

Team Note of Powered by Zigui

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ALL BELOW HERE ARE USELESS IF YOU READ THE STATEMENT WRONG

0 Quotes and Prerequisites

evenharder : Mental Abuse To Humans
 djkim0613 : 열심히 응원하겠습니다.
 SoulTch : How much is this bus ticket?
 * This template is brought from that of 'Deobureo Minkyu Party'

Run script

```
#!/bin/bash
g++ -fsanitize=undefined -std=c++14 -O2 -o /tmp/pow $1.cpp
time /tmp/pow < $1.in
# export PATH=~:$PATH
```

Debug Code

```
#define setz(x) memset(x, 0, sizeof(x))
#define sz(x) ((int)(x).size())
#define rep(i, e) for (int i = 0, _##i = (e); i < _##i; i++)
#define repp(i, s, e) for (int i = (s), _##i = (e); i < _##i; i++)
#define repr(i, s, e) for (int i = (s)-1, _##i = (e); i >= _##i; i--)
#define repi(i, x) for (auto &i : (x))
// using namespace std;
using ll = long long;
using pii = pair<int, int>;
using pll = pair<ll, ll>;
template<typename T>
ostream &operator<<(ostream &os, const vector<T>& v) {
    cout << "[";
    for (auto p : v) cout << p << ", ";
    cout << "]";
    return os;
}
#ifdef __SOULTCH
#define debug(...) 0
#define endl '\n'
#else
#define debug(...) cout << " [-] ", _dbg(#__VA_ARGS__, __VA_ARGS__)
template<class TH> void _dbg(const char *sdbg, TH h){ cout << sdbg << '=' << h << endl; }
template<class TH, class... TA> void _dbg(const char *sdbg, TH h, TA... a) {
    while(*sdbg != ',') cout << *sdbg++;
    cout << '=' << (h) << ', ';
    _dbg(sdbg+1, a...);
}
#endif
```

Reminders

Pre-submit	Wrong answer:
예제 작성해보기 (최소, 최대) 메모리, overflow 분석하기 올바른 문제에 제출하기	코드 + debug output 출력 다중 테케 문제에서 초기화 확인하기 알고리즘이 제한조건을 전부 다루는지 확인하기 지문 다시 읽어보기 corner case 찾아보기 초기화 안 된 지역변수 찾아보기 N, M, i, j 등 변수 확인하기 풀이 증명하기 STL 함수 다시 생각해보기 팀노트에서 그대로 가져온 변수값 다시 확인하기 이 목록 다시 읽어보기 알고리즘 팀원에게 설명하기 팀원이랑 코드 보기 잠깐 일어나서 생각 재정비하고 오기 입출력 형식 확인하기 (whitespace 포함)
Runtime error:	Time limit exceeded: / Memory limit exceeded:
코너 케이스 처리해보기 초기화 안 된 변수 찾기 out-of-range 확인하기 팀노트에서 그대로 가져온 변수값 다시 확인하기 assertion 넣어보기 무한 재귀 확인하기 null pointer 확인하기 메모리 사용량 확인하기	무한 루프 확인하기 알고리즘 시간 복잡도 확인하기 data copy 어느 정도 하는지 확인하기 (reference) 입출력 규모 생각하기 (scanf 고려해보기) vector, map 최소화하기 팀원에게 알고리즘 물어보기 최대 메모리 사용량 계산하기 다중 테케 문제에서 초기화하기

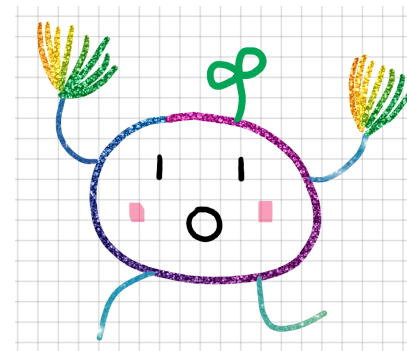


Figure 1: 풀다가 막힐 때는 이 그림을 봅시다. 아자아자 화이팅!

1 Math

1.1 Basic Mathematics

1.1.1 Trigonometry

- $\sin(\alpha \pm \beta) = \sin \alpha \cos \beta \pm \cos \alpha \sin \beta$
- $\cos(\alpha \pm \beta) = \cos \alpha \cos \beta \mp \sin \alpha \sin \beta$
- $\tan(\alpha \pm \beta) = \frac{\tan \alpha \pm \tan \beta}{1 \mp \tan \alpha \tan \beta}$
- $\sin 2\theta = 2 \sin \theta \cos \theta$
- $c^2 = a^2 + b^2 - 2ab \cos \gamma$

1.1.2 Generating Function

- $\sum_n (pn + q)x^n = \frac{p}{1-x} + \frac{q}{(1-x)^2}$ (Arithmetic progression)
- $\sum_n (rx)^n = (1 - rx)^{-1}$ (Geometric progression)
- $\sum_n \binom{m}{n} x^n = (1 + x)^m$ (Binomial coefficient)
- $\sum_n \binom{m+n-1}{n} x^n = (1 - x)^{-m}$ (Multiset coefficient)

1.1.3 Calculus

- $\int_a^b f(x) dx = \frac{b-a}{6} \left[f(a) + 4f\left(\frac{a+b}{2}\right) + f(b) \right]$ (Simpson's Rule, for cubic poly)
- $\int u'v dx = uv - \int uv' dx$ (Integration by parts)

1.1.4 Combinatorics

$\begin{bmatrix} n \\ k \end{bmatrix}$ (Stirling numbers of the first kind / n elem, k cycle)

- $\begin{bmatrix} n+1 \\ k \end{bmatrix} = n \begin{bmatrix} n \\ k \end{bmatrix} + \begin{bmatrix} n \\ k-1 \end{bmatrix}$, $\begin{bmatrix} n \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ n \end{bmatrix} = 1$

$\begin{Bmatrix} n \\ k \end{Bmatrix}$ (Stirling numbers of the second kind / n elem, k unlabeled subset)

- $\begin{Bmatrix} n+1 \\ k \end{Bmatrix} = k \begin{Bmatrix} n \\ k \end{Bmatrix} + \begin{Bmatrix} n \\ k-1 \end{Bmatrix}$, $\begin{Bmatrix} n \\ 0 \end{Bmatrix} = \begin{Bmatrix} 0 \\ n \end{Bmatrix} = 1$

B_n (Bell number, n elem, partition)

- $B_{n+1} = \sum_{k=0}^n \binom{n}{k} B_k$, $B_{n+1} = \sum_{k=0}^n \begin{Bmatrix} n \\ k \end{Bmatrix}$

- $B_{p^m+n} \equiv mB_n + B_{n+1}$

1.2 Number Theory

1.2.1 Lattice Points under Line

$$\text{divsum}(\text{to}, c, k, m) = \sum_{i=0}^{\text{to}-1} \left\lfloor \frac{ki + c}{m} \right\rfloor, \text{modsum}(\text{to}, c, k, m) = \sum_{i=0}^{\text{to}-1} (ki + c) \% m$$

```
ull sumsq(ull to) { return to / 2 * ((to-1) | 1); }
ull divsum(ull to, ull c, ull k, ull m) {
    ull res = k / m * sumsq(to) + c / m * to;
    k %= m; c %= m;
    if (!k) return res;
    ull to2 = (to * k + c) / m;
    return res + (to - 1) * to2 - divsum(to2, m-1 - c, m, k);
}
ll modsum(ull to, ll c, ll k, ll m) {
    c = ((c % m) + m) % m; k = ((k % m) + m) % m;
    return to * c + k * sumsq(to) - m * divsum(to, c, k, m);
}
```

1.2.2 Shanks' Baby-step Giant-step

```
ll mexp(ll x, ll y, ll p) {
    if (!y) return 1;
    if (y & 1) return x * mexp(x*x%p, y>>1, p) % p;
    return mexp(x*x%p, y>>1, p);
}
vector<ll> get_factor(ll n) {
    vector<ll> v;
    for (ll i=2; i*i<=n; i++) {
        if (n % i == 0) {
            v.push_back(i);
            while (n % i == 0) n /= i;
        }
    }
    if (n > 1) v.push_back(n);
    return v;
}
ll get_primitive(ll n) {
    ll phi = n-1; // assume n is prime
    vector<ll> fact = get_factor(phi);
    for (ll x=2; x<=n; x++) {
        int yes = 1;
        for (ll y : fact) {
            yes &= (mexp(x, phi / y, n) != 1);
        }
        if (yes) return x;
    }
    return -1;
}
// find k s.t. g^k = b mod n
ll bsgs(ll g, ll b, ll n) {
```

```

ll sq = ceil(sqrt(n) + 1e-9);
vector<pl> prec(sq);
for(ll i=0; i<sq; i++) {
    prec[i] = {mexp(g, i, n), i};
}
sort(prec.begin(), prec.end());
ll base = mexp(g, n-1-sq, n); // g^(-m), assume n : prime
ll cur = b;
for(int i=0; i<sq; i++) {
    auto it = lower_bound(prec.begin(), prec.end(), pl(cur, 0));
    if(it->first == cur) {
        return (i*sq + it->second) % (n-1);
    }
    cur = cur * base % n;
}
return -1;
}

