[n]) continue;
    for (int u : G[v])
        if (d[R[u]] == LLONG_MAX) d[R[u]] = d[v]+1, q.push(R[u]);
}
return d[n] != LLONG_MAX;
}

bool dfs(int v) {
    if (v == n) return true;
    for (int u : G[v])
        if (d[R[u]] == d[v]+1 && dfs(R[u])) {
            R[u] = v; L[v] = u; return true;
        }
    d[v] = LLONG_MAX; return false;
}

int maxmatch() {
    while (bfs()) REP(i, n) s += L[i] < 0 && dfs(i);
    return s;
}

void dfs2(int v, vb &alt) {
    alt[v] = true;
    for (int u : G[v]) {
        alt[u+n] = true;
        if (R[u] != n && !alt[R[u]]) dfs2(R[u], alt);
    }
}

vi minvertexcover() {
    vb alt(n+m, false); vi res;
    maxmatch();
    REP(i, n) if (L[i] < 0) dfs2(i, alt);
    // !alt[i] (i < n) OR alt[i] (i >= n)
    REP(i, n+m) if (alt[i] != (i < n)) res.pb(i);
    return res;
}
```

3.2.3. Blossom matching $\mathcal{O}(EV^2)$. Hash: 3ce0fb

```
vb marked;
vbb emarked;
vi S;
ll n;
vi find_augmenting_path(const vvi &adj, const vi &m) {
    int n = sz(adj), s = 0;
    vi par(n,-1), height(n), root(n,-1), q, a, b;
    marked = vb(n, false);
    emarked = vvb(n, vb(n, false));
    REP(i, n) if (m[i] >= 0) emarked[i][m[i]] = true;
                else root[i] = i, S[s++] = i;
    while (s) {
        int v = S[--s];
        for (ll w:adj[v]) {
            if (emarked[v][w]) continue;
            if (root[w] == -1) {
```

```
int x = S[s++] = m[w];
par[w]=v, root[w]=root[v],
    ↪ height[w]=height[v]+1;
par[x]=w, root[x]=root[w],
    ↪ height[x]=height[w]+1;
} else if (height[w] % 2 == 0) {
    if (root[v] != root[w]) {
        while(v != -1) q.pb(v), v = par[v];
        reverse(all(q));
        while(w != -1) q.pb(w), w = par[w];
        return q;
    } else {
        int c = v;
        while(c != -1) a.pb(c), c = par[c];
        c = w;
        while(c != -1) b.pb(c), c = par[c];
        while(!a.empty() && !b.empty() && a.back() ==
            ↪ == b.back())
            c = a.back(), a.pop_back(),
            ↪ b.pop_back();
        marked = vb(n, false);
        fill(par.begin(), par.end(), 0);
        for (ll it : a) par[it] = 1; for (ll it : b)
            ↪ par[it] = 1;
        par[c] = s = 1;
        REP(i, n) root[par[i]] = par[i] ? 0 : s++ =
            ↪ i;
        vvi adj2(s);
        REP(i, n) for (ll it : adj[i]) {
            if (par[it] == 0) continue;
            if (par[i] == 0) {
                if (!marked[par[it]]) {
                    adj2[par[i]].pb(par[it]);
                    adj2[par[it]].pb(par[i]);
                    marked[par[it]] = true;
                } else adj2[par[i]].pb(par[it]); }
        vi m2(s, -1);
        if (m[c] != -1) m2[m2[par[m[c]]]] = 0 =
            ↪ par[m[c]];
        REP(i, n) if (par[i] != 0 && m[i] != -1 &&
            ↪ par[m[i]] != 0)
            m2[par[i]] = par[m[i]];
        vi p = find_augmenting_path(adj2, m2);
        int t = 0;
        while (t < sz(p) && p[t]) t++;
        if (t == sz(p)) {
            REP(i, sz(p)) p[i] = root[p[i]];
            return p; }
        if (!p[0] || (m[c] != -1 && p[t+1] !=
            ↪ par[m[c]]))
            reverse(all(p)), t = sz(p)-t-1;
        rep(i, 0, t) q.pb(root[p[i]]);
        for (ll it : adj[root[p[t-1]]]) {
            if (par[it] != (s = 0)) continue;
            a.pb(c), reverse(all(a));
            for (ll jt : b) a.pb(jt);
            while (a[s] != it) s++;
```

```

if ((height[it] & 1) ^ (s < sz(a) - 
    → sz(b)))
    reverse(all(a)), s = sz(a)-s-1;
while(a[s]!=c) q.pb(a[s]), s=(s+1) %
    → sz(a);
q.pb(c);
rep(i,t+1,sz(p)) q.pb(root[p[i]]);
return q; } }

emarked[v][w] = emarked[w][v] = true; }
marked[v] = true; } return q; }

vvi max_matching(const vvi &adj) {
n = sz(adj);
marked = vb(n);
emarked = vvb(n,vb(n));
S = vi(n);
vi m(sz(adj), -1), ap; vii res, es;
REP(i,sz(adj)) for(ll it:adj[i]) es.eb(i,it);
random_shuffle(all(es));
for(ii it: es) if (m[it.x] == -1 && m[it.y] == -1)
    m[it.x] = it.y, m[it.y] = it.x;
do { ap = find_augmenting_path(adj, m);
    REP(i,sz(ap)) m[m[ap[i^1]] = ap[i]] =
        → ap[i^1];
} while (!ap.empty());
REP(i,sz(m)) if (i < m[i]) res.eb(i, m[i]);
return res; }

```

3.2.4. Stable marriage. With n men, $m \geq n$ women, n preference lists of women for each men, and for every woman j an preference of men defined by $\text{pref}[][][j]$ (lower is better) find for every man a women such that no pair of a men and a woman want to run off together. Hash: a74574

```

// n = aantal mannen, m = aantal vrouwen
// voor een man i, is order[i] de prefere
vi stable(int n, int m, vvi order, vvi pref) {
queue<int> q;
REP(i, n) q.push(i);
vi mas(m,-1), mak(n,-1), p(n,0);
while (!q.empty()) {
    int k = q.front();
    q.pop();
    int s = order[k][p[k]], k2 = mas[s];
    if (mas[s] == -1) {
        mas[s] = k;
        mak[k] = s;
    } else if (pref[k][s] < pref[k2][s]) {
        mas[s] = k;
        mak[k] = s;
        mak[k2] = -1;
        q.push(k2);
    } else {
        q.push(k);
    }
    p[k]++;
}
return mak;
}

```

3.3. Depth first searches.

3.3.1. Topological Sort $O(V + E)$. Hash: be0f5e

```

vi topo(vvi &adj) { // requires C++14
int n=sz(adj); vb vis(n,0); vi ans;
auto dfs = [&](int v, const auto& f)->void {
    vis[v] = true;
    for (int w : adj[v]) if (!vis[w]) f(w, f);
    ans.pb(v);
};
REP(i, n) if (!vis[i]) dfs(i, dfs);
reverse(all(ans));
return ans;
}

```

3.4. Cycle Detection $O(V + E)$. Hash: 566bb0

```

vvi G;
vb vis, done;
vi p;
ii backedge(ll i) {
    vis[i] = true;
    for(ll j : G[i])
        if(!vis[j]) {
            p[j] = i;
            ii antw = backedge(j);
            if(antw.x != -1) return antw;
        }
    else if(!done[j]) return {i,j};
    done[i] = true;
    return {-1,-1}; }
//directed
vi findcycledir() {
    ll n = sz(G);
    vis = vb(n, false), done = vb(n, false);
    p = vi(n, -1);
    REP(i,n) if(!vis[i]) {
        ii antw = backedge(i);
        if(antw.x != -1) {
            vi c; ll v = antw.x, w = antw.y;
            c.pb(v);
            while(v != w) c.pb(v = p[v]);
            reverse(all(c));
            return c;
        }
    }
    return {};}
}

```

//undirected

```

vi findcycleundir(const vvi &G, int v0) {
    vi p(sz(G), -1), s{v0};
    while (!s.empty()) {
        int v = s.back(); s.pop_back();
        for (int w : G[v])
            if (p[w] == -1) s.pb(w), p[w] = v;
            else if (w != p[v]) {
                vi c;
                while (v != w) c.pb(v = p[v]);
                return c;
            }
    }
}

```

```

    }
    return {};
}

```

3.4.1. Cut Points and Bridges $O(V + E)$. Vertices/edges that when removed split their connected component in two. Leaves are true in iscut and not in cp. Looping over all blocks and then over all edges can be quadratic! Hash: b4155e

```

struct bicomp {
    vvi adj; int n;
    vi low, num, block, cp; vvi blocks;
    vii bs; int curnum;

void dfs(int u, int p) {
    block.pb(u);
    low[u] = num[u] = curnum++;
    int cnt = 0; bool found = false;
    for(int v : adj[u]) {
        if (num[v] == -1) {
            dfs(v, u);
            low[u] = min(low[u], low[v]);
            cnt++;
            found = found || low[v] >= num[u];
            if (low[v] > num[u]) bs.eb(u, v);
            if (low[v] >= num[u]) {
                vi b2;
                while(true) {
                    int cur = block.back();
                    → block.pop_back();
                    b2.pb(cur); if(cur == v) break;
                } b2.pb(u);
                if (low[v] == num[u])
                    → blocks.pb(b2); //excludes bridges
            }
        } else if (p != v) low[u] = min(low[u],
            → num[v]);
    }
    if (found && (p != -1 || cnt > 1)) cp.pb(u); }

bicom(vvi &_adj) : n(sz(_adj)), adj(_adj) {
    num = vi(n, -1); low = vi(n);
    curnum = 0;
    REP(i,n) if (num[i] < 0) dfs(i, -1); }

vvi blockadj; vb iscut; set<i> bsset;
void addedge(ll u, ll v){ blockadj[u].pb(v);
    → blockadj[v].pb(u); }

void makecpdecomp() {
    for(ii p : bs) bsset.emplace(ii(min(p.x,p.y),
        → max(p.x,p.y)));
    iscut = vb(n, false);
    for(ll x : cp) iscut[x] = true;
    REP(i, n) if(sz(adj[i]) <= 1) iscut[i] = true;
    blockadj = vvi(n + sz(blocks));
    REP(i, sz(blocks)) for(ll x : blocks[i])
        if(iscut[x]) addedge(i + n, x);
    for(ii p : bs) addedge(p.x, p.y); }

```

```

vector<map<ll, vi>> inblockedge; vi wblock;
void dfsbe(ll i, ll p) {
    for(ll j : blockadj[i])
        if(j != p && (i >= n || j >= n)) dfsbe(j, i);
    if(i >= n) {
        for(ll x : blocks[i - n]) wblock[x] = i - n;
        for(ll j : blockadj[i])
            if(j < n && j != p)
                for(ll k : adj[j])
                    if(bsset.count(ii(min(j, k), max(j, k)))
                        → == 0)
                        inblockedge[wblock[k]][j].pb(k);
    }
}
void makeblockedges() {
    inblockedge = vector<map<ll, vi>>(sz(blocks));
    REP(i, sz(blocks)) for(ll j : blocks[i])
        → inblockedge[i].emplace(j, vi());
    wblock = vi(n, -1);
    REP(i, sz(blocks)) {
        if (wblock[blocks[i][0]] == -1) dfsbe(i + n,
            → -1);
        for(ll j : blocks[i])
            if (!iscut[j])
                for(ll k : adj[j])
                    inblockedge[i][j].pb(k);
    }
}

```

3.4.2. Strongly Connected Components $\mathcal{O}(V + E)$. Hash: d35c19

```

struct SCC {
    int n, age=0, ncomps=0; vvi adj, comps;
    vi tidx, lnk, cnr, st; vb vis;
    SCC(vvi &_adj) : n(sz(_adj)), adj(_adj),
        tidx(n, 0), lnk(n), cnr(n), vis(n, false) {
        REP(i, n) if (!tidx[i]) dfs(i);
    }

    void dfs(int v) {
        tidx[v] = lnk[v] = ++age;
        vis[v] = true; st.pb(v);
        for (int w : adj[v]) {
            if (!tidx[w])
                dfs(w), lnk[v] = min(lnk[v], lnk[w]);
            else if (vis[w]) lnk[v] = min(lnk[v],
                → tidx[w]);
        }
        if (lnk[v] != tidx[v]) return;
        comps.pb(vi());
        int w;
        do {
            vis[w = st.back()] = false; cnr[w] = ncomps;
            comps.back().pb(w);
            st.pop_back();
        } while (w != v);
        ncomps++;
    }
};

```

3.4.3. 2-SAT $\mathcal{O}(V + E)$. Uses SCC. Hash: 943a72

```

struct TwoSat {
    int n; SCC *scc = nullptr; vvi adj;
    TwoSat(int _n) : n(_n), adj(_n*2, vi()) {}
    ~TwoSat() { delete scc; }

    // a => b, i.e. b is true or ~a
    void imply(int a, int b) {
        adj[n+a].pb(n+b); adj[n+~b].pb(n+~a); }
    void OR(int a, int b) { imply(~a, b); }
    void CONST(int a) { OR(a, a); }
    void IFF(int a, int b) { imply(a,b); imply(b,a); }

    bool solve(vb &sol) {
        delete scc; scc = new SCC(adj);
        REP(i, n) if (scc->cnr[n+i] == scc->cnr[n+~i])
            return false;
        vb seen(n, false);
        sol.assign(n, false);
        for (vi &cc : scc->comps) for (int v : cc) {
            int i = v < n ? n + (~v) : v - n;
            if (!seen[i]) seen[i] = true, sol[i] = v >= n;
        }
        return true;
    }
}

```

3.4.4. Dominator graph.

- A node d dominates a node n if every path from the entry node to n must go through d .
- The immediate dominator (idom) of a node n is the unique node that strictly dominates n but does not strictly dominate any other node that strictly dominates n .

Hash: f1cfea

```

vvi g, grev, bucket;
vi pos, order, par, sdom, p, best, idom, lnk;
int cnt;

void create(ll n) {
    g = vvi(n), grev = vvi(n), bucket = vvi(n);
    pos = vi(n, -1), order = vi(n), par = vi(n), sdom
        → = vi(n);
    p = vi(n), best = vi(n), idom = vi(n), lnk =
        → vi(n);
}

void addedge(int a, int b) {
    g[a].pb(b), grev[b].pb(a);
}

void dfs(int v) {
    pos[v] = cnt;
    order[cnt++] = v;
    for (int u : g[v])
        if (pos[u] < 0) par[u] = v, dfs(u);
}

```

