

# Team notebook

TryOurBest

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# 1 DP

## 1.1 DivideAndConquerDP

---

```
const ll INF = 1e18;

void calc(int i, int l, int r, int optL, int optR) {
    if (l > r) return;
    int mid = (l + r) / 2;
    f[i][mid] = INF; // change to -INF to find max
    int opt = -1;
    for (int k = optL; k <= min(mid, optR); ++k) {
        ll c = f[i - 1][k] + cost(k + 1, mid);
        if (c < f[i][mid]) {
            f[i][mid] = c;
            opt = k;
        }
    }
    calc(i, l, mid - 1, optL, opt);
    calc(i, mid + 1, r, opt, optR);
}
```

---

## 1.2 LineContainer

---

```
struct Line {
    mutable ll k, m, p;
    bool operator<(const Line& o) const { return k < o.k; } // change '<' to '>' to get min
    bool operator<(ll x) const { return p < x; }
};

struct LineContainer : multiset<Line, less<>> {
    // (for doubles, use inf = 1/.0, div(a,b) = a/b)
    static 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()) return x->p = inf, 0;
        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) {
        assert(!empty());
        auto l = *lower_bound(x);
        return l.k * x + l.m;
    }
};
```

---

## 1.3 lis

---

```
template<typename T>
int lis(const vector<T>& a) {
    vector<T> u;
    for (const T& x : a) {
        auto it = lower_bound(u.begin(), u.end(), x);
        if (it == u.end()) {
            u.push_back(x);
        } else {
            *it = x;
        }
    }
    return (int) u.size();
}
```

---

# 2 Data Structure

## 2.1 Fenwick2D

---

```
struct Fenwick2D {
#define gb(x) (x) & -(x)
    vector<vector<int>> nodes;
    vector<vector<int>> bit;
    int sx;
    void init(int _sx) {
        sx = _sx;
        nodes.resize(sx + 1);
        bit.resize(sx + 1);
    }
    void init_nodes() {
        for (int i = 1; i <= sx; ++i) {
            sort(all(nodes[i]));
            nodes[i].resize(unique(all(nodes[i])) -
                nodes[i].begin());
            bit[i].resize(sz(nodes[i]) + 1);
        }
    }
    void fake_update(int x, int y) {
        for (; x <= sx; x += gb(x)) nodes[x].push_back(y);
    }
    void fake_get(int x, int y) {
        for (; x > 0; x -= gb(x)) nodes[x].push_back(y);
    }
    void update(int x, int yy, int val) {
        for (; x <= sx; x += gb(x))
            for (int y = lower_bound(all(nodes[x]), yy) -
                nodes[x].begin() + 1;
                 y <= sz(nodes[x]); y += gb(y))
                bit[x][y] = max(bit[x][y], val);
    }
    int get(int x, int yy) {
        int res = 0;
        for (; x > 0; x -= gb(x))
```

---

```
        for (int y = upper_bound(all(nodes[x]), yy) -
            nodes[x].begin(); y > 0;
             y -= gb(y))
            res = max(res, bit[x][y]);
    }
};
```

---

## 2.2 ImplicitTreap

---

```
// Implicit Treap
// Tested: https://oj.vnoi.info/problem/sqrt\_b
struct Treap {
    ll val;
    int prior, size;
    ll sum;
    Treap *left, *right;
    Treap(ll val)
        : val(val), prior(rng()), size(1), sum(val),
          left(NULL), right(NULL){};
    int size(Treap *t) { return t == NULL ? 0 : t->size; }
    void down(Treap *t) {
        // do lazy propagation here
    }
    void refine(Treap *t) {
        if (t == NULL) return;
        t->size = 1;
        t->sum = t->val;
        if (t->left != NULL) {
            t->size += t->left->size;
            t->sum += t->left->sum;
        }
        if (t->right != NULL) {
            t->size += t->right->size;
            t->sum += t->right->sum;
        }
    }
    void split(Treap *t, Treap *&left, Treap *&right, int val) {
        if (t == NULL) return void(left = right = NULL);
        down(t);
        if (size(t->left) < val) {
            split(t->right, t->right, right, val - size(t->left) - 1);
            left = t;
        } else {
            split(t->left, left, t->left, val);
            right = t;
        }
        refine(t);
    }
    void merge(Treap *&t, Treap *left, Treap *right) {
        if (left == NULL) {
            t = right;
            return;
        }
        if (right == NULL) {
```

---

```

t = left;
return;
}

down(left);
down(right);
if (left->prior < right->prior) {
    merge(left->right, left->right, right);
    t = left;
} else {
    merge(right->left, left, right->left);
    t = right;
}
refine(t);
}

array<Treap *, 2> split(Treap *root, int val) {
    array<Treap *, 2> t;
    split(root, t[0], t[1], val);
    return t;
}
array<Treap *, 3> split(Treap *root, int l, int r) {
    array<Treap *, 3> t;
    Treap *tmp;

    split(root, t[0], t[1], l - 1);
    tmp = t[1];
    split(tmp, t[1], t[2], r - l + 1);

    return t;
}
Treap *root;

```

## 2.3 MeldableHeap

```

mt19937 gen(0x94949);
template<typename T>
struct Node {
    Node *l, *r;
    T v;
    Node(T x): l(0), r(0), v(x){}
};
template<typename T>
Node<T>* Meld(Node<T>* A, Node<T>* B) {
    if (!A) return B; if (!B) return A;
    if (B->v < A->v) swap(A, B);
    if (gen() & 1) A->l = Meld(A->l, B);
    else A->r = Meld(A->r, B);
    return A;
}
template<typename T>
struct Heap {
    Node<T> *r; int s;
    Heap(): r(0), s(0){}
    void push(T x) {
        r = Meld(new Node<T>(x), r);
        ++s;
    }
    int size(){ return s; }
    bool empty(){ return s == 0; }
}

```

```

T top(){ return r->v; }
void pop() {
    Node<T>* p = r;
    r = Meld(r->l, r->r);
    delete p;
    --s;
}
void Meld(Heap x) {
    s += x->s;
    r = Meld(r, x->r);
}
};
```

## 2.4 OrderStatisticTree

```

#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/tree_policy.hpp>
using namespace __gnu_pbds;
template <class T>
using Tree =
    tree<T, null_type, less<T>, rb_tree_tag,
          tree_order_statistics_node_update>;
void example() {
    Tree<int> t, t2;
    t.insert(8);
    auto it = t.insert(10).first;
    assert(it == t.lower_bound(9));
    assert(t.order_of_key(10) == 1);
    assert(t.order_of_key(11) == 2);
    assert(*t.find_by_order(0) == 8);
    t.join(t2); // assuming T < T2 or T > T2, merge t2 into t
}
```

## 2.5 PalindromeTree

```

template <int MAXC = 26>
struct PalindromicTree {
    PalindromicTree(const string& str) : _sz(str.size() +
                                              5), next(_sz, vector<int>(MAXC, 0)), link(_sz, 0),
                                             qlink(_sz, 0), cnt(_sz, 0), right_id(_sz, 0),
                                             len(_sz, 0), s(_sz, 0) {
        init();
        for (int i = 0; i < (int)str.size(); ++i) {
            add(str[i], i);
        }
        count();
    }
    int _sz;
    // returns vector of (left, right, frequency)
    vector<tuple<int, int, int>> get_palindromes() {
        vector<tuple<int, int, int>> res;
        dfs(0, res);
        dfs(1, res);
        return res;
    }
};
```

```

void dfs(int u, vector<tuple<int, int, int>>& res) {
    if (u > 1) { // u = 0 and u = 1 are two empty nodes
        res.emplace_back(right_id[u] - len[u] + 1,
                          right_id[u], cnt[u]);
    }
    for (int i = 0; i < MAXC; ++i) {
        if (next[u][i]) dfs(next[u][i], res);
    }
}

int last, n, p;
vector<vector<int>> next, dlink;
vector<int> link, qlink, cnt, right_id, len, s;

int newnode(int l, int right) {
    len[p] = l;
    right_id[p] = right;
    return p++;
}
void init() {
    p = 0;
    newnode(0, -1), newnode(-1, -1);
    n = last = 0;
    s[n] = -1, link[0] = 1;
}
int getlink(int x) {
    while (s[n - len[x] - 1] != s[n]) {
        if (s[n - len[link[x]] - 1] == s[n]) {
            x = link[x];
        } else
            x = qlink[x];
    }
    return x;
}
void add(char c, int right) {
    c -= 'a';
    s[++n] = c;
    int cur = getlink(last);
    if (!next[cur][(int)c]) {
        int now = newnode(len[cur] + 2, right);
        link[now] = next[getlink(link[cur])][(int)c];
        next[cur][(int)c] = now;
        if (s[n - len[link[now]]] == s[n - len[link[link[now]]]]) {
            qlink[now] = qlink[link[now]];
        } else {
            qlink[now] = link[link[now]];
        }
    }
    last = next[cur][(int)c];
    cnt[last]++;
}
void count() {
    for (int i = p - 1; i >= 0; i--) {
        cnt[link[i]] += cnt[i];
    }
}
```

## 2.6 RMQ

```
// RMQ O(1): 1-indexed
// remember to change the constants, types
using ll = long long;
#define For(i, j, k) for ( int i = (j) ; i <= (k) ; i++ )
#define Forl(i, j, k) for ( int i = (j) ; i >= (k) ; i-- )
namespace RMQ {
{
    using T = int; constexpr int N = 2e6 + 6; // change
    this
    inline bool cmp(T x, T y) { return x < y; } // change to '>'
        to query max
    inline T calc(T x, T y) { return cmp(x, y) ? x : y;
    }
    T val[N], pre[N], st[33];
    __attribute__((target("bmi")))
    lb(unsigned x) { return __builtin_ctz(x); }
    __attribute__((target("lzcnt")))
    hb(unsigned x) { return __builtin_clz(x) ^ 31;
    }
    inline void build(int n, T *a)
    {
        int m = (n - 1) >> 5, o = hb(m + 1),
            stk[33]; copy(a + 1, a + n + 1, val);
        For(i, 0, n - 1) pre[i] = i & 31 ?
            calc(pre[i - 1], val[i]) : val[i];
        For(i, 0, m) st[0][i] = pre[min(n - 1, i <<
            5 | 31)];
        For(i, 1, o) For(j, 0, m + 1 - (1 << i))
            st[i][j] = calc(st[i - 1][j], st[i -
                1][j + (1 << (i - 1))]);
        For(i, 0, n - 1)
            if (i & 31)
            {
                f[i] = f[i - 1];
                while (o &&
                    !cmp(val[stk[o]],
                        val[i])) f[i] &= ~(1u
                        << (stk[o - 1] & 31));
                f[i] |= 1u << ((stk[o + 1] =
                    i) & 31);
            }
            else f[i] = 1u << ((stk[o + 1] = i
                ) & 31);
    }
    inline T qry(int l, int r)
    {
        if ((--l >> 5) == (--r >> 5)) return
            val[l + hb(f[r] >> (1 & 31))];
        T z = calc(pre[r], val[l + hb(f[l + 31] >>
            (1 & 31))]);
        if ((l = (l >> 5) + 1) == (r >> 5))
            return z;
        int t = hb(r - 1); return calc(z,
            calc(st[t][l], st[t][r - (1 << t)]));
    }
}
// build: RMQ::build(n, a), a is an array (not a vector!)
// query: RMQ::qry(l, r)
```

## 2.7 SegmentTree

```
struct Tree {
    typedef int T;
    static constexpr T unit = INT_MIN;
    T f(T a, T b) { return max(a, b); } // (any associative
    fn)
    vector<T> s;
    int n;
    Tree(int n = 0, T def = unit) : s(2 * n, def), n(n) {}
    void update(int pos, T val) {
        for (s[pos += n] = val; pos /= 2; s[pos] = f(s[pos *
            2], s[pos * 2 + 1]));
    }
    T query(int b, int e) { // query [b , e)
        T ra = unit, rb = unit;
        for (b += n, e += n; b < e; b /= 2, e /= 2) {
            if (b % 2) ra = f(ra, s[b++]);
            if (e % 2) rb = f(s[--e], rb);
        }
        return f(ra, rb);
    }
};
```

## 2.8 WalkOnBIT

```
template<class T>
class FenwickTree {
public:
    int n;
    vector<T> bit;
    int LOG;
    FenwickTree(int _n) {
        init(_n);
    }
    void init(int _n) {
        n = _n;
        bit = vector<T>(n, 0);
        LOG = __lg(n);
    }
    T sum(int idx) {
        assert(0 <= idx && idx < n);
        T ret = 0;
        for (; idx >= 0; idx &= idx + 1, --idx)
            ret += bit[idx];
        return ret;
    }
    T sum(int l, int r) {
        return sum(r) - sum(l - 1);
    }
    void add(int idx, int delta) {
        for (; idx < n; idx |= idx + 1)
            bit[idx] += delta;
    }
    int bit_search(T v) { // lower_bound in the prefix
        sums array of A
        T sum = 0;
        int pos = -1;
```

```
for(int i = LOG; i >= 0; i--) {
    if (pos + (1 << i) < n && sum +
        bit[pos + (1 << i)] < v) {
        sum += bit[pos + (1 << i)];
        pos += (1 << i);
    }
}
return pos + 1; // +1 because 'pos' will
    have position of largest value less
    than 'v',
};
```

## 3 Geometry

### 3.1 AngleBisector

```
// bisector vector of <abc
PT angle_bisector(PT &a, PT &b, PT &c){
    PT p = a - b, q = c - b;
    return p + q * sqrt(dot(p, p) / dot(q, q));
}
```

### 3.2 Centroid

```
// centroid of a (possibly non-convex) polygon,
// assuming that the coordinates are listed in a clockwise
    or
// counterclockwise fashion. Note that the centroid is
    often known as
// the "center of gravity" or "center of mass".
PT centroid(vector<PT> &p) {
    int n = p.size(); PT c(0, 0);
    double sum = 0;
    for (int i = 0; i < n; i++) sum += cross(p[i], p[(i +
        1) % n]);
    double scale = 3.0 * sum;
    for (int i = 0; i < n; i++) {
        int j = (i + 1) % n;
        c = c + (p[i] + p[j]) * cross(p[i], p[j]);
    }
    return c / scale;
}
```

### 3.3 ClosestPair

```
typedef Point<ll> P;
pair<P, P> closest(vector<P> v) {
    assert(sz(v) > 1);
    set<P> S;
    sort(all(v), [](P a, P b) { return a.y < b.y; });
    pair<P, P> ret{LLONG_MAX, {P(), P()}};
    for (int i = 0; i < sz(v); i++) {
        for (int j = i + 1; j < sz(v); j++) {
            if (dist(v[i], v[j]) < ret.first) {
                ret = {dist(v[i], v[j]), {v[i], v[j]}};
            }
        }
    }
    return ret;
}
```

```

int j = 0;
for (P p : v) {
    P d{1 + (ll)sqrt(ret.first), 0};
    while (v[j].y <= p.y - d.x) S.erase(v[j++]);
    auto lo = S.lower_bound(p - d), hi = S.upper_bound(p +
        d);
    for (; lo != hi; ++lo) ret = min(ret, {(*lo -
        p).dist2(), {*lo, p}});
    S.insert(p);
}
return ret.second;

```

## 3.4 ConvexPolygon

```

// checks if convex or not
bool is_convex(vector<PT>& p) {
    bool s[3];
    s[0] = s[1] = s[2] = 0;
    int n = p.size();
    for (int i = 0; i < n; i++) {
        int j = (i + 1) % n;
        int k = (j + 1) % n;
        s[sign(cross(p[j] - p[i], p[k] - p[i])) + 1] = 1;
        if (s[0] && s[2])
            return 0;
    }
    return 1;
}
// -1 if strictly inside, 0 if on the polygon, 1 if
// strictly outside
// it must be strictly convex, otherwise make it strictly
// convex first
int is_point_in_convex(vector<PT>& p, const PT& x) { // O(log n)
    int n = p.size();
    assert(n >= 3);
    int a = orientation(p[0], p[1], x), b =
        orientation(p[0], p[n - 1], x);
    if (a < 0 || b > 0)
        return 1;
    int l = 1, r = n - 1;
    while (l + 1 < r) {
        int mid = l + r >> 1;
        if (orientation(p[0], p[mid], x) >= 0) l = mid;
        else r = mid;
    }
    int k = orientation(p[l], p[r], x);
    if (k <= 0)
        return -k;
    if (l == 1 && a == 0)
        return 0;
    if (r == n - 1 && b == 0)
        return 0;
    return -1;
}