```

1.2.3 Extended Euclidean Algorithm

```

// ax + by = gcd(a,b). x, y?
pll ext_gcd(ll a, ll b) {
    if(b) {
        auto tmp = ext_gcd(b, a%b);
        return {tmp.second, tmp.first - (a/b) * tmp.second};
    }
    else return {1, 0};
}
// ax = gcd(a, m) mod m. x?
ll mod_inv(ll a, ll m) {
    return (ext_gcd(a, m).first + m) % m;
}

```

1.2.4 Chinese Remainder Theorem

```

ll pos_rem(ll a, ll m) { // m > 0. a % m?
    ll res = abs(a) % m;
    return a > 0 ? res : (res ? m - res : 0);
}
// ax = c mod m, bx = d mod n. x?
ll solve(ll a, ll c, ll m, ll b, ll d, ll n) {
    a = pos_rem(a, m); c = pos_rem(c, m); // if a, c not in [0, m)
    b = pos_rem(b, n); d = pos_rem(d, n); // if b, d not in [0, n)
    ll g = _gcd(a, _gcd(c, m)); a /= g, c /= g, m /= g;
    g = _gcd(b, _gcd(d, n)); b /= g, d /= g, n /= g;
    if(c % _gcd(a, m) || d % _gcd(b, n)) return inf;
    ll t1 = (mod_inv(a, m) * c) % m;
    ll t2 = (mod_inv(b, n) * d) % n;
    g = _gcd(m, n);
    ll lc = m * n / g;
    if(abs(t1 - t2) % g) return inf;
}

```

```

pl p = ext_gcd(m, n);
ll q = (t1 * p.second * n/g + t2 * p.first * m/g);
return pos_rem(q, lc);
}

```

1.2.5 Möbius Inversion Formula

$$\forall n \in \mathbb{N} \ g(n) = \sum_{d|n} f(d) \implies f(n) = \sum_{d|n} \mu(d) g(n/d)$$

1.3 FFT

$$\text{FFT} : (a_0, a_1, \dots, a_{n-1}) \mapsto (\sum_{j=0}^{n-1} a_j (\omega^0)^j, \sum_{j=0}^{n-1} a_j (\omega^1)^j, \dots, \sum_{j=0}^{n-1} a_j (\omega^{n-1})^j)$$

```

using base = complex<double>;
void fft(vector<base>& a, bool inv) {
    int n = a.size(), j = 0;
    vector<base> roots(n/2);
    for(int i=1; i<n; i++) {
        int bit = (n >> 1);
        while(j >= bit) {
            j -= bit;
            bit >>= 1;
        }
        j += bit;
        if(i < j) swap(a[i], a[j]);
    }

    double ang = 2 * acos(-1) / n * (inv ? -1 : 1);
    for(int i=0; i<n/2; i++)
        roots[i] = base(cos(ang * i), sin(ang * i));
    /* In NTT, let prr = primitive root. Then,
    int prr = 3, ang = mexp(prr, (mod - 1) / n);
    if(inv) ang = mexp(ang, mod - 2);
    for(int i=0; i<n/2; i++){
        roots[i] = (i ? (1ll * roots[i-1] * ang % mod) : 1);
    }
    also, make sure to apply modulus under here
    and pre-compute mexp(n, mod-2)
    */
    for(int i=2; i<=n; i<=<1) {
        int step = n / i;
        for(int j=0; j<n; j+=i) {
            for(int k=0; k<i/2; k++) {
                base u = a[j+k], v = a[j+k+i/2] * roots[step * k];
                a[j+k] = u+v;
                a[j+k+i/2] = u-v;
            }
        }
    }
    if(inv) for(int i=0; i<n; i++) a[i] /= n;
}

```

```

void conv(vector<base>& x, vector<base>& y) {
    int n = 2; while(n < x.size()+y.size()) n <= 1;
    x.resize(n); y.resize(n);
    fft(x, false); fft(y, false);
    for(int i=0; i<n; i++) x[i] *= y[i];
    fft(x, true); // access (ll)round(x[i].real())
}

```

1.4 Miller-Rabin + Pollard-Rho

//Prove By Solving - <https://www.acmicpc.net/problem/4149>

```

namespace miller_rabin{
    lint mul(lint x, lint y, lint mod){ return (__int128) x * y % mod; }
    lint ipow(lint x, lint y, lint p){
        lint ret = 1, piv = x % p;
        while(y){
            if(y&1) ret = mul(ret, piv, p);
            piv = mul(piv, piv, p);
            y >>= 1;
        }
        return ret;
    }
    bool miller_rabin(lint x, lint a){
        if(x % a == 0) return 0;
        lint d = x - 1;
        while(1){
            lint tmp = ipow(a, d, x);
            if(d&1) return (tmp != 1 && tmp != x-1);
            else if(tmp == x-1) return 0;
            d >>= 1;
        }
    }
    bool isprime(lint x){
        for(auto &i : {2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37}){
            if(x == i) return 1;
            if(x > 40 && miller_rabin(x, i)) return 0;
        }
        if(x <= 40) return 0;
        return 1;
    }
}

namespace pollard_rho{
    lint f(lint x, lint n, lint c){
        return (c + miller_rabin::mul(x, x, n)) % n;
    }
    void rec(lint n, vector<lint> &v){
        if(n == 1) return;
        if(n % 2 == 0){
            v.push_back(2);

```

```

            rec(n/2, v);
            return;
        }
        if(miller_rabin::isprime(n)){
            v.push_back(n);
            return;
        }
        lint a, b, c;
        while(1){
            a = rand() % (n-2) + 2;
            b = a;
            c = rand() % 20 + 1;
            do{
                a = f(a, n, c);
                b = f(f(b, n, c), n, c);
            }while(gcd(abs(a-b), n) == 1);
            if(a != b) break;
        }
        lint x = gcd(abs(a-b), n);
        rec(x, v);
        rec(n/x, v);
    }
    vector<lint> factorize(lint n){
        vector<lint> ret;
        rec(n, ret);
        sort(ret.begin(), ret.end());
        return ret;
    }
};

```

1.5 Black Box Linear Algebra + Kitamasa

```

const int mod = 998244353;
using lint = long long;
lint ipow(lint x, lint p){
    lint ret = 1, piv = x;
    while(p){
        if(p & 1) ret = ret * piv % mod;
        piv = piv * piv % mod;
        p >>= 1;
    }
    return ret;
}

vector<int> berlekamp_massey(vector<int> x){
    vector<int> ls, cur;
    int lf, ld;
    for(int i=0; i<x.size(); i++){
        lint t = 0;
        for(int j=0; j<cur.size(); j++){
            t = (t + 1ll * x[i-j-1] * cur[j]) % mod;
        }

```

```

    if((t - x[i]) % mod == 0) continue;
    if(cur.empty()){
        cur.resize(i+1);
        lf = i;
        ld = (t - x[i]) % mod;
        continue;
    }
    lint k = -(x[i] - t) * ipow(ld, mod - 2) % mod;
    vector<int> c(i-lf-1);
    c.push_back(k);
    for(auto &j : ls) c.push_back(-j * k % mod);
    if(c.size() < cur.size()) c.resize(cur.size());
    for(int j=0; j<cur.size(); j++){
        c[j] = (c[j] + cur[j]) % mod;
    }
    if(i-lf+(int)ls.size()>=(int)cur.size()){
        tie(ls, lf, ld) = make_tuple(cur, i, (t - x[i]) % mod);
    }
    cur = c;
}
for(auto &i : cur) i = (i % mod + mod) % mod;
return cur;
}
int get_nth(vector<int> rec, vector<int> dp, lint n){
    int m = rec.size();
    vector<int> s(m), t(m);
    s[0] = 1;
    if(m != 1) t[1] = 1;
    else t[0] = rec[0];
    auto mul = [&rec](vector<int> v, vector<int> w){
        int m = v.size();
        vector<int> t(2 * m);
        for(int j=0; j<m; j++){
            for(int k=0; k<m; k++){
                t[j+k] += 111 * v[j] * w[k] % mod;
                if(t[j+k] >= mod) t[j+k] -= mod;
            }
        }
        for(int j=2*m-1; j>=m; j--){
            for(int k=1; k<=m; k++){
                t[j-k] += 111 * t[j] * rec[k-1] % mod;
                if(t[j-k] >= mod) t[j-k] -= mod;
            }
        }
        t.resize(m);
        return t;
    };
    while(n){
        if(n & 1) s = mul(s, t);
        t = mul(t, t);

