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1 Basic

1.1 Pragma / IO

```
#pragma GCC optimize("Ofast,no-stack-protector")
#pragma GCC optimize("no-math-errno,unroll-loops")
#pragma GCC target("sse,sse2,sse3,ssse3,sse4")
#pragma GCC target("popcnt,abm,mmx,avx,arch=skylake")
__builtin_ia32_ldmxcsr(__builtin_ia32_stmxcsr()|0x8040)
#include<unistd.h>
char OB[65536]; int OP;
inline char RC() {
    static char buf[65536], *p = buf, *q = buf;
    return p == q && (q = (p = buf) + read(0, buf, 65536)) == buf ? -1 : *p++;
}
inline int R() {
    static char c;
    while((c = RC()) < '0'); int a = c ^ '0';
    while((c = RC()) >= '0') a *= 10, a += c ^ '0';
    return a;
}
inline void W(int n) {
    static char buf[12], p;
    if (n == 0) OB[OP++] = '0'; p = 0;
    while (n) buf[p++] = '0' + (n % 10), n /= 10;
    for (--p; p >= 0; --p) OB[OP++] = buf[p];
}
```

```
if (OP > 65520) write(1, OB, OP), OP = 0;
}
```

1.2 Debug Macro

```
void db() { cerr << endl; }
template <typename T, typename ...U>
void db(T i, U ...j) { cerr << i << ' ', db(j...); }
#define ABS
#define bug(x...) db("[ " + string(#x) + "] ", x)
#define safe cerr << __PRETTY_FUNCTION__ << endl
<< " line " << __LINE__ << " safe" << endl
#else
#define bug(x...) void()
#define safe void()
#endif
```

2 Data Structure

2.1 Heavy-Light Decomposition

```
int n, q, dfn = 0;
int val[maxn], sz[maxn], head[maxn], dep[maxn],
    st[maxn * 4], par[maxn], loc[maxn], id[maxn];
vector<int> adj[maxn];

void dfs(int pos, int prev){
    sz[pos] = 1;
    if(prev != -1) adj[pos].erase(
        find(adj[pos].begin(), adj[pos].end(), prev));
    for(auto &x : adj[pos]){
        par[x] = pos, dep[x] = dep[pos] + 1;
        dfs(x, pos);
        sz[pos] += sz[x];
        if(sz[x] > sz[adj[pos][0]]) swap(x, adj