```

int find_best(int x) {
    if (p[x] == x) return best[x];
    int u = find_best(p[x]);
    if (pos[sdom[u]] < pos[sdom[best[x]]])
        best[x] = u;
    p[x] = p[p[x]];
    return best[x];
}

void dominators(int n, int root) {
    pos = vi(n, -1);
    cnt = 0;
    dfs(root);
    REP(i, n) p[i] = best[i] = sdom[i] = i;

    for (int it = cnt - 1; it >= 1; it--) {
        int w = order[it];
        for (int u : grev[w]) {
            if(pos[u] == -1) continue;
            int t = find_best(u);
            if (pos[sdom[t]] < pos[sdom[w]])
                sdom[w] = sdom[t];
        }
        bucket[sdom[w]].pb(w);
        idom[w] = sdom[w];
        for (int u : bucket[par[w]])
            lnk[u] = find_best(u);
        bucket[par[w]].clear();
        p[w] = par[w];
    }

    for (int it = 1; it < cnt; it++) {
        int w = order[it];
        idom[w] = idom[lnk[w]];
    }
    REP(i, n) if(pos[i] == -1) idom[i] = -1;
    idom[root] = root;
}

```

3.5. Min Cut / Max Flow.

3.5.1. Dinic's Algorithm $\mathcal{O}(V^2E)$. Hash: 90ea92

```

struct Edge { int t; ll c, f; };
struct Dinic {
    vi H, P; vvi E;
    vector<Edge> G;
    Dinic(int n) : H(n), P(n), E(n) {}

    void addEdge(int u, int v, ll c) {
        E[u].pb(sz(G)); G.pb({v, c, OLL});
        E[v].pb(sz(G)); G.pb({u, OLL, OLL});
    }

    ll dfs(int t, int v, ll f) {
        if (v == t || !f) return f;
        for ( ; P[v] < sz(E[v]); P[v]++)
            int e = E[v][P[v]], w = G[e].t;
            if (H[w] != H[v] + 1) continue;
            ll df = dfs(t, w, min(f, G[e].c - G[e].f));

```

```

if (df > 0) {
    G[e].f += df, G[e ^ 1].f -= df;
    return df;
}
} return 0;

void bfs(int s) {
    fill(all(H), 0); H[s] = 1;
    queue<int> q; q.push(s);
    while (!q.empty()) {
        int v = q.front(); q.pop();
        for (int w : E[v])
            if (G[w].f < G[w].c && !H[G[w].t])
                H[G[w].t] = H[v] + 1, q.push(G[w].t);
    }
}

ll maxflow(int s, int t, ll f = 0) {
    while (1) {
        bfs(s);
        if (!H[t]) return f;
        fill(all(P), 0);
        while (ll df = dfs(t, s, LLONG_MAX)) f += df;
    }
}

vb mincut(int s, int t) {
    maxflow(s, t);
    bfs(s);
    vb antw(sz(H));
    REP(i, sz(H)) antw[i] = !H[i];
    return antw;
}

void resetflow() {
    REP(i, sz(G)) G[i].f = 0;
}
};

3.5.2. Min-cost max-flow  $O(n^2m^2)$ . Find the cheapest possible way of sending a certain amount of flow through a flow network.
Hash: 7558bd

struct edge { ll x, y, f, c, w; };
ll V; vi par, D; vector<edge> g;
vvi e;
void create(ll n) {
    V = n; e = vvi(n);
    par = vi(n), D = vi(n);
}
inline void addEdge(int u, int v, ll c, ll w) {
    e[u].pb(sz(g)); g.pb({u, v, 0, c, w});
    e[v].pb(sz(g)); g.pb({v, u, 0, 0, -w});
}

void spBF(int s) {
    D = vi(V, LLONG_MAX); D[s] = 0;
    for (int ng = sz(g), _ = V; _--;) {
        bool ok = false;
        for (int i = 0; i < ng; i++)
            if (D[g[i].x] != LLONG_MAX && g[i].f < g[i].c
                && D[g[i].x] + g[i].w < D[g[i].y]) {
                D[g[i].y] = D[g[i].x] + g[i].w;
                par[g[i].y] = i; ok = true;
            }
        if (!ok) break;
    }

    //Can be omitted if n small enough
    void spDijk(int s) {
        vi ed(V, LLONG_MAX); ed[s] = 0;
        set<ii> front({{0, s}});
        while (sz(front) > 0) {
            ll v = front.begin() -> y;
            front.erase(front.begin());
            for (ll i : e[v]) if (g[i].f < g[i].c) {
                ll y = g[i].y, now = g[i].w + ed[v] - D[y] +
                    D[v];
                if (now < ed[y]) {
                    front.erase(ii(ed[y], y));
                    ed[y] = now;
                    front.emplace(ii(now, y));
                    par[y] = i;
                }
            }
        }
        REP(i, V)
            if (ed[i] < LLONG_MAX) D[i] += ed[i];
            else D[i] = LLONG_MAX;
    }
}

void minCostMaxFlow(int s, int t, ll &c, ll &f) {
    spBF(s);
    for (c = f = 0; spDijk(s), D[t] < LLONG_MAX; ) {
        ll df = LLONG_MAX, dc = 0;
        for (int v = t, e; e = par[v], v != s; v =
            g[e].x) df = min(df, g[e].c - g[e].f);
        for (int v = t, e; e = par[v], v != s; v =
            g[e].x) g[e].f += df, g[e ^ 1].f -= df, dc +=
            g[e].w;
        f += df; c += dc * df;
    }
}

```

3.5.3. *Gomory-Hu Tree - All Pairs Maximum Flow*. An implementation of the Gomory-Hu Tree. The spanning tree is constructed using Gusfield's algorithm in $O(|V|^2)$ plus $|V|-1$ times the time it takes to calculate the maximum flow. If Dinic's algorithm is used to calculate the max flow, the running time is $O(|V|^3|E|)$. **NOTE:** Not sure if it works correctly with disconnected graphs or produces the correct min cut. **DOES NOT WORK FOR DIRECTED GRAPHS.**

Hash: b2364a

```

struct GHTree {
    Dinic d; int n;
    vvii tree;
    GHTree(int _n) : n(_n), d(_n) {}
    void addEdge(int u, int v, int c) {
        d.addEdge(u, v, c); d.G.back().c = c;
    }
}

```

```

ll build(vi& nodes) {
    if (sz(nodes) == 1) return nodes[0];
    d.resetflow(); ll f = d.maxflow(nodes[0],
        & nodes[1]);
    vb cut = d.mincut(nodes[0], nodes[1]);
    vi n1, n2;
    for (ll i : nodes) {
        if (cut[i]) n1.pb(i);
        else n2.pb(i);
    }
    ll p1 = build(n1), p2 = build(n2);
    tree[p1].eb(p2, f);
    tree[p2].eb(p1, f);
    if (cut[0]) return p1;
    return p2;
}

void buildTree() {
    tree = vvii(n);
    vi nodes; REP(i, n) nodes.pb(i);
    build(nodes);
}

void dfsedge(int i, int p,
    & vector<tuple<int,int,ll>> prev) {
    for (ii e : tree[i])
        if (e.x != p) {
            prev[e.x] = {i, e.x, e.y};
            dfsedge(e.x, i, prev);
        }
}

tuple<int, int, ll> findtreeCut(int s, int t) {
    vector<tuple<int,int,ll>> prev(n); dfsedge(s,
        -1, prev);
    int small = t;
    for (int c = t; c != s; c = get<0>(prev[c]))
        if (get<2>(prev[c]) < get<2>(prev[small]))
            small = c;
    return prev[small];
}

ll maxflow(int s, int t) {
    auto e = findtreeCut(s, t); return get<2>(e);
}

void dfscut(int i, int p, vb& cut) {
    cut[i] = true;
    for (ii e : tree[i])
        if (e.x != p) dfscut(e.x, i, cut);
}

vb mincut(int s, int t) {
    auto e = findtreeCut(s, t);
    vb cut = vb(n, false); dfscut(get<0>(e),
        & get<1>(e), cut);
    return cut;
}

```

3.6. *Minimal Spanning Tree* $\mathcal{O}(E \log V)$. Hash: 17c710

```

struct edge { int x, y; ll w; };
ll kruskal(int n, vector<edge> edges) {

```

```

dsu D(n);
sort(all(edges), [] (edge a, edge b) -> bool {
    return a.w < b.w; });
ll ret = 0;
for (edge e : edges)
    if (D.find(e.x) != D.find(e.y))
        ret += e.w, D.unite(e.x, e.y);
return ret;
}

```

3.7. Euler Path $O(V + E)$ hopefully. Finds an Euler Path (or circuit) in a *directed* graph iff one exists. Hash: 2447dd

```

vvi adj;
int n, m;
vi indeg, outdeg, res;
ii start_end() {
    int start = -1, end = -1, any = 0, c = 0;
    REP(i, n) {
        if(outdeg[i] > 0) any = i;
        if(indeg[i] + 1 == outdeg[i]) start = i, c++;
        else if(indeg[i] == outdeg[i] + 1) end = i, c++;
        else if(indeg[i] != outdeg[i]) return ii(-1, -1);
    }
    if ((start == -1) != (end == -1) || (c != 2 && c))
        return ii(-1, -1);
    if (start == -1) start = end = any;
    return ii(start, end);
}
void makepath(ll i) {
    while(outdeg[i] > 0)
        makepath(adj[i][--outdeg[i]]);
    res.pb(i);
}
bool euler_path() {
    ii se = start_end();
    if (se.x == -1) return false;
    makepath(se.x); reverse(all(res));
    return (sz(res) == m + 1);
}

```

Finds an Euler Path (or circuit) in a *undirected* graph: Hash: b1890e

```

vector<multiset<int>> adj;
int n, m;
vi res;
ii start_end() {
    vi odd; int any = 0;
    REP(i, n) {
        if(sz(adj[i]) % 2 == 1) odd.pb(i);
        if(sz(adj[i]) > 0) any = i;
    }
    if(sz(odd) == 2) return ii(odd[0], odd[1]);
    if(sz(odd) == 0) return ii(any, any);
    return ii(-1, -1);
}
void makepath(ll i) {
    while(sz(adj[i]) > 0) {
        ll j = *adj[i].begin();
        adj[i].erase(adj[i].find(j));
        adj[j].erase(adj[j].find(i));
        makepath(j);
    }
}

```

res.pb(i);

```

}
bool euler_path() {
    ii se = start_end();
    if (se.x == -1) return false;
    makepath(se.x); reverse(all(res));
    return (sz(res) == m + 1);
}

3.8. Heavy-Light Decomposition. Hash: ad4690
struct HLD {
    vvi adj; int cur_pos = 0;
    vi par, dep, hvy, head, pos;
    segmenttree st;
    HLD(int n, const vvi &A) : adj(all(A)), par(n),
        dep(n), hvy(n, -1), head(n), pos(n), st(n) {
        cur_pos = 0; dfs(0); decomp(0, 0);
    }

    int dfs(int v) { // determine parent/depth/sizes
        int wei = 1, mw = 0;
        for (int c : adj[v]) if (c != par[v]) {
            par[c] = v, dep[c] = dep[v]+1;
            int w = dfs(c);
            wei += w;
            if (w > mw) mw = w, hvy[v] = c;
        }
        return wei;
    }

    // pos: index in SegmentTree, head: root of path
    void decomp(int v, int h) {
        head[v] = h, pos[v] = cur_pos++;
        if (hvy[v] != -1) decomp(hvy[v], h);
        for (int c : adj[v])
            if (c != par[v] && c != hvy[v]) decomp(c, c);
    }

    void update(int i, ll v){ st.update(pos[i], v); }

    // requires queryST(a, b) = SUM{A[i] | a <= i <= b}.
    ll query(int a, int b) {
        ll res = 0;
        for (; head[a] != head[b]; b = par[head[b]]) {
            if (dep[head[a]] > dep[head[b]]) swap(a, b);
            res += st.query(pos[head[b]], pos[b]);
        }
        if (dep[a] > dep[b]) swap(a, b);
        return res + st.query(pos[a], pos[b]);
    }
}

```

3.9. Centroid Decomposition. Hash: 168da7

```

struct centroid_decomposition {
    int n; vvi adj;
    vi parent, dist;
    vi sz, sepdepth;
    vvi children, tree;
    int logn, center;
}

```

centroid_decomposition(**int** _n): n(_n), adj(n) {
 for(logn = 0; (1 << logn) < n; logn++);
 logn++;
 parent = dist = children = tree = vvi(n,
 → vi(logn));
 sz = sepdepth = vi(n);
}
void add_edge(**int** a, **int** b) {
 adj[a].pb(b); adj[b].pb(a);
}
int dfs(**int** u, **int** p) {
 sz[u] = 1;
 for(**int** v : adj[u])
 if(v != p)
 sz[u] += dfs(v, u);
 return sz[u];
}
void makepaths(**int** sep, **int** u, **int** p, **int** len) {
 parent[u][sepdepth[sep]] = sep,
 → dist[u][sepdepth[sep]] = len;
 int bad = -1;
 REP(i, sz(adj[u])) {
 if(adj[u][i] == p) bad = i;
 else makepaths(sep, adj[u][i], u, len + 1);
 }
 if(p == sep)
 swap(adj[u][bad], adj[u].back()),
 → adj[u].pop_back();
}
int findcentroid(**int** u, **int** sep) {
 for(**int** v : adj[sep])
 if(sz[v] < sz[sep] && sz[v] > sz[u] / 2)
 return findcentroid(u, v);
 return sep;
}
int separate(**int** h, **int** u) {
 dfs(u, -1); **int** sep = findcentroid(u, u);
 sepdepth[sep] = h, makepaths(sep, sep, -1, 0);
 for(**int** v : adj[sep]) separate(h + 1, v);
 return sep;
}
void makeDecomp() {
 center = separate(0, 0);
 REP(i, n) children[i].clear(), tree[i].clear();
 REP(i, n) {
 if(sepdepth[i] != 0)
 children[parent[i][sepdepth[i] - 1]].pb(i);
 REP(j, sepdepth[i] + 1)
 tree[parent[i][j]].pb(i);
 }
}

3.10. Least Common Ancestors, Binary Jumping. Hash: d680d3

```

ll n, logn;
vi P; vvi BP; vi H;
//n, P, H input, assert p[root] = root
void initLCA() {
}

```

```

for(logn = 0; (1 << (logn++)) < n; ) ;
BP = vvi(n, vi(logn));
REP(i, n) BP[i][0] = P[i];
rep(j, 1, logn) REP(i, n)
    BP[i][j] = BP[BP[i][j-1]][j-1];
}

int query(int a, int b) {
    if (H[a] > H[b]) swap(a, b);
    int dh = H[b] - H[a], j = 0;
    REP(i, logn) if (dh & (1 << i)) b = BP[b][i];
    while (BP[a][j] != BP[b][j]) j++;
    while (--j >= 0) if (BP[a][j] != BP[b][j])
        a = BP[a][j], b = BP[b][j];
    return a == b ? a : P[a];
}

```

3.11. Miscellaneous.

3.11.1. *Misra-Gries D+1-edge coloring*. Finds a $\max_i \deg(i) + 1$ -edge coloring where there all incident edges have distinct colors. Finding a D -edge coloring is NP-hard. Hash: 1cff2f

```

struct Edge { int to, col, rev; };

struct MisraGries {
    int N, K=0; vvi F;
    vector<vector<Edge>> G;