```

```

        n >>= 1;
    }
    lint ret = 0;
    for(int i=0; i<m; i++) ret += 111 * s[i] * dp[i] % mod;
    return ret % mod;
}
int guess_nth_term(vector<int> x, lint n){ // init with > 3k, 0(1~2 lg n)
    if(n < x.size()) return x[n];
    vector<int> v = berlekamp_massey(x);
    if(v.empty()) return 0;
    return get_nth(v, x, n);
}
struct elem{int x, y, v;}; // A(x, y) <- v, 0-based. no duplicate please..
vector<int> get_min_poly(int n, vector<elem> M){
    // smallest poly P such that A^i = sum_{j < i} {A^j \times P_j}
    vector<int> rnd1, rnd2;
    mt19937 rng(0x14004);
    auto randint = [&rng](int lb, int ub){
        return uniform_int_distribution<int>(lb, ub)(rng);
    };
    for(int i=0; i<n; i++){
        rnd1.push_back(randint(1, mod - 1));
        rnd2.push_back(randint(1, mod - 1));
    }
    vector<int> gobs;
    for(int i=0; i<2*n+2; i++){
        int tmp = 0;
        for(int j=0; j<n; j++){
            tmp += 111 * rnd2[j] * rnd1[j] % mod;
            if(tmp >= mod) tmp -= mod;
        }
        gobs.push_back(tmp);
        vector<int> nxt(n);
        for(auto &i : M){ // sparse matrix * vector
            nxt[i.x] += 111 * i.v * rnd1[i.y] % mod;
            if(nxt[i.x] >= mod) nxt[i.x] -= mod;
        }
        rnd1 = nxt;
    }
    auto sol = berlekamp_massey(gobs);
    reverse(sol.begin(), sol.end());
    return sol;
}
lint det(int n, vector<elem> M){
    vector<int> rnd;
    mt19937 rng(0x14004);
    auto randint = [&rng](int lb, int ub){
        return uniform_int_distribution<int>(lb, ub)(rng);
    };
    for(int i=0; i<n; i++) rnd.push_back(randint(1, mod - 1));

```

```

for(auto &i : M){
    i.v = 111 * i.v * rnd[i.y] % mod;
}
auto sol = get_min_poly(n, M)[0];
if(n % 2 == 0) sol = mod - sol;
for(auto &i : rnd) sol = 111 * sol * ipow(i, mod - 2) % mod;
return sol;
}

```

2 Geometry

2.1 struct Point

```

const double eps = 1e-10;
template <class T>
struct point{
    typedef point P;
    T x, y;
    point(T x=0, T y=0) : x(x), y(y) {}
    bool operator< (P a) const {return x!=a.x ? x<a.x : y<a.y;}
    bool operator== (P a) const {return x==a.x && y==a.y;}
    P operator+ (P a) const {return P(x+a.x, y+a.y);}
    P operator- (P a) const {return P(x-a.x, y-a.y);}
    P operator- () const {return P(-x, -y);}
    T operator* (P a) const {return x*a.x + y*a.y;} // inner prod
    T operator/ (P a) const {return x*a.y - y*a.x;} // outer prod
    T dist2() const {return x*x + y*y;}
    double dist() const {return sqrt(double(dist2()));}
    P perp() const {return P(-y, x);} // rotate 90 deg ccw
    P mult(T t) const {return P(x*t, y*t);}
    P unit() const {return P(x/dist(), y/dist());}
    P rotate(double a){
        return P(x*cos(a)-y*sin(a), x*sin(a)+y*cos(a));
    }
};
int sgn(double x) {return (x > eps) - (x < -eps);}
typedef point<ll> P; // use point<double> at caution with fabs, eps

```

2.2 Distance, Intersection

2.2.1 Point-to-Line

```

double lineDist(P a, P b, P p) {
    return ((b-a)/(p-a))/(b-a).dist(); // a->b : left (+), right : (-);
}

```

2.2.2 Point-to-Segment

```

double segDist(P s, P e, P p) {
    if(s == e) return (p-s).dist(); // mind the eps
    double d = (e-s).dist2(), t = min(d, max(.0, (p-s)*(e-s)));

```

```

    return ((p-s).mult(d)-(e-s).mult(t)).dist() / d;
}

```

2.2.3 Line intersection

```

template<class P>
pair<int, P> lineInter(P a, P b, P c, P d){
    if((b-a)/(d-c) == 0) // parallel, mind the eps
        return {-(b-a)/(c-a) == 0}, a;
    double oa = (d-c)/(a-c), ob = (d-c)/(b-c);
    return {(a.mult(ob) - b.mult(oa)).mult(1/(ob-oa))};
} // 1,0,-1(inf) : inter

```

2.2.4 Segment Intersection

```

bool onSegment(P s, P e, P p) {return segDist(s, e, p) < eps;}

```

```

template<class P> vector<P> segInter(P a, P b, P c, P d){
    double oa = (d-c)/(a-c), ob = (d-c)/(b-c),
           oc = (b-a)/(c-a), od = (b-a)/(d-a);
    if(sgn(oa)*sgn(ob) < 0 && sgn(oc)*sgn(od) < 0)
        return {(a.mult(ob) - b.mult(oa)).mult(1/(ob-oa))};
    set<P> S;
    if(onSegment(c, d, a)) S.insert(a);
    if(onSegment(c, d, b)) S.insert(b);
    if(onSegment(a, b, c)) S.insert(c);
    if(onSegment(a, b, d)) S.insert(d);
    return vector<P>(S.begin(), S.end());
}

```

2.2.5 Circle-Line Intersection

```

vector<P> circLine(P A, P B, P O, double r){
    vector<P> v;
    P X = O-A, D = B-A;
    double rat = 1.0 * (X*D) / (D*D);
    double det = (X*D)*(X*D) - (D*D)*(X*X - r*r);
    if(det < 0) return {};
    else if(det < eps) return {P(A + D.mult(rat))};
    det = sqrt(det);
    return {P(A + D.mult(rat + det/(D*D))),
            P(A + D.mult(rat - det/(D*D)))};
}

```

2.2.6 Circle-Line Tangent

```

vector<P> circTangent(P A, P O, double r){
    if((O-A).dist2() < r*r + eps) return {};
    double th = asin(r/(O-A).dist());
    return {A + (O-A).rotate(th).mult(cos(th)),
            A + (O-A).rotate(-th).mult(cos(th))};
}

```

2.3 Convex Hull

```
vector<P> make_hull(vector<P>& v) {
    sort(v.begin(), v.end());
    int n = v.size(), sz = 0;
    vector<P> L, U;
    for(int i=0; i<n; i++) {
        while(sz >= 2 && (L[sz-1]-L[sz-2])/(v[i]-L[sz-1]) <= 0)
            L.pop_back(), sz--;
        L.push_back(v[i]); sz++;
    }
    sz = 0;
    for(int i=n-1; i>=0; i--) {
        while(sz >= 2 && (U[sz-1]-U[sz-2])/(v[i]-U[sz-1]) <= 0)
            U.pop_back(), sz--;
        U.push_back(v[i]); sz++;
    }
    L.pop_back(), U.pop_back();
    L.insert(L.end(), U.begin(), U.end());
    return L;
}
```

2.4 Sorting Points by Angle

```
// credit : http://koosaga.com/97
auto angle_sort = [&] (P &a, P &b){
    if((a < P(0, 0)) ^ (b < P(0, 0))) return b < a;
    if(a / b != 0) return a / b > 0;
    return a.dist2() < b.dist2(); // norm
}; // counter-clockwise sort
```

2.5 Rotating Calipers

```
ll rotating_calipers(vector<P> v) {
    v = make_hull(v);
    ll mdist = 0;
    int j = 1, n = v.size();
    v.insert(v.end(), v.begin(), v.end());
    for(int i=0; i<n; i++) {
        while((v[i+1]-v[i])/(v[j+1]-v[j]) > 0) j++;
        for(int k=0; k<2; k++)
            mdist = max(mdist, (v[j+k]-v[i]).dist2());
    }
    return mdist;
}
```

2.6 Smallest Enclosing Circle

```
//Prove By Solving - https://www.acmicpc.net/problem/11930
int main(){
    scanf("%d", &N);
```

```
for(int i = 1 ; i <= N ; i++) scanf("%lf%lf%lf", &A[i].x, &A[i].y, &A[i].z);

int t = 70000;
double rate = 1.0;
point cur = (point){0, 0, 0};
for(int i = 1 ; i <= t; i++){
    int ind = 1;
    for(int j = 1 ; j <= N ; j++)
        if( (A[j] - cur) * (A[j] - cur) >
            (A[ind] - cur) * (A[ind] - cur)) ind = j;
    cur = cur + (A[ind] - cur).mult(rate);
    rate *= 0.99;
}
double r = 0;
for(int i = 1 ; i <= N ; i++) r = max(r, (A[i] - cur) * (A[i] - cur));
cout << setprecision(10) << fixed << sqrt(r);
return 0;
} // Non-deterministic, deterministic O(n lg n) requires Voronoi diagram
```

2.7 Circumcircle

```
double cc_radius(P& A, P& B, P& C){
    return (B-A).dist() * (C-B).dist() * (A-C).dist() / fabs((A-B) / (B-C)) / 2;
}

P cc_center(P& A, P& B, P& C){
    P b = C-A, c = B-A;
    return A + (b.mult(c.dist2()) - c.mult(b.dist2())).perp().mult(0.5/(b/c));
}
```

2.8 Polygon Area

```
double ans = 0; // ans : double area
for(int i=0; i<points.size(); i++)
    ans += points[i] / points[(i+1 == points.size() ? 0 : i+1)];
```