```

## 3.5 ExtremeVertex

---

```

// id of the vertex having maximum dot product with z
// polygon must need to be convex
// top - upper right vertex
// for minimum dot prout negate z and return -dot(z,
//     p[id])
int extreme_vertex(vector<PT> &p, const PT &z, const int
    top) { // O(log n)
    int n = p.size();
    if (n == 1) return 0;
    double ans = dot(p[0], z); int id = 0;
    if (dot(p[top], z) > ans) ans = dot(p[top], z), id =
        top;
    int l = 1, r = top - 1;
    while (l < r) {
        int mid = l + r >> 1;
        if (dot(p[mid + 1], z) >= dot(p[mid], z)) l = mid +
            1;
        else r = mid;
    }
    if (dot(p[l], z) > ans) ans = dot(p[l], z), id = l;
    l = top + 1, r = n - 1;
    while (l < r) {
        int mid = l + r >> 1;
        if (dot(p[(mid + 1) % n], z) >= dot(p[mid], z)) l =
            mid + 1;
        else r = mid;
    }
    l %= n;
    if (dot(p[l], z) > ans) ans = dot(p[l], z), id = l;
    return id;
}

```

---

## 3.6 GeometricMedian

---

```

// it returns a point such that the sum of distances
// from that point to all points in p is minimum
// O(n log^2 Mx)
PT geometric_median(vector<PT> p) {
    auto tot_dist = [&](PT z) {
        double res = 0;
        for (int i = 0; i < p.size(); i++) res +=
            dist(p[i], z);
        return res;
    };
    auto findY = [&](double x) {
        double yl = -1e5, yr = 1e5;
        for (int i = 0; i < 60; i++) {
            double ym1 = yl + (yr - yl) / 3;
            double ym2 = yr - (yr - yl) / 3;
            double d1 = tot_dist(PT(x, ym1));
            double d2 = tot_dist(PT(x, ym2));
            if (d1 < d2) yr = ym2;
            else yl = ym1;
        }
        return pair<double, double> (yl, tot_dist(PT(x,
            yl)));
    };

```

---

```

};

double xl = -1e5, xr = 1e5;
for (int i = 0; i < 60; i++) {
    double xm1 = xl + (xr - xl) / 3;
    double xm2 = xr - (xr - xl) / 3;
    double y1, d1, y2, d2;
    auto z = findY(xm1); y1 = z.first; d1 = z.second;
    z = findY(xm2); y2 = z.first; d2 = z.second;
    if (d1 < d2) xr = xm2;
    else xl = xm1;
}
return {xl, findY(xl).first };
}

```

---

## 3.7 GeometryTemplate

---

```

const long double PI = acos(-1);
struct Vector {
    using type = long long;
    type x, y;
    Vector operator-(const Vector &other) const {
        return {x - other.x, y - other.y};
    }
    type operator*(const Vector &other) const {
        return x * other.y - other.x * y;
    }
    type operator%(const Vector &other) const {
        return x * other.x + y * other.y;
    }
    bool operator==(const Vector &other) const {
        return x == other.x and y == other.y;
    }
    bool operator!=(const Vector &other) const { return
        !(*this == other); }
    friend type cross(const Vector &A, const Vector &B,
        const Vector &C) {
        return (B - A) * (C - A);
    }
    friend type dist(Vector A) { return A.x * A.x + A.y *
        A.y; }
    friend type dot(const Vector &A, const Vector &B, const
        Vector &C) {
        Vector u = (B - A), v = (C - A);
        return u % v;
    }
    friend istream &operator>>(istream &is, Vector &V) {
        is >> V.x >> V.y;
        return is;
    }
    friend ostream &operator<<(ostream &os, Vector &V) {
        os << V.x << ',' << V.y;
        return os;
    }
    friend double angle(const Vector &A, const Vector &B,
        const Vector &C) {
        double x = dot(B, A, C) / sqrt(dist(A - B) * dist(C -
            B));
        return acos(min(1.0, max(-1.0, x))) * 180.0 / PI;
    }
}

```

---

```

};

using Point = Vector;
const Point origin = {0, 0};

long double area(Point A, Point B, Point C) {
    long double res =
        cross(origin, A, B) + cross(origin, B, C) +
        cross(origin, C, A);
    return abs(res) / 2.0;
}

```

## 3.8 HalfPlane

```

// contains all points p such that: cross(b - a, p - a) >=
// 0
struct HP {
    PT a, b;
    HP() {}
    HP(PT a, PT b) : a(a), b(b) {}
    HP(const HP& rhs) : a(rhs.a), b(rhs.b) {}
    int operator < (const HP& rhs) const {
        PT p = b - a;
        PT q = rhs.b - rhs.a;
        int fp = (p.y < 0 || (p.y == 0 && p.x < 0));
        int fq = (q.y < 0 || (q.y == 0 && q.x < 0));
        if (fp != fq) return fp == 0;
        if (cross(p, q)) return cross(p, q) > 0;
        return cross(p, rhs.b - a) < 0;
    }
    PT line_line_intersection(PT a, PT b, PT c, PT d) {
        b = b - a; d = c - d; c = c - a;
        return a + b * cross(c, d) / cross(b, d);
    }
    PT intersection(const HP &v) {
        return line_line_intersection(a, b, v.a, v.b);
    }
    int check(HP a, HP b, HP c) {
        return cross(a.b - a.a, b.intersection(c) - a.a) >
            -eps; // -eps to include polygons of zero area
            // (straight lines, points)
    }
    // consider half-plane of counter-clockwise side of each
    // line
    // if lines are not bounded add infinity rectangle
    // returns a convex polygon, a point can occur multiple
    // times though
    // complexity: O(n log(n))
    vector<PT> half_plane_intersection(vector<HP> h) {
        sort(h.begin(), h.end());
        vector<HP> tmp;
        for (int i = 0; i < h.size(); i++) {
            if (!i || cross(h[i].b - h[i].a, h[i - 1].b - h[i -
                1].a)) {
                tmp.push_back(h[i]);
            }
        }
        h = tmp;
        vector<HP> q(h.size() + 10);

```

```

        int qh = 0, qe = 0;
        for (int i = 0; i < h.size(); i++) {
            while (qe - qh > 1 && !check(h[i], q[qe - 2], q[qe -
                1])) qe--;
            while (qe - qh > 1 && !check(h[i], q[qh], q[qh +
                1])) qh++;
            q[qe++] = h[i];
        }
        while (qe - qh > 2 && !check(q[qh], q[qe - 2], q[qe -
            1])) qe--;
        while (qe - qh > 2 && !check(q[qe - 1], q[qh], q[qh +
            1])) qh++;
        vector<HP> res;
        for (int i = qh; i < qe; i++) res.push_back(q[i]);
        vector<PT> hull;
        if (res.size() > 2) {
            for (int i = 0; i < res.size(); i++) {
                hull.push_back(res[i].intersection(res[(i + 1) %
                    (int)res.size()])));
            }
        }
        return hull;
    }

```

## 3.9 IsPoint

```

// -1 if strictly inside, 0 if on the polygon, 1 if
// strictly outside
int is_point_in_triangle(PT a, PT b, PT c, PT p) {
    if (sign(cross(b - a, c - a)) < 0) swap(b, c);
    int c1 = sign(cross(b - a, p - a));
    int c2 = sign(cross(c - b, p - b));
    int c3 = sign(cross(a - c, p - c));
    if (c1 < 0 || c2 < 0 || c3 < 0) return 1;
    if (c1 + c2 + c3 != 3) return 0;
    return -1;
}

bool is_point_on_polygon(vector<PT> &p, const PT& z) {
    int n = p.size();
    for (int i = 0; i < n; i++) {
        if (is_point_on_seg(p[i], p[(i + 1) % n], z))
            return 1;
    }
    return 0;
}

// returns 1e9 if the point is on the polygon
int winding_number(vector<PT> &p, const PT& z) { // 0(n)
    if (is_point_on_polygon(p, z)) return 1e9;
    int n = p.size(), ans = 0;
    for (int i = 0; i < n; ++i) {
        int j = (i + 1) % n;
        bool below = p[i].y < z.y;
        if (below != (p[j].y < z.y)) {
            auto orient = orientation(z, p[j], p[i]);
            if (orient == 0) return 0;
            if (below == (orient > 0)) ans += below ? 1 :
                -1;
        }
    }
}
```

```

    }
    return ans;
}
// -1 if strictly inside, 0 if on the polygon, 1 if
// strictly outside
int is_point_in_polygon(vector<PT> &p, const PT& z) { // 0(n)
    int k = winding_number(p, z);
    return k == 1e9 ? 0 : k == 0 ? 1 : -1;
}

```

## 3.10 Line

```

struct line {
    PT a, b; // goes through points a and b
    PT v; double c; //line form: direction vec [cross] (x,
    y) = c
    line() {}
    //direction vector v and offset c
    line(PT v, double c) : v(v), c(c) {
        auto p = get_points();
        a = p.first; b = p.second;
    }
    // equation ax + by + c = 0
    line(double _a, double _b, double _c) : v({_b, -_a}),
    c(-_c) {
        auto p = get_points();
        a = p.first; b = p.second;
    }
    // goes through points p and q
    line(PT p, PT q) : v(q - p), c(cross(v, p)), a(p), b(q)
    {
        pair<PT, PT> get_points() { //extract any two
            points from this line
        PT p, q; double a = -v.y, b = v.x; // ax + by = c
        if (sign(a) == 0) {
            p = PT(0, c / b);
            q = PT(1, c / b);
        }
        else if (sign(b) == 0) {
            p = PT(c / a, 0);
            q = PT(c / a, 1);
        }
        else {
            p = PT(0, c / b);
            q = PT(1, (c - a) / b);
        }
        return {p, q};
    }
    //ax + by + c = 0
    array<double, 3> get_abc() {
        double a = -v.y, b = v.x;
        return {a, b, c};
    }
    // 1 if on the left, -1 if on the right, 0 if on the
    // line
    int side(PT p) { return sign(cross(v, p) - c); }
}

```

```

// line that is perpendicular to this and goes through
// point p
line perpendicular_through(PT p) { return {p, p +
    perp(v)}; }
// translate the line by vector t i.e. shifting it by
// vector t
line translate(PT t) { return {v, c + cross(v, t)}; }
// compare two points by their orthogonal projection on
// this line
// a projection point comes before another if it comes
// first according to vector v
bool cmp_by_projection(PT p, PT q) { return dot(v, p) <
    dot(v, q); }
line shift_left(double d) {
    PT z = v.perp().truncate(d);
    return line(a + z, b + z);
}

```

### 3.11 LineLineIntersection

```

// intersection point between ab and cd assuming unique
// intersection exists
bool line_line_intersection(PT a, PT b, PT c, PT d, PT
    &ans) {
    double a1 = a.y - b.y, b1 = b.x - a.x, c1 = cross(a, b);
    double a2 = c.y - d.y, b2 = d.x - c.x, c2 = cross(c, d);
    double det = a1 * b2 - a2 * b1;
    if (det == 0) return 0;
    ans = PT((b1 * c2 - b2 * c1) / det, (c1 * a2 - a1 * c2)
        / det);
    return 1;
}

```

### 3.12 MaximumCircleCover

```

// find a circle of radius r that contains as many points
// as possible
// O(n^2 log n);
double maximum_circle_cover(vector<PT> p, double r, circle
    &c) {
    int n = p.size();
    int ans = 0;
    int id = 0; double th = 0;
    for (int i = 0; i < n; ++i) {
        // maximum circle cover when the circle goes
        // through this point
        vector<pair<double, int>> events = {{-PI, +1}, {PI,
            -1}};
        for (int j = 0; j < n; ++j) {
            if (j == i) continue;
            double d = dist(p[i], p[j]);
            if (d > r * 2) continue;
            double dir = (p[j] - p[i]).arg();
            double ang = acos(d / 2 / r);
            double st = dir - ang, ed = dir + ang;
    }

```

```

        if (st > PI) st -= PI * 2;
        if (st <= -PI) st += PI * 2;
        if (ed > PI) ed -= PI * 2;
        if (ed <= -PI) ed += PI * 2;
        events.push_back({st - eps, +1}); // take care
            of precisions!
        events.push_back({ed, -1});
        if (st > ed) {
            events.push_back({-PI, +1});
            events.push_back({+PI, -1});
        }
    }
    sort(events.begin(), events.end());
    int cnt = 0;
    for (auto &e: events) {
        cnt += e.second;
        if (cnt > ans) {
            ans = cnt;
            id = i; th = e.first;
        }
    }
    PT w = PT(p[id].x + r * cos(th), p[id].y + r * sin(th));
    c = circle(w, r); //best_circle
    return ans;
}

```

### 3.13 MaximumInscribedCircle

```

// radius of the maximum inscribed circle in a convex
// polygon
double maximum_inscribed_circle(vector<PT> p) {
    int n = p.size();
    if (n <= 2) return 0;
    double l = 0, r = 20000;
    while (r - l > eps) {
        double mid = (l + r) * 0.5;
        vector<HP> h;
        const int L = 1e9;
        h.push_back(HP(PT(-L, -L), PT(L, -L)));
        h.push_back(HP(PT(L, -L), PT(L, L)));
        h.push_back(HP(PT(L, L), PT(-L, L)));
        h.push_back(HP(PT(-L, L), PT(-L, -L)));
        for (int i = 0; i < n; i++) {
            PT z = (p[(i + 1) % n] - p[i]).perp();
            z = z.truncate(mid);
            PT y = p[i] + z, q = p[(i + 1) % n] + z;
            h.push_back(HP(p[i] + z, p[(i + 1) % n] + z));
        }
        vector<PT> nw = half_plane_intersection(h);
        if (!nw.empty()) l = mid;
        else r = mid;
    }
    return l;
}

```

### 3.14 MinimumEnclosingCircle

```

// given n points, find the minimum enclosing circle of
// the points
// call convex_hull() before this for faster solution
// expected O(n)
circle minimum_enclosing_circle(vector<PT> &p) {
    random_shuffle(p.begin(), p.end());
    int n = p.size();
    circle c(p[0], 0);
    for (int i = 1; i < n; i++) {
        if (sign(dist(c.p, p[i]) - c.r) > 0) {
            c = circle(p[i], 0);
            for (int j = 0; j < i; j++) {
                if (sign(dist(c.p, p[j]) - c.r) > 0) {
                    c = circle((p[i] + p[j]) / 2, dist(p[i],
                        p[j]) / 2);
                for (int k = 0; k < j; k++) {
                    if (sign(dist(c.p, p[k]) - c.r) > 0) {
                        c = circle(p[i], p[j], p[k]);
                    }
                }
            }
        }
    }
    return c;
}

```

### 3.15 MinimumEnclosingRectangle

```

// minimum perimeter
double minimum_enclosing_rectangle(vector<PT> &p) {
    int n = p.size();
    if (n <= 2) return perimeter(p);
    int mndot = 0; double tmp = dot(p[1] - p[0], p[0]);
    for (int i = 1; i < n; i++) {
        if (dot(p[i] - p[0], p[i]) <= tmp) {
            tmp = dot(p[i] - p[0], p[i]);
            mndot = i;
        }
    }
    double ans = inf;
    int i = 0, j = 1, mxdot = 1;
    while (i < n) {
        PT cur = p[(i + 1) % n] - p[i];
        while (cross(cur, p[(j + 1) % n] - p[j]) >= 0) j =
            (j + 1) % n;
        while (dot(p[(mxdot + 1) % n], cur) >=
            dot(p[mxdot], cur)) mxdot = (mxdot + 1) % n;
        while (dot(p[(mndot + 1) % n], cur) <=
            dot(p[mndot], cur)) mndot = (mndot + 1) % n;
        ans = min(ans, 2.0 * ((dot(p[mxdot], cur) /
            cur.norm() - dot(p[mndot], cur) / cur.norm()) +
            dist_from_point_to_line(p[i], p[(i + 1) %
            n], p[j])));
        i++;
    }
}