    MisraGries(int n) : N(n), G(n) {}  

    // add an undirected edge, NO DUPLICATES ALLOWED
    void addEdge(int u, int v) {
        G[u].pb({v, -1, sz(G[v]))});
        G[v].pb({u, -1, sz(G[u]) - 1});
    }

    void color(int v, int i) {
        vi fan = { i };
        vb used(sz(G[v]));
        used[i] = true;
        for (int j = 0; j < sz(G[v]); j++)
            if (!used[j] && G[v][j].col >= 0 &&
                → F[G[v][fan.back()].to][G[v][j].col] < 0)
                used[j] = true, fan.pb(j), j = -1;
        int c = 0; while (F[v][c] >= 0) c++;
        int d = 0; while (F[G[v][fan.back()].to][d] >=
            → 0) d++;
        int w = v, a = d, k = 0, ccol;
        while (true) {
            swap(F[w][c], F[w][d]);
            if (F[w][c] >= 0) G[w][F[w][c]].col = c;
            if (F[w][d] >= 0) G[w][F[w][d]].col = d;
            if (F[w][a^=c^d] < 0) break;
            w = G[w][F[w][a]].to;
        }
        do {
            Edge &e = G[v][fan[k]];
            ccol = F[e.to][d] < 0 ? d :
            → G[v][fan[k+1]].col;
            if (e.col >= 0) F[e.to][e.col] = -1;
            F[e.to][ccol] = e.rev;
        }
    }
}

```

```

F[v][ccol] = fan[k];
e.col = G[e.to][e.rev].col = ccol;
k++;
} while (ccol != d);

// finds a K-edge-coloring
void color() {
    REP(v, N) K = max(K, sz(G[v]) + 1);
    F = vvi(N, vi(K, -1));
    REP(v, N) for (int i = sz(G[v]); i--;) if (G[v][i].col < 0) color(v, i);
}

```

3.11.2. *Minimum Mean Weight Cycle*. Given a strongly connected directed graph, finds the cycle of minimum mean weight. If you have a graph that is not strongly connected, run this on each strongly connected component. $\mathcal{O}(EV)$ runtime. Hash: 9e9183

```

double min_mean_cycle(vector<vector<pair<int, ld>>>
    → adj) {
    int n = sz(adj); ld mn = INFINITY;
    vvd arr(n+1, vd(n, mn));
    arr[0][0] = 0;
    rep(k, 1, n+1) REP(j, n) for(auto p : adj[j])
        arr[k][p.x] = min(arr[k][p.x], p.y +
            → arr[k-1][j]);
    REP(k, n) {
        ld mx = -INFINITY;
        REP(i, n) mx = max(mx,
            → (arr[n][i]-arr[k][i]) / (n-k));
        mn = min(mn, mx);
    }
    return mn;
}

```

3.11.3. *Minimum Arborescence*. Given a weighted directed graph, finds a subset of edges of minimum total weight so that there is a unique path from the root r to each vertex. Returns a vector of size n , where the i th element is the edge for the i th vertex. The answer for the root is undefined!

$\mathcal{O}(V^2 \log V)$ runtime and $\mathcal{O}(E)$ memory: Hash: ea35fc

```

const ll oo = 1e9;
int N, R;
vvii g;
vi pred, label, node, helper;

int get_node(int n) {
    return node[n] == n ? n :
        (node[n] = get_node(node[n]));
}

ll update_node(int n) {
    ll m = oo;
    for (auto ed : g[n]) m = min(m, ed.y);
    REP(j, sz(g[n])) {
        g[n][j].y -= m;
    }
}

```

```

if (g[n][j].y == 0)
    pred[n] = g[n][j].x;
}
return m;
}

ll cycle(vi &active, int n, int &cend) {
    n = get_node(n);
    if (label[n] == 1) return false;
    if (label[n] == 2) { cend = n; return 0; }

    active.pb(n);
    label[n] = 2;
    auto res = cycle(active, pred[n], cend);
    if (cend == n) {
        int F = find(all(active), n)-active.begin();
        vi todo(active.begin() + F, active.end());
        active.rs(F);
        vi newg;
        for (auto i: todo) node[i] = n;
        for (auto i: todo) for(auto &ed : g[i])
            helper[ed.x] = get_node(ed.x) = ed.y;
        for (auto i: todo) for(auto ed : g[i])
            helper[ed.x] = min(ed.y, helper[ed.x]);
        for (auto i: todo) for(auto ed: g[i])
            if (helper[ed.x] != oo && ed.x != n) {
                newg.eb(ed.x, helper[ed.x]);
                helper[ed.x] = oo;
            }
        }
        g[n] = newg;
        res += update_node(n);
        label[n] = 0;
        cend = -1;
        return cycle(active, n, cend) + res;
    }
    if (cend == -1) {
        active.pop_back();
        label[n] = 1;
    }
    return res;
}

// Calculates value of minimal arborescence from R,
// assuming it exists.
// adj[i] contains (j, v) with edge i → j with
// → value v
// pred[i] is parent in arborescence
ll min_arbor(vvii adj, int r) {
    N = sz(adj); R = r; g = vvii(N);
    REP(i, N) for(ii p : adj[i]) g[p.x].eb(i, p.y);
    pred = label = node = helper = vi(N);
    ll res = 0;
    REP(i, N) {
        node[i] = i;
        if (i != R) res += update_node(i);
    }
    REP(i, N) label[i] = (i==R);
}

```

```

REP(i, N) {
    if (label[i] == 1 || get_node(i) != i)
        continue;
    vi active;
    int cend = -1;
    res += cycle(active, i, cend);
}
return res;
}

```

3.11.4. Maximum Density Subgraph. Given (weighted) undirected graph G . Binary search density. If g is current density, construct flow network: (S, u, m) , $(u, T, m + 2g - d_u)$, $(u, v, 1)$, where m is a large constant (larger than sum of edge weights). Run floating-point max-flow. If minimum cut has empty S -component, then maximum density is smaller than g , otherwise it's larger. Distance between valid densities is at least $1/(n(n-1))$. Edge case when density is 0. This also works for weighted graphs by replacing d_u by the weighted degree, and doing more iterations (if weights are not integers).

3.11.5. Maximum-Weight Closure. Given a vertex-weighted directed graph G . Turn the graph into a flow network, adding weight ∞ to each edge. Add vertices S, T . For each vertex v of weight w , add edge (S, v, w) if $w \geq 0$, or edge $(v, T, -w)$ if $w < 0$. Sum of positive weights minus minimum $S-T$ cut is the answer. Vertices reachable from S are in the closure. The maximum-weight closure is the same as the complement of the minimum-weight closure on the graph with edges reversed.

3.11.6. Maximum Weighted Independent Set in a Bipartite Graph. This is the same as the minimum weighted vertex cover. Solve this by constructing a flow network with edges $(S, u, w(u))$ for $u \in L$, $(v, T, w(v))$ for $v \in R$ and (u, v, ∞) for $(u, v) \in E$. The minimum S, T -cut is the answer. Vertices adjacent to a cut edge are in the vertex cover.

3.11.7. Synchronizing word problem. A DFA has a synchronizing word (an input sequence that moves all states to the same state) iff. each pair of states has a synchronizing word. That can be checked using reverse DFS over pairs of states. Finding the shortest synchronizing word is NP-complete.

4. STRING ALGORITHMS

4.1. Trie. Node content derived from position in tree, not in node. E.g. for each node a child per next character and then deriving the string from the path from the root. Hash: c1d464

```

const int SIGMA = 26;

struct trie {
    bool word;
    trie **adj;
}

```

```

trie() : word(false), adj(new trie*[SIGMA]) {
    for (int i = 0; i < SIGMA; i++) adj[i] = NULL;
}

```

```

void addWord(const string &str) {
    trie *cur = this;
    for (char ch : str) {
        int i = ch - 'a';
        if (!cur->adj[i]) cur->adj[i] = new trie();
        cur = cur->adj[i];
    }
    cur->word = true;
}

bool isWord(const string &str) {
    trie *cur = this;
    for (char ch : str) {
        int i = ch - 'a';
        if (!cur->adj[i]) return false;
        cur = cur->adj[i];
    }
    return cur->word;
}

```

4.2. Z-algorithm $\mathcal{O}(n)$. Hash: c038c2

```

// z[i] = length of longest substring starting from
// → s[i] which is also a prefix of s.
vi z_function(const string &s) {
    int n = (int) s.length();
    vi z(n);
    for (int i = 1, k = 0, r = 0; i < n; ++i) {
        if (i <= r) z[i] = min (r - i + 1, (int)z[i - 
        ↪ k]);
        while(i+z[i] < n && s[z[i]] == s[i+z[i]])
            ++z[i];
        if (i + z[i] - 1 > r) k = i, r = i + z[i] - 1;
    }
    return z;
}

```

4.3. Manacher algorithm $\mathcal{O}(n)$. Returns longest palindrome centered at letter i (index $2 \cdot i$) or between letters i and $i+1$ (index $2 \cdot i+1$). Hash: 42bcf9

```

vi manacher(const string& s) {
    ll n = sz(s); vi res(2 * n - 1);
    ll k = 0, r = 0;
    REP(i, 2 * n - 1) {
        res[i] = i % 2;
        if(r > i) res[i] = res[r + k - i];
        if(i + res[i] >= r) {
            r = i + res[i];
            k = i - res[i];
            while(k >= 0 && r <= 2 * n - 2 && s[k / 
            ↪ 2] == s[r / 2])
                r += 2, k -= 2;
            r -= 2; k += 2;
            res[i] = r - i; } }
}

```

```

REP(i, 2 * n - 1) res[i]++;
return res; }

```

4.4. Suffix array $\mathcal{O}(n \log n)$. Lexicographically sorts the cyclic shifts of S where $p[0]$ is the index of the smallest string, etc. Efficient lookup of all indices where a substring occurs. Hash: 2b9060

```

vi sort_cyclic_shifts(const string &s) {
    const int alphabet = 256, n = sz(s);

    vi p(n), c(n), cnt(max(alphabet, n), 0);
    REP(i, n) cnt[s[i]]++;
    partial_sum(all(cnt), cnt.begin());
    REP(i, n) p[-cnt[s[i]]] = i;
    c[p[0]] = 0;
    int cl = 1;
    rep(i, 1, n) {
        if (s[p[i]] != s[p[i-1]]) cl++;
        c[p[i]] = cl - 1;
    }

    vi pn(n), cn(n);
    for (int h = 0, l = 1; l < n; l*=2, ++h) {
        REP(i, n) {
            pn[i] = p[i] - (l << h);
            if (pn[i] < 0) pn[i] += n;
        }
        fill(cnt.begin(), cnt.begin() + cl, 0);
        REP(i, n) cnt[c[pn[i]]]++;
        rep(i, 1, cl) cnt[i] += cnt[i-1];
        for (int i = n-1; i >= 0; i--) {
            p[-cnt[c[pn[i]]]] = pn[i];
        }
        cn[p[0]] = 0;
        cl = 1;
        rep(i, 1, n) {
            if (c[p[i]] != c[p[i-1]] || c[(p[i]+1)%n] 
            ↪ != c[(p[i-1]+1)%n]) cl++;
            cn[p[i]] = cl - 1;
        }
        c.swap(cn);
    }
    return p;
}

vi suffix_array(string s) {
    s += '\0';
    vi v = sort_cyclic_shifts(s);
    v.erase(v.begin());
    return v;
}

```

4.5. **Levenshtein Distance** $\mathcal{O}(n^2)$. Minimal number of insertions, removals and edits required to transform one string in the other. Hash: 1b7ea8

```
int levDist(const string &w1, const string &w2) {
    int n1 = sz(w1)+1, n2 = sz(w2)+1;
    vvi dp(n1, vi(n2));
    REP(i, n1) dp[i][0] = i; // removal
    REP(j, n2) dp[0][j] = j; // insertion
    rep(i, 1, n1) rep(j, 1, n2)
        dp[i][j] = min(
            1 + min(dp[i-1][j], dp[i][j-1]),
            dp[i-1][j-1] + (w1[i-1] != w2[j-1])
        );
    return dp[sz(w1)][sz(w2)];
}
```

4.6. **Knuth-Morris-Pratt algorithm** $\mathcal{O}(N + M)$. Finds all occurrences of a word in a longer string. Hash: a9684c

```
int kmp(const string &word, const string &text) {
    int n = sz(word);
    vi T(n+1, 0);
    for (int i = 1, j = 0; i < n; ) {
        if (word[i] == word[j]) T[++i] = ++j; // match
        else if (j > 0) j = T[j]; // fallback
        else i++; // no match, keep zero
    }
    int matches = 0;
    for (int i = 0, j = 0; i < sz(text); ) {
        if (text[i] == word[j]) {
            i++;
            if (++j == n) // match at interval [i - n, i)
                matches++, j = T[j];
            else if (j > 0) j = T[j];
            else i++;
        }
    }
    return matches;
}
```

4.7. **Aho-Corasick Algorithm** $\mathcal{O}(N + \sum_{i=1}^m |S_i|)$. Dictionary substring matching as automaton. All given P must be unique! Matches all words in a dictionary simultaneously. Hash: ec6c33

```
const int sigma = 26;
const char base = 'a';
vi pnr, ploc, sLink, dLink;
vvi to;
vs P;
void makeNode() {
    pnr.pb(-1); sLink.pb(0);
    dLink.pb(0); to.pb(vi(sigma, 0));
}
void makeTrie(vs& p) {
    // STEP 1: MAKE A TREE
    p = p;
    pnr.clear(), sLink.clear(), dLink.clear();
    to.clear(), ploc.clear();
    makeNode();
    for (int i = 0; i < sz(p); i++) {
```

```
        int cur = 0;
        for (char c : p[i]) {
            int i = c - base;
            if (to[cur][i] == 0) {
                makeNode();
                to[cur][i] = sz(to) - 1;
            }
            cur = to[cur][i];
        }
        pnr[cur] = i; ploc.pb(cur);
    }
    // STEP 2: CREATE SUFFIX_LINKS AND DICT_LINKS
    queue<int> q; q.push(0);
    while (!q.empty()) {
        int cur = q.front(); q.pop();
        for (int c = 0; c < sigma; c++) {
            if (to[cur][c]) {
                int sl = sLink[to[cur][c]] = cur == 0 ? 0 :
                    to[sLink[cur]][c];
                // if all strings have equal length, remove
                // this:
                dLink[to[cur][c]] = pnr[sl] >= 0 ? sl :
                    dLink[sl];
                q.push(to[cur][c]);
            } else to[cur][c] = to[sLink[cur]][c];
        }
    }
    void traverse(string& s) {
        for (int cur = 0, i = 0, n = sz(s); i < n; i++) {
            cur = to[cur][s[i] - base];
            for (int hit = pnr[cur] >= 0 ? cur : dLink[cur];
                 hit; hit = dLink[hit]) {
                cerr << P[pnr[hit]] << " found at [" << (i + 1
                - P[pnr[hit]].size()) << ", " << i << "]"
                << endl;
            }
        }
    }
}
```

4.8. **eerTree**. Constructs an eerTree in $\mathcal{O}(n)$, one character at a time. Allows for fast access to all palindromes contained in a string. They can be used to solve the longest palindromic substring, the k-factorization problem[2] (can a given string be divided into exactly k palindromes), palindromic length of a string[3] (what is the minimum number of palindromes needed to construct the string), and finding and counting all distinct sub-palindromes. Hash: 555dcd