3 Strings

3.1 Aho-Corasick Algorithm

```
// required macro : rep, repi, setz
namespace aho_corasick {
    const int MAXN = 200002, MAXC = 26;
    int go[MAXN+1][MAXC];
    int fail[MAXN+1];
    bool term[MAXN+1];

    void build(const vector<string> &v) {
        setz(go), setz(fail), setz(term);
        int cnode = 1;

        repi(s, v) {
            int p = 0; // root is 0
            repi(j, s) {
                char c = j-'a'; // check starting alphabet
                if (!go[p][c]) go[p][c] = cnode++;
                p = go[p][c];
            }
            term[p] = true;
        }

        queue<int> q; rep(i, MAXC) if (go[0][i]) q.push(go[0][i]);
        while(!q.empty()) {
            int t = q.front(); q.pop();
            rep(i, MAXC) {
                if (go[t][i]) {
                    int p = fail[t];
                    while(p and not go[p][i]) p = fail[p];
                    p = go[p][i];
                    fail[go[t][i]] = p;
                    if (term[p]) term[go[t][i]] = true;
                    q.push(go[t][i]);
                }
            }
        }

        int step(int p, int c) {
            if(go[p][c]) return go[p][c];
            if(p) return go[p][c] = step(fail[p], c); // if not root
            return go[p][c] = -1; // -1 is same as 0, but is visited
        }

        bool query(string &t) {
            int p = 0;
            repi(i, t) {
                char c = i-'a'; // check starting alphabet
```

```
                p = max(0, step(p, c));
                /* if you need the original trie, use this or make length array
                while(p and not go[p][c]) p = fail[p];
                p = max(0, go[p][c]);
                */
                if (term[p]) return true;
            }
            return false;
        }
    }
}
```

3.2 Suffix Array

```
// required macro : rep, repr, repp
// str : abracadabra
// SA : 10 7 0 3 5 8 1 4 6 9 2 (0-based)
// LCP : 1 4 1 1 0 3 0 0 2 (lcp[i] : lcp of sa[i], sa[i+1])
vector<int> make_sa(const string& s) {
    int n = s.length();
    int lim = max(128, n+1);
    vector<int> sa(n), g(n+1), ng(n+1), cnt(lim), ind(lim+1);
    rep(i, n) sa[i] = i, g[i] = s[i];
    g[n] = 0;
    for(int t=1; t<s.length(); t<=1)
    {
        auto cmp = [&] (int a, int b) {
            return g[a] != g[b] ? g[a] < g[b] : g[a+t] < g[b+t];
        };
        rep (i, n) cnt[g[min(i+t, n)]]++;
        repp(i, 1, lim) cnt[i] += cnt[i-1];
        repr(i, n, 0) ind[--cnt[g[min(i+t, n)]]] = i;
        rep (i, lim) cnt[i] = 0;
        rep (i, n) cnt[g[i]]++; // same as cnt[g[ind[i]]]++
        repp(i, 1, lim) cnt[i] += cnt[i-1];
        repr(i, n, 0) sa[--cnt[g[ind[i]]]] = ind[i];
        ng[sa[0]] = 1;
        repp(i, 1, n) ng[sa[i]] = ng[sa[i-1]] + cmp(sa[i-1], sa[i]);
        g = ng;

        fill(cnt.begin(), cnt.end(), 0);
        fill(ind.begin(), ind.end(), 0);
    }
    return sa;
}

vector<int> make_lcp(const string& s, const vector<int>& sa) {
    int n = s.length(), len = 0;
    vector<int> lcp(n-1), rank(n);
    rep(i, n) rank[sa[i]] = i;
    rep(i, n) {
        if(rank[i]) {
            int j = sa[rank[i]-1];
```

```

        int lc = n - max(i,j);
        while(len < lc && s[i+len] == s[j+len]) len++;
        lcp[rank[i]-1] = len;
    }
    if(len) len--;
}
return lcp;
}

```

3.3 Lexicographically Smallest String Rotation

```

int min_rotation(string s) {
    int a=0, N=s.size(); s += s;
    rep(b,N) rep(i,N) {
        if (a+i == b || s[a+i] < s[b+i]) {b += max(0, i-1); break;}
        if (s[a+i] > s[b+i]) { a = b; break; }
    }
    return a; // rotate(v.begin(), v.begin()+min_rotation(v), v.end());
}

```

3.4 Manacher's Algorithm

```

// 0-based
// s  = # h # e # l # l # o #
// ret = 0 1 0 1 0 1 2 1 0 1 0

vector<int> manacher(const string& s) {
    int n = s.size(), r = -1, k = -1;
    vector<int> p(n);
    for (int i=0; i<n; i++) {
        if (i<=r) p[i] = min(r-i, p[2*k-i]);
        while (i-p[i]-1>=0 and i+p[i]+1<n and s[i-p[i]-1] == s[i+p[i]+1]) p[i]++;
        if (r < i+p[i]) r = i+p[i], k = i;
    }
    return p;
}

```

3.5 Z Algorithm

```

// 0-based
// s  = a b c a b a b c a
// ret = 9 0 0 2 0 4 0 0 1

vector<int> z_algo(const string &s) {
    int l = 0, r = 0, N = sz(s);
    vector<int> Z(N);
    Z[0] = N;
    repp(i, 1, N) {
        if (i > r) {
            l = r = i;
            while(r < N and s[r] == s[r-l]) r++;

```

```

        r--;
        Z[i] = r-l+1;
    } else {
        int k = i-1;
        if (Z[k] < r-i+1) Z[i] = Z[k];
        else {
            l = i;
            while(r < N and s[r] == s[r-l]) r++;
            r--;
            Z[i] = r-l+1;
        }
    }
}
return Z;
}

```

4 Graph Theory

4.1 Biconnected Component

```

// https://gist.github.com/koosaga/6f6fd50dd7067901f1b1
int dfn[MAXN], low[MAXN], vis[MAXN]; // graph, bcc not mentioned
int piv = 0, cpiv = 1; // reset -> dfs(x, 0) -> color(x, 1)
void dfs(int x, int p){
    dfn[x] = low[x] = ++piv;
    for(int i=0; i<graph[x].size(); i++){
        int w = graph[x][i];
        if(w == p) continue;
        if(!dfn[w]){
            dfs(w, x);
            low[x] = min(low[x], low[w]);
        }
        else low[x] = min(low[x], dfn[w]);
    }
}

void color(int x, int c){
    vis[x] = 1;
    for(int i=0; i<graph[x].size(); i++){
        int w = graph[x][i];
        if(vis[w]) continue;
        if(dfn[x] <= low[w]){ // cut vertex : '<=', bridge : '<'
            bcc[c].push_back(++cpiv);
            bcc[cpiv].push_back(c);
            color(w, cpiv);
        }
        else color(w, c);
    }
}

```

4.2 Strongly Connected Component

```
const int MAXN = 2e5 + 10; // > 2*N
int N, M;
int dfsn[MAXN], low[MAXN], finished[MAXN], cnt;
vector<int> ADJ[MAXN];
vector<vector<int>> G;
stack<int> S;
int f(int x){ // f(1) f(-1) f(2) f(-2) f(3) f(-3) ... -> 0 1 2 3 4 5 ...
    return 2 * (abs(x) - 1) + (x < 0);
}

void add_edge(int x, int y){ // call by f(x), f(y)
    ADJ[x ^ 1].push_back(y);
    ADJ[y ^ 1].push_back(x);
}

// memset(finished, -1, sizeof(finished));
int scc(int here){
    static vector<int> tmp;
    S.push(here);
    dfsn[here] = low[here] = ++cnt;
    int &ret = low[here];
    for(int there : ADJ[here]){
        if(dfsn[there] == 0) ret = min(ret, scc(there));
        else if(finished[there] == -1) ret = min(ret, dfsn[there]);
    }

    if(dfsn[here] == low[here]){
        while(1){
            int x = S.top(); S.pop();
            finished[x] = G.size();
            tmp.push_back(x);
            if(x == here) break;
        }
        G.push_back(tmp);
        tmp.clear();
    }
    return ret;
}
```

4.2.1 2-SAT

scc를 실행시켜 $f(i)$ 와 $f(-i)$ 가 같은 component에 있다면, 모순. $f(i)$ 와 $f(-i)$ 중 finished 배열의 수가 작은 것이 참이다. (SCC numbering의 역순이 위상정렬이기때문에, $F \rightarrow T$ 를 유지하기 위함)

4.3 Euler Tour

```
struct Edge{
    int to, cnt; // to: 인접한 정점, cnt: 남은 사용 횟수
    Edge *dual; // dual: 역방향 간선을 가리키는 포인터
};
```

```
Edge(): Edge(-1, 0){}
Edge(int to1, int cnt1): to(to1), cnt(cnt1), dual(nullptr){}
};

void Eulerian(int curr){
    for(Edge *e: adj[curr]){
        if(e->cnt > 0){
            e->cnt--;
            e->dual->cnt--;
            Eulerian(e->to); // dfs
        }
    }
    cout << curr << '\n';
}
```