```

```
    return ans;
}
```

### 3.16 MinkowskiSum

---

```
// a and b are strictly convex polygons of DISTINCT points
// returns a convex hull of their minkowski sum with
// distinct points
vector<PT> minkowski_sum(vector<PT> &a, vector<PT> &b) {
    int n = (int)a.size(), m = (int)b.size();
    int i = 0, j = 0; //assuming a[i] and b[j] both are
    // (left, bottom)-most points
    vector<PT> c;
    c.push_back(a[i] + b[j]);
    while (1) {
        PT p1 = a[i] + b[(j + 1) % m];
        PT p2 = a[(i + 1) % n] + b[j];
        int t = orientation(c.back(), p1, p2);
        if (t >= 0) j = (j + 1) % m;
        if (t <= 0) i = (i + 1) % n, p1 = p2;
        if (t == 0) p1 = a[i] + b[j];
        if (p1 == c[0]) break;
        c.push_back(p1);
    }
    return c;
}
```

---

### 3.17 MonotoneChain

---

```
vector<Point> convex_hull(vector<Point> p, int n){
    sort(p.begin(), p.end(), [](const Point &A, const Point &B){
        return A.x != B.x ? A.x < B.x : A.y < B.y;
    });
    Point st = p[0], en = p[n - 1];
    vector<Point> up = {p[0]};
    vector<Point> down = {p[0]};
    for(int i = 1; i < n; ++i){
        if(i == n - 1 or cross(st, p[i], en) < 0){
            while((int)up.size() >= 2 and
                  cross(up[up.size() - 2], up.back(), p[i])
                  >= 0)
                up.pop_back();
            up.push_back(p[i]);
        }
        if(i == n - 1 or cross(st, p[i], en) > 0){
            while((int)down.size() >= 2 and
                  cross(down[down.size() - 2], down.back(),
                        p[i]) <= 0)
                down.pop_back();
            down.push_back(p[i]);
        }
    }
    p.clear();
    for(int i = 0; i < (int)up.size(); ++i)
        p.push_back(up[i]);
}
```

---



---

```
    for(int i = down.size() - 2; i >= 1; --i)
        p.push_back(down[i]);
    // return hull in clockwise order
    return p;
}
```

---

### 3.18 Point2D

---

```
const double inf = 1e100;
const double eps = 1e-9;
const double PI = acos((double)-1.0);
int sign(double x) { return (x > eps) - (x < -eps); }
struct PT {
    double x, y;
    PT() { x = 0, y = 0; }
    PT(double x, double y) : x(x), y(y) {}
    PT(const PT &p) : x(p.x), y(p.y) {}
    PT operator + (const PT &a) const { return PT(x + a.x,
                                                    y + a.y); }
    PT operator - (const PT &a) const { return PT(x - a.x,
                                                    y - a.y); }
    PT operator * (const double a) const { return PT(x * a,
                                                    y * a); }
    friend PT operator * (const double &a, const PT &b) {
        return PT(a * b.x, a * b.y); }
    PT operator / (const double a) const { return PT(x / a,
                                                    y / a); }
    bool operator == (PT a) const { return sign(a.x - x) ==
        0 && sign(a.y - y) == 0; }
    bool operator != (PT a) const { return !(*this == a); }
    bool operator < (PT a) const { return sign(a.x - x) ==
        0 ? y < a.y : x < a.x; }
    bool operator > (PT a) const { return sign(a.x - x) ==
        0 ? y > a.y : x > a.x; }
    double norm() { return sqrt(x * x + y * y); }
    double norm2() { return x * x + y * y; }
    PT perp() { return PT(-y, x); }
    double arg() { return atan2(y, x); }
    PT truncate(double r) { // returns a vector with norm r
        // and having same direction
        double k = norm();
        if (!sign(k)) return *this;
        r /= k;
        return PT(x * r, y * r);
    }
};
inline double dot(PT a, PT b) { return a.x * b.x + a.y *
    b.y; }
inline double dist2(PT a, PT b) { return dot(a - b, a -
    b); }
inline double dist(PT a, PT b) { return sqrt(dot(a - b, a -
    b)); }
inline double cross(PT a, PT b) { return a.x * b.y - a.y *
    b.x; }
inline double cross2(PT a, PT b, PT c) { return cross(b -
    a, c - a); }
inline int orientation(PT a, PT b, PT c) { return
    sign(cross(b - a, c - a)); }
PT perp(PT a) { return PT(-a.y, a.x); }
```

---



---

```
PT rotateccw90(PT a) { return PT(-a.y, a.x); }
PT rotatecw90(PT a) { return PT(a.y, -a.x); }
PT rotateccw(PT a, double t) { return PT(a.x * cos(t) -
    a.y * sin(t), a.x * sin(t) + a.y * cos(t)); }
PT rotatecw(PT a, double t) { return PT(a.x * cos(t) + a.y
    * sin(t), -a.x * sin(t) + a.y * cos(t)); }
double SQ(double x) { return x * x; }
double rad_to_deg(double r) { return (r * 180.0 / PI); }
double deg_to_rad(double d) { return (d * PI / 180.0); }
double get_angle(PT a, PT b) {
    double costheta = dot(a, b) / a.norm() / b.norm();
    return acos(max((double)-1.0, min((double)1.0,
        costheta)));
}
bool is_point_in_angle(PT b, PT a, PT c, PT p) { // does
    point p lie in angle <bac
    assert(orientation(a, b, c) != 0);
    if (orientation(a, c, b) < 0) swap(b, c);
    return orientation(a, c, p) >= 0 && orientation(a, b,
        p) <= 0;
}
```

---

### 3.19 PointInsideHull

---

```
bool on_segment(const Point &A, const Point &B, const
    Point &C) { return cross(A, B, C) == 0 and dot(C, A,
        B) <= 0; }

bool check(vector<Point> &hull, Point &a) {
    int n = sz(hull);
    if (n == 1) return hull[0] == a;
    if (n == 2) return on_segment(hull[0], hull[1], a);
    if (cross(hull[0], hull[1], a) > 0) return 0;
    if (cross(hull[n - 1], hull[0], a) >= 0) return
        on_segment(hull[n - 1], hull[0], a);
    int l = 2, r = n - 1, ans = -1;
    while (l <= r) {
        int mid = (l + r) / 2;
        if (cross(hull[0], hull[mid], a) >= 0) {
            ans = mid;
            r = mid - 1;
        } else
            l = mid + 1;
    }
    debug(hull[0], hull[ans - 1], hull[ans], a, ans);
    return cross(hull[ans - 1], hull[ans], a) < 0 or
        on_segment(hull[ans - 1], hull[ans], a);
}
```

---

### 3.20 PointPolygonTangents

---

```
pair<PT, PT> convex_line_intersection(vector<PT> &p, PT a,
    PT b) {
    return {{0, 0}, {0, 0}};
}
```

---

```

pair<PT, int> point_poly_tangent(vector<PT> &p, PT Q, int
    dir, int l, int r) {
    while (r - l > 1) {
        int mid = (l + r) >> 1;
        bool pvs = orientation(Q, p[mid], p[mid - 1]) != -dir;
        bool nxt = orientation(Q, p[mid], p[mid + 1]) != -dir;
        if (pvs && nxt) return {p[mid], mid};
        if (!(pvs || nxt)) {
            auto p1 = point_poly_tangent(p, Q, dir, mid + 1, r);
            auto p2 = point_poly_tangent(p, Q, dir, l, mid - 1);
            return orientation(Q, p1.first, p2.first) ==
                dir ? p1 : p2;
        }
        if (!pvs) {
            if (orientation(Q, p[mid], p[l]) == dir) r =
                mid - 1;
            else if (orientation(Q, p[l], p[r]) == dir) r =
                mid - 1;
            else l = mid + 1;
        }
        if (!nxt) {
            if (orientation(Q, p[mid], p[l]) == dir) l =
                mid + 1;
            else if (orientation(Q, p[l], p[r]) == dir) r =
                mid - 1;
            else l = mid + 1;
        }
    }
    pair<PT, int> ret = {p[l], l};
    for (int i = l + 1; i <= r; i++) ret = orientation(Q,
        ret.first, p[i]) != dir ? make_pair(p[i], i) :
        ret;
    return ret;
}

// (cw, ccw) tangents from a point that is outside this
// convex polygon
// returns indexes of the points
pair<int, int> tangents_from_point_to_polygon(vector<PT>
    &p, PT Q) {
    int cw = point_poly_tangent(p, Q, 1, 0, (int)p.size() - 1).second;
    int ccw = point_poly_tangent(p, Q, -1, 0, (int)p.size() - 1).second;
    return make_pair(cw, ccw);
}

```

## 3.21 PolarSort

```

bool half(PT p) {
    return p.y > 0.0 || (p.y == 0.0 && p.x < 0.0);
}

void polar_sort(vector<PT> &v) { // sort points in
    // counterclockwise
    sort(v.begin(), v.end(), [](PT a, PT b) {

```

```

        return make_tuple(half(a), 0.0, a.norm2()) <
            make_tuple(half(b), cross(a, b), b.norm2());
    });
}

void polar_sort(vector<PT> &v, PT o) { // sort points in
    // counterclockwise with respect to point o
    sort(v.begin(), v.end(), [&](PT a, PT b) {
        return make_tuple(half(a - o), 0.0, (a -
            o).norm2()) < make_tuple(half(b - o), cross(a -
            o, b - o), (b - o).norm2());
    });
}

```

## 3.22 PolygonCircleIntersection

```

// intersection between a simple polygon and a circle
double polygon_circle_intersection(vector<PT> &v, PT p,
    double r) {
    int n = v.size();
    double ans = 0.00;
    PT org = {0, 0};
    for(int i = 0; i < n; i++) {
        int x = orientation(p, v[i], v[(i + 1) % n]);
        if(x == 0) continue;
        double area = triangle_circle_intersection(org, r,
            v[i] - p, v[(i + 1) % n] - p);
        if (x < 0) ans -= area;
        else ans += area;
    }
    return abs(ans);
}

```

## 3.23 PolygonCut

```

// returns a vector with the vertices of a polygon with
// everything
// to the left of the line going from a to b cut away.
vector<PT> cut(vector<PT> &p, PT a, PT b) {
    vector<PT> ans;
    int n = (int)p.size();
    for (int i = 0; i < n; i++) {
        double c1 = cross(b - a, p[i] - a);
        double c2 = cross(b - a, p[(i + 1) % n] - a);
        if (sign(c1) >= 0) ans.push_back(p[i]);
        if (sign(c1 * c2) < 0) {
            if (!is_parallel(p[i], p[(i + 1) % n], a, b)) {
                PT tmp; line_line_intersection(p[i], p[(i +
                    1) % n], a, b, tmp);
                ans.push_back(tmp);
            }
        }
    }
    return ans;
}

```

## 3.24 PolygonDiameter

```

// Maximum distance of 2 points
double diameter(vector<PT> &p) {
    int n = (int)p.size();
    if (n == 1) return 0;
    if (n == 2) return dist(p[0], p[1]);
    double ans = 0;
    int i = 0, j = 1;
    while (i < n) {
        while (cross(p[(i + 1) % n] - p[i], p[(j + 1) % n] -
            p[j]) >= 0) {
            ans = max(ans, dist2(p[i], p[j]));
            j = (j + 1) % n;
        }
        ans = max(ans, dist2(p[i], p[j]));
        i++;
    }
    return sqrt(ans);
}

```

## 3.25 PolygonDistances

```

// minimum distance from a point to a convex polygon
// it assumes point lie strictly outside the polygon
double dist_from_point_to_polygon(vector<PT> &p, PT z) {
    double ans = inf;
    int n = p.size();
    if (n <= 3) {
        for(int i = 0; i < n; i++) ans = min(ans,
            dist_from_point_to_seg(p[i], p[(i + 1) % n],
            z));
        return ans;
    }
    auto [r, l] = tangents_from_point_to_polygon(p, z);
    if (l > r) r += n;
    while (l < r) {
        int mid = (l + r) >> 1;
        double left = dist2(p[mid % n], z), right=
            dist2(p[(mid + 1) % n], z);
        ans = min({ans, left, right});
        if(left < right) r = mid;
        else l = mid + 1;
    }
    ans = sqrt(ans);
    ans = min(ans, dist_from_point_to_seg(p[l % n], p[(l +
        1) % n], z));
    ans = min(ans, dist_from_point_to_seg(p[l % n], p[(l -
        1 + n) % n], z));
    return ans;
}

// minimum distance from convex polygon p to line ab
// returns 0 if it intersects with the polygon
// top - upper right vertex
double dist_point_to_polygon(vector<PT> &p, PT a, PT
    b, int top) { //O(log n)
    PT orth = (b - a).perp();
    if (orientation(a, b, p[0]) > 0) orth = (a - b).perp();

```

```

int id = extreme_vertex(p, orth, top);
if (dot(p[id] - a, orth) > 0) return 0.0; //if orth and
// a are in the same half of the line, then poly and
// line intersects
return dist_from_point_to_line(a, b, p[id]); //does not
// intersect
}
// minimum distance from a convex polygon to another
// convex polygon
// the polygon doesn't overlap or touch
// tested in https://toph.co/p/the-wall
double dist_from_polygon_to_polygon(vector<PT> &p1,
    vector<PT> &p2) { //O(n log n)
    double ans = inf;
    for (int i = 0; i < p1.size(); i++) {
        ans = min(ans, dist_from_point_to_polygon(p2,
            p1[i]));
    }
    for (int i = 0; i < p2.size(); i++) {
        ans = min(ans, dist_from_point_to_polygon(p1,
            p2[i]));
    }
    return ans;
}
// maximum distance from a convex polygon to another
// convex polygon
double maximum_dist_from_polygon_to_polygon(vector<PT> &u,
    vector<PT> &v){ //O(n)
    int n = (int)u.size(), m = (int)v.size();
    double ans = 0;
    if (n < 3 || m < 3) {
        for (int i = 0; i < n; i++) {
            for (int j = 0; j < m; j++) ans = max(ans,
                dist2(u[i], v[j]));
        }
        return sqrt(ans);
    }
    if (u[0].x > v[0].x) swap(n, m), swap(u, v);
    int i = 0, j = 0, step = n + m + 10;
    while (j + 1 < m && v[j].x < v[j + 1].x) j++;
    while (step--) {
        if (cross(u[(i + 1)%n] - u[i], v[(j + 1)%m] - v[j])
            >= 0) j = (j + 1) % m;
        else i = (i + 1) % n;
        ans = max(ans, dist2(u[i], v[j]));
    }
    return sqrt(ans);
}

```

## 3.26 PolygonLineIntersection

```

// not necessarily convex, boundary is included in the
// intersection
// returns total intersected length
double polygon_line_intersection(vector<PT> p, PT a, PT b)
{
    int n = p.size();
    p.push_back(p[0]);
    line l = line(a, b);