```
const int sigma = 26;
const char base = 'a';
struct state {
    int len, link, to[sigma];
};
struct eertree {
    int last, size, n;
    vector<state> nodes;
    string s;
```

```
eertree() : last(1), size(2), n(0) {
    nodes.pb({-1, -1});
    nodes.pb({0, 0});
    void extend(char c) {
        s.pb(c); n++; int p = last;
        while (n - nodes[p].len - 2 < 0 || c != s[n -
            nodes[p].len - 2])
            p = nodes[p].link;
        if (!nodes[p].to[c-base]) {
            int q = last = size++;
            nodes.pb({nodes[p].len + 2, 1});
            nodes[p].to[c-base] = q;
            do { p = nodes[p].link;
            } while (p != -1 && (n < nodes[p].len + 2 ||
                c != s[n - nodes[p].len - 2]));
            if (p != -1) nodes[q].link =
                nodes[p].to[c-base];
        } else
            last = nodes[p].to[c-base];
    }};
```

4.9. **Suffix Tree**. Compressed suffix trie with $\leq 2n$ vertices. Works with characters in ASCII range [64, 128). Preprocesses for fast substring queries. Also used to find longest substring that is prefix (return index in loop). Hash: 377cbd

```
const char base = 'A';
const int sigma = 26;
struct suffixtree {
    string a;
    vvi t; vi l, r, p, s; // p: parent, s: suffix link
    int tv, tp, ts, la; // edge p[v] -> v, contains
    → a[l[v]..r[v]-1]
    suffixtree(const string& _a) : a(_a) {
        int n = sz(a) * 2; t = vvi(n, vi(sigma, -1));
        t[1] = vi(sigma, 0); r = vi(n, sz(a));
        l = p = s = vi(n); l[0]=l[1]=-1;
        la = tv = tp = r[0] = r[1] = 0; s[0] = 1; ts =
        → 2;
        for (; la < sz(a); la++) ukkadd(a[la] - base);
    }
    void ukkadd(int c) {
        if (r[tv] <= tp) {
            if (t[tv][c] == -1) {
                t[tv][c]=ts; l[ts]=la; p[ts+1]=tv;
                tv=s[tv]; tp=r[tv]; ukkadd(c); return;
            }
            tv=t[tv][c]; tp=l[tv];
        }
        if (tp == -1 || c == a[tp]-base) { tp++; return;
        → }
        l[ts+1]=la; p[ts+1]=ts;
        l[ts]=l[tv]; r[ts]=tp; p[ts]=p[tv];
        t[ts][c]=ts+1; t[ts][a[tp]-base]=tv;
    }}
```

```

l[tv]=tp; p[tv]=ts; t[p[ts]][a[l[ts]]-base]=ts;
tv=s[p[ts]]; tp=l[ts];
while (tp < r[ts])
    tv = t[tv][a[tp]-base], tp += r[tv] - l[tv];
if (tp == r[ts]) s[ts]=tv;
else s[ts]=ts+2;
tp = r[tv] - (tp - r[ts]); ts += 2; ukkadd(c);
}

ll max_substr(const string &s) { // O(|S|)
int v = 0, it = 0, n = sz(s);
while (it < n) {
    int c = S[it++]-base;
    if ((v = t[v][c]) < 0) return it - 1;
    for (int i = 1[v]; it < n && ++i < r[v]; )
        if (S[it++] != a[i]) return it - 1;
}
return n;
}

```

4.10. Suffix Automaton. Minimum automata that accepts all suffixes of a string with $O(n)$ construction. The automata itself is a DAG therefore suitable for DP, examples are counting unique substrings, occurrences of substrings and suffix. Hash: 9f7b1d

```

typedef vector<char> vc;
struct suffix_automaton {
    vi len, link;
    vi first, topo; //reversed topological ordering
    vector<map<char, int>> next;
    vi previd; vc prevc;
    vvi linkinv;
    int sz, last;
    string s;
    suffix_automaton() : len(1), link(1),
    next(1), first(1), previd(1), prevc(1) {
        sz = 1; last = 0; }
    suffix_automaton(string s) : suffix_automaton() {
        for(char c : s) extend(c);
        maketopo(); makelinkinvs(); }
    void extend(char c){ s.pb(c);
        int cur = sz++; len.pb(len[last]+1); link.pb(0);
        next.pb(map<char, int>()); first.pb(sz(s));
        previd.pb(last); prevc.pb(c);
        int p = last;
        for; p != -1 && !next[p].count(c); p = link[p])
            next[p][c] = cur;
        if(p != -1) { int q = next[p][c];
            if(len[p] + 1 == len[q])( link[cur] = q; )
            else { int clone = sz++;
                len.pb(len[p] + 1); first.pb(first[q]);
                link.pb(link[q]); next.pb(next[q]);
                previd.pb(p); prevc.pb(c);
                for; p != -1 && next[p].count(c) &&
                    next[p][c] == q;
                    p = link[p]);
                next[p][c] = clone; }
    }
}

```

```

link[q] = link[cur] = clone;
} } last = cur; }
void makelinkinvs() {
    linkinv = vvi(sz);
    rep(i,1,sz) linkinv[link[i]].pb(i); }
void maketopo() {
    topo.clear();
    topo = vi(sz); REP(i,sz) topo[i] = i;
    sort(all(topo), [&](ll a, ll b)
        { return len[a] > len[b]; });
}
int locstr(string& other){//returns location of
    leftrightarrow other (or -1)
    int cur = 0;
    for(int i = 0; i < sz(other); ++i){
        if(cur == -1) return -1;
        cur = next[cur][other[i]]; }
    return cur; }
string maxstring(int loc) {
    string res;
    while(loc > 0) {
        res.pb(prevc[loc]); loc = previd[loc]; }
    reverse(all(res)); return res;
}

```

DP examples Hash: 7f3fba

```

//cnt[sa.locstr(s)] = #distinct substrings of sa
// with prefix s
vi distinct(suffix_automaton& sa) {
    vi cnt = vi(sa.sz, 1); cnt[0] = 0;
    for(ll i : sa.topo)
        for(auto p : sa.next[i])
            cnt[i] += cnt[p.y];
    return cnt;
}

//cnt[sa.locstr(s)] = #locations of s in sa
vi occur(suffix_automaton& sa) {
    vi cnt = vi(sa.sz, 0);
    for(int cur = 0, i = 0; i < sz(sa.s); i++) {
        cnt[cur = sa.next[cur][sa.s[i]]]++;
        for(ll i : sa.topo) cnt[sa.link[i]] += cnt[i];
    return cnt;
}

//return endpositions of occurrences of t
// (unsorted!)
vi location(suffix_automaton& sa, string& t) {
    int cur = sa.locstr(t);
    if(cur == -1) return vi();
    vi res, stack(1,cur);
    while(sz(stack) > 0) {
        cur = stack.back(); stack.pop_back();
        res.pb(sa.first[cur]);
        for(ll n : sa.linkinv[cur]) stack.pb(n); }
    return res; }

//find the longest common substring

```

```

string lcs(vs& s) {
    //Make the automaton
    vc extra;
    REP(i,sz(s))
        extra.pb(i + 256); //assert not in s!
    suffix_automaton sa;
    REP(i,sz(s)) {
        for(char c : s[i]) sa.extend(c);
        sa.extend(extra[i]);
    }
    sa.maketopo();
    sa.makelinkinvs();

    //Determine possible locations
    vvb pos; int cur;
    REP(i, sz(s)) {
        pos.pb(vb(sz(s[i]), false));
        vi stack; cur = sa.next[0][extra[i]];
        for(char c : s[i]) {
            cur = sa.next[cur][c]; stack.pb(cur);
        }
        while(sz(stack) > 0) {
            cur = stack.back(); stack.pop_back();
            if(!pos[i][cur]) {
                pos[i][cur] = true;
                for(ll p : sa.linkinv[cur])
                    stack.pb(p);
            }
        }
    }

    //Determine the answer
    for(ll i : sa.topo) {
        bool can = true;
        REP(j, sz(s)) if(!pos[j][i]) {
            can = false;
            break; }
        if(can)
            return sa.maxstring(i); //sa.length[i]
    }
    return "";
}

```

4.11. Hashing. Modulus should be a large prime. Can also use multiple instances with different moduli to minimize chance of collision. Hash: 71ce96

```

struct hasher {
    int b = 311, m; vi h, p;
    hasher(string s, int _m) :
        m(_m), h(sz(s)+1), p(sz(s)+1) {
            p[0] = 1; h[0] = 0;
            REP(i,sz(s)) p[i+1] = p[i] * b % m;
            REP(i,sz(s)) h[i+1] = (h[i] * b + s[i]) % m;
        }
    int hash(int k, int r) {
        return (h[r+1] + m - h[k]*p[r-k+1] % m) % m;
    }
}

```

5. GEOMETRY

Hash: bcc240

```

const ld EPS = 1e-7, PI = acos(-1.0);
typedef ld NUM; // EITHER ld OR ll
typedef pair<NUM, NUM> pt;
typedef vector<pt> poly;

pt operator+(pt p, pt q) { return {p.x+q.x, p.y+q.y}; }
pt operator-(pt p, pt q) { return {p.x-q.x, p.y-q.y}; }
pt operator*(pt p, NUM n) { return {p.x*n, p.y*n}; }

pt& operator+=(pt &p, pt q) { return p = p+q; }
pt& operator-=(pt &p, pt q) { return p = p-q; }

NUM operator*(pt p, pt q) { return p.x*q.x+p.y*q.y; }
NUM operator^(pt p, pt q) { return p.x*q.y-p.y*q.x; }

// square distance from p to q
NUM dist2(pt p, pt q) {
    return (q - p) * (q - p);
}

// Normal distance from p to q
ld dist(pt p, pt q) { return sqrt(dist2(p, q)); }

// distance from p to line ab
ld distPtLine(pt p, pt a, pt b) {
    p -= a; b -= a;
    return sqrt(ld(p^b) * (p^b) / (b*b));
}

// distance from p to linesegment ab
ld distPtSegment(pt p, pt a, pt b) {
    p -= a; b -= a;
    NUM dot = p*b, len = b*b;
    if (dot <= 0) return sqrt(p*p);
    if (dot >= len) return sqrt((p-b)*(p-b));
    return sqrt(p*p - ld(dot)*dot/len);
}

// projects p onto the line ab
// NUM has to be ld
pt proj(pt p, pt a, pt b) {
    p -= a; b -= a;
    return a + b*((b*p) / (b*b));
}

bool col(pt a, pt b, pt c) {
    return abs((a-b) ^ (a-c)) < EPS;
}

// note: to accept collinear points, change '> 0'
// returns true if r is on the left side of line pq
bool ccw(pt p, pt q, pt r) {
    return ((q - p) ^ (r - p)) > 0;
}

// true => 1 intersection, false => parallel or same
bool linesIntersect(pt a, pt b, pt c, pt d) {
    return abs((a-b) ^ (c-d)) > EPS;
}

// Test if p is on line segment ab

```

```

bool segmentHasPoint(pt p, pt a, pt b) {
    pt u = p-a, v = p-b;
    return abs(u^v) < EPS && u*v <= 0;
}

// Test if segments a, b and c, d intersect (in point
// or line segment)
bool segmentsIntersect(pt a, pt b, pt c, pt d) {
    if (!linesIntersect(a, b, c, d)) {
        return segmentHasPoint(a, c, d) ||
               segmentHasPoint(b, c, d) ||
               segmentHasPoint(c, a, b) || segmentHasPoint(d,
               a, b);
    }
    return (sign((c - a) ^ (b - a)) * sign((d - a) ^
               (b - a)) <= 0 &&
            sign((a - c) ^ (d - c)) * sign((b - c) ^ (d -
               c)) <= 0);
}

// Check lines intersect!
// NUM has to be ld
pt lineLineIntersection(pt a, pt b, pt c, pt d) {
    ld det = (a-b) ^ (c-d);
    return ((c-d)*(a^b) - (a-b)*(c^d)) * (1.0/det);
}

// Check lines intersect!
// Num has to be ld
bool segmentIntersection(pt a, pt b, pt c, pt d, pt&
                           res) {
    res = lineLineIntersection(a, b, c, d);
    return segmentHasPoint(res, a, b) &&
           segmentHasPoint(res, c, d);
}

// Lines can be parallel: segments overlap from
// seg(start, end)
// 0 = no intersect, 1 = 1 lines not parallel (res =
// start), 2 = lines parallel
// Num has to be ld
int segmentIntersection(pt a, pt b, pt c, pt d, pt&
                        start, pt& end) {
    pt d1 = b - a, d2 = d - c;
    if (abs(d1 ^ d2) > EPS) return
        segmentIntersection(a, b, c, d, start);
    if (abs((c - a) ^ d1) > EPS) return 0;
    if (d1 * d2 < 0) swap(c, d), d2 = d - c;
    ld s = max((ld)0, (c - a) * d1), e = min(d1 * d1,
        (d - a) * d1);
    s /= (d1 * d1), e /= (d1 * d1);
    if (s > e + EPS) return 0;
    start = a + d1 * s; end = a + d1 * e; return 2;
}

// line segment p-q intersect with line A-B.
// NUM has to be ld!
bool lineIntersectSeg(pt p, pt q, pt a, pt b, pt&
                       res) {

```

```

    res = lineLineIntersection(p, q, a, b);
    return segmentHasPoint(res, p, q);
}

5.1. Convex Hull  $\mathcal{O}(n \log n)$ . Hash: 706f63
// the convex hull consists of: { pts[ret[0]], ...
//   pts[ret[1]], ... pts[ret.back()] } in
//   counterclockwise order
vi convexHull(const poly &pts) {
    if (pts.empty()) return vi();
    vi ret, ord;
    int n = sz(pts), st = min_element(all(pts)) -
        pts.begin();
    REP(i, n)
        if (pts[i] != pts[st]) ord.pb(i);
    sort(all(ord), [&pts, &st] (int a, int b) {
        pt p = pts[a] - pts[st], q = pts[b] - pts[st];
        return (p ^ q) != 0 ? (p ^ q) > 0 : p * p > q *
            q;
    });
    ord.pb(st); ret.pb(st);
    for (int i : ord) {
        // use '=>' in ccw to include ALL points on the
        // hull-line
        for (int s = sz(ret) - 1; s > 1 && !ccw(pts[ret[s]-
            1]], pts[ret[s]], pts[i]); s--)
            ret.pop_back();
        ret.pb(i);
    }
    ret.pop_back();
    return ret;
}