4.4 Heavy-Light Decomposition

```
int par[16][MAXN], head[MAXN], sz[MAXN], in[MAXN], out[MAXN], lv[MAXN];
vector<int> v[MAXN];
int dfs0(int x, int p) {
    lv[x] = lv[p] + 1; // lv[0] = -1;
    sz[x] = 1;
    for(int& y : v[x]) {
        if(y == p) continue;
        par[0][y] = x;
        sz[x] += dfs0(y, x);
        if(sz[v[x][0]] < sz[y]) swap(y, v[x][0]);
    }
    return sz[x];
}

void dfs1(int x, int p) {
    static int cnt = 0;
    in[x] = ++cnt;
    for(int y : v[x]) {
        if(y == p) continue;
        head[y] = y == v[x][0] ? head[x] : y;
        dfs1(y, x);
    }
    out[x] = cnt;
}

int get_query(segtree& seg, int x, int p) {
    int ret = 0;
    while(head[x] != head[p]) {
        // query(in[head[x]], in[x]);
        x = par[0][head[x]];
    }
    // query(in[p], in[x]);
    return ret;
}

// for(int i=1;i<=n;i++) if(!in[i]) head[i] = i, dfs0(i, 0), dfs1(i, 0);
```

4.5 Dominator Tree

```
namespace Dtree {
    const int MAXN = 250001;
    vector<int> E[MAXN], RE[MAXN], rdom[MAXN];

    int S[MAXN], RS[MAXN], cs;
    int par[MAXN], val[MAXN];
    int sdom[MAXN], rp[MAXN];
    int dom[MAXN];

    int Find(int x, int c = 0) {
        if (par[x] == x) return c?-1:x;
        int p = Find(par[x], 1);
        if (p == -1) return c?par[x]:val[x];
        if (sdom[val[x]] > sdom[val[par[x]]]) val[x] = val[par[x]];
        par[x] = p;
        return c?p:val[x];
    }

    void Union(int x, int y) {
        par[x] = y;
    }

    void dfs(int x) {
        RS[S[x] = ++cs] = x;
        par[cs] = sdom[cs] = val[cs] = cs;
        for(int e : E[x]) {
            if (S[e] == 0) dfs(e), rp[S[e]] = S[x];
            RE[S[e]].pb(S[x]);
        }
    }

    int Do(int s, int *up) {
        dfs(s);
        for (int i = cs; i-->0) {
            for (int e : RE[i]) sdom[i] = min(sdom[i], sdom[Find(e)]);
            if (i > 1) rdom[sdom[i]].pb(i);
            for (int e:rdom[i]) {
                int p = Find(e);
                if (sdom[p] == i) dom[e] = i;
                else dom[e] = p;
            }
            if (i > 1) Union(i, rp[i]);
        }
        for (int i = 2; i <= cs; i++) if (sdom[i] != dom[i]) dom[i] = dom[dom[i]];
        for (int i = 2; i <= cs; i++) {
            up[RS[i]] = RS[dom[i]];
        }
        return cs;
    }
}
```

```
void addE(int x, int y) {E[x].pb(y);}
}
```

4.6 Global Min Cut

```
// Stoer-Wagner Algorithm, O(VE lg E)
int minimum_cut_phase(int n, int &s, int &t,
    vector<vector<int>> &adj, vector<int> vis){
    vector<int> dist(n);
    int mincut = 1e9;
    while(true){
        int pos = -1, cur = -1e9;
        for(int i=0; i<n; i++){
            if(!vis[i] && dist[i] > cur){
                cur = dist[i];
                pos = i;
            }
        }
        if(pos == -1) break;
        s = t;
        t = pos;
        mincut = cur;
        vis[pos] = 1;
        for(int i=0; i<n; i++){
            if(!vis[i]) dist[i] += adj[pos][i];
        }
    }
    return mincut; // optimal s-t cut here is, {t} and V \ {t}
}

int solve(int n, vector<vector<int>> adj){
    if(n <= 1) return 0;
    vector<int> vis(n);
    int ans = 1e9;
    for(int i=0; i<n-1; i++){
        int s, t;
        ans = min(ans, minimum_cut_phase(n, s, t, adj, vis));
        vis[t] = 1;
        for(int j=0; j<n; j++){
            if(!vis[j]){
                adj[s][j] += adj[t][j];
                adj[j][s] += adj[j][t];
            }
        }
        adj[s][s] = 0;
    }
    return ans;
}
```

5 Network Flow

5.1 Theorems

Max-flow Min-cut theorem : 정점 s 에서 정점 t 까지 흐를 수 있는 최대 유량(max-flow)은 정점 s 와 정점 t 를 분리하는 간선들의 가중치 합(min-cut)과 같다.

Vertex cover : 어떤 그래프의 정점의 집합 S 에 대해 그래프의 모든 간선이 S 의 원소 중 최소 하나와 연결되어 있을 때, S 를 해당 그래프의 vertex cover라고 하며, minimum vertex cover는 최소 개수의 정점을 사용한 vertex cover이다.

Independent set : 어떤 그래프의 정점의 집합 S 에 대해 S 의 서로 다른 두 정점을 연결하는 간선이 없을 때, S 를 해당 그래프의 independent set이라고 하며, maximum independent set은 최대 개수의 정점을 사용한 independent set이다.

Matching (independent edge set) : 어떤 그래프의 간선의 집합 S 에 대해 S 의 서로 다른 두 간선이 공통된 정점을 가지지 않을 때, S 를 해당 그래프의 matching이라고 하며, maximum matching은 최대 개수의 간선을 사용한 matching이다.

König's theorem : 이분 그래프의 maximum matching의 크기는 minimum vertex cover의 것과 같다.

Dinic's Algorithm : 시간 복잡도 $O(V^2E)$, unit capacity에서는 $\min(V^{2/3}E, E^{3/2})$.

Circulation Problem : 새로운 source/sink s_n, t_n 를 만들어서 다음과 같이 간선을 추가하고 $\maxflow(s_n \rightarrow t_n) = \sum l_i$ 인지 확인, 이후 $s \rightarrow t$ 로 maxflow

- $s_n \rightarrow b(l), a \rightarrow t_n(l), a \rightarrow b(r-l), t \rightarrow s(\infty)$

5.2 Dinic's Algorithm

```
template<typename T>
struct Dinic{
    const T INF = 1e9;
    int N;
    struct edge{
        T index, cap, rev;
        edge(T index=0, T cap=0, T rev=0) : index(index), cap(cap), rev(rev) {}
    };

    vector<vector<edge>> ADJ;
    vector<int> R, W;

    Dinic(int N=0) : N(N), ADJ(N), R(N), W(N) {}

    void CE(int node1, int node2, int cap){
        ADJ[node1].push_back(edge(node2, cap, ADJ[node2].size()));
        ADJ[node2].push_back(edge(node1, 0, ADJ[node1].size() - 1));
    }

    bool bfs(int src, int sink){
        fill(R.begin(), R.end(), -1); R[src] = 0;
        queue<int> Q; Q.push(src);
        while(Q.size()){
            int here = Q.front(); Q.pop();
            for(auto e : ADJ[here]){
                if(e.cap > 0 && R[e.index] == -1)
                    R[e.index] = R[here] + 1, Q.push(e.index);
            }
        }
    }
};
```

```
    }
    return R[sink] != -1;
}

T dfs(int here, int sink, T f){
    if(here == sink) return f;
    for(int &i = W[here] ; i < ADJ[here].size() ; i++){
        auto &e = ADJ[here][i];
        if(e.cap > 0 && R[here] < R[e.index]){
            T res = dfs(e.index, sink, min(f, e.cap));
            if(res) {
                e.cap -= res;
                ADJ[e.index][e.rev].cap += res;
                return res;
            }
        }
    }
    return 0;
}

T solve(int src, int sink){
    T ret = 0;
    while(bfs(src, sink)){
        fill(W.begin(), W.end(), 0);
        T res;
        while((res = dfs(src, sink, INF))) ret += res;
    }
    return ret;
}
};
```

5.3 MCMF with SPFA

```
template <typename T>
struct MCMF {
    const T INF = 1e9;
    struct edge {
        T there, cap, cost, rev;
        edge(T there=0, T cap=0, T cost=0, T rev=0)
            : there(there), cap(cap), cost(cost), rev(rev) {}
    };
    int N;
    vector<vector<edge>> ADJ;
    vector<T> R, INQ, C, I;

    MCMF(int N=0) : N(N), ADJ(N + 1), R(N + 1), INQ(N + 1), C(N + 1), I(N + 1) {}

    void CE(int i, int j, T cap, T cost) {
        ADJ[i].push_back(edge(j, cap, cost, ADJ[j].size()));
        ADJ[j].push_back(edge(i, 0, -cost, ADJ[i].size() - 1));
    }
};
```

```

bool SPFA(int src, int sink) {
    queue<int> Q;    Q.push(src);
    fill(R.begin(), R.end(), -1);    R[src] = 0;
    fill(C.begin(), C.end(), INF);    C[src] = 0;
    fill(INQ.begin(), INQ.end(), 0);    INQ[src] = 1;
    while (Q.size()) {
        int here = Q.front();    Q.pop();
        INQ[here] = 0;
        for (int i = 0; i < ADJ[here].size(); i++) {
            auto e = ADJ[here][i];
            if ((C[e.there] == INF || C[e.there] > C[here] + e.cost) &&
                e.cap > 0) {
                C[e.there] = C[here] + e.cost;
                R[e.there] = here;
                I[e.there] = i;
                if (!INQ[e.there]) INQ[e.there] = 1, Q.push(e.there);
            }
        }
        if (C[sink] == INF) return false;
        return true;
    }
}

pair<T, T> mcmf(int src, int sink) {
    pair<T, T> ret{};
    while (SPFA(src, sink)) {
        T flow = INF, cost = 0;
        for (int here = sink; here != src; here = R[here])
            flow = min(flow, ADJ[R[here]][I[here]].cap);
        for (int here = sink; here != src; here = R[here]) {
            auto &e = ADJ[R[here]][I[here]];
            cost += e.cost * flow;
            e.cap -= flow;
            ADJ[e.there][e.rev].cap += flow;
        }
        ret.first += flow, ret.second += cost;
    }
    return ret;
}
};