```

```

    double ans = 0.0;
    vector< pair<double, int> > vec;
    for (int i = 0; i < n; i++) {
        int s1 = sign(cross(b - a, p[i] - a));
        int s2 = sign(cross(b - a, p[i+1] - a));
        if (s1 == s2) continue;
        line t = line(p[i], p[i + 1]);
        PT inter = (t.v * l.c - l.v * t.c) / cross(l.v,
            t.v);
        double tmp = dot(inter, l.v);
        int f;
        if (s1 > s2) f = s1 && s2 ? 2 : 1;
        else f = s1 && s2 ? -2 : -1;
        vec.push_back(make_pair(tmp, f));
    }
    sort(vec.begin(), vec.end());
    for (int i = 0, j = 0; i + 1 < (int)vec.size(); i++){
        j += vec[i].second;
        if (j) ans += vec[i + 1].first - vec[i].first;
    }
    ans = ans / sqrt(dot(l.v, l.v));
    p.pop_back();
    return ans;
}

```

## 3.27 PolygonUnion

```

// calculates the area of the union of n polygons (not
// necessarily convex).
// the points within each polygon must be given in CCW
// order.
// complexity: O(N^2), where N is the total number of
// points
double rat(PT a, PT b, PT p) {
    return !sign(a.x - b.x) ? (p.y - a.y) / (b.y - a.y)
        : (p.x - a.x) / (b.x - a.x);
}
double polygon_union(vector<vector<PT>> &p) {
    int n = p.size();
    double ans=0;
    for(int i = 0; i < n; ++i) {
        for (int v = 0; v < (int)p[i].size(); ++v) {
            PT a = p[i][v], b = p[i][(v + 1) % p[i].size()];
            vector<pair<double, int>> segs;
            segs.emplace_back(0, 0), segs.emplace_back(1,
                0);
            for(int j = 0; j < n; ++j) {
                if(i != j) {
                    for(size_t u = 0; u < p[j].size(); ++u) {
                        PT c = p[j][u], d = p[j][(u + 1) %
                            p[j].size()];
                        int sc = sign(cross(b - a, c - a)),
                            sd = sign(cross(b - a, d - a));
                        if(!sc && !sd) {
                            if(sign(dot(b - a, d - c)) > 0 &&
                                i > j) {
                                segs.emplace_back(rat(a, b,
                                    c), 1),
                                segs.emplace_back(rat(a,

```

```

                                    b, d), -1);
                            }
                        }
                    }
                }
            }
            else {
                double sa = cross(d - c, a - c),
                    sb = cross(d - c, b - c);
                if(sc >= 0 && sd < 0)
                    segs.emplace_back(sa / (sa -
                        sb), 1);
                else if(sc < 0 && sd >= 0)
                    segs.emplace_back(sa / (sa -
                        sb), -1);
            }
        }
    }
    sort(segs.begin(), segs.end());
    double pre = min(max(segs[0].first, 0.0), 1.0),
        now, sum = 0;
    int cnt = segs[0].second;
    for(int j = 1; j < segs.size(); ++j) {
        now = min(max(segs[j].first, 0.0), 1.0);
        if (!cnt) sum += now - pre;
        cnt += segs[j].second;
        pre = now;
    }
    ans += cross(a, b) * sum;
}
return ans * 0.5;
}

```

## 3.28 PolygonWidth

```

// Maximum distance between 2 points IN the polygon
double width(vector<PT> &p) {
    int n = (int)p.size();
    if (n <= 2) return 0;
    double ans = inf;
    int i = 0, j = 1;
    while (i < n) {
        while (cross(p[(i + 1) % n] - p[i], p[(j + 1) % n]
            - p[j]) >= 0) j = (j + 1) % n;
        ans = min(ans, dist_from_point_to_line(p[i], p[(i +
            1) % n], p[j]));
        i++;
    }
    return ans;
}

```

## 3.29 Ray

```

// minimum distance from point c to ray (starting point a
// and direction vector b)
double dist_from_point_to_ray(PT a, PT b, PT c) {
    b = a + b;

```

```

    double r = dot(c - a, b - a);
    if (r < 0.0) return dist(c, a);
    return dist_from_point_to_line(a, b, c);
}
// starting point as and direction vector ad
bool ray_ray_intersection(PT as, PT ad, PT bs, PT bd) {
    double dx = bs.x - as.x, dy = bs.y - as.y;
    double det = bd.x * ad.y - bd.y * ad.x;
    if (fabs(det) < eps) return 0;
    double u = (dy * bd.x - dx * bd.y) / det;
    double v = (dy * ad.x - dx * ad.y) / det;
    if (sign(u) >= 0 && sign(v) >= 0) return 1;
    else return 0;
}
double ray_ray_distance(PT as, PT ad, PT bs, PT bd) {
    if (ray_ray_intersection(as, ad, bs, bd)) return 0.0;
    double ans = dist_from_point_to_ray(as, ad, bs);
    ans = min(ans, dist_from_point_to_ray(bs, bd, as));
    return ans;
}

```

### 3.30 Segment

```

// returns true if point p is on line segment ab
bool is_point_on_seg(PT a, PT b, PT p) {
    if (fabs(cross(p - b, a - b)) < eps) {
        if (p.x < min(a.x, b.x) || p.x > max(a.x, b.x))
            return false;
        if (p.y < min(a.y, b.y) || p.y > max(a.y, b.y))
            return false;
        return true;
    }
    return false;
}
// minimum distance point from point c to segment ab that
// lies on segment ab
PT project_from_point_to_seg(PT a, PT b, PT c) {
    double r = dist2(a, b);
    if (sign(r) == 0) return a;
    r = dot(c - a, b - a) / r;
    if (r < 0) return a;
    if (r > 1) return b;
    return a + (b - a) * r;
}
// minimum distance from point c to segment ab
double dist_from_point_to_seg(PT a, PT b, PT c) {
    return dist(c, project_from_point_to_seg(a, b, c));
}
// intersection point between segment ab and segment cd
// assuming unique intersection exists
bool seg_seg_intersection(PT a, PT b, PT c, PT d, PT &ans)
{
    double oa = cross2(c, d, a), ob = cross2(c, d, b);
    double oc = cross2(a, b, c), od = cross2(a, b, d);
    if (oa * ob < 0 && oc * od < 0){
        ans = (a * ob - b * oa) / (ob - oa);
        return 1;
    }
    else return 0;
}

```

```

    }
    // intersection point between segment ab and segment cd
    // assuming unique intersection may not exists
    // se.size()==0 means no intersection
    // se.size()==1 means one intersection
    // se.size()==2 means range intersection
    set<PT> seg_seg_intersection_inside(PT a, PT b, PT c, PT
                                         d) {
        PT ans;
        if (seg_seg_intersection(a, b, c, d, ans)) return {ans};
        set<PT> se;
        if (is_point_on_seg(c, d, a)) se.insert(a);
        if (is_point_on_seg(c, d, b)) se.insert(b);
        if (is_point_on_seg(a, b, c)) se.insert(c);
        if (is_point_on_seg(a, b, d)) se.insert(d);
        return se;
    }
    // intersection between segment ab and line cd
    // 0 if do not intersect, 1 if proper intersect, 2 if
    // segment intersect
    int seg_line_relation(PT a, PT b, PT c, PT d) {
        double p = cross2(c, d, a);
        double q = cross2(c, d, b);
        if (sign(p) == 0 && sign(q) == 0) return 2;
        else if (p * q < 0) return 1;
        else return 0;
    }
    // intersection between segment ab and line cd assuming
    // unique intersection exists
    bool seg_line_intersection(PT a, PT b, PT c, PT d, PT
                               &ans) {
        bool k = seg_line_relation(a, b, c, d);
        assert(k != 2);
        if (k) line_line_intersection(a, b, c, d, ans);
        return k;
    }
    // minimum distance from segment ab to segment cd
    double dist_from_seg_to_seg(PT a, PT b, PT c, PT d) {
        PT dummy;
        if (seg_seg_intersection(a, b, c, d, dummy)) return 0.0;
        else return min({dist_from_point_to_seg(a, b, c),
                        dist_from_point_to_seg(a, b, d),
                        dist_from_point_to_seg(c, d, a),
                        dist_from_point_to_seg(c, d, b)});
    }

```

### 3.31 SmallestEnclosingCircle

```

double eps = 1e-9;
using Point = complex<double>;
struct Circle{ Point p; double r; };
double dist(Point p, Point q){ return abs(p-q); }
double area2(Point p, Point q){ return (conj(p)*q).imag(); }
bool in(const Circle& c, Point p){ return dist(c.p, p) <
                                         c.r + eps; }
Circle INVAL = Circle{Point(0, 0), -1};
Circle mCC(Point a, Point b, Point c){
    b -= a; c -= a;

```

```

    double d = 2*(conj(b)*c).imag(); if(abs(d)<eps)
        return INVAL;
    Point ans = (c*norm(b) - b*norm(c)) * Point(0, -1)
               / d;
    return Circle{a + ans, abs(ans)};
}
Circle solve(vector<Point> p) {
    mt19937 gen(0x94949); shuffle(p.begin(), p.end(),
                                     gen);
    Circle c = INVAL;
    for(int i=0; i<p.size(); ++i) if(c.r<0 || !in(c,
                                                    p[i])){
        c = Circle{p[i], 0};
        for(int j=0; j<i; ++j) if(!in(c, p[j])){
            Circle ans{(p[i]+p[j])*0.5,
                        dist(p[i], p[j])*0.5};
            if(c.r == 0) {c = ans; continue;}
            Circle l, r; l = r = INVAL;
            Point pq = p[j]-p[i];
            for(int k=0; k<=j; ++k) if(!in(ans,
                                              p[k])){
                double a2 = area2(pq,
                                   p[k]-p[i]);
                Circle c = mCC(p[i], p[j],
                                p[k]);
                if(c.r<0) continue;
                else if(a2 > 0 &&
                        (l.r<0||area2(pq,
                                      c.p-p[i]) > area2(pq,
                                      l.p-p[i]))) l = c;
                else if(a2 < 0 &&
                        (r.r<0||area2(pq,
                                      c.p-p[i]) < area2(pq,
                                      r.p-p[i]))) r = c;
            }
            if(l.r<0&r.r<0) c = ans;
            else if(l.r<0) c = r;
            else if(r.r<0) c = l;
            else c = l.r<=r.r?l:r;
        }
    }
    return c;
}

```

### 3.32 TriangleCircleIntersection

```

// system should be translated from circle center
double triangle_circle_intersection(PT c, double r, PT a,
                                    PT b) {
    double sd1 = dist2(c, a), sd2 = dist2(c, b);
    if(sd1 > sd2) swap(a, b), swap(sd1, sd2);
    double sd = dist2(a, b);
    double d1 = sqrtl(sd1), d2 = sqrtl(sd2), d = sqrt(sd);
    double x = abs(sd2 - sd - sd1) / (2 * d);
    double h = sqrtl(sd1 - x * x);
    if(r >= d2) return h * d / 2;
    double area = 0;
    if(sd + sd1 < sd2) {

```

```

if(r < d1) area = r * r * (acos(h / d2) - acos(h / d1)) / 2;
else {
    area = r * r * (acos(h / d2) - acos(h / r)) / 2;
    double y = sqrtl(r * r - h * h);
    area += h * (y - x) / 2;
}
else {
    if(r < h) area = r * r * (acos(h / d2) + acos(h / d1)) / 2;
    else {
        area += r * r * (acos(h / d2) - acos(h / r)) / 2;
        double y = sqrtl(r * r - h * h);
        area += h * y / 2;
        if(r < d1) {
            area += r * r * (acos(h / d1) - acos(h / r)) / 2;
            area += h * y / 2;
        }
        else area += h * x / 2;
    }
}
return area;
}

```

---

### 3.33 Utilities

```

double perimeter(vector<PT> &p) {
    double ans=0; int n = p.size();
    for (int i = 0; i < n; i++) ans += dist(p[i], p[(i + 1) % n]);
    return ans;
}

double area(vector<PT> &p) {
    double ans = 0; int n = p.size();
    for (int i = 0; i < n; i++) ans += cross(p[i], p[(i + 1) % n]);
    return fabs(ans) * 0.5;
}

double area_of_triangle(PT a, PT b, PT c) {
    return fabs(cross(b - a, c - a) * 0.5);
}

// 0 if cw, 1 if ccw
bool get_direction(vector<PT> &p) {
    double ans = 0; int n = p.size();
    for (int i = 0; i < n; i++) ans += cross(p[i], p[(i + 1) % n]);
    if (sign(ans) > 0) return 1;
    return 0;
}

// find a point from a through b with distance d
PT point_along_line(PT a, PT b, double d) {
    assert(a != b);
    return a + ((b - a) / (b - a).norm()) * d;
}

```

```

// projection point c onto line through a and b assuming a != b
PT project_from_point_to_line(PT a, PT b, PT c) {
    return a + (b - a) * dot(c - a, b - a) / (b - a).norm2();
}

// reflection point c onto line through a and b assuming a != b
PT reflection_from_point_to_line(PT a, PT b, PT c) {
    PT p = project_from_point_to_line(a,b,c);
    return p + p - c;
}

// minimum distance from point c to line through a and b
double dist_from_point_to_line(PT a, PT b, PT c) {
    return fabs(cross(b - a, c - a) / (b - a).norm());
}

// 0 if not parallel, 1 if parallel, 2 if collinear
int is_parallel(PT a, PT b, PT c, PT d) {
    double k = fabs(cross(b - a, d - c));
    if (k < eps){
        if (fabs(cross(a - b, a - c)) < eps && fabs(cross(c - d, c - a)) < eps) return 2;
        else return 1;
    }
    else return 0;
}

// check if two lines are same
bool are_lines_same(PT a, PT b, PT c, PT d) {
    if (fabs(cross(a - c, c - d)) < eps && fabs(cross(b - c, c - d)) < eps) return true;
    return false;
}

// 1 if point is ccw to the line, 2 if point is cw to the line, 3 if point is on the line
int point_line_relation(PT a, PT b, PT p) {
    int c = sign(cross(p - a, b - a));
    if (c < 0) return 1;
    if (c > 0) return 2;
    return 3;
}

```

---

## 4 Graph

### 4.1 2SAT

```

struct TwoSatSolver {
    int n_vars;
    int n_vertices;
    vector<vector<int>> adj, adj_t;
    vector<bool> used;
    vector<int> order, comp;
    vector<bool> assignment;
    TwoSatSolver(int _n_vars)
        : n_vars(_n_vars),
        n_vertices(2 * n_vars),
        adj(n_vertices),
        adj_t(n_vertices),

```

```

        used(n_vertices),
        order(),
        comp(n_vertices, -1),
        assignment(n_vars) {
            order.reserve(n_vertices);
        }
    void dfs1(int v) {
        used[v] = true;
        for (int u : adj[v]) {
            if (!used[u]) dfs1(u);
        }
        order.push_back(v);
    }
    void dfs2(int v, int cl) {
        comp[v] = cl;
        for (int u : adj_t[v]) {
            if (comp[u] == -1) dfs2(u, cl);
        }
    }
    bool solve_2SAT() {
        order.clear();
        used.assign(n_vertices, false);
        for (int i = 0; i < n_vertices; ++i) {
            if (!used[i]) dfs1(i);
        }

        comp.assign(n_vertices, -1);
        for (int i = 0, j = 0; i < n_vertices; ++i) {
            int v = order[n_vertices - i - 1];
            if (comp[v] == -1) dfs2(v, j++);
        }

        assignment.assign(n_vars, false);
        for (int i = 0; i < n_vertices; i += 2) {
            if (comp[i] == comp[i + 1]) return false;
            assignment[i / 2] = comp[i] > comp[i + 1];
        }
        return true;
    }
    void add_disjunction(int a, bool na, int b, bool nb) {
        // na and nb signify whether a and b are to be negated
        a = 2 * a ^ na;
        b = 2 * b ^ nb;
        int neg_a = a ^ 1;
        int neg_b = b ^ 1;
        adj[neg_a].push_back(b);
        adj[neg_b].push_back(a);
        adj_t[b].push_back(neg_a);
        adj_t[a].push_back(neg_b);
    }
    static void example_usage() {
        TwoSatSolver solver(3); // a, b, c
        solver.add_disjunction(0, false, 1, true); // a v not b
        solver.add_disjunction(0, true, 1, true); // not a v not b
        solver.add_disjunction(1, false, 2, false); // b v c
        solver.add_disjunction(0, false, 0, false); // a v a
        assert(solver.solve_2SAT() == true);
        auto expected = vector<bool>(True, False, True);
    }
}