5.2. Closest points  $\mathcal{O}(n \log n)$ . Hash: 7ab1d9
poly pts;

struct byY {
    bool operator()(int a, int b) const { return
        pts[a].y < pts[b].y; }
};

inline NUM dist(ii p) { pt a = (pts[p.x] -
    pts[p.y]); return a * a; }

ii minpt(ii p1, ii p2) { return dist(p1) < dist(p2)
    ? p1 : p2; }

// closest pts (by index) inside pts[l ... r - 1],
// with sorted y values in ys
// check pts is sorted on x!
ii closest(int l, int r, vi &ys) {
    if (r - l == 2) { // don't assume 1 here.
        ys = { l, l + 1 };
        sort(all(ys), byY());
        return ii(l, l + 1);
    } else if (r - l == 3) { // brute-force
        ys = { l, l + 1, l + 2 };
        sort(all(ys), byY());
    }
}

```

```

    return minpt(ii(l, l + 1), minpt(ii(l, l + 2),
        ↪ ii(l + 1, l + 2)));
}
int m = (l + r) / 2; vi yl, yr;
ii delta = minpt(closest(l, m, yl), closest(m, r,
    ↪ yr));
NUM ddelta = dist(delta), xm = (pts[m-1].x +
    ↪ pts[m].x) / 2;
merge(all(yl), all(yr), back_inserter(ys), byY());
deque<int> q;
for (int i : ys) if (abs(pts[i].x - xm) <= ddelta)
    ↪ {
        for (int j : q) delta = minpt(delta, ii(i, j));
        q.pb(i);
        if (sz(q) > 8) q.pop_front(); // magic from
            ↪ Introduction to Algorithms.
    }
return delta;
}

```

5.3. Great-Circle Distance. Computes the distance between two points (given as latitude/longitude coordinates) on a sphere of radius r . Hash: d850b6

```

ld gc_distance(ld pLat, ld pLong, ld qLat, ld qLong,
    ↪ ld r) {
    pLat *= PI / 180; pLong *= PI / 180;
    qLat *= PI / 180; qLong *= PI / 180;
    return r * acos(cos(pLat)*cos(qLat)*cos(pLong -
        ↪ qLong) + sin(pLat)*sin(qLat)); }

```

5.4. Delaunay triangulation. Hash: 742901

```

int sgn(const ll& a) { return (a > 0) - (a < 0); }

const pt inf_pt = make_pair(1e18, 1e18);

struct Quad { // `QuadEdge` originally
    pt O; // origin
    Quad *rot = nullptr, *onext = nullptr;
    bool used = false;
    Quad* rev() const { return rot->rot; }
    Quad* lnext() const {
        return rot->rev()->onext->rot; }
    Quad* oprev() const {
        return rot->onext->rot; }
    pt dest() const { return rev()->O; }
};

Quad* make_edge(pt from, pt to) {
    Quad* e1 = new Quad, *e2 = new Quad;
    Quad* e3 = new Quad, *e4 = new Quad;
    e1->O = from; e2->O = to;
    e3->O = e4->O = inf_pt;
    e1->rot = e3; e2->rot = e4;
    e3->rot = e2; e4->rot = e1;
    e1->onext = e1; e2->onext = e2;
    e3->onext = e4; e4->onext = e3;
    return e1;
}

```

```

void splice(Quad* a, Quad* b) {
    swap(a->onext->rot->onext, b->onext->rot->onext);
    swap(a->onext, b->onext);
}

void delete_edge(Quad* e) {
    splice(e, e->oprev());
    splice(e->rev(), e->rev()->oprev());
}

Quad* connect(Quad* a, Quad* b) {
    Quad* e = make_edge(a->dest(), b->O);
    splice(e, a->lnext());
    splice(e->rev(), b);
    return e;
}

bool left_of(pt p, Quad* e) {
    return ((e->O - p) ^ (e->dest() - p)) > 0; }
bool right_of(pt p, Quad* e) {
    return ((e->O - p) ^ (e->dest() - p)) < 0; }

template <class T> T det3(T a1, T a2, T a3,
    T b1, T b2, T b3, T c1, T c2, T c3) {
    return a1*(b2*c3 - c2*b3) - a2*(b1*c3 - c1*b3)
        + a3*(b1*c2 - c1*b2);
}

// Calculate directly with __int128, or with angles
bool in_circle(pt a, pt b, pt c, pt d) {
    __int128 det = 0;
    det -= det3<__int128>(b.x,b.y,b * b,
        c.x,c.y,c * c, d.x,d.y,d * d);
    det += det3<__int128>(a.x,a.y,a * a,
        c.x,c.y,c * c, d.x,d.y,d * d);
    det -= det3<__int128>(a.x,a.y,a * a,
        b.x,b.y,b * b, d.x,d.y,d * d);
    det += det3<__int128>(a.x,a.y,a * a,
        b.x,b.y,b * b, c.x,c.y,c * c);
    return det > 0;
}

pair<Quad*, Quad*> build_tr(int k, int r,
    poly& p) {
    if (r - k == 3) {
        Quad* res = make_edge(p[k], p[r]);
        return make_pair(res, res->rev());
    }
    if (r - k == 4) {
        Quad* a = make_edge(p[k], p[k+1]);
        Quad* b = make_edge(p[k+1], p[r]);
        splice(a->rev(), b);
        int sg = sgn((p[k+1] - p[k]) ^ (p[r] - p[k]));
        if (sg == 0) return make_pair(a, b->rev());
        Quad* c = connect(b, a);
        if (sg == 1) return make_pair(a, b->rev());
        return make_pair(c->rev(), c);
    }
    int mid = (k + r) / 2;
}

```

```

Quad *ldo, *ldi, *rdo, *rdi;
tie(ldo, ldi) = build_tr(k, mid, p);
tie(rdi, rdo) = build_tr(mid + 1, r, p);
while (true) {
    if (left_of(rdi->O, ldi)) {
        ldi = ldi->lnext(); continue; }
    if (right_of(ldi->O, rdi)) {
        rdi = rdi->rev()->onext; continue; }
    break;
}
Quad* B = connect(rdi->rev(), ldi);
auto valid = [&B](Quad* e) {
    return right_of(e->dest(), B); };

if (ldi->O == ldo->O) ldo = B->rev();
if (rdi->O == rdo->O) rdo = B;
while (true) {
    Quad* lc = B->rev()->onext; // left candidate
    if (valid(lc)) {
        while (in_circle(B->dest(), B->O,
            lc->dest(), lc->onext->dest())) {
            Quad* t = lc->onext;
            delete_edge(lc);
            lc = t;
        }
    }
    Quad* rc = B->oprev(); // right candidate
    if (valid(rc)) {
        while (in_circle(B->dest(), B->O,
            rc->dest(), rc->oprev()->dest())) {
            Quad* t = rc->oprev();
            delete_edge(rc);
            rc = t;
        }
    }
    if (!valid(lc) && !valid(rc)) break;
    if (!valid(lc) || (valid(rc) && in_circle(
        lc->dest(), lc->O, rc->O, rc->dest())))
        B = connect(rc, B->rev());
    else B = connect(B->rev(), lc->rev());
}
return make_pair(ldo, rdo);
}

vector<tuple<pt, pt, pt>> delaunay(poly p) {
    sort(all(p), [](const pt& a, const pt& b) {
        return a.x < b.x ||
            (a.x == b.x && a.y < b.y);
    });
    auto res = build_tr(0, sz(p) - 1, p);
    Quad* e = res.first;
    vector<Quad*> edges = {e};
    while (((e->dest() - e->onext->dest()) ^ (e->O -
        ↪ e->onext->dest()) < 0)
        e = e->onext;
    auto add = [&p, &e, &edges]() {
        Quad* cur = e;
        do {

```

```

cur->used = true;
p.pb(cur->O);
edges.pb(cur->rev());
cur = cur->lnext();
} while (cur != e);
};

add(); p.clear();

int kek = 0;
while (kek < sz(edges))
    if (!(e = edges[kek++])->used) add();
vector<tuple<pt, pt, pt>> ans;
for (int i = 0; i < sz(p); i += 3)
    ans.pb(make_tuple(p[i], p[i + 1], p[i + 2]));
return ans;
}

```

5.5. 3D Primitives. Hash: 84ea9e

```

#define P(p) const point3d &p
#define L(p0, p1) P(p0), P(p1)
#define PL(p0, p1, p2) P(p0), P(p1), P(p2)
struct point3d {
    double x, y, z;
    point3d() : x(0), y(0), z(0) {}
    point3d(double _x, double _y, double _z)
        : x(_x), y(_y), z(_z) {}
    point3d operator+(P(p)) const {
        return point3d(x + p.x, y + p.y, z + p.z); }
    point3d operator-(P(p)) const {
        return point3d(x - p.x, y - p.y, z - p.z); }
    point3d operator-() const {
        return point3d(-x, -y, -z); }
    point3d operator*(double k) const {
        return point3d(x * k, y * k, z * k); }
    point3d operator/(double k) const {
        return point3d(x / k, y / k, z / k); }
    double operator%(P(p)) const {
        return x * p.x + y * p.y + z * p.z; }
    point3d operator*(P(p)) const {
        return point3d(y*p.z - z*p.y,
                      z*p.x - x*p.z, x*p.y - y*p.x); }
    double length() const {
        return sqrt(*this % *this); }
    double distTo(P(p)) const {
        return (*this - p).length(); }
    double distTo(P(A), P(B)) const {
        // A and B must be two different points
        return ((*this - A) * (*this - B)).length() /
            A.distTo(B); }
    point3d normalize(double k = 1) const {
        // length() must not return 0
        return (*this) * (k / length()); }
    point3d getProjection(P(A), P(B)) const {
        point3d v = B - A;
        return A + v.normalize((v % (*this - A)) /
            v.length()); }
    point3d rotate(P(normal)) const {
        //normal must have length 1 and be orthogonal to
        → the vector
}

```

```

    return (*this) * normal; }
point3d rotate(double alpha, P(normal)) const {
    return (*this) * cos(alpha) + rotate(normal) *
        → sin(alpha); }
point3d rotatePoint(P(O), P(axe), double alpha)
    → const{
    point3d Z = axe.normalize(axe % (*this - O));
    return O + Z + (*this - O - Z).rotate(alpha, O);
    → }
bool isZero() const {
    return abs(x) < EPS && abs(y) < EPS && abs(z) <
        → EPS; }
bool isOnLine(L(A, B)) const {
    return ((A - *this) * (B - *this)).isZero(); }
bool isInSegment(L(A, B)) const {
    return isOnLine(A, B) && ((A - *this) % (B -
        → *this))<EPS; }
bool isInSegmentStrictly(L(A, B)) const {
    return isOnLine(A, B) && ((A - *this) % (B -
        → *this))<-EPS; }
double getAngle() const {
    return atan2(y, x); }
double getAngle(P(u)) const {
    return atan2((*this * u).length(), *this % u); }
bool isOnPlane(PL(A, B, C)) const {
    return
        abs((A - *this) * (B - *this) % (C - *this)) <
        → EPS; } );
int line_line_intersect(L(A, B), L(C, D), point3d
    → &O){
    if (abs((B - A) * (C - A) % (D - A)) > EPS) return
    → 0;
    if (((A - B) * (C - D)).length() < EPS)
        return A.isOnLine(C, D) ? 2 : 0;
    point3d normal = ((A - B) * (C - B)).normalize();
    double s1 = (C - A) * (D - A) % normal;
    O = A + ((B - A) / (s1 + ((D - B) * (C - B) %
        → normal))) * s1;
    return 1; }
int line_plane_intersect(L(A, B), PL(C, D, E),
    → point3d &O) {
    double V1 = (C - A) * (D - A) % (E - A);
    double V2 = (D - B) * (C - B) % (E - B);
    if (abs(V1 + V2) < EPS)
        return A.isOnPlane(C, D, E) ? 2 : 0;
    O = A + ((B - A) / (V1 + V2)) * V1;
    return 1; }
bool plane_plane_intersect(P(A), P(nA), P(B), P(nB),
    point3d &P, point3d &Q) {
    point3d n = nA * nB;
    if (n.isZero()) return false;
    point3d v = n * nA;
    P = A + (n * nA) * ((B - A) % nB / (v % nB));
    Q = P + n;
    return true; }

```

5.6. Polygon Centroid.

$$C_x = \frac{1}{6A} \sum_{i=0}^{n-1} (x_i + x_{i+1})(x_i y_{i+1} - x_{i+1} y_i)$$

$$C_y = \frac{1}{6A} \sum_{i=0}^{n-1} (y_i + y_{i+1})(x_i y_{i+1} - x_{i+1} y_i)$$

$$A = \frac{1}{2} \sum_{i=0}^{n-1} (x_i y_{i+1} - x_{i+1} y_i)$$

5.7. Rectilinear Minimum Spanning Tree. Given a set of n points in the plane, and the aim is to find a minimum spanning tree connecting these n points, assuming the Manhattan distance is used. The function candidates returns at most $4n$ edges that are a superset of the edges in a minimum spanning tree, and then one can use Kruskal's algorithm. Hash: 3e3b82

```

struct RMST {
    struct point {
        int i; ll x, y;
        point() : i(-1) { }
        point(ll _x, ll _y, int _i) : x(_x), y(_y),
            → i(_i) {}
        ll d1() { return x + y; }
        ll d2() { return x - y; }
        ll dist(point other) {
            return abs(x - other.x) + abs(y - other.y); }
        bool operator <(const point &other) const {
            return y==other.y ? x > other.x : y < other.y; }
    };
    vector<point> A, best, tmp;
    int n;
    RMST() : n(0) {}
    void add_point(int x, int y) {
        A.pb(point(x,y,n++)); }
    void rec(int l, int r) {
        if (l >= r) return;
        int m = (l+r)/2;
        rec(l,m), rec(m+1,r);
        point bst;
        for(int i=l, j=m+1, k=l; i <= m || j <= r; k++) {
            if(j>r || (i <= m && A[i].d1() < A[j].d1())){
                tmp[k] = A[i++];
            if(bst.i != -1 && (best[tmp[k].i].d1() < bst.d1()))
                best[tmp[k].i] = bst;
            } else {
                tmp[k] = A[j++];
            if(bst.i == -1 || bst.d2() < tmp[k].d2())
                bst = tmp[k]; }
            rep(i,l,r+1) A[i] = tmp[i];
        }
        vector<pair<ll, ii>> candidates() {
            vector<pair<ll, ii>> es;
            tmp = best = vector<point>(n);
            REP(p, 2) {
                REP(q, 2) {

```

```

sort(all(A));
REP(i, n) best[i].i = -1;
rec(0, n-1);
REP(i, n) {
    if(best[A[i].i].i != -1)
        es.eb(A[i].dist(best[A[i].i]),
               i(A[i].i, best[A[i].i].i));
    swap(A[i].x, A[i].y);
    A[i].x *= -1, A[i].y *= -1; }
    REP(i, n) A[i].x *= -1; }
return es; } };

```

5.8. Points and lines (CP3). Hash: a7aab7