```

5.4 Hungarian Method

```

namespace Hung {
    const int MX = 2000;
    // IMPORTANT : n <= m, 1-based
    using T = long double;

    T maxv = 1e200;
    T a[MX][MX], n, m;

```

```

void init(int nn, int mm) { n = nn; m = mm; }
void set_value(int x, int y, T val) { a[x][y] = val; }
T solve(vector<int> &ans) {
    vector<T> v(m+1), u(n+1);
    vector<int> p (m+1), way (m+1);
    for (int i=1; i<=n; ++i) {
        p[0] = i;
        int j0 = 0;
        vector<T> minv (m+1, maxv);
        vector<char> used (m+1, false);
        do {
            used[j0] = true;
            T delta = maxv;
            int i0 = p[j0], j1;
            for (int j=1; j<=m; ++j) if (!used[j]) {
                T cur = a[i0][j]-u[i0]-v[j];
                if (cur < minv[j]) minv[j] = cur, way[j] = j0;
                if (minv[j] < delta) delta = minv[j], j1 = j;
            }
            for (int j=0; j<=m; ++j) {
                if (used[j]) u[p[j]] += delta, v[j] -= delta;
                else minv[j] -= delta;
            }
            j0 = j1;
        } while (p[j0] != 0);
        do {
            int j1 = way[j0];
            p[j0] = p[j1];
            j0 = j1;
        } while (j0);
    }
    ans.resize(n + 1);
    for(int j=1; j<=m; ++j) {
        ans[p[j]] = j;
    }
    return -v[0];
}
}

```

5.5 Hopcroft-Karp Algorithm

```

struct hopcroft_karp{
    int N;
    vector<vector<int>>> ADJ;
    vector<int> L, rev, used;

    hopcroft_karp() {}
    hopcroft_karp(int N) : N(N) {
        ADJ.resize(N);
        L.resize(N), rev.resize(N, -1), used.resize(N, 0);
    }

```

```

}

void CE(int here, int there){
    ADJ[here].push_back(there);
}

void bfs(){
    queue<int> Q;
    for(int i = 0 ; i < N ; i++) {
        if(used[i]) L[i] = -1;
        else L[i] = 0, Q.push(i);
    }

    while(Q.size()){
        int here = Q.front(); Q.pop();
        for(int there : ADJ[here]){
            if(rev[there] != -1 && L[rev[there]] == -1) {
                L[rev[there]] = L[here] + 1;
                Q.push(rev[there]);
            }
        }
    }
}

bool dfs(int here){
    for(int there : ADJ[here]){
        if(rev[there] == -1 || (L[here] < L[rev[there]] && dfs(rev[there]))){
            rev[there] = here;
            used[here] = 1;
            return true;
        }
    }
    return false;
}

int solve(){
    int ret = 0;
    while(1){
        bfs();
        int res = 0;
        for(int i = 0 ; i < N ; i++) {
            if(used[i]) continue;
            res += dfs(i);
        }
        if(res == 0) break;
        ret += res;
    }
    return ret;
}
};

```

6 Optimization Tricks

An array $P[i][j]$ is **Monge** array if $\forall a \leq b \leq c \leq d, C[a][c] + C[b][d] \leq C[a][d] + C[b][c]$.

6.1 Knuth Optimization

- Recurrence : $D[i][j] = \min_{i < k < j} (D[i][k] + D[k][j]) + C[i][j]$
- Condition : $\forall a \leq b \leq c \leq d, C[i][j]$ is Monge array and $C[b][c] \leq C[a][d]$ (monotonic)
- $A[i][j] = (\min. k \text{ s.t. } D[i][j] \text{ is min.})$. Then $A[i][j-1] \leq A[i][j] \leq A[i+1][j]$
- Time Complexity: $O(N^3) \rightarrow O(N^2)$

```

// opt[i-1][i] = i
for(int d=2;d<=n;d++) {
    for(int i=1;i+d<=n+1;i++) {
        for(int k=opt[i][j-1], j=i+d; k<=opt[i+1][j]; k++) {
            int v = dp[i][k] + dp[k][j] + c[i][j];
            if(dp[i][j] > v) dp[i][j] = v, opt[i][j] = k;
        }
    }
}
}

```

6.2 Divide and Conquer Optimization

- Recurrence : $D[t][i] = \min_{k < i} (D[t-1][k] + C[k][i])$
- Condition: $C[i][j]$ is Monge array.
- $A[t][i] \leq A[t][i+1]$ ($A[t][i] = (\min. k \text{ s.t. } D[t][i] \text{ is min.})$) holds
- Able to Divide and Conquer base on calculating $D[t][i]$
- Time Complexity: $O(TN^2) \rightarrow O(TN \lg N)$

```

// range of index : [l,r]
// range of dp : [s,e]
void dnc(int t, int l, int r, int s, int e)
{
    if(s > e) return;
    int m = (s+e)/2;
    D[t][m] = 2e9;
    for(int k=l;k<=m&&k<=r;k++)
    {
        int tmp = D[t-1][k] + C[k][m];
        if(D[t][m] > tmp)
            D[t][m] = tmp, A[t][m] = k;
    }
    dnc(t, l, A[t][m], s, D[t][m]-1);
    dnc(t, A[t][m], r, D[t][m]+1, e);
}

```

6.3 Convex Hull Trick

- Recurrence : $dp[i] = \min_{j < i} (dp[j] + a[i]b[j])$
- Condition: None, but usually $b[i]$ is monotonic. If not, refer to Section 7.3.
- Time Complexity: $O(N^2) \rightarrow O(N \lg N)$, $O(N)$ if $a[i]$ is monotonic by taking valid front.

```
using ll = long long;
struct line {
    ll a, b, i;
    line(ll a=0, ll b=0, ll i=0) : a(a), b(b), i(i) {}
    ll calc(ll x) { return a*x+b; }
    double inter(line l) { return double(l.b - b) / (a - l.a); }
};
bool check_back(line& p0, line& p1, line& p2) {
    return (p1.b - p0.b) * (p1.a - p2.a) >= (p0.a - p1.a) * (p2.b - p1.b);
    return p0.inter(p1) > p1.inter(p2); // double
}
bool check_front(ll x, line& p0, line& p1) {
    return x * (p0.a - p1.a) >= (p1.b - p0.b);
    return x > p0.inter(p1);
}
struct ConvexHull {
    int l = 0, r = 0;
    vector<line> v;
    void insert(line p) {
        while(r - l >= 2 && check_back(v[r-2], v[r-1], p))
            v.pop_back(), r--;
        v.push_back(p);
    }
    pair<ll, ll> query(ll x) { // if x is increasing, else do binary search
        while(r - l >= 2 && check_front(x, v[l], v[l+1]))
            l++;
        return pair<ll, ll>{v[l].calc(x), v[l].i};
    }
};
void calc() { // psuedo-code
    ConvexHull ch;
    ll val = 0, cnt = 0; // current dp and track
    for(int i=0; i<N; i++) {
        ch.insert(line{p[i], q[i]}); // j-dependent values (b[j], dp[j])
        pll res = ch.query(x[i]);
        val = res.first + c[i]; // i-dependent values
        cnt = res.second + 1;
    }
    return pll{val, cnt};
}
```

6.4 Centroid Decomposition

```
// credit : https://gist.github.com/igorcarpanese/75162f3253bd230abd0f32f9950bf384
int dfs(int u, int p) {
    sub[u] = 1;
    for (auto v : tree[u])
        if (v != p and !chk[v]) sub[u] += dfs(v, u);
    return sub[u] + 1;
} // calc subtree size, chk means that node was a centroid

// each tree has at most two centroids
int centroid(int u, int p, int r) { // r : root
    for (auto v : tree[u])
        if (v != p and !chk[v] and sub[v] > sub[r]/2) return centroid(v, u, r);
    return u;
}
```