```

```

    assert(solver.assignment == expected);
}

```

## 4.2 Dinic

```

const ll INF = 1e18;
struct Dinic {
    const static bool SCALING = false; // scaling = EV
    log(max C) with larger constant
    ll lim = 1;
    struct Edge {
        int u, v;
        ll cap, flow;
    };
    int n, s, t;
    vector<int> level, ptr;
    vector<Edge> e;
    vector<vector<int>> g;
    Dinic(int _n : n(_n), level(_n), ptr(_n), g(_n) {
        e.clear();
        for (int i = 0; i < n; ++i) {
            ptr[i] = 0;
            g[i].clear();
        }
    }
    void add_edge(int u, int v, ll c) {
        debug(u, v, c);
        g[u].push_back(sz(e));
        e.push_back({u, v, c, 0});
        g[v].push_back(sz(e));
        e.push_back({v, u, 0, 0});
    }
    ll get_max_flow(int _s, int _t) {
        s = _s, t = _t;
        ll flow = 0;
        for (lim = SCALING ? (1 << 30) : 1; lim > 0; lim >>= 1)
            {
                while (1) {
                    if (!bfs()) break;
                    fill(all(ptr), 0);
                    while (ll pushed = dfs(s, INF)) flow += pushed;
                }
            }
        return flow;
    }
private:
bool bfs() {
    queue<int> q;
    q.push(s);
    fill(all(level), -1);
    level[s] = 0;
    while (!q.empty()) {
        int u = q.front();
        q.pop();
        for (int id : g[u]) {
            if (e[id].cap - e[id].flow < 1) continue;
            if (level[e[id].v] != -1) continue;

```

```

                if (SCALING and e[id].cap - e[id].flow < lim)
                    continue;
                level[e[id].v] = level[u] + 1;
                q.push(e[id].v);
            }
        }
        return level[t] != -1;
    }
    ll dfs(int u, ll flow) {
        if (!flow) return 0;
        if (u == t) return flow;
        for (; ptr[u] < sz(g[u]); ++ptr[u]) {
            int id = g[u][ptr[u]], to = e[id].v;
            if (level[to] != level[u] + 1) continue;
            ll pushed = dfs(to, min(flow, e[id].cap -
                e[id].flow));
            if (pushed) {
                e[id].flow += pushed;
                e[id ^ 1].flow -= pushed;
                return pushed;
            }
        }
        return 0;
    }
}

```

## 4.3 EulerPath

```

struct EulerUndirected {
    EulerUndirected(int _n) : n(_n), m(0), adj(_n), deg(_n,
        0) {}
    void add_edge(int u, int v) {
        adj[u].push_front(Edge(v));
        auto it1 = adj[u].begin();
        adj[v].push_front(Edge(u));
        auto it2 = adj[v].begin();
        it1->rev = it2;
        it2->rev = it1;
        ++deg[u];
        ++deg[v];
        ++m;
    }
    pair<bool, vector<int>> solve() {
        int cntOdd = 0;
        int start = -1;
        for (int i = 0; i < n; i++) {
            if (deg[i] % 2) {
                ++cntOdd;
                if (cntOdd > 2) return {false, {}};
            }
            if (start < 0) start = i;
        }
        // no odd vertex -> start from any vertex with positive
        // degree
        if (start < 0) {
            for (int i = 0; i < n; i++) {

```

```

                if (deg[i]) {
                    start = i;
                    break;
                }
            }
            if (start < 0) {
                // no edge -> empty path
                return {true, {}};
            }
        }
        vector<int> path;
        find_path(start, path);
        if (m + 1 != static_cast<int>(path.size())) {
            return {false, {}};
        }
        return {true, path};
    }
    struct Edge {
        int to;
        list<Edge>::iterator rev;
        Edge(int _to) : to(_to) {}
    };
    // private:
    int n, m;
    vector<list<Edge>> adj;
    vector<int> deg;
    void find_path(int v, vector<int>& path) {
        while (adj[v].size() > 0) {
            int next = adj[v].front().to;
            adj[next].erase(adj[v].front().rev);
            adj[v].pop_front();
            find_path(next, path);
        }
        path.push_back(v);
    }
}

```

## 4.4 EulerPathDirected

```

struct EulerDirected {
    EulerDirected(int _n) : n(_n), adj(n), in_deg(n, 0),
        out_deg(n, 0) {}
    void add_edge(int u, int v) { // directed edge
        assert(0 <= u && u < n);
        assert(0 <= v && v < n);
        adj[u].push_front(v);
        in_deg[v]++;
        out_deg[u]++;
    }
    pair<bool, vector<int>> solve() {
        int start = -1, last = -1;
        for (int i = 0; i < n; i++) {
            // for all u, |in_deg(u) - out_deg(u)| <= 1

```

```

if (abs(in_deg[i] - out_deg[i]) > 1) return {false, {}};

if (out_deg[i] > in_deg[i]) {
    // At most 1 vertex with out_deg[u] - in_deg[u] = 1
    // (start vertex)
    if (start >= 0) return {false, {}};
    start = i;
}

if (in_deg[i] > out_deg[i]) {
    // At most 1 vertex with in_deg[u] - out_deg[u] = 1
    // (last vertex)
    if (last >= 0) return {false, {}};
    last = i;
}

// can start at any vertex with degree > 0
if (start < 0) {
    for (int i = 0; i < n; i++) {
        if (in_deg[i]) {
            start = i;
            break;
        }
    }
    // no start vertex --> all vertices have degree == 0
    if (start < 0) return {true, {}};
}
vector<int> path;
find_path(start, path);
reverse(path.begin(), path.end());

// check that we visited all vertices with degree > 0
vector<bool> visited(n, false);
for (int u : path) visited[u] = true;

for (int u = 0; u < n; u++) {
    if (in_deg[u] && !visited[u])
        return {false, {}};
}
}

return {true, path};
}

private:
int n;
vector<list<int>> adj;
vector<int> in_deg, out_deg;

void find_path(int v, vector<int>& path) {
    while (adj[v].size() > 0) {
        int next = adj[v].front();
        adj[v].pop_front();
        find_path(next, path);
    }
    path.push_back(v);
}
};
```

## 4.5 GeneralMatching

```

const int MAXN = 2020 + 1;
struct GM { // 1-based Vertex index
    int vis[MAXN], par[MAXN], orig[MAXN], match[MAXN],
        aux[MAXN], t, N;
    vector<int> conn[MAXN];
    queue<int> Q;
    void addEdge(int u, int v) {
        conn[u].push_back(v);
        conn[v].push_back(u);
    }
    void init(int n) {
        N = n;
        t = 0;
        for (int i = 0; i <= n; ++i) {
            conn[i].clear();
            match[i] = aux[i] = par[i] = 0;
        }
    }
    void augment(int u, int v) {
        int pv = v, nv;
        do {
            pv = par[v];
            nv = match[pv];
            match[v] = pv;
            match[pv] = v;
            v = nv;
        } while (u != pv);
    }
    int lca(int v, int w) {
        ++t;
        while (true) {
            if (v) {
                if (aux[v] == t) return v;
                aux[v] = t;
                v = orig[par[match[v]]];
            }
            swap(v, w);
        }
    }
    void blossom(int v, int w, int a) {
        while (orig[v] != a) {
            par[v] = w;
            w = match[v];
            if (vis[w] == 1) Q.push(w), vis[w] = 0;
            orig[v] = orig[w] = a;
            v = par[w];
        }
    }
    bool bfs(int u) {
        fill(vis + 1, vis + 1 + N, -1);
        iota(orig + 1, orig + N + 1, 1);
        Q = queue<int>();
        Q.push(u);
        vis[u] = 0;
        while (!Q.empty()) {
            int v = Q.front();
            Q.pop();
            for (int x : conn[v]) {
                if (vis[x] == -1) {
```

```

                    par[x] = v;
                    vis[x] = 1;
                    if (!match[x]) return augment(u, x), true;
                    Q.push(match[x]);
                    vis[match[x]] = 0;
                } else if (vis[x] == 0 && orig[v] != orig[x]) {
                    int a = lca(orig[v], orig[x]);
                    blossom(x, v, a);
                    blossom(v, x, a);
                }
            }
        }
        return false;
    }
    int Match() {
        int ans = 0;
        // find random matching (not necessary, constant improvement)
        vector<int> V(N - 1);
        iota(V.begin(), V.end(), 1);
        shuffle(V.begin(), V.end(), mt19937(0x94949));
        for (auto x : V)
            if (!match[x]) {
                for (auto y : conn[x])
                    if (!match[y]) {
                        match[x] = y, match[y] = x;
                        ++ans;
                        break;
                    }
            }
        for (int i = 1; i <= N; ++i)
            if (!match[i] && bfs(i)) ++ans;
        return ans;
    }
};
```

## 4.6 GlobalMinCut

```

pair<int, vi> GetMinCut(vector<vi>& weights) {
    int N = sz(weights);
    vi used(N), cut, best_cut;
    int best_weight = -1;
    for (int phase = N - 1; phase >= 0; phase--) {
        vi w = weights[0], added = used;
        int prev, k = 0;
        rep(i, 0, phase) {
            prev = k;
            k = -1;
            rep(j, 1, N) if (!added[j] && (k == -1 || w[j] > w[k])) k = j;
            if (i == phase - 1) {
                rep(j, 0, N) weights[prev][j] += weights[k][j];
                rep(j, 0, N) weights[j][prev] = weights[prev][j];
                used[k] = true;
                cut.push_back(k);
            }
            if (best_weight == -1 || w[k] < best_weight) {
                best_cut = cut;
                best_weight = w[k];
            }
        }
```

```

} else {
    rep(j, 0, N) w[j] += weights[k][j];
    added[k] = true;
}
}
return {best_weight, best_cut};
}

```

## 4.7 HopcroftKarp

```

struct maximum_bipartite_matching {
    int n, m, turn, matched;
    vector<int> matchR, matchL, vis;
    vector<vector<int>> adj;
    vector<pair<int, int>> edges;
    maximum_bipartite_matching(int _n, int _m): n(_n),
        m(_m), matchL(n + 1), matchR(m + 1, -1), vis(n +
        1), adj(n + 1), turn(0), matched(0) {
    }

    void add_edge(int u, int v) {
        edges.push_back({u, v});
    }

    bool dfs(int u) {
        if (vis[u] == turn) return false;
        vis[u] = turn;

        for (int v: adj[u]) {
            if (matchR[v] == -1 || dfs(matchR[v])) {
                matchR[v] = u;
                return true;
            }
        }
        return false;
    }

    void match() {
        shuffle(edges.begin(), edges.end(), rng);
        for (pair<int, int> edge: edges) {
            adj[edge.first].push_back(edge.second);
        }
        bool flag = 1;

        while(flag) {
            flag = 0;
            ++turn;
            for (int u = 0; u < n; ++u) {
                if (matchL[u])
                    continue;
                if (dfs(u)) {
                    flag = matchL[u] = true;
                    ++matched;
                }
            }
        }
    }
}

```

```

vector< pair<int, int>> get_edges() {
    vector< pair<int, int>> res;
    for (int v = 0; v < m; ++v) {
        if (matchR[v] != -1) {
            res.push_back({matchR[v], v});
        }
    }
    return res;
}

```

## 4.8 JointsnBridges

```

const int maxN = 10010;
int n, m;
bool joint[maxN];
int timeDfs = 0, bridge = 0;
int low[maxN], num[maxN];
vector<int> g[maxN];
void dfs(int u, int pre) {
    int child = 0;
    num[u] = low[u] = ++timeDfs;
    for (int v : g[u]) {
        if (v == pre) continue;
        if (!num[v]) {
            dfs(v, u);
            low[u] = min(low[u], low[v]);
            if (low[v] == num[v]) bridge++;
            child++;
            if (u == pre) // if u is root of DFS tree
                if (child > 1) joint[u] = true;
        }
        else if (low[v] >= num[u]) joint[u] = true;
        else low[u] = min(low[u], num[v]);
    }
}
int main() {
    cin >> n >> m;
    for (int i = 1; i <= m; i++) {
        int u, v;
        cin >> u >> v;
        g[u].push_back(v);
        g[v].push_back(u);
    }
    for (int i = 1; i <= n; i++)
        if (!num[i]) dfs(i, i);
    int cntJoint = 0;
    for (int i = 1; i <= n; i++) cntJoint += joint[i];
    cout << cntJoint << ' ' << bridge;
}

```

*// Time Complexity: O(F \* (V \* E))*

## 4.9 MCMF slow

```

class mcmf {
    public:
        static constexpr T eps = (T) 1e-9;

        struct edge {
            int from;
            int to;
            T c;
            T f;
            C cost;
        };

        vector<vector<int>> g;
        vector<edge> edges;
        vector<C> d;
        vector<int> q;
        vector<bool> in_queue;
        vector<int> pe;
        int n;
        int st, fin;
        T flow;
        C cost;
}

mcmf(int _n, int _st, int _fin) : n(_n), st(_st),
    fin(_fin) {
    assert(0 <= st && st < n && 0 <= fin && fin < n && st
        != fin);
    g.resize(n);
    d.resize(n);
    in_queue.resize(n);
    pe.resize(n);
    flow = 0;
    cost = 0;
}

void clear_flow() {
    for (const edge &e : edges) {
        e.f = 0;
    }
    flow = 0;
}

void add(int from, int to, T forward_cap, T
    backward_cap, C cost) {
    assert(0 <= from && from < n && 0 <= to && to < n);
    g[from].push_back((int) edges.size());
    edges.push_back({from, to, forward_cap, 0, cost});
    g[to].push_back((int) edges.size());
    edges.push_back({to, from, backward_cap, 0, -cost});
}

bool expath() {
    fill(d.begin(), d.end(), numeric_limits<C>::max());
    q.clear();
    q.push_back(st);
    d[st] = 0;
    in_queue[st] = true;
    int beg = 0;
    bool found = false;
    while (beg < (int q.size()) {
        int i = q[beg++];
        if (i == fin) {

```

```

        found = true;
    }
    in_queue[i] = false;
    for (int id : g[i]) {
        const edge &e = edges[id];
        if (e.c - e.f > eps && d[i] + e.cost < d[e.to]) {
            d[e.to] = d[i] + e.cost;
            pe[e.to] = id;
            if (!in_queue[e.to]) {
                q.push_back(e.to);
                in_queue[e.to] = true;
            }
        }
    }
    if (found) {
        T push = numeric_limits<T>::max();
        int v = fin;
        while (v != st) {
            const edge &e = edges[pe[v]];
            push = min(push, e.c - e.f);
            v = e.from;
        }
        v = fin;
        while (v != st) {
            edge &e = edges[pe[v]];
            e.f += push;
            edge &back = edges[pe[v] ^ 1];
            back.f -= push;
            v = e.from;
        }
        flow += push;
        cost += push * d[fin];
    }
    return found;
}

pair<T, C> max_flow_min_cost() {
    while (expath()) {}
    return {flow, cost};
}
};

```

## 4.10 MCMF

---

```

// Time Complexity: O(F * (E * log V))
template <typename T, typename C>
class MCMF {
public:
    static constexpr T eps = (T) 1e-9;

    struct edge {
        int from;
        int to;
        T c;
        T f;
        C cost;
    };