```

ld DEG_to_RAD(ld d) { return d*PI/180.0; }
ld RAD_to_DEG(ld r) { return r*180.0/PI; }

// rotate p by rad RADIANS CCW w.r.t origin (0, 0)
// NUM has to be ld
pt rotate(pt p, ld rad) {
    return make_pair(p.x*cos(rad) - p.y*sin(rad),
                     p.x*sin(rad) + p.y*cos(rad)); }

// lines are (x,y) s.t. ax + by + c = 0 AND b=0,1.
struct line { ld a, b, c; };

// gives line through p1, p2
line pointsToLine(pt p1, pt p2) {
    if(fabs(p1.x - p2.x) < EPS) // vertical line
        return { 1.0, 0.0, -(ld)p1.x };
    else {
        ld a = -(ld)(p1.y - p2.y) / (p1.x - p2.x);
        return {
            a,
            1.0,
            -(ld)(a * p1.x) - p1.y
        };
    }
}

// returns the reflection of p on the line through a
// and b
//NUM has to be ld
pt reflectionPoint(pt p, pt a, pt b) {
    pt m = proj(p, a, b);
    return m * 2 - p; }

// returns angle aob in rad in [0, 2 PI)
ld angle(pt a, pt o, pt b) {
    pt oa = a - o, ob = b - o;
    ld antw = atan2(ob.y, ob.x) - atan2(oa.y, oa.x);
    if(antw < 0)
        antw += 2 * PI;
    return antw;
}

```

5.9. Polygon (CP3). Polygons have $P_0 = P_{n-1}$ here. Hash: 4b9bcb

```

// returns the perimeter: sum of Euclidean distances
// of consecutive line segments (polygon edges)
ld perimeter(const poly &P) {
    ld result = 0.0;
    REP(i, sz(P)-1)
        result += dist(P[i], P[i+1]);
    return result; }

// Returns TWICE the area of a polygon (for
// integers)
NUM polygonTwiceArea(const poly &P) {
    NUM area = 0;
    REP(i, sz(P) - 1)
        area += P[i] ^ P[i + 1];
    return abs(area); // area < 0 <=> p ccw
}

// returns true if we always make the same turn
// throughout the polygon (strict)
bool isConvex(const poly &P) {
    int n = sz(P);
    if(n <= 3) return false; // point=2; line=3
    bool isLeft = ccw(P[0], P[1], P[2]);
    REP(i, n-2) if(ccw(P[i], P[i+1],
                        P[i+2] == n ? 1 : i+2)) != isLeft ||
        col(P[i], P[i+1], P[(i+2) == n ? 1 : i+2])
    return false; // different sign -> concave
    return true; } // convex

bool insidePolygon(const poly &P, pt p, bool strict
    → = true) {
    int n = 0;
    REP(i, sz(P) - 1) {
        // if p is on edge of polygon
        if(segmentHasPoint(p, P[i], P[i + 1])) return
            → !strict;
        // or: if(distPtSegmentSq(p, pts[i], pts[i + 1])
        → <= EPS) return !strict;

        // increment n if segment intersects line from p
        n += (max(P[i].y, P[i + 1].y) > p.y &&
            → min(P[i].y, P[i + 1].y) <= p.y &&
            (((P[i + 1] - P[i])^(p-P[i])) > 0) == (P[i].y
            → <= p.y));
    }
    return n & 1; // inside if odd number of
    → intersections
}

// cuts polygon Q along the line formed by a -> b
// (note: Q[0] == Q[n-1] is assumed)
// NUM has to be ld
poly cutPolygon(pt a, pt b, const poly &Q) {
    poly P;
    REP(i, sz(Q)) {
        ld left1 = (b - a) ^ (Q[i] - a);
        ld left2 = 0;
        if(i != sz(Q)-1)

```

```

            left2 = (b - a) ^ (Q[i+1] - a);
        if(left1 > -EPS)
            P.pb(Q[i]); // Q[i] is left of ab
        if(left1 * left2 < -EPS)
            // edge Q[i]--Q[i+1] crosses line ab
            P.pb(pt()); lineIntersectSeg(Q[i], Q[i+1],
                → a, b, P.back());
    }
    if(!P.empty() && !(P.back() == P.front()))
        P.pb(P.front()); // make P[0] == P[n-1]
    return P; }

5.10. Triangle (CP3). Hash: afa849
ld perimeter(pt a, pt b, pt c) {
    return dist(a, b) + dist(b, c) + dist(c, a); }

ld area(ld ab, ld bc, ld ca) {
    // Heron's formula
    ld s = 0.5 * (ab+bc+ca);
    return sqrt(s)*sqrt(s-ab)*sqrt(s-bc)*sqrt(s-ca);
}

ld area(pt a, pt b, pt c) {
    return area(dist(a, b), dist(b, c), dist(c, a));
}

ld rInCircle(ld ab, ld bc, ld ca) {
    return area(ab,bc,ca)*2.0 / (ab+bc+ca);
}

ld rInCircle(pt a, pt b, pt c) {
    return rInCircle(dist(a,b),dist(b,c),dist(c,a));
}

// assumption: the required points/lines functions
// have been written.
// Returns if there is an inCircle center
// if it returns TRUE, ctr will be the inCircle
// center and r is the same as rInCircle
bool inCircle(point p1, point p2, point p3, point
    → &ctr, ld &r) {
    r = rInCircle(p1, p2, p3);
    if(fabs(r) < EPS) return false;

    ld ratio = dist(p1, p2) / dist(p1, p3);
    pt q1 = p2 + (p3 - p2) * (ratio / (1 + ratio));
    ratio = dist(p2, p1) / dist(p2, p3);
    pt q2 = p1 + (p3 - p1) * (ratio / (1 + ratio));

    // get their intersection point:
    ctr = lineLineIntersection(p1, q1, p2, q2);
    return true;
}

ld rCircumCircle(ld ab, ld bc, ld ca) {
    return ab * bc * ca / (4.0 * area(ab, bc, ca)); }

ld rCircumCircle(pt a, pt b, pt c) {
    return rCircumCircle(
        dist(a,b), dist(b,c), dist(c,a));
}

```

```

}

// assumption: the required points/lines functions
// have been written.
// Returns 1 iff there is a circumCenter center
// if this function returns 1, ctr will be the
// circumCircle center and r = rCircumCircle
bool circumCircle(pt p1, pt p2, pt p3, pt &ctr, ld
→ &r) {
    ld a = p2.x - p1.x, b = p2.y - p1.y;
    ld c = p3.x - p1.x, d = p3.y - p1.y;
    ld e = a * (p1.x + p2.x) + b * (p1.y + p2.y);
    ld f = c * (p1.x + p3.x) + d * (p1.y + p3.y);
    ld g = 2.0 * (a * (p3.y - p2.y) - b * (p3.x - p2.x));
    if (fabs(g) < EPS) return false;

    ctr.x = (d*e - b*f) / g;
    ctr.y = (a*f - c*e) / g;
    r = dist(p1, ctr); // r = dist(center, p_i)
    return true;
}

// returns if pt d is strictly inside the
// circumCircle defined by a,b,c
// for non strict, change < to <=
bool inCircumCircle(pt a, pt b, pt c, pt d) {
    pt va=(d - a), vb=(d - b), vc=(d - c);
    return 0 <
        va.x * vb.y * (vc.x*vc.x + vc.y*vc.y) +
        va.y * (vb.x*vb.x + vb.y*vb.y) * vc.x +
        (va.x*va.x + va.y*va.y) * vb.x * vc.y -
        (va.x*va.x + va.y*va.y) * vb.y * vc.x -
        va.y * vb.x * (vc.x*vc.x + vc.y*vc.y) -
        va.x * (vb.x*vb.x+vb.y*vb.y) * vc.y;
}

bool canFormTriangle(NUM a, NUM b, NUM c) {
    return a+b > c && a+c > b && b+c > a;
}

5.11. Circle (CP3). Hash: e07ae5
// 0 is in circle, 1 on the border and 2 outside the
→ circle
int insideCircle(pt p, pt c, NUM r) {
    NUM d = dist2(p,c), r2 = r * r;
    return d < r2 ? 0 : d == r2 ? 1 : 2;
    → //inside/border/outside

//c becomes center of the circle through p1 and p2
→ with radius r
//For other option, reverse p1 and p2
//Requires NUM = ld
bool circle2PtsRad(pt p1, pt p2, NUM r, pt &c) {
    ld d2 = dist2(p1,p2);
    ld det = r * r / d2 - 0.25;
    if (det < 0.0) return false;
    ld h = sqrt(det);
    c.x = (p1.x + p2.x) * 0.5 + (p1.y - p2.y) * h;
    c.y = (p1.y + p2.y) * 0.5 + (p2.x - p1.x) * h;
    return true;
}

```

5.12. **Formulas.** Let $a = (a_x, a_y)$ and $b = (b_x, b_y)$ be two-dimensional vectors.

- $a \cdot b = |a||b| \cos \theta$, where θ is the angle between a and b .
- $a \times b = |a||b| \sin \theta$, where θ is the signed angle between a and b .
- $a \times b$ is equal to the area of the parallelogram with two of its sides formed by a and b . Half of that is the area of the triangle formed by a and b .
- **Euler's formula:** $V - E + F = 2$
- Side lengths a, b, c can form a triangle iff. $a + b > c, b + c > a$ and $a + c > b$.
- Sum of internal angles of a regular convex n -gon is $(n - 2)\pi$.
- **Law of sines:** $\frac{a}{\sin A} = \frac{b}{\sin B} = \frac{c}{\sin C}$
- **Law of cosines:** $b^2 = a^2 + c^2 - 2ac \cos B$
- Internal tangents of circles $(c_1, r_1), (c_2, r_2)$ intersect at $(c_1r_2 + c_2r_1)/(r_1 + r_2)$, external intersect at $(c_1r_2 - c_2r_1)/(r_1 + r_2)$.

6. MISCELLANEOUS

6.1. **Fast Fourier Transform** $\mathcal{O}(n \log n)$. Given two polynomials $A(x) = a_0 + a_1x + \dots + a_{n/2}x^{n/2}$ and $B(x) = b_0 + b_1x + \dots + b_{n/2}x^{n/2}$, FFT calculates all coefficients of $C(x) = A(x) \cdot B(x) = c_0 + c_1x + \dots + c_nx^n$, with $c_i = \sum_{j=0}^i a_j b_{i-j}$. Hash: 34d39d

```

typedef complex<ld> cpx;
typedef vector<cpx> vc;
vi rev; vc rt;
void fft(vc& A) {
    REP(i, sz(A)) if (i < rev[i]) swap(A[i],
→ A[rev[i]]);
    for (int k = 1; k < sz(A); k *= 2)
        for (int i = 0; i < sz(A); i += 2*k) REP(j, k) {
            cpx t = rt[j + k] * A[i + j + k];
            A[i + j + k] = A[i + j] - t;
            A[i + j] += t;
        }
}
void multiply(vc& a, vc& b) { // a = a * b
    ll logn = 0; for(; (1 << logn) < sz(a); logn++);
    ll n = (1 << logn); a.rs(n); b.rs(n);
    const ld PI = acos(-1.0);
    rev = vi(n); rt = vc(n);
    rev[0] = 0; rt[1] = cpx(1, 0);
    REP(i, n) rev[i] = (rev[i/2] | (i&1)<<logn)/2;
    for (int k = 2; k < n; k *= 2) {
        cpx z(cos(PI/k), sin(PI/k));
        rep(i, k/2, k) rt[2*i]=rt[i], rt[2*i+1]=rt[i]*z;
    }
    fft(a); fft(b);
    REP(i, n) a[i] *= b[i] / (ld)(n);
    REP(i, n) rt[i] = 1 / rt[i]; fft(a); }

```

NTT $\mathcal{O}(n \log(n))$. Requires $2^{e_2(\text{mod}-1)} \geq n$. Can be calculated exact by taking (multiple) large primes as modulus (and combining them with CRT). Hash: 70a119

```

//include mod_pow
const ll mod = 998244353, g = 2;//g is primitive
→ root of mod

vi rev, rt;
ll inv(ll x) { return mod_pow(x, mod - 2, mod); }
void ntt(vi &A) {
    REP(i, sz(A)) if (i < rev[i]) swap(A[i],
→ A[rev[i]]);
    for (int k = 1; k < sz(A); k *= 2)
        for (int i = 0; i < sz(A); i += 2*k) REP(j, k) {
            ll t = rt[j + k] * A[i + j + k];
            A[i + j + k] = (A[i + j] - t + mod * mod) %
→ mod;
            A[i + j] = (A[i + j] + t) % mod;
        }
}
void multiply(vi &A, vi &B) { //A = A * B
    ll logn; for(logn = 1; (1 << logn) < sz(A);
→ logn++);
    ll n = 1 << logn; rev = rt = vi(n);
    A.rs(n), B.rs(n);
    rev[0] = 0; rt[1] = 1;
    REP(i, n) rev[i] = (rev[i/2] | (i&1)<<logn)/2;
    for (int i = 1; (1 << i) < n; ++i) {
        int k = 1<<i;
        ll z = mod_pow(g, (mod - 1) >> (i + 2), mod);
        rep(i, k/2, k) rt[2*i] = rt[i], rt[2*i+1] =
→ (rt[i] * z) % mod;
    }
    ntt(A); ntt(B);
    REP(i, n) A[i] = (((A[i] * B[i]) % mod) * inv(n))
→ % mod;
    REP(i, n) rt[i] = inv(rt[i]);
    ntt(A); }

```

6.2. **Minimum Assignment (Hungarian Algorithm)** $\mathcal{O}(n^3)$. Hash: 1c5dea

```

//a[i][j] gives value for 1 <= i <= n and 1 <= j <=
→ m (1-based!)
//pm[j] gives assigned i and pn[i] assigned j
ll minimum_assignment(int n, int m, vvi& a, vi& pm,
→ vi& pn) {
    vi u(n + 1), v(m + 1), way(m + 1); pm = vi(m + 1);
    for (int i = 1; i <= n; i++) {
        pm[0] = i;
        int j0 = 0;
        vi mv(m + 1, INT_MAX);
        vb used(m + 1, false);
        do {
            used[j0] = true;
            int i0 = pm[j0], delta = INT_MAX, j1;
            for (int j = 1; j <= m; j++) {
                if (!used[j]) {

```

```

int cur = a[i0][j] - u[i0] - v[j];
if (cur < mv[j]) mv[j] = cur, way[j] = j0;
if (mv[j] < delta) delta = mv[j], j1 = j;
}
for (int j = 0; j <= m; j++) {
    if (used[j]) u[pm[j]] += delta, v[j] -=
        delta;
    else mv[j] -= delta;
}
j0 = j1;
} while (pm[j0] != 0);
do {
    int j1 = way[j0]; pm[j0] = pm[j1]; j0 = j1;
} while (j0);
}
pn = vi(n + 1); rep(i, 1, m + 1) pn[pm[i]] = i;
return -v[0];
}

```

6.3. Partial linear equation solver $\mathcal{O}(N^3)$. Hash: 79998e