6.5 Aliens Trick

- Recurrence: $dp[i][j] = \min_{k < j} (dp[i-1][k] + C[k+1][j])$
- Condition: $dp[*][n]$ is convex (implied if $dp[*][n]$ is Monge array)

```
ll calc(...) {
    // (...)
    k = min(k, (int)v.size());
    ll leff = some_min_value, reff = some_big_value; // check range and overflow
    int lind = v.size(), rind = 1; // range of k, decreases when eff increase
    while(reff - leff >= 2) {
        ll meff = (leff + reff) / 2;
        pll res = calc_with_lambda(v, meff); // {value, k'}
        if(res.second < rind) res.second = rind; // rind (<) lind
        if(res.second > lind) res.second = lind; // lind (>) rind
        if(res.second == k) return res.first - k * meff;
        else if(res.second > k) lind = res.second; leff = meff; // lind (>) rind
        else rind = res.second; reff = meff;
    }
    // when minimizing, ans is max(calc_with_lambda().first - k * eff) for all eff
    // when maximizing, calculate min instead
    return max(calc_with_lambda(v, leff).first - k * leff,
               calc_with_lambda(v, reff).first - k * reff);
}
```

7 Data Structure

7.1 Persistent Segment Tree

```
const MAXN = 1e5 + 10;
struct node {
    node *l, *r;
    int val;
};
```



```

int pcnt;
node pool[MAXN * 22];
node head[MAXN];
node* alloc() {
    memset(pool + pcnt, 0, sizeof(node));
    return pool + pcnt++;
}

void init(node *here, int l, int r){
    if(l == r) return;

    int mid = (l + r) / 2;
    here->l = alloc();
    here->r = alloc();

    init(here->l, l, mid);
    init(here->r, mid + 1, r);
}

void update(node *par, node *here, int l, int r, int pos, int val){
    here->val += val;
    if(l == r) return;

    int mid = (l + r) / 2;
    here->l = par->l;
    here->r = par->r;
    if(pos <= mid) {
        here->l = alloc();
        here->l->val = par->l->val;
        update(par->l, here->l, l, mid, pos, val);
    }
    else {
        here->r = alloc();
        here->r->val = par->r->val;
        update(par->r, here->r, mid + 1, r, pos, val);
    }
}

```

7.2 Link-Cut Tree

```

struct node{
    node *pp, *p, *l, *r;
    int val;
    node(){ p = 0, l = 0, r = 0;}
    node(int val) : val(val) { p = 0, l = 0, r = 0;}
};

void push(node *x){}
void pull(node *x){}

```

```

void rotate(node *x){
    if(!x->p) return;
    push(x->p); // if there's lazy stuff
    push(x);
    node *p = x->p;
    bool is_left = (p->l == x);
    node *b = (is_left ? x->r : x->l);
    x->p = p->p;
    if(x->p && x->p->l == p) x->p->l = x;
    if(x->p && x->p->r == p) x->p->r = x;
    if(is_left){
        if(b) b->p = p;
        p->l = b;
        p->p = x;
        x->r = p;
    }
    else{
        if(b) b->p = p;
        p->r = b;
        p->p = x;
        x->l = p;
    }
    pull(p); // if there's something to pull up
    pull(x);
    //if(!x->p) root = x; // IF YOU ARE SPLAY TREE
    if(p->pp){ // IF YOU ARE LINK CUT TREE
        x->pp = p->pp;
        p->pp = nullptr;
    }
}

void splay(node *x){
    while(x->p){
        node *p = x->p;
        node *g = p->p;
        if(g){
            if((p->l == x) ^ (g->l == p)) rotate(x);
            else rotate(p);
        }
        rotate(x);
    }
}

void access(node *x){
    splay(x);
    push(x);
    if(x->r){
        x->r->pp = x;
        x->r->p = nullptr;
        x->r = nullptr;
    }
    pull(x);
}

```

```

while(x->pp){
    node *nxt = x->pp;
    splay(nxt);
    push(nxt);
    if(nxt->r){
        nxt->r->pp = nxt;
        nxt->r->p = nullptr;
        nxt->r = nullptr;
    }
    nxt->r = x;
    x->p = nxt;
    x->pp = nullptr;
    pull(nxt);
    splay(x);
}
}

node *root(node *x){
    access(x);
    while(x->l){
        push(x);
        x = x->l;
    }
    access(x);
    return x;
}

node *par(node *x){
    access(x);
    if(!x->l) return nullptr;
    push(x);
    x = x->l;
    while(x->r){
        push(x);
        x = x->r;
    }
    access(x);
    return x;
}

node *lca(node *s, node *t){
    access(s);
    access(t);
    splay(s);
    if(s->pp == nullptr) return s;
    return s->pp;
}

void link(node *par, node *son){
    access(par);
    access(son);
    //son->rev ^= 1; // remove if needed
    push(son);
    son->l = par;

```

```

par->p = son;
pull(son);
}

void cut(node *p){
    access(p);
    push(p);
    if(p->l){
        p->l->p = nullptr;
        p->l = nullptr;
    }
    pull(p);
}

```

7.3 Dynamic Convex Hull

```

// https://github.com/niklasb/contest-algos/blob/master/convex_hull/dynamic.cpp
const ll is_query = -(1LL<<62);
struct Line {
    ll m, b;
    mutable function<const Line*> succ;
    bool operator<(const Line& rhs) const {
        if (rhs.b != is_query) return m < rhs.m;
        const Line* s = succ();
        if (!s) return 0;
        return b - s->b < (s->m - m) * rhs.m;
    }
};

struct HullDynamic : public multiset<Line> { // will maintain upper hull for maximum
    bool bad(iterator y) {
        auto z = next(y);
        if (y == begin()) {
            if (z == end()) return 0;
            return y->m == z->m && y->b <= z->b;
        }
        auto x = prev(y);
        if (z == end()) return y->m == x->m && y->b <= x->b;
        return (x->b - y->b)*(z->m - y->m) >= (y->b - z->b)*(y->m - x->m);
    }
    void insert_line(Line l) {
        auto y = insert(l);
        y->succ = [=] { return next(y) == end() ? 0 : &*next(y); };
        if (bad(y)) { erase(y); return; }
        while (next(y) != end() && bad(next(y))) erase(next(y));
        while (y != begin() && bad(prev(y))) erase(prev(y));
    }
    ll eval(ll x) {
        auto l = *lower_bound((Line) { x, is_query });
        return l.m * x + l.b;
    }
};

```

7.4 Stern-Brocot Tree

```
// __int128 is recommended
bool test(ll a, ll b) { // for testing directions, vary by prob
    // return true if (true value) >= a/b
    ll n = 0, m = 1;

    rep(i, N) {
        if (n < m*A[i].fi) n = A[i].fi, m = 1;

        ll c = b*n+m*a, d = m*b;
        ll g = gcd(c, d);
        n = c/g;
        m = d/g;

        if (n > m*A[i].se) return false;
    }
    return true;
}

pair<ll, ll> stern_brocot(ll M, ll N) {
    // M : max value
    // N : max divisor
    // if result is a/b, return as {a, b}
    ll a = 0, b = 1; // l
    ll c = 1, d = 0; // r
    int l, r;
    bool chg = true;

    while(chg) {
        chg = false;

        // to left
        l = 0, r = (N-d-1)/b+1;
        while(l < r) {
            int mid = (l+r+1)/2;
            if (test(a*mid+c, b*mid+d)) r = mid-1;
            else l = mid;
        }

        c += a*l;
        d += b*l;
        chg |= (l > 0);

        // to right
        l = 0, r = (d?(N-b-1)/d+1:M);
        while(l < r) {
            int mid = (l+r+1)/2;
            if (test(a+mid*c, b+mid*d)) l = mid;
            else r = mid-1;
        }
    }
}
```

```
        a += c*l;
        b += d*l;
        chg |= (l > 0);
    }

    return {a, b};
}
```

7.5 Li-Chao Tree

```
const ll inf = 2e18;

struct Line{
    ll a, b;
    ll get(ll x){
        return a * x + b;
    }
};

struct Node{
    int l, r; //child
    ll s, e; //range
    Line line;
};

struct Li_Chao{
    vector<Node> tree;

    void init(ll s, ll e){
        tree.push_back({ -1, -1, s, e, { 0, -inf } });
    }

    void update(int node, Line v){
        ll s = tree[node].s, e = tree[node].e;
        ll m = s + e >> 1;

        Line low = tree[node].line, high = v;
        if (low.get(s) > high.get(s)) swap(low, high);

        if (low.get(e) <= high.get(e)){
            tree[node].line = high; return;
        }

        if (low.get(m) < high.get(m)){
            tree[node].line = high;
            if (tree[node].r == -1){
                tree[node].r = tree.size();
                tree.push_back({ -1, -1, m + 1, e, { 0, -inf } });
            }
            update(tree[node].r, low);
        }
    }
}
```

```

    }
    else{
        tree[node].line = low;
        if (tree[node].l == -1){
            tree[node].l = tree.size();
            tree.push_back({ -1, -1, s, m, { 0, -inf } });
        }
        update(tree[node].l, high);
    }
}

ll query(int node, ll x){
    if (node == -1) return -inf;
    ll s = tree[node].s, e = tree[node].e;
    ll m = s + e >> 1;
    if (x <= m) return max(tree[node].line.get(x), query(tree[node].l, x));
    else return max(tree[node].line.get(x), query(tree[node].r, x));
}
} seg;