```

```

        int n;
        vector<vector<int>> g;
        vector<edge> edges;
        vector<C> d;
        vector<C> pot;
        _gnu_pbds::priority_queue<pair<C, int>> q;
        vector<typename decltype(q)::point_iterator> its;
        vector<int> pe;
        const C INF_C = numeric_limits<C>::max() / 2;

        explicit MCMF(int n_) : n(n_), g(n_), d(n_), pot(n, 0),
                               its(n), pe(n) {}

        int add(int from, int to, T forward_cap, T backward_cap,
                C edge_cost) {
            assert(0 <= from && from < n && 0 <= to && to < n);
            assert(forward_cap >= 0 && backward_cap >= 0);
            int id = static_cast<int>(edges.size());
            g[from].push_back(id);
            edges.push_back({from, to, forward_cap, 0, edge_cost});
            g[to].push_back(id + 1);
            edges.push_back({to, from, backward_cap, 0,
                             -edge_cost});
            return id;
        }

        void expath(int st) {
            fill(d.begin(), d.end(), INF_C);
            q.clear();
            fill(its.begin(), its.end(), q.end());
            its[st] = q.push({pot[st], st});
            d[st] = 0;
            while (!q.empty()) {
                int i = q.top().second;
                q.pop();
                its[i] = q.end();
                for (int id : g[i]) {
                    const edge &e = edges[id];
                    int j = e.to;
                    if (e.c - e.f > eps && d[i] + e.cost < d[j]) {
                        d[j] = d[i] + e.cost;
                        pe[j] = id;
                        if (its[j] == q.end()) {
                            its[j] = q.push({pot[j] - d[j], j});
                        } else {
                            q.modify(its[j], {pot[j] - d[j], j});
                        }
                    }
                }
            }
            swap(d, pot);
        }

        pair<T, C> max_flow_min_cost(int st, int fin) {
            T flow = 0;
            C cost = 0;
            bool ok = true;
            for (auto& e : edges) {
                if (e.c - e.f > eps && e.cost + pot[e.from] -
                    pot[e.to] < 0) {
                    ok = false;
                    break;
                }
            }
            if (ok) {
                expath(st);
            } else {
                vector<int> deg(n, 0);
                for (int i = 0; i < n; i++) {
                    for (int eid : g[i]) {
                        auto& e = edges[eid];
                        if (e.c - e.f > eps) {
                            deg[e.to] += 1;
                        }
                    }
                }
                vector<int> que;
                for (int i = 0; i < n; i++) {
                    if (deg[i] == 0) {
                        que.push_back(i);
                    }
                }
                for (int b = 0; b < (int) que.size(); b++) {
                    for (int eid : g[que[b]]) {
                        auto& e = edges[eid];
                        if (e.c - e.f > eps) {
                            deg[e.to] -= 1;
                            if (deg[e.to] == 0) {
                                que.push_back(e.to);
                            }
                        }
                    }
                }
                fill(pot.begin(), pot.end(), INF_C);
                pot[st] = 0;
                if (static_cast<int>(que.size()) == n) {
                    for (int v : que) {
                        if (pot[v] < INF_C) {
                            for (int eid : g[v]) {
                                auto& e = edges[eid];
                                if (e.c - e.f > eps) {
                                    if (pot[v] + e.cost < pot[e.to]) {
                                        pot[e.to] = pot[v] + e.cost;
                                        pe[e.to] = eid;
                                    }
                                }
                            }
                        }
                    }
                } else {
                    que.assign(1, st);
                    vector<bool> in_queue(n, false);
                    in_queue[st] = true;
                    for (int b = 0; b < (int) que.size(); b++) {
                        int i = que[b];
                        in_queue[i] = false;
                        for (int id : g[i]) {
                            const edge &e = edges[id];
                            if (e.c - e.f > eps && pot[i] + e.cost <
                                pot[e.to]) {
                                pot[e.to] = pot[i] + e.cost;
                                pe[e.to] = id;
                                if (!in_queue[e.to]) {
                                    que.push_back(e.to);
                                }
                            }
                        }
                    }
                }
            }
        }
    };

```

```

        in_queue[e.to] = true;
    }
}
}

while (pot[fin] < INF_C) {
    T push = numeric_limits<T>::max();
    int v = fin;
    while (v != st) {
        const edge &e = edges[pe[v]];
        push = min(push, e.c - e.f);
        v = e.from;
    }
    v = fin;
    while (v != st) {
        edge &e = edges[pe[v]];
        e.f += push;
        edge &back = edges[pe[v] ^ 1];
        back.f -= push;
        v = e.from;
    }
    flow += push;
    cost += push * pot[fin];
    expath(st);
}
return {flow, cost};
}

```

---

## 4.11 Notes

### 4.11.1 Mo on Tree

Let a query be  $(u, v)$ . We will try to map each query to a range in the flattened array. Let  $ST(u)ST(v)$  where  $ST(u)$  denotes visit time of node  $u$  in  $T$ . Let  $P=LCA(u, v)$  denote the lowest common ancestor of nodes  $u$  and  $v$ . There are 2 possible cases:

Case 1:  $P=u$ : our query range would be  $[ST(u), ST(v)]$

Case 2:  $P \neq u$ : our query range would be  $[EN(u), ST(v)] + [ST(P), ST(P)]$

## 4.12 SCC

---

```

struct DirectedDfs {
    vector<vector<int>> g;
    int n;
    vector<int> num, low, current, S;
    int counter;
    vector<int> comp_ids;
    vector<vector<int>> scc;

    DirectedDfs(const vector<vector<int>>& _g)
        : g(_g),
          n(g.size()),

```

```

        num(n, -1),
        low(n, 0),
        current(n, 0),
        counter(0),
        comp_ids(n, -1) {
            for (int i = 0; i < n; i++) {
                if (num[i] == -1) dfs(i);
            }
        }

        void dfs(int u) {
            low[u] = num[u] = counter++;
            S.push_back(u);
            current[u] = 1;
            for (auto v : g[u]) {
                if (num[v] == -1) dfs(v);
                if (current[v]) low[u] = min(low[u], low[v]);
            }
            if (low[u] == num[u]) {
                scc.push_back(vector<int>());
                while (1) {
                    int v = S.back();
                    S.pop_back();
                    current[v] = 0;
                    scc.back().push_back(v);
                    comp_ids[v] = ((int)scc.size()) - 1;
                    if (u == v) break;
                }
            }
        }
    }

    // build DAG of strongly connected components
    // Returns: adjacency list of DAG
    std::vector<std::vector<int>> build_scc_dag() {
        std::vector<std::vector<int>> dag(scc.size());
        for (int u = 0; u < n; u++) {
            int x = comp_ids[u];
            for (int v : g[u]) {
                int y = comp_ids[v];
                if (x != y) {
                    dag[x].push_back(y);
                }
            }
        }
        return dag;
    }
}

```

---

## 4.13 TopoSort

---

```

pair<bool, vector<int>> topo_sort(const
    vector<vector<int>>& g) {
    int n = g.size();
    // init in_deg
    vector<int> in_deg(n, 0);
    for (int u = 0; u < n; u++) {
        for (int v : g[u]) {
            in_deg[v]++;
        }
    }
}

```

```

    }

    // find topo order
    vector<int> res;
    queue<int> qu;
    for (int u = 0; u < n; u++) {
        if (in_deg[u] == 0) {
            qu.push(u);
        }
    }

    while (!qu.empty()) {
        int u = qu.front();
        qu.pop();
        res.push_back(u);
        for (int v : g[u]) {
            in_deg[v]--;
            if (in_deg[v] == 0) {
                qu.push(v);
            }
        }
    }

    if ((int)res.size() < n) {
        return {false, {}};
    }
    return {true, res};
}

```

---

## 4.14 spfa

---

```

#include<bits/stdc++.h>
typedef pair<int, int> ii;
const int MaxN = 1e5 + 5;
const int Inf = 1e9;
vector<vector<ii>> AdjList;
int Dist[MaxN];
int Cnt[MaxN];
bool inqueue[MaxN];
int S;
int N;
queue<int> q;

bool spfa() {
    for(int i = 1 ; i <= N ; i++) {
        Dist[i] = Inf;
        Cnt[i] = 0;
        inqueue[i] = false;
    }
    Dist[S] = 0;
    q.push(S);
    inqueue[S] = true;
    while(!q.empty()) {
        int u = q.front();
        q.pop();
        inqueue[u] = false;

        for (ii tmp: AdjList[u]) {
            int v = tmp.first;

```

```

    int w = tmp.second;

    if (Dist[u] + w < Dist[v]) {
        Dist[v] = Dist[u] + w;
        if (!inqueue[v]) {
            q.push(v);
            inqueue[v] = true;
            Cnt[v]++;
            if (Cnt[v] > N)
                return false;
        }
    }
    return true;
}

```

## 5 Math

### 5.1 CRT

```

template<typename T>
T extgcd(T a, T b, T &x, T &y) {
    if (a == 0) {
        x = 0;
        y = 1;
        return b;
    }
    T p = b / a;
    T g = extgcd(b - p * a, a, y, x);
    x -= p * y;
    return g;
}

template<typename T>
bool diophantine(T a, T b, T c, T &x, T &y, T &g) {
    if (a == 0 && b == 0) {
        if (c == 0) {
            x = y = g = 0;
            return true;
        }
        return false;
    }
    if (a == 0) {
        if (c % b == 0) {
            x = 0;
            y = c / b;
            g = abs(b);
            return true;
        }
        return false;
    }
    if (b == 0) {
        if (c % a == 0) {
            x = c / a;
            y = 0;
            g = abs(a);
            return true;
        }
    }
}

```

```

    }
    return false;
}
g = extgcd(a, b, x, y);
if (c % g != 0) {
    return false;
}
T dx = c / a;
c -= dx * a;
T dy = c / b;
c -= dy * b;
x = dx + (T) ((__int128) x * (c / g) % b);
y = dy + (T) ((__int128) y * (c / g) % a);
g = abs(g);
return true;
// |x|, |y| <= max(|a|, |b|, |c|) [tested]
}

bool crt(int64_t k1, int64_t m1, int64_t k2, int64_t m2,
         int64_t &k, int64_t &m) {
    k1 %= m1;
    if (k1 < 0) k1 += m1;
    k2 %= m2;
    if (k2 < 0) k2 += m2;
    int64_t x, y, g;
    if (!diophantine(m1, -m2, k2 - k1, x, y, g)) {
        return false;
    }
    int64_t dx = m2 / g;
    int64_t delta = x / dx - (x % dx < 0);
    k = m1 * (x - dx * delta) + k1;
    m = m1 / g * m2;
    assert(0 <= k && k < m);
    return true;
}

// for distinct prime modulos
template <typename T>
void crt_garner(const vector<int>& p, const vector<int>&
                 a, T& res) {
    assert(p.size() == a.size());
    auto inverse = [&](int q, int m) {
        q %= m;
        if (q < 0) q += m;
        int b = m, u = 0, v = 1;
        while (q) {
            int t = b / q;
            b -= t * q; swap(q, b);
            u -= t * v; swap(u, v);
        }
        assert(b == 1);
        if (u < 0) u += m;
        return u;
    };
    vector<int> x(p.size());
    for (int i = 0; i < (int) p.size(); i++) {
        assert(0 <= a[i] && a[i] < p[i]);
        x[i] = a[i];
        for (int j = 0; j < i; j++) {
            x[i] = int(int64_t(x[i] - x[j]) * inverse(p[j], p[i])
                       % p[i]);
            if (x[i] < 0) x[i] += p[i];
        }
    }
}

```

```

    }
    res = 0;
    for (int i = (int) p.size() - 1; i >= 0; i--) {
        res = res * p[i] + x[i];
    }
}

```

### 5.2 Euclid

```

// x, y such that ax + by = gcd(a, b)
ll gcd(ll a, ll b) { return __gcd(a, b); }
ll euclid(ll a, ll b, ll &x, ll &y) {
    if (b) {
        ll d = euclid(b, a % b, y, x);
        return y -= a / b * x, d;
    }
    return x = 1, y = 0, a;
}

```

### 5.3 FFT

```

using ld = double;
// Can use std::complex<ld> instead to make code shorter
// (but it will be slightly slower)
struct Complex {
    ld x[2];

    Complex() { x[0] = x[1] = 0.0; }
    Complex(ld a) { x[0] = a; }
    Complex(ld a, ld b) {
        x[0] = a;
        x[1] = b;
    }
    Complex(const std::complex<ld> &c) {
        x[0] = c.real();
        x[1] = c.imag();
    }

    Complex conj() const { return Complex(x[0], -x[1]); }

    Complex operator+(const Complex& c) const {
        return Complex{
            x[0] + c.x[0],
            x[1] + c.x[1],
        };
    }
    Complex operator-(const Complex& c) const {
        return Complex{
            x[0] - c.x[0],
            x[1] - c.x[1],
        };
    }
    Complex operator*(const Complex& c) const { return
        Complex(x[0] * c.x[0] - x[1] * c.x[1], x[0] *
                c.x[1] + x[1] * c.x[0]); }
}

```

```

Complex& operator+=(const Complex& c) { return *this =
    *this + c; }
Complex& operator-=(const Complex& c) { return *this =
    *this - c; }
Complex& operator*=(const Complex& c) { return *this =
    *this * c; }

void fft(vector<Complex>& a) {
    int n = a.size();
    int L = 31 - __builtin_clz(n);
    static vector<Complex> R(2, 1);
    static vector<Complex> rt(2, 1);
    for (static int k = 2; k < n; k *= 2) {
        R.resize(n);
        rt.resize(n);
        auto x = Complex(polar(ld(1.0), acos(ld(-1.0)) / k));
        for (int i = k; i < 2 * k; ++i) {
            rt[i] = R[i] = i & 1 ? R[i / 2] * x : R[i / 2];
        }
    }
    vector<int> rev(n);
    for (int i = 0; i < n; ++i) rev[i] = (rev[i / 2] | (i &
        1) << L) / 2;
    for (int i = 0; i < n; ++i)
        if (i < rev[i]) swap(a[i], a[rev[i]]);

    for (int k = 1; k < n; k *= 2) {
        for (int i = 0; i < n; i += 2 * k) {
            for (int j = 0; j < k; ++j) {
                auto x = (ld*)&rt[j + k].x, y = (ld*)&a[i + j +
                    k].x;
                Complex z(x[0] * y[0] - x[1] * y[1], x[0] * y[1] +
                    x[1] * y[0]);
                a[i + j + k] = a[i + j] - z;
                a[i + j] += z;
            }
        }
    }
    vector<ld> multiply(const vector<ld>& a, const vector<ld>&
        b) {
        if (a.empty() || b.empty()) return {};
        vector<ld> res(a.size() + b.size() - 1);
        int L = 32 - __builtin_clz(res.size()), n = 1 << L;
        vector<Complex> in(n), out(n);

        for (size_t i = 0; i < a.size(); ++i) in[i].x[0] = a[i];
        for (size_t i = 0; i < b.size(); ++i) in[i].x[1] = b[i];

        fft(in);
        for (Complex& x : in) x *= x;

        for (int i = 0; i < n; ++i) out[i] = in[-i & (n - 1)] -
            in[i].conj();
        fft(out);

        for (size_t i = 0; i < res.size(); ++i) res[i] =
            out[i].x[1] / (4 * n);
        return res;
    }
    long long my_round(ld x) {

```

```

        if (x < 0) return -my_round(-x);
        return (long long)(x + 1e-2);
    }
    vector<long long> multiply(const vector<int>& a, const
        vector<int>& b) {
        vector<ld> ad(a.begin(), a.end());
        vector<ld> bd(b.begin(), b.end());
        auto rd = multiply(ad, bd);
        vector<long long> res(rd.size());
        for (int i = 0; i < (int)res.size(); ++i) {
            res[i] = my_round(rd[i]);
        }
        return res;
    }