```

typedef ld NUM;
const NUM EPS = 1e-5;
bool is0(NUM a) { return -EPS < a && a < EPS; }
// finds x such that Ax = b
// A_ij is M[i][j], b_i is M[i][m]
// 0 is no solution, 1 is unique, 2 is multiple
// peq is index of pivot equation
int solveM(int n, int m, vector<vector<NUM>> &M,
    vector<NUM> &val, vi &peq) {
    int pr = 0, pc = 0;
    while (pc < m) {
        //Pick first nonzero element (ld largest
        // stabsler)
        int r = pr, c;
        while (r < n && is0(M[r][pc])) r++;
        if (r == n) { pc++; continue; }
        for (c = 0; c <= m; c++)
            swap(M[pr][c], M[r][c]);
        r = pr++; c = pc++;
        NUM div = 1 / M[r][c]; //mult inv if mod
        for (int col = c; col <= m; col++)
            M[r][col] *= div;
        REP(row, n) {
            if (row == r) continue;
            // F2: if (M[row].test(c)) M[row] ^= M[r];
            NUM times = -M[row][c];
            for (int col = c; col <= m; col++)
                M[row][col] += times * M[r][col];
        }
    } // now M is in RREF

    for (int r = pr; r < n; r++)
        if (!is0(M[r][m])) return 0;
    peq = vi(m, -1);
    val = vector<NUM>(m, 0);
    for (int col = 0, row = 0; col < m && row < n;
        col++)
        if (!is0(M[row][col])) {
            peq[col] = row;

```

```

            val[col] = M[row][m];
            row++;
        }
    REP(i, m) if (peq[i] == -1) return 2;
    return 1;
}

```

6.4. Cycle-Finding. Hash: a1f2e7

```

int find_cycle(int xo, int (*f)(int)) {
    int t = f(xo), h = f(t), mu = 0, lam = 1;
    while (t != h) t = f(t), h = f(f(h));
    h = xo;
    while (t != h) t = f(t), h = f(h), mu++;
    h = f(t);
    while (t != h) h = f(h), lam++;
    return ii(mu, lam);
}

```

6.5. Longest Increasing Subsequence. Hash: 1bc3da

```

vi lis(vi arr) {
    vi seq, back(sz(arr)), ans;
    REP(i, sz(arr)) {
        int res = 0, lo = 1, hi = sz(seq);
        while (lo <= hi) {
            int mid = (lo+hi)/2;
            if (arr[seq[mid-1]] < arr[i]) res = mid, lo =
                mid + 1;
            else hi = mid - 1;
        }
        if (res < sz(seq)) seq[res] = i;
        else seq.pb(i);
        back[i] = res == 0 ? -1 : seq[res-1];
    }
    int at = seq.back();
    while (at != -1) ans.pb(at), at = back[at];
    reverse(all(ans));
    return ans;
}

```

6.6. Dates. Hash: 28e80c

```

int intToDate(int jd) { return jd % 7; }
int dateToInt(int y, int m, int d) {
    return 1461 * (y + 4800 + (m - 14) / 12) / 4 +
        367 * (m - 2 - (m - 14) / 12 * 12) / 12 -
        3 * ((y + 4900 + (m - 14) / 12) / 100) / 4 +
        d - 32075;
}
void intToDate(int jd, int &y, int &m, int &d) {
    int x, n, i, j;
    x = jd + 68569;
    n = 4 * x / 146097;
    x -= (146097 * n + 3) / 4;
    i = (4000 * (x + 1)) / 1461001;
    x -= 1461 * i / 4 - 31;
    j = 80 * x / 2447;
    d = x - 2447 * j / 80;
    x = j / 11;
    m = j + 2 - 12 * x;
    y = 100 * (n - 49) + i + x;
}

```

6.7. Simplex. Hash: 7dcfea

```

const ld EPS = 1e-9;
struct LPSolver {
    int m, n; vi B, N; vvd D;
    LPSolver(const vvd &A, const vd &b, const vd &c) :
        m(sz(b)), n(sz(c)),
        N(n + 1), B(m), D(m + 2, vd(n + 2)) {
        REP(i, m) REP(j, n) D[i][j] = A[i][j];
        REP(i, m) { B[i] = n + i; D[i][n] = -1;
            D[i][n + 1] = b[i]; }
        REP(j, n) N[j] = j, D[m][j] = -c[j];
        N[n] = -1; D[m + 1][n] = 1;
    }
    void Pivot(int r, int s) {
        ld inv = 1.0 / D[r][s];
        REP(i, m+2) if (i != r) REP(j, n+2) if (j != s)
            D[i][j] -= D[r][j] * D[i][s] * inv;
        REP(j, n+2) if (j != s) D[r][j] *= inv;
        REP(i, m+2) if (i != r) D[i][s] *= -inv;
        D[r][s] = inv;
        swap(B[r], N[s]);
    }
    bool Simplex(int phase) {
        int x = phase == 1 ? m + 1 : m;
        while (true) {
            int s = -1;
            for (int j = 0; j <= n; j++) {
                if (phase == 2 && N[j] == -1) continue;
                if (s == -1 || D[x][j] < D[x][s] ||
                    D[x][j] == D[x][s] && N[j] < N[s]) s = j;
            }
            if (D[x][s] > -EPS) return true;
            int r = -1;
            REP(i, m) {
                if (D[i][s] < EPS) continue;
                if (r == -1 || D[i][n + 1] / D[i][s] < D[r][n +
                    1] /
                    D[r][s] || (D[i][n + 1] / D[i][s]) ==
                    (D[r][n + 1] /
                    D[r][s]) && B[i] < B[r]) r = i;
            }
            if (r == -1) return false;
            Pivot(r, s);
        }
    }
    ld Solve(vd &x) {
        int r = 0;
        rep(i, 1, m) if (D[i][n+1] < D[r][n+1]) r = i;
        if (D[r][n + 1] < -EPS) {
            Pivot(r, n);
            if (!Simplex(1) || D[m + 1][n + 1] < -EPS)
                return numeric_limits<ld>::infinity();
        }
        REP(i, m) if (B[i] == -1) {
            int s = -1;
            for (int j = 0; j <= n; j++) {
                if (s == -1 || D[i][j] < D[i][s] ||
                    D[i][j] == D[i][s] && N[j] < N[s])
                    s = j;
            }
            Pivot(i, s);
        }
        if (!Simplex(2)) return
            numeric_limits<ld>::infinity();
        x = vd(n);
        for (int i = 0; i < m; i++) if (B[i] < n)

```

```

x[B[i]] = D[i][n + 1];
return D[m][n + 1]; } };
// 2-phase simplex solves linear system:
// maximize c^T x
// subject to Ax <= b, x >= 0
// INPUT: A -- an m x n matrix
//        b -- an m-dimensional vector
//        c -- an n-dimensional vector
//        x -- optimal solution (by reference)
// OUTPUT: c^T x (inf. if unbounded above, nan if
//         infeasible)
// *** Example ***
// const int m = 4, n = 3;
// ld _A[m][n] = {{6,-1,0}, {-1,-5,0},
// {1,5,1}, {-1,-5,-1}};
// ld _b[m] = {10,-4,5,-5}, _c[n] = {1,-1,0};
// vvd A(m);
// vd b(_b, _b + m), c(_c, _c + n), x;
// REP(i, m) A[i] = vd(_A[i], _A[i] + n);
// LPSolver solver(A, b, c);
// ld value = solver.Solve(x);
// cerr << "VALUE: " << value << endl; // 1.29032
// cerr << "SOLUTION: "; // 1.74194 0.451613 1
// REP(i, sz(x)) cerr << " " << x[i];
// cerr << endl;

```

7. COMBINATORICS

- Catalan numbers (valid bracket seq's of length $2n$):
 $C_0 = 1, C_n = \frac{1}{n+1} \binom{2n}{n} = \sum_{i=0}^{n-1} C_i C_{n-i-1}$.
- Stirling 1th kind (# $\pi \in \mathfrak{S}_n$ with exactly k cycles):
 $\left[\begin{smallmatrix} n \\ 0 \end{smallmatrix} \right] = \delta_{0n}, \left[\begin{smallmatrix} n \\ k \end{smallmatrix} \right] = (n-1) \left[\begin{smallmatrix} n-1 \\ k \end{smallmatrix} \right] + \left[\begin{smallmatrix} n-1 \\ k-1 \end{smallmatrix} \right]$.
- Stirling 2nd kind (k -partitions of $[n]$):
 $\left\{ \begin{smallmatrix} n \\ 1 \end{smallmatrix} \right\} = \left\{ \begin{smallmatrix} n \\ n \end{smallmatrix} \right\} = 1, \left\{ \begin{smallmatrix} n \\ k \end{smallmatrix} \right\} = k \left\{ \begin{smallmatrix} n-1 \\ k \end{smallmatrix} \right\} + \left\{ \begin{smallmatrix} n-1 \\ k-1 \end{smallmatrix} \right\}$.
- Bell numbers (partitions of $[n]$):
 $B_0 = 1, B_n = \sum_{k=0}^{n-1} B_k \binom{n-1}{k} = \sum_{k=0}^n \left\{ \begin{smallmatrix} n \\ k \end{smallmatrix} \right\}$.
- Euler (# $\pi \in \mathfrak{S}_n$ with exactly k ascents):
 $\left\langle \begin{smallmatrix} n \\ 0 \end{smallmatrix} \right\rangle = \left\langle \begin{smallmatrix} n \\ -1 \end{smallmatrix} \right\rangle = 1, \left\langle \begin{smallmatrix} n \\ k \end{smallmatrix} \right\rangle = (k+1) \left\langle \begin{smallmatrix} n-1 \\ k \end{smallmatrix} \right\rangle + (n-k) \left\langle \begin{smallmatrix} n-1 \\ k-1 \end{smallmatrix} \right\rangle$.
- Euler 2nd order (nr perms of $1, 1, 2, 2, \dots, n, n$ with exactly k ascents):
 $\left\langle \begin{smallmatrix} n \\ k \end{smallmatrix} \right\rangle = (k+1) \left\langle \begin{smallmatrix} n-1 \\ k \end{smallmatrix} \right\rangle + (2n-k-1) \left\langle \begin{smallmatrix} n-1 \\ k-1 \end{smallmatrix} \right\rangle$.
- Rooted trees: n^{n-1} , unrooted: n^{n-2} .
- Forests of k rooted trees: $\binom{n}{k} k \cdot n^{n-k-1}$.
- $1^2 + \dots + n^2 = \frac{n(n+1)(2n+1)}{6}, \quad 1^3 + \dots + n^3 = \frac{n^2(n+1)^2}{4}$
- $\sum_{i=1}^n \binom{n}{i} F_i = F_{2n}, \quad \sum_i \binom{n-i}{i} = F_{n+1}$
- $\sum_{k=0}^n \binom{k}{m} = \binom{n+1}{m+1}, \quad x^k = \sum_{i=0}^k i! \binom{k}{i} \binom{x}{i} = \sum_{i=0}^k \binom{k}{i} \binom{x+i}{k}$
- $a \equiv b \pmod{x, y} \Leftrightarrow a \equiv b \pmod{\text{lcm}(x, y)}$.
- $ac \equiv bc \pmod{m} \Leftrightarrow a \equiv b \pmod{m/\gcd(c, m)}$.
- $\gcd(n^a - 1, n^b - 1) = \gcd(a, b) - 1$.

- Möbius inversion formula:** If $f(n) = \sum_{d|n} g(d)$, then $g(n) = \sum_{d|n} \mu(d) f(n/d)$. If $f(n) = \sum_{m=1}^n g(\lfloor n/m \rfloor)$, then $g(n) = \sum_{m=1}^n \mu(m) f(\lfloor \frac{n}{m} \rfloor)$.
- Inclusion-Exclusion:** If $g(T) = \sum_{S \subseteq T} f(S)$, then

$$f(T) = \sum_{S \subseteq T} (-1)^{|T \setminus S|} g(T).$$

Corollary: $b_n = \sum_{k=0}^n \binom{n}{k} a_k \Leftrightarrow a_n = \sum_{k=0}^n (-1)^{n-k} \binom{n}{k} b_k$.

- The Twelvefold Way:** Putting n balls into k boxes. $p(n, k)$ is # partitions of n in k parts, each > 0 . $p_k(n) = \sum_{i=0}^k p(n, k)$.

Balls Boxes	same same	distinct same	same distinct	distinct distinct
-	$p_k(n)$	$\sum_{i=0}^k \binom{n}{i}$	$\binom{n+k-1}{k-1}$	k^n
size ≥ 1	$p(n, k)$	$\binom{n}{k}$	$\binom{n-1}{k-1}$	$k! \binom{n}{k}$
size ≤ 1	$[n \leq k]$	$[n \leq k]$	$\binom{k}{n}$	$n! \binom{k}{n}$

8. FORMULAS

- Legendre symbol:** $\left(\frac{a}{b} \right) = a^{(b-1)/2} \pmod{b}$, b odd prime.
- Heron's formula:** A triangle with side lengths a, b, c has area $\sqrt{s(s-a)(s-b)(s-c)}$ where $s = \frac{a+b+c}{2}$.
- Shoelace formula:** $A = \frac{1}{2} \left| \sum_{i=0}^{n-1} x_i y_{i+1} - x_{i+1} y_i \right|$.
- Pick's theorem:** A polygon on an integer grid strictly containing i lattice points and having b lattice points on the boundary has area $i + \frac{b}{2} - 1$. (Nothing similar in higher dimensions)
- Absorption probabilities** A random walk on $[0, n]$ with probability p to increase and q to decrease, starting at k has at n absorption probability $\frac{(q/p)^k - 1}{(q/p)^n - 1}$ if $q \neq p$, and k/n if $q = p$.
- A minimum Steiner tree for n vertices requires at most $n-2$ additional Steiner vertices.
- Lagrange polynomial** through points $(x_0, y_0), \dots, (x_k, y_k)$ is

$$L(x) = \sum_{j=0}^k y_j \prod_{\substack{0 \leq m \leq k \\ m \neq j}} \frac{x - x_m}{x_j - x_m}.$$

- Hook length formula:** If λ is a Young diagram and $h_\lambda(i, j)$ is the hook-length of cell (i, j) , then the number of Young tableaux $d_\lambda = n! / \prod h_\lambda(i, j)$.
- # primitive pythagorean triples with hypotenuse $< n$ approx $n/(2\pi)$.
- Frobenius Number:** largest number which can't be expressed as a linear combination of numbers a_1, \dots, a_n with non-negative coefficients. $g(a_1, a_2) = a_1 a_2 - a_1 - a_2$, $N(a_1, a_2) = (a_1 - 1)(a_2 - 1)/2$. $g(d \cdot a_1, d \cdot a_2, a_3) =$

$d \cdot g(a_1, a_2, a_3) + a_3(d-1)$. An integer $x > (\max_i a_i)^2$ can be expressed in such a way iff. $x \mid \text{gcd}(a_1, \dots, a_n)$.

- Snell's law:** $v_2 \sin \theta_1 = v_1 \sin \theta_2$ gives the shortest path between two media.
- BEST theorem:** The number of Eulerian cycles in a *directed* graph G is:

$$t_w(G) \prod_{v \in G} (\deg v - 1)!,$$

where $t_w(G)$ is the number of arborescences ("directed spanning" tree) rooted at w : $t_w(G) = \det(q_{ij})_{i,j \neq w}$, with $q_{ij} = [i=j] \text{indeg}(i) - \#\{(i, j) \in E\}$.

- Burnside's Lemma:** Let a finite group G act on a set X . Denote $X^g = \{x \in X \mid gx = x\}$. For each g in G let X^g denote the set of elements in X that are fixed by g . Then the number of orbits is:

$$|X/G| = \frac{1}{|G|} \sum_{g \in G} |X^g|.$$

- Bézout's identity:** If (x, y) is a solution to $ax + by = d$ (x, y can be found with EGCD), then all solutions are given by

$$(x + k \cdot \text{lcm}(a, b)/a, y - k \cdot \text{lcm}(a, b)/b), \quad k \in \mathbb{Z}$$

9. GAME THEORY

A game can be reduced to Nim if it is a finite impartial game. Nim and its variants include:

- Nim:** Let $X = \bigoplus_{i=1}^n x_i$, then $(x_i)_{i=1}^n$ is a winning position iff $X \neq 0$. Find a move by picking k such that $x_k > x_k \oplus X$.
- Misère Nim:** Regular Nim, except that the last player to move loses. Play regular Nim until there is only one pile of size larger than 1, reduce it to 0 or 1 such that there is an odd number of piles. The second player wins (a_1, \dots, a_n) if 1) there is a pile $a_i > 1$ and $\bigoplus_{i=1}^n a_i = 0$ or 2) all $a_i \leq 1$ and $\bigoplus_{i=1}^n a_i = 1$.
- Staircase Nim:** Stones are moved down a staircase and only removed from the last pile. $(x_i)_{i=1}^n$ is an *L*-position if $(x_{2i-1})_{i=1}^{n/2}$ is (i.e. only look at odd-numbered piles).
- Moore's Nim_k:** The player may remove from at most k piles ($\text{Nim} = \text{Nim}_1$). Expand the piles in base 2, do a carry-less addition in base $k+1$ (i.e. the number of ones in each column should be divisible by $k+1$).
- Dim⁺:** The number of removed stones must be a divisor of the pile size. The Sprague-Grundy function is $k+1$ where 2^k is the largest power of 2 dividing the pile size.
- Aliquot game:** Same as above, except the divisor should be proper (hence 1 is also a terminal state, but watch out for size 0 piles). Now the Sprague-Grundy function is just k .

- **Nim (at most half):** Write $n+1 = 2^m y$ with m maximal, then the Sprague-Grundy function of n is $(y-1)/2$.
- **Lasker's Nim:** Players may alternatively split a pile into two new non-empty piles. $g(4k+1) = 4k+1$, $g(4k+2) = 4k+2$, $g(4k+3) = 4k+4$, $g(4k+4) = 4k+3$ ($k \geq 0$).
- **Hackenbush on trees:** A tree with stalks $(x_i)_{i=1}^n$ may be replaced with a single stalk with length $\bigoplus_{i=1}^n x_i$.

10. SCHEDULING THEORY

Let p_j be the time task j takes on a machine, d_j the deadline, C_j the time it is completed, $L_j = C_j - d_j$ the lateness, $T_j = \max(L_j, 0)$ the tardiness, $U_j = 1$ iff $T_j > 0$ and else 0.

- One machine, minimise L_{\max} : do the tasks in increasing deadline
- One machine, minimise $\sum_j w_j C_j$: do the task increasing in p_j/w_j
- One machine, minimise $\sum_{j=1}^n C_j$ under the condition that all tasks can be done on time:
 - (1) Initialise $k = n, \tau = \sum_j p_j, J = [n]$
 - (2) Take $i_k \in J$ with $d_{i_k} \geq \tau$ and $p_{i_k} \geq p_\ell$ for $\ell \in J$ with $d_\ell \geq \tau$
 - (3) $\tau := \tau - p_{i_k}, k := k - 1, J := J - \{i_k\}$. If $k \neq 0$, go to step 2.
 - (4) The optimale schedule is i_1, \dots, i_n .
- One machine, minimise $\sum_j U_j$. Add all tasks in order of increasing deadline; if adding a task makes it contrary with its deadline, remove the processed task with the highest processing time.
- Two machines (all tasks have to be done on both machines, in any order), minimise C_{\max} : a greedy algorithm, when a machine is free it picks a task that hasn't been done yet on either machine and has longest processing time on the other machine.
- Two machines (all tasks have to be done first on machine 1, then machine 2), minimise C_{\max} . There is an optimal schedule with on both machines the same order of tasks. Take $X = \{j : p_{1j} \leq p_{2j}\}$ and Y the complement. Sort X increasing in p_{1j} and Y decreasing in p_{2j} . Then X, Y is an optimal schedule.
- Two machines (all tasks have to be done first on machine 1, then on 2, or vice versa), minimise C_{\max} : let J_{12} be the tasks that have to be done first on machine 1, then on 2 and similar J_{21} . Use the above algorithm to find S_{12}, S_{21} optimal for J_{12}, J_{21} . Then optimal is S_{12}, S_{21} for M1 and S_{21}, S_{12} for M2. (If there are tasks that have to be done on only one machine, do them in the middle.)

11. DEBUGGING TIPS

- Stack overflow? Recursive DFS on tree that is actually a long path?
- Floating-point numbers
 - Getting NaN? Make sure acos etc. are not getting values out of their range (perhaps 1+eps).
 - Rounding negative numbers?
 - Outputting in scientific notation?
- Wrong Answer?
 - Read the problem statement again!
 - Are multiple test cases being handled correctly? Try repeating the same test case many times.
 - Integer overflow?
 - Think very carefully about boundaries of all input parameters
 - Try out possible edge cases:
 - * $n = 0, n = -1, n = 1, n = 2^{31} - 1$ or $n = -2^{31}$
 - * List is empty, or contains a single element
 - * n is even, n is odd
 - * Graph is empty, or contains a single vertex
 - * Graph is a multigraph (loops or multiple edges)
 - * Polygon is concave or non-simple
 - Is initial condition wrong for small cases?
 - Are you sure the algorithm is correct?
 - Explain your solution to someone.
 - Are you using any functions that you don't completely understand? Maybe STL functions?
 - Maybe you (or someone else) should rewrite the solution?
 - Can the input line be empty?
- Run-Time Error?
 - Is it actually Memory Limit Exceeded?
- TLE?
 - Replace endl with newline
 - Replace vector with const size array
 - ```
#pragma GCC optimize("O3,unroll-loops") #pragma
GCC target("avx2,bmi,bmi2,popcnt")
```
  - for loop with const upper bound  $N \leq 1000 \rightarrow$ 