```

7.6 Rope

```

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

int main()
{
    ios::sync_with_stdio(false);
    cin.tie(0);

    crope rp; // rope<char>
    string s("Lorem- ipsum");
    int n = s.length();
    rp.append(s.c_str()); // add element

    int x = 3, y = 8; // split and merge below
    rp = rp.substr(x, y-x) + rp.substr(0, x) + rp.substr(y, n);
    cout << rp.at(0) << '\n'; // get element, 'e'
    cout << rp << '\n'; // print, "em-ip|Lor|sum"
}

```

7.7 Bitset

```

#include <bitset>
#include <iostream>
using namespace std;

int main() {
    bitset<8> b1(13); // 00001101

```

```

    bitset<8> b2("10111"); // 00010111

    cout << b1.count() << endl; // 3
    cout << b1.test(6) << endl; // 0, since 2^6-th bit is 0
    b1.set(6); // set to 1, 1-fill if no param
    b2.reset(2); // set to 0, 0-fill if no param
    // use 'flip' for flipping

    cout << "b1:" << b1 << endl; // b1:01001101
    cout << "b2:" << b2 << endl; // b2:00010011
    // use any, none, all (c++11) for bit checking
    // supported operators : &, |, ^, <<, >>, ~, ==, !=
    // these operators must match size (given to template)

    cout << "&:" << (b1 & b2) << endl; // &: 00000001
    cout << "^:" << (b1 ^ b2) << endl; // ^: 01011110
    cout << "|:" << (b1 | b2) << endl; // |: 01011111
    cout << "~:" << (~b1) << endl; // ~: 10110010
    cout << "<<:" << (b1 << 3) << endl; // <<:01101000
    cout << b2.to_ulong() << endl; // 19, c++11 supports ullong
}

```

7.8 Policy Based Data Structure

```

#include <bits/stdc++.h>
#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/tree_policy.hpp>
#include <ext/pb_ds/detail/standard_policies.hpp>

using namespace std;
using namespace __gnu_pbds;

typedef tree<
    int,
    null_type,
    less<int>,
    rb_tree_tag,
    tree_order_statistics_node_update >
    ordered_set;

// less<int> : not allow for duplicate
// less_equal<int> : allow for duplicate
// use upper_bound when you erase from set used less_equal

int N;

int main(void) {
    iosstream::sync_with_stdio(false);
    cin.tie(nullptr);

    ordered_set X;

```

```
X.insert(1);
X.insert(2);
X.insert(4);
X.insert(8);
X.insert(16);

cout<<*X.find_by_order(1)<<endl; // 2
cout<<*X.find_by_order(2)<<endl; // 4
cout<<*X.find_by_order(4)<<endl; // 16
cout<<(end(X)==X.find_by_order(6))<<endl; // true

cout<<X.order_of_key(-5)<<endl; // 0
cout<<X.order_of_key(1)<<endl; // 0
cout<<X.order_of_key(3)<<endl; // 2
cout<<X.order_of_key(4)<<endl; // 2
cout<<X.order_of_key(400)<<endl; // 5
}
```

8 Miscellaneous

8.1 Misc Formulae and Algorithms

8.1.1 Faulhaber's Formula

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

Also use

$$(x+1)^d - x^d = 1 + \binom{d}{1}x + \binom{d}{2}x^2 + \cdots + \binom{d}{d-1}x^{d-1}$$

to get each coef.

8.1.2 Maximum Clique

```
typedef long long ll;
ll G[40]; // 0-index
int N, M;
int cur;
void get_clique(int R = 0, ll P = (1ll<<N)-1, ll X = 0){
    if((P/X) == 0){
        cur = max(cur, R);
        return;
    }
    int u = __builtin_ctzll(P/X);
    ll c = P&~G[u];
    while(c){
        int v = __builtin_ctzll(c);
        get_clique(R + 1, P&G[v], X&G[v]);
        P ^= 1ll << v;
    }
}
```

```

    X |= 111 << v;
    c ^= 111 << v;
}
}

```

8.1.3 De Bruijn Sequence

```
// https://github.com/koosaga/DeobureoMinkyuParty/blob/master/teamnote.tex
// alphabet = [0, k - 1], substr length n, res starts with 0 (cyclic)
int res[10000000], aux[10000000]; // >= k^n, k*n
int de_bruijn(int k, int n, int lim) { // returns size (k^n)
    if(k == 1) {
        res[0] = 0;
        return 1;
    }
    for(int i = 0; i < k * n; i++) aux[i] = 0;
    int sz = 0;
    function<void(int, int)> db = [&](int t, int p) {
        if(sz > lim) return;
        if(t > n) {
            if(n % p == 0)
                for(int i = 1; i <= p; i++)
                    res[sz++] = aux[i];
        }
        else {
            aux[t] = aux[t - p];
            db(t + 1, p);
            for(int i = aux[t - p] + 1; i < k; i++) {
                aux[t] = i;
                db(t + 1, t);
            }
        }
    };
    db(1, 1);
    return sz;
}
```

8.2 Highly Composite Numbers, Large Prime

[illegible]

11	97772875200	4032	6 3 2 2 1 1 1 1
12	963761198400	6720	6 4 2 1 1 1 1 1 1
13	9316358251200	10752	6 3 2 1 1 1 1 1 1 1
14	97821761637600	17280	5 4 2 2 1 1 1 1 1 1
15	866421317361600	26880	6 4 2 1 1 1 1 1 1 1 1
16	8086598962041600	41472	8 3 2 2 1 1 1 1 1 1 1
17	74801040398884800	64512	6 3 2 2 1 1 1 1 1 1 1 1
18	897612484786617600	103680	8 4 2 2 1 1 1 1 1 1 1 1 1

	< 10 ^k prime	> 10 ^k prime	# of prime
1	7	11	4
2	97	101	25
3	997	1009	168
4	9973	10007	1229
5	99991	100003	9592
6	999983	1000003	78498
7	9999991	10000019	664579
8	99999989	100000007	5761455
9	999999937	1000000007	50847534

	< 10 ^k prime	> 10 ^k prime
10	9999999967	100000000019
11	99999999977	1000000000003
12	999999999989	10000000000039
13	9999999999971	100000000000037
14	99999999999973	1000000000000031
15	999999999999989	10000000000000037
16	9999999999999937	100000000000000061
17	9999999999999997	100000000000000003
18	99999999999999989	1000000000000000003

NTT Prime:

$469762049 = 7 \times 2^{26} + 1$. Primitive root : 3.
 $998244353 = 119 \times 2^{23} + 1$. Primitive root: 3.
 $985661441 = 235 \times 2^{22} + 1$. Primitive root: 3.
 $1012924417 = 483 \times 2^{21} + 1$. Primitive root: 5.

Primes near 10^9 : $10^9 + [7, 9, 21, 33, 87]$

8.3 Fast Integer IO

```
// credit : https://github.com/koosaga/DeobureoMinkyuParty/blob/master/teamnote.tex
static char buf[1 << 19]; // size : any number geq than 1024
static int idx = 0;
static int bytes = 0;
static inline int _read() {
    if (!bytes || idx == bytes) {
        bytes = (int)fread(buf, sizeof(buf[0]), sizeof(buf), stdin);
        idx = 0;
    }
}
```

```
    return buf[idx++];
}
static inline int _readInt() {
    int x = 0, s = 1;
    int c = _read();
    while (c <= 32) c = _read();
    if (c == '-') s = -1, c = _read();
    while (c > 32) x = 10 * x + (c - '0'), c = _read();
    if (s < 0) x = -x;
    return x;
}
```

8.4 C++ Tips / Environments

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

struct StupidGCCantEvenCompileThisSimpleCode{
    pair<int, int> array[1000000];
}; // https://gcc.gnu.org/bugzilla/show_bug.cgi?id=68203

// how to use rand (in 2017)
mt19937 rng(0xdeadbeef);
mt19937 rng(chrono::steady_clock::now().time_since_epoch().count());
int randint(int lb, int ub){ return uniform_int_distribution<int>(lb, ub)(rng); }
shuffle(permutation.begin(), permutation.end(), rng);
mt19937_64 _R(chrono::steady_clock::now().time_since_epoch().count()); // _R()

// comparator overload
auto cmp = [](seg a, seg b){return a.func() < b.func(); };
set<seg, decltype(cmp)> s(cmp);
map<seg, int, decltype(cmp)> mp(cmp);
priority_queue<seg, vector<seg>, decltype(cmp)> pq(cmp); // max heap

// hash func overload
struct point{
    int x, y;
    bool operator==(const point &p)const{ return x == p.x && y == p.y; }
};
struct hasher {
    size_t operator()(const point &p)const{ return p.x * 2 + p.y * 3; }
};
unordered_map<point, int, hasher> hsh;

// c++ setprecision example
#include <iostream> // std::cout, std::fixed
#include <iomanip> // std::setprecision

int main () {
    double f = 3.14159;
    std::cout << std::setprecision(5) << f << '\n'; // 3.1416
}
```

```
std::cout << std::setprecision(9) << f << '\n'; // 3.14159
std::cout << std::fixed;
std::cout << std::setprecision(5) << f << '\n'; // 3.14159
std::cout << std::setprecision(9) << f << '\n'; // 3.141590000
}
```