```

## 5.4 Factorization

```

inline long long qpow(long long a, int b) {
    long long ans = 1;
    while (b) {
        if (b & 1) ans = ans * a % mod;
        a = a * a % mod;
        b >>= 1;
    }
    return ans;
}
inline long long rv(int x) { return qpow(x, mod - 2) %
    mod; }
bool is_prime(long long n) {
    if (n <= 1) return false;
    for (int a : {2, 3, 5, 13, 19, 73, 193, 407521,
        299210837}) {
        if (n == a) return true;
        if (n % a == 0) return false;
    }
    long long d = n - 1;
    while (!(d & 1)) d >>= 1;
    for (int a : {2, 325, 9375, 28178, 450775, 9780504,
        1795265022}) {
        long long t = d, y = ipow(a, t, n);
        while (t != n - 1 && y != 1 && y != n - 1) y = mul(y,
            y, n), t <<= 1;
        if (y != n - 1 && !(t & 1)) return false;
    }
    return true;
}

long long pollard(long n) {
    auto f = [n](long x) { return mul(x, x, n) + 1; };
    long long x = 0, y = 0, t = 0, prd = 2, i = 1, q;
    while (t++ % 40 || gcd(prd, n) == 1) {
        if ((x == y) x = ++i, y = f(x);
            if ((q = mul(prd, max(x, y) - min(x, y), n))) prd = q;
            x = f(x), y = f(f(y));
        }
        return gcd(prd, n);
    }
    vector<long long> factor(long n) {
        if (n == 1) return {};

```

```

        if (is_prime(n)) return {n};
        long x = pollard(n);
        auto l = factor(x), r = factor(n / x);
        l.insert(l.end(), r.begin(), r.end());
        return l;
    }

```

## 5.5 FastSubsetTransform

```

// fast and/or/xor convolution
void FST(vi& a, bool inv) {
    for (int n = sz(a), step = 1; step < n; step *= 2) {
        for (int i = 0; i < n; i += 2 * step) rep(j, i, i +
            step) {
            int &u = a[j], &v = a[j + step];
            tie(u, v) = inv ? pii(v - u, u) : pii(v, u + v); // AND
            inv ? pii(v, u - v) : pii(u + v, u); // OR
            pii(u + v, u - v); // XOR
        }
        if (inv)
            for (int& x : a) x /= sz(a); // XOR only
    }
    vi conv(vi a, vi b) {
        FST(a, 0);
        FST(b, 0);
        rep(i, 0, sz(a)) a[i] *= b[i];
        FST(a, 1);
        return a;
    }
}

```

## 5.6 Interpolate

```

const int mod = 1e9 + 7;
const int N = 1e6 + 6;

long long inv[N], po[N], pre[N], suf[N], dakdak[N];
long long ans, num;

inline long long qpow(long long a, int b) {
    long long ans = 1;
    while (b) {
        if (b & 1) ans = ans * a % mod;
        a = a * a % mod;
        b >>= 1;
    }
    return ans;
}
inline long long rv(int x) { return qpow(x, mod - 2) %

    mod; }
void prec() {
    inv[0] = 1;
    for (int i = 1; i <= k + 1; ++i) {
        inv[i] = (1LL * inv[i - 1] * rv(i)) % mod;
        po[i] = (po[i - 1] + qpow(i, k)) % mod;
    }
}

```

```

}
for (int i = 1; i <= k + 1; ++i) {
    dakdak[i] = (inv[i] * inv[k + 1 - i]) % mod;
}
}

inline long long interpolate(int x, int k, bool bf =
    false) {
if (k == 0) return x;
if (x <= k + 1 || bf) {
    return po[x];
}
pre[0] = x;
suf[k + 1] = x - (k + 1);
for (int i = 1; i <= k; i++) pre[i] = (pre[i - 1] * (x -
    i)) % mod;
for (int i = k; i >= 1; i--) suf[i] = (suf[i + 1] * (x -
    i)) % mod;
ans = 0;
for (int i = 0; i <= k + 1; i++) {
    if (i == 0)
        num = suf[1];
    else if (i == k + 1)
        num = pre[k];
    else
        num = (pre[i - 1] * suf[i + 1]) % mod; // numerator
    if ((i + k) & 1)
        ans = (ans + ((po[i] * num % mod) * dakdak[i])) % mod;
    else
        ans = (ans - ((po[i] * num % mod) * dakdak[i])) % mod;
    ans = (ans + mod) % mod;
}
return ans;
}

```

## 5.7 Lucas

```

// computing nCk mod p in O(p + log_p n)
// if p isn't prime -> prime factorize p = p1^a1 * p2^a2 *
... * pr^ar
// -> calculate nCk mod p1, mod p2, ..., mod pr
// -> use chinese remainder theorem to recover nCk mod p
ll lucas(ll n, ll k, int p, vi& fact, vi& invfact) {
    ll c = 1;
    while (n || k) {
        ll a = n % p, b = k % p;
        if (a < b) return 0;
        c = c * fact[a] % p * invfact[b] % p * invfact[a - b] %
            p;
        n /= p;
        k /= p;
    }
    return c;
}

```

## 5.8 Matrix

---

```

template <class T, int N>
struct Matrix {
    typedef Matrix M;
    array<array<T, N>, N> d{};
    M operator*(const M& m) const {
        M a;
        rep(i, 0, N) rep(j, 0, N) rep(k, 0, N) a.d[i][j] +=
            d[i][k] * m.d[k][j];
        return a;
    }
    vector<T> operator*(const vector<T>& vec) const {
        vector<T> ret(N);
        rep(i, 0, N) rep(j, 0, N) ret[i] += d[i][j] * vec[j];
        return ret;
    }
    M operator(ll p) const {
        assert(p >= 0);
        M a, b(*this);
        rep(i, 0, N) a.d[i][i] = 1;
        while (p) {
            if (p & 1) a = a * b;
            b = b * b;
            p >>= 1;
        }
        return a;
    }
};

```

---

## 5.9 MillerRabin

---

```

inline uint64_t mod_mult64(uint64_t a, uint64_t b,
    uint64_t m) { return __int128_t(a) * b % m; }
uint64_t mod_pow64(uint64_t a, uint64_t b, uint64_t m) {
    uint64_t ret = (m > 1);
    for (;;) {
        if (b & 1) ret = mod_mult64(ret, a, m);
        if (!(b >>= 1)) return ret;
        a = mod_mult64(a, a, m);
    }
}

// Works for all primes p < 2^64
bool is_prime(uint64_t n) {
    if (n <= 3) return (n >= 2);
    static const uint64_t small[] = {
        2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37,
        41, 43, 47, 53, 59, 61, 67, 71, 73, 79, 83,
        89, 97, 101, 103, 107, 109, 113, 127, 131, 137, 139,
        149, 151, 157, 163, 167, 173, 179, 181, 191,
        193, 197, 199,
    };
    for (size_t i = 0; i < sizeof(small) / sizeof(uint64_t);
        ++i) {
        if (n % small[i] == 0) return n == small[i];
    }
}

```

---

```

// Makes use of the known bounds for Miller-Rabin
// pseudoprimes.
static const uint64_t millerrabin[] = {
    2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37,
};

static const uint64_t A014233[] = {
    // From OEIS.
    2047LL, 1373653LL, 25326001LL, 3215031751LL,
    2152302898747LL, 3474749660383LL,
    341550071728321LL, 341550071728321LL,
    3825123056546413051LL, 3825123056546413051LL,
    3825123056546413051LL, 0,
};

uint64_t s = n - 1, r = 0;
while (s % 2 == 0) {
    s /= 2;
    r++;
}

for (size_t i = 0, j; i < sizeof(millerrabin) /
    sizeof(uint64_t); i++) {
    uint64_t md = mod_pow64(millerrabin[i], s, n);
    if (md != 1) {
        for (j = 1; j < r; j++) {
            if (md == n - 1) break;
            md = mod_mult64(md, md, n);
        }
        if (md != n - 1) return false;
    }
    if (n < A014233[i]) return true;
}
return true;
}

```

---

## 5.10 Mobius

---

```

mobius[1] = 1;
for (int i = 2; i < N; ++i) {
    --mobius[i];
    for (int j = i + 1; j < N; j += i) mobius[j] -=
        mobius[i];
}

```

---

## 5.11 ModInverse

---

```

const ll mod = 1000000007, LIM = 200000;
ll* inv = new ll[LIM] - 1; inv[1] = 1;
for (ll i = 2; i < LIM; ++i) inv[i] = mod - (mod / i) *
    inv[mod % i] % mod;

```

---

## 5.12 ModMulLL

---

```

typedef unsigned long long ull;

```

```

const int bits = 10; // i f a l l numbers are less than
    2^k , set bits = 64k
const ull po = 1 << bits;
ull mod_mul(ull a, ull b, ull &c) {
    ull x = a * (b & (po - 1)) % c;
    while ((b >>= bits) > 0) {
        a = (a << bits) % c;
        x += (a * (b & (po - 1))) % c;
    }
    return x % c;
}
ull mod_pow(ull a, ull b, ull mod) {
    if (b == 0) return 1;
    ull res = mod_pow(a, b / 2, mod);
    res = mod_mul(res, res, mod);
    if (b & 1) return mod_mul(res, a, mod);
    return res;
}

```

## 5.13 Modular Arithmetic

```

const ll mod = 17; // change to something else
struct Mod {
    ll x;
    Mod(ll xx) : x(xx) {}
    Mod operator+(Mod b) { return Mod((x + b.x) % mod); }
    Mod operator-(Mod b) { return Mod((x - b.x + mod) %
        mod); }
    Mod operator*(Mod b) { return Mod((x * b.x) % mod); }
    Mod operator/(Mod b) { return *this * invert(b); }
    Mod invert(Mod a) {
        ll x, y, g = euclid(a.x, mod, x, y);
        assert(g == 1);
        return Mod((x + mod) % mod);
    }
    Mod operator(ll e) {
        if (!e) return Mod(1);
        Mod r = *this (e / 2);
        r = r * r;
        return e & 1 ? *this * r : r;
    }
};

```

## 5.14 NTT

```

/* NTT with modulo 998244353
notes:
NTT with mod m
g is any primitive root modulo m (g = 3 works well for
998244353)
n divides m - 1 evenly
wn = g^((m - 1) / n)
https://codeforces.com/blog/entry/75326
*/
const int N = 1 << 21;

```

```

const ll mod = 998244353;
const ll g = 3;

int rev[N];
ll w[N], iw[N], wt[N], inv_n;

ll binpow(ll a, ll b) {
    ll res = 1;
    for (; b; b >>= 1, a = (1ll * a * a) % mod)
        if (b & 1) res = (1ll * res * a) % mod;
    return res;
}

void precalc(int lg) {
    int n = 1 << lg;
    inv_n = binpow(n, mod - 2);
    for (int i = 0; i < n; ++i) {
        rev[i] = 0;
        for (int j = 0; j < lg; ++j)
            if (i & (1 << j)) rev[i] |= (1 << (lg - j - 1));
    }
    ll wn = binpow(g, (mod - 1) / n);
    w[0] = 1;
    for (int i = 1; i < n; ++i) w[i] = (1ll * w[i - 1] * wn) %
        mod;
    ll iwn = binpow(wn, mod - 2);
    iw[0] = 1;
    for (int i = 1; i < n; ++i) iw[i] = (1ll * iw[i - 1] * iwn) %
        mod;
}

void ntt(vector<ll> &a, int lg, bool inv = 0) {
    int n = (1 << lg);
    for (int i = 0; i < n; ++i)
        if (i < rev[i]) swap(a[i], a[rev[i]]);
    for (int len = 2; len <= n; len <= 1) {
        int d = n / len;
        for (int j = 0; j < (len >> 1); ++j) wt[j] = (inv ?
            iw[d * j] : w[d * j]);
        for (int i = 0; i < n; i += len) {
            for (int j = 0; j < (len >> 1); ++j) {
                ll x = a[i + j], y = (1ll * a[i + j + (len >> 1)] *
                    wt[j]) % mod;
                a[i + j] = (x + y) % mod;
                a[i + j + (len >> 1)] = (x - y + mod) % mod;
            }
        }
        if (inv)
            for (int i = 0; i < n; ++i) a[i] = (1ll * a[i] * inv_n) %
                mod;
    }
}

vector<ll> multiply(vector<ll> a, vector<ll> b) {
    int n = 1, lg = 0;
    int na = sz(a), nb = sz(b);
    while (n < na + nb) n <<= 1, ++lg;
    precalc(lg);
    a.resize(n);
    b.resize(n);
    ntt(a, lg);

```

```

    ntt(b, lg);
    for (int i = 0; i < n; ++i) a[i] = (1ll * a[i] * b[i]) %
        mod;
    ntt(a, lg, 1);
    vector<ll> c;
    for (int i = 0; i < na + nb - 1; ++i) c.push_back(a[i]);
    // while(!c.empty() and c.back() == 0)
    //     c.pop_back();
    return c;
}

```

## 5.15 Notes

### 5.15.1 Cycles

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

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

### 5.15.2 Derangements

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

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

### 5.15.3 Burnside's lemma

Given a group  $G$  of symmetries and a set  $X$ , the number of elements of  $X$  up to symmetry equals

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

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

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

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

### 5.15.4 Partition function

Number of ways of writing  $n$  as a sum of positive integers, disregarding the order of the summands.

$$p(0) = 1, p(n) = \sum_{k \in \mathbb{Z} \setminus \{0\}} (-1)^{k+1} p(n - k(3k - 1)/2)$$

$$p(n) \sim 0.145/n \cdot \exp(2.56\sqrt{n})$$

$n$	0	1	2	3	4	5	6	7	8	9	20	50	100
$p(n)$	1	1	2	3	5	7	11	15	22	30	627	$\sim 2e5$	$\sim 2e8$

### 5.15.5 Lucas' Theorem

Let  $n, m$  be non-negative integers and  $p$  a prime. Write  $n = n_k p^k + \dots + n_1 p + n_0$  and  $m = m_k p^k + \dots + m_1 p + m_0$ . Then  $\binom{n}{m} \equiv \prod_{i=0}^k \binom{n_i}{m_i} \pmod{p}$ .

### 5.15.6 Bernoulli numbers

EGF of Bernoulli numbers is  $B(t) = \frac{t}{e^t - 1}$  (FFT-able).  $B[0, \dots] = [1, -\frac{1}{2}, \frac{1}{6}, 0, -\frac{1}{30}, 0, \frac{1}{42}, \dots]$

Sums of powers:

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

Euler-Maclaurin formula for infinite sums:

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

### 5.15.7 Stirling numbers of the first kind

Number of permutations on  $n$  items with  $k$  cycles.

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

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

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

$$c(n, 2) = 0, 0, 1, 3, 11, 50, 274, 1764, 13068, 109584, \dots$$

### 5.15.8 Eulerian numbers

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

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

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

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

### 5.15.9 Stirling numbers of the second kind

Partitions of  $n$  distinct elements into exactly  $k$  groups.