```
#pragma
GCC unroll(N)
```
  - Replace conditional assignment with  $a = c \cdot t + !c \cdot f$  / ternary when  $t/f$  computationally expensive
  - Reduce modulo usage / replace with bit operations
  - Still not enough? Try to reduce asymptotic runtime

### 11.1. Dynamic programming optimizations.

- Convex Hull
  - $dp[i] = \min_{j < i} \{dp[j] + b[j] \times a[i]\}$

- $b[j] \geq b[j+1]$
- optionally  $a[i] \leq a[i+1]$
- $O(n^2)$  to  $O(n)$  (see 2.11).
- Divide & Conquer
  - $dp[i][j] = \min_{k < j} \{dp[i-1][k] + C[k][j]\}$
  - $A[i][j] \leq A[i][j+1]$
  - sufficient:
  - $C[a][c] + C[b][d] \leq C[a][d] + C[b][c], (a \leq b \leq c \leq d)$  (QI)
  - $O(kn^2)$  to  $O(kn \log n)$
- Knuth
  - $dp[i][j] = \min_{i < k < j} \{dp[i][k] + dp[k][j] + C[i][j]\}$
  - $A[i][j-1] \leq A[i][j] \leq A[i+1][j]$
  - $O(n^3)$  to  $O(n^2)$
  - sufficient: QI and  $C[b][c] \leq C[a][d], a \leq b \leq c \leq d$
- 11.2. Solution Ideas.
- Dynamic Programming
  - Parsing CFGs: CYK Algorithm
  - Drop a parameter, recover from others
  - Swap answer and a parameter
  - When grouping: try splitting in two
  - $2^k$  trick
- Greedy
- Randomized
- Optimizations
  - Use bitset (/64)
  - Switch order of loops (cache locality)
- Process queries offline
  - Mo's algorithm
- Square-root decomposition
- Precomputation
- Efficient simulation
  - Mo's algorithm
  - Sqrt decomposition
  - Store  $2^k$  jump pointers
  - Simulate in reverse order
- Data structure techniques
  - Sqrt buckets
  - Store  $2^k$  jump pointers
  - $2^k$  merging trick
- Counting
  - Inclusion-exclusion principle
  - Generating functions
- Graphs
  - Can we model the problem as a graph?
  - Can we use any properties of the graph?
  - Strongly connected components

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| <ul style="list-style-type: none"> <li>– Cycles (or odd cycles)</li> <li>– Bipartite (no odd cycles)           <ul style="list-style-type: none"> <li>* Bipartite matching</li> <li>* Hall's marriage theorem</li> <li>* Stable Marriage</li> </ul> </li> <li>– Cut vertex/bridge</li> <li>– Biconnected components</li> <li>– Degrees of vertices (odd/even)</li> <li>– Trees           <ul style="list-style-type: none"> <li>* Heavy-light decomposition</li> <li>* Centroid decomposition</li> <li>* Least common ancestor</li> <li>* Centers of the tree</li> </ul> </li> <li>– Eulerian path/circuit</li> <li>– Chinese postman problem</li> <li>– Topological sort</li> <li>– (Min-Cost) Max Flow</li> <li>– Min Cut           <ul style="list-style-type: none"> <li>* Maximum Density Subgraph</li> </ul> </li> <li>– Huffman Coding</li> <li>– Min-Cost Arborescence</li> <li>– Steiner Tree</li> <li>– Kirchoff's matrix tree theorem</li> <li>– Prüfer sequences</li> <li>– Lovász Toggle</li> <li>– Look at the DFS tree (which has no cross-edges)</li> <li>– Is the graph a DFA or NFA?           <ul style="list-style-type: none"> <li>* Is it the Synchronizing word problem?</li> </ul> </li> <li>● math           <ul style="list-style-type: none"> <li>– Is the function multiplicative?</li> <li>– Look for a pattern</li> <li>– Permutations           <ul style="list-style-type: none"> <li>* Consider the cycles of the permutation</li> </ul> </li> <li>– Functions           <ul style="list-style-type: none"> <li>* Sum of piecewise-linear functions is a piecewise-linear function</li> <li>* Sum of convex (concave) functions is convex (concave)</li> </ul> </li> <li>– Modular arithmetic           <ul style="list-style-type: none"> <li>* Chinese Remainder Theorem</li> <li>* Linear Congruence</li> </ul> </li> <li>– Sieve</li> <li>– System of linear equations</li> <li>– Values too big to represent?           <ul style="list-style-type: none"> <li>* Compute using the logarithm</li> <li>* Divide everything by some large value</li> </ul> </li> <li>– Linear programming           <ul style="list-style-type: none"> <li>* Is the dual problem easier to solve?</li> </ul> </li> </ul> </li> </ul> | <ul style="list-style-type: none"> <li>– Can the problem be modeled as a different combinatorial problem? Does that simplify calculations?</li> <li>● Logic           <ul style="list-style-type: none"> <li>– 2-SAT</li> <li>– XOR-SAT (Gauss elimination or Bipartite matching)</li> </ul> </li> <li>● Meet in the middle</li> <li>● Only work with the smaller half (<math>\log(n)</math>)</li> <li>● Strings           <ul style="list-style-type: none"> <li>– Trie (maybe over something weird, like bits)</li> <li>– Suffix array</li> <li>– Suffix automaton (+DP?)</li> <li>– Aho-Corasick</li> <li>– eerTree</li> <li>– Work with <math>S + S</math></li> </ul> </li> <li>● Hashing</li> <li>● Euler tour, tree to array</li> <li>● Segment trees           <ul style="list-style-type: none"> <li>– Lazy propagation</li> <li>– Persistent</li> <li>– Implicit</li> <li>– Segment tree of X</li> </ul> </li> <li>● Geometry           <ul style="list-style-type: none"> <li>– Minkowski sum (of convex sets)</li> <li>– Rotating calipers</li> <li>– Sweep line (horizontally or vertically?)</li> <li>– Sweep angle</li> <li>– Convex hull</li> </ul> </li> <li>● Fix a parameter (possibly the answer).</li> <li>● Are there few distinct values?</li> <li>● Binary search</li> <li>● Sliding Window (+ Monotonic Queue)</li> <li>● Computing a Convolution? Fast Fourier Transform</li> <li>● Computing a 2D Convolution? FFT on each row, and then on each column</li> <li>● Exact Cover (+ Algorithm X)</li> <li>● Cycle-Finding</li> <li>● What is the smallest set of values that identify the solution? The cycle structure of the permutation? The powers of primes in the factorization?</li> <li>● Look at the complement problem           <ul style="list-style-type: none"> <li>– Minimize something instead of maximizing</li> </ul> </li> <li>● Immediately enforce necessary conditions. (All values greater than 0? Initialize them all to 1)</li> <li>● Add large constant to negative numbers to make them positive</li> <li>● Counting/Bucket sort</li> </ul> | <p><b>PRACTICE CONTEST CHECKLIST</b></p> <ul style="list-style-type: none"> <li>● How many operations per second? Compare to local machine.</li> <li>● What is the stack size?</li> <li>● How to use printf/scanf with long long/long double?</li> <li>● Are <code>__int128</code> and <code>__float128</code> available?</li> <li>● Does MLE give RTE or MLE as a verdict? What about stack overflow?</li> <li>● What is <code>RAND_MAX</code>?</li> <li>● How does the judge handle extra spaces (or missing newlines) in the output?</li> <li>● Look at documentation for programming languages.</li> <li>● Try different programming languages: C++, Java and Python.</li> <li>● Try the submit script.</li> <li>● Try local programs: <code>i?python[23]</code>, <code>factor</code>.</li> <li>● Try submitting with <code>assert(false)</code> and <code>assert(true)</code>.</li> <li>● Omitting <code>return 0;</code> still works?</li> <li>● Look for directory with sample test cases.</li> <li>● Make sure printing works.</li> </ul> |
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