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

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

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

### 5.15.10 Bell numbers

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

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

### 5.15.11 Labeled unrooted trees

```
# on n vertices: n^{n-2}
# on k existing trees of size n_i: n_1 n_2 \dots n_k n^{k-2}
# with degrees d_i: (n-2)!/((d_1-1)! \dots (d_n-1)!)
```

### 5.15.12 Catalan numbers

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

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

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

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

### 5.15.13 Hockey Stick Identity

$$\sum_{k=r}^n \binom{k}{r} = \binom{n+1}{r+1}$$

### 5.16 PhiFunction

---

```
const int LIM = 5000000;
int phi[LIM];
void calculatePhi() {
    rep(i, 0, LIM) phi[i] = i & 1 ? i : i / 2;
    for (int i = 3; i < LIM; i += 2)
        if (phi[i] == i)
            for (int j = i; j < LIM; j += i) (phi[j] /= i) *= i - 1;
```

---

### 5.17 PollardFactorize

---

```
using ll = long long;
using ull = unsigned long long;
using ld = long double;
ll mult(ll x, ll y, ll md) {
    ull q = (ld)x * y / md;
    ll res = ((ull)x * y - q * md);
    if (res >= md) res -= md;
    if (res < 0) res += md;
    return res;
}

ll powMod(ll x, ll p, ll md) {
    if (p == 0) return 1;
    if (p & 1) return mult(x, powMod(x, p - 1, md), md);
    return powMod(mult(x, x, md), p / 2, md);
}

bool checkMillerRabin(ll x, ll md, ll s, int k) {
    x = powMod(x, s, md);
    if (x == 1) return true;
    while (k--) {
        if (x == md - 1) return true;
        x = mult(x, x, md);
        if (x == 1) return false;
    }
    return false;
}

bool isPrime(ll x) {
    if (x == 2 || x == 3 || x == 5 || x == 7) return true;
    if (x % 2 == 0 || x % 3 == 0 || x % 5 == 0 || x % 7 == 0) return false;
    if (x < 121) return x > 1;
    ll s = x - 1;
    int k = 0;
    while (s % 2 == 0) {
        s >>= 1;
        k++;
    }
    if (x < 1LL << 32) {
        for (ll z : {2, 7, 61}) {
            if (!checkMillerRabin(z, x, s, k)) return false;
        }
    } else {
        for (ll z : {2, 325, 9375, 28178, 450775, 9780504, 1795265022}) {
            if (!checkMillerRabin(z, x, s, k)) return false;
        }
    }
    return true;
}

ll gcd(ll x, ll y) { return y == 0 ? x : gcd(y, x % y); }

void pollard(ll x, vector<ll> &ans) {
    if (isPrime(x)) {
        ans.push_back(x);
        return;
    }
    ll c = 1;
```

```

while (true) {
    c = 1 + get_rand(x - 1);
    auto f = [&](ll y) {
        ll res = mult(y, y, x) + c;
        if (res >= x) res -= x;
        return res;
    };
    ll y = 2;
    int B = 100;
    int len = 1;
    ll g = 1;
    while (g == 1) {
        ll z = y;
        for (int i = 0; i < len; i++) {
            z = f(z);
        }
        ll zs = -1;
        int lft = len;
        while (g == 1 && lft > 0) {
            zs = z;
            ll p = 1;
            for (int i = 0; i < B && i < lft; i++) {
                p = mult(p, abs(z - y), x);
                z = f(z);
            }
            g = gcd(p, x);
            lft -= B;
        }
        if (g == 1) {
            y = z;
            len <= 1;
            continue;
        }
        if (g == x) {
            g = 1;
            z = zs;
            while (g == 1) {
                g = gcd(abs(z - y), x);
                z = f(z);
            }
        }
        if (g == x) break;
        assert(g != 1);
        pollard(g, ans);
        pollard(x / g, ans);
        return;
    }
}

// return list of all prime factors of x (can have
// duplicates)
vector<ll> factorize(ll x) {
    vector<ll> ans;
    for (ll p : {2, 3, 5, 7, 11, 13, 17, 19}) {
        while (x % p == 0) {
            x /= p;
            ans.push_back(p);
        }
    }
    if (x != 1) {
        pollard(x, ans);
    }
}

```

```

sort(ans.begin(), ans.end());
return ans;
}

// return pairs of (p, k) where x = product(p^k)
vector<pair<ll, int>> factorize_pk(ll x) {
    auto ps = factorize(x);
    ll last = -1, cnt = 0;
    vector<pair<ll, int>> res;
    for (auto p : ps) {
        if (p == last)
            ++cnt;
        else {
            if (last > 0) res.emplace_back(last, cnt);
            last = p;
            cnt = 1;
        }
    }
    if (cnt > 0)
        res.emplace_back(last, cnt);
    return res;
}

vector<ll> get_all_divisors(ll n) {
    auto pks = factorize_pk(n);

    vector<ll> res;
    function<void(int, ll)> gen = [&](int i, ll prod) {
        if (i == static_cast<int>(pks.size())) {
            res.push_back(prod);
            return;
        }

        ll cur_power = 1;
        for (int cur = 0; cur <= pks[i].second; ++cur) {
            gen(i + 1, prod * cur_power);
            cur_power *= pks[i].first;
        }

        gen(0, 1LL);
        sort(res.begin(), res.end());
        return res;
    };
}

```

## 5.18 PrimitiveRoot

```

// Primitive root of modulo n is integer g iff for all a <
// n & gcd(a, n) == 1, there exist k: g^k ≡ a mod n
// k is called discrete log of a (in case P is prime, can
// find in O(sqrt(P)) by noting that (P-1) is divisible
// by k)
//
// Exist if:
// - n is 1, 2, 4
// - n = p^k for odd prime p
// - n = 2*p^k for odd prime p
int powmod (int a, int b, int p) {
    int res = 1;
    while (b)

```

```

        if (b & 1)
            res = int (res * 1LL * a % p), --b;
        else
            a = int (a * 1LL * a % p), b >>= 1;
    return res;
}

int generator (int p) {
    vector<int> fact;
    int phi = p-1, n = phi;
    for (int i=2; i*i<=n; ++i)
        if (n % i == 0) {
            fact.push_back (i);
            while (n % i == 0)
                n /= i;
        }
    if (n > 1)
        fact.push_back (n);

    for (int res=2; res<=p; ++res) {
        bool ok = true;
        for (size_t i=0; i<fact.size() && ok; ++i)
            ok &= powmod (res, phi / fact[i], p) != 1;
        if (ok) return res;
    }
    return -1;
}

```

## 5.19 TernarySearch

```

// Find the smallest i in [a; b] that maximizes f(i),
// assuming
// that f(a) < ... < f(i) >= ... >= f(b)
// Usage: int ind = ternSearch(0,n-1,[&](int i){return
// a[i];});
template <class F>
int ternSearch(int a, int b, F f) {
    assert(a <= b);
    while (b - a >= 5) {
        int mid = (a + b) / 2;
        if (f(mid) < f(mid + 1))
            a = mid; // (A)
        else
            b = mid + 1;
    }
    rep(i, a + 1, b + 1) if (f(a) < f(i)) a = i; // (B)
    return a;
}

```

## 5.20 XorBasis

```

struct XorBasis {
    vector<T> basis;
    bool add(T mask) {
        for (auto u : basis) mask = min(mask, mask ^ u);
        for (auto& u : basis) u = min(u, u ^ mask);
    }
}

```

```

if (mask) {
    basis.push_back(mask);
    return true;
}
return false;
}
T getMax() {
    T res = 0;
    for (auto u : basis) res = max(res, res ^ u);
    return res;
}
void init() { sort(basis.begin(), basis.end()); }
bool InSpan(T mask) {
    for (auto u : basis) mask = min(mask, mask ^ u);
    return (mask == 0);
}
T getK(T k) // 0-indexed
{
    T res = 0;
    for (int i = sz(basis) - 1; i >= 0; i--)
        if (k >> i & 1) res ^= basis[i];
    return res;
}

```

---

## 6 String

### 6.1 AhoCorasick

```

template <int MAXC = 26>
struct AhoCorasick {
    vector<array<int, MAXC>> C;
    vector<int> F;
    vector<vector<int>> FG;
    vector<bool> E;

    int node() {
        int r = C.size();
        E.push_back(0);
        F.push_back(-1);
        C.emplace_back();
        fill(C.back().begin(), C.back().end(), -1);
        return r;
    }

    int ctrans(int n, int c) {
        if (C[n][c] == -1) C[n][c] = node();
        return C[n][c];
    }

    int ftrans(int n, int c) const {
        while (n && C[n][c] == -1) n = F[n];
        return C[n][c] != -1 ? C[n][c] : 0;
    }

    AhoCorasick(vector<vector<int>> P) {
        node();
        for (int i = 0; i < (int)P.size(); i++) {
            int n = 0;
            for (int c : P[i]) n = ctrans(n, c);
            E[n] = 1;
        }
    }
};

```

---

```

    }
    queue<int> Q;
    F[0] = 0;
    for (int c : C[0])
        if (c != -1) Q.push(c), F[c] = 0;
    while (!Q.empty()) {
        int n = Q.front();
        Q.pop();
        for (int c = 0; c < MAXC; ++c)
            if (C[n][c] != -1) {
                int f = F[n];
                while (f && C[f][c] == -1) f = F[f];
                F[C[n][c]] = C[f][c] != -1 ? C[f][c] : 0;
                Q.emplace(C[n][c]);
            }
    }
    FG.resize(F.size());
    for (int i = 1; i < (int)F.size(); i++) {
        FG[F[i]].push_back(i);
        if (E[i]) Q.push(i);
    }
    while (!Q.empty()) {
        int n = Q.front();
        Q.pop();
        for (int f : FG[n]) E[f] = 1, Q.push(f);
    }
}

bool check(vector<int> V) {
    if (E[0]) return 1;
    int n = 0;
    for (int c : V) {
        n = ftrans(n, c);
        if (E[n]) return 1;
    }
    return 0;
}

```

---

### 6.2 KMP

```

// prefix function: *length* of longest prefix which is
// also suffix:
// pi[i] = max(k: s[0..k-1] == s[i-(k-1)..i]
//
// KMP {{{
template <typename Container>
std::vector<int> prefix_function(const Container& s) {
    int n = s.size();
    std::vector<int> pi(n);
    for (int i = 1; i < n; ++i) {
        int j = pi[i - 1];
        while (j > 0 && s[i] != s[j]) j = pi[j - 1];
        if (s[i] == s[j]) ++j;
        pi[i] = j;
    }
    return pi;
}

// Tested: https://oj.vnoi.info/problem/substr

```

---

```

// Return all positions (0-based) that pattern 'pat'
// appears in 'text'
std::vector<int> kmp(const std::string& pat, const
                      std::string& text) {
    auto pi = prefix_function(pat + '\0' + text);
    std::vector<int> res;
    for (size_t i = pi.size() - text.size(); i < pi.size(); ++i) {
        if (pi[i] == (int)pat.size()) {
            res.push_back(i - 2 * pat.size());
        }
    }
    return res;
}

// Tested: https://oj.vnoi.info/problem/icpc22_mt_b
// Returns cnt[i] = # occurrences of length-i
// NOTE: cnt[0] = n+1 (0-length prefix appears n+1 times)
std::vector<int> prefix_occurrences(const string& s) {
    int n = s.size();
    auto pi = prefix_function(s);
    std::vector<int> res(n + 1);
    for (int i = 0; i < n; ++i) res[pi[i]]++;
    for (int i = n - 1; i > 0; --i) res[pi[i - 1]] += res[i];
    for (int i = 0; i <= n; ++i) res[i]++;
    return res;
}

```

---

### 6.3 Manacher

```

vector<int> manacher_odd(string s) {
    int n = s.size();
    s = "$" + s + "#";
    vector<int> p(n + 2);
    int l = 1, r = 1;
    for (int i = 1; i <= n; i++) {
        p[i] = max(0, min(r - i, p[l + (r - i)]));
        while (s[i - p[i]] == s[i + p[i]]) {
            p[i]++;
        }
        if (i + p[i] > r) {
            l = i - p[i], r = i + p[i];
        }
    }
    return vector<int>(begin(p) + 1, end(p) - 1);
}

vector<int> manacher(string s) {
    string t;
    for (auto c : s) {
        t += string("#") + c;
    }
    auto res = manacher_odd(t + "#");
    return vector<int>(begin(res) + 1, end(res) - 1);
}

```

---

### 6.4 StringHashing

```
const int MOD1 = 127657753, MOD2 = 987654319;
const int p1 = 137, p2 = 277;
```

## 6.5 SuffixArray

```
/** 
 * Author:      , chilli
 * Date: 2019-04-11
 * License: Unknown
 * Source: Suffix array - a powerful tool for dealing with
 *          strings
 * (Chinese IOI National team training paper, 2009)
 * Description: Builds suffix array for a string.
 * \texttt{sa[i]} is the starting index of the suffix which
 * is $i$'th in the sorted suffix array.
 * The returned vector is of size $n+1$, and \texttt{sa[0] = n}.
 * The \texttt{lcp} array contains longest common prefixes
 * for
 * neighbouring strings in the suffix array:
 * \texttt{lcp[i] = lcp(sa[i], sa[i-1])}, \texttt{lcp[0] = 0}.
 * The input string must not contain any zero bytes.
 * Time: O(n \log n)
 * Status: stress-tested
 */
struct SuffixArray {
    vi sa, lcp;
    SuffixArray(string& s, int lim=256) { // or
        basic_string<int>
            int n = sz(s) + 1, k = 0, a, b;
        vi x(all(s)), y(n), ws(max(n, lim));
        x.push_back(0), sa = lcp = y, iota(all(sa),
            0);
        for (int j = 0, p = 0; p < n; j = max(1, j *
            2), lim = p) {
            p = j, iota(all(y), n - j);
            rep(i, 0, n) if (sa[i] >= j) y[p++] =
                sa[i] - j;
            fill(all(ws), 0);
            rep(i, 0, n) ws[x[i]]++;
            rep(i, 1, lim) ws[i] += ws[i - 1];
            for (int i = n; i--;) {
                sa[-ws[x[y[i]]]] = y[i];
                swap(x, y), p = 1, x[sa[0]] = 0;
                rep(i, 1, n) a = sa[i - 1], b = sa[i],
                    x[b] =
                        (y[a] == y[b] && y[a + j] ==
                            y[b + j]) ? p - 1 : p++;
            }
            for (int i = 0, j; i < n - 1; lcp[x[i++]] =
                k)
                for (k && k--, j = sa[x[i] - 1];
                    s[i + k] == s[j + k];
                    k++);
        }
    }
}
```

```
}
};

int64_t cnt_distinct_substrings(const std::string& s) {
    auto lcp = LCP(s, suffix_array(s, 0, 255));
    return s.size() * (int64_t) (s.size() + 1) / 2
        - std::accumulate(lcp.begin(), lcp.end(), 0LL);
}
```

## 6.6 Z

```
vector<int> zfunc(const string& s) {
    int n = (int)s.length();
    vector<int> z(n);
    z[0] = n;
    for (int i = 1, l = 0, r = 0; i < n; ++i) {
        if (i <= r) z[i] = min(r - i + 1, z[i - 1]);
        while (i + z[i] < n && s[z[i]] == s[i + z[i]]) ++z[i];
        if (i + z[i] - 1 > r) l = i, r = i + z[i] - 1;
    }
    return z;
}
```

## 7 Utilities

### 7.1 FastInput

```
inline char gc() { // like getchar()
    static char buf[1 << 16];
    static size_t bc, be;
    if (bc >= be) {
        buf[0] = 0, bc = 0;
        be = fread(buf, 1, sizeof(buf), stdin);
    }
    return buf[bc++];
}

int readInt() {
    int a, c;
    while ((a = gc()) < 40)
        ;
    if (a == '-') return -readInt();
    while ((c = gc()) >= 48) a = a * 10 + c - 480;
    return a - 48;
}
```

### 7.2 template

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

```
mt19937_64
rng(chrono::steady_clock::now().time_since_epoch().count());
ll get_rand(ll l, ll r) {
    return uniform_int_distribution<ll>(l, r)(rng);
}
int32_t main() {
    ios::sync_with_stdio(false);
    cin.tie(nullptr);
    cerr << "\n[Time]: " << 1000.0 * clock() /
        CLOCKS_PER_SEC << " ms.\n";
    return 0;
}
```

## 7.3 vimrc

```
source $VIMRUNTIME/defaults.vim
let mapleader = " "
runtime! ftplugin/man.vim
packadd! matchit
set modeline
set autoread
set hidden
set undofile
set undodir="~/.vim/undo//"
set noswapfile
set tabstop=4
set softtabstop=4
set shiftwidth=4
set expandtab
set smarttab
set autoindent
set nojoinspaces
set nostartofline
set hlsearch
set ignorecase
set smartcase
set mouse=a
set background=dark
set number
set laststatus=2
set belloff=all
set splitbelow
set splitright
set scrolloff=2
nnoremap Y y$
nnoremap <C-L> :nohlsearch<Bar>normal! <C-L><CR>
nnoremap <Leader>h :tab h
nnoremap <Leader>e :e $MYVIMRC<CR>
nnoremap <Leader>r :source $MYVIMRC<CR>
nnoremap <Leader>c :w <Bar> !g++ -std=c++20 -O2 -Wall % -o
    %:r<CR>
nnoremap <Leader>x :!.%:r<CR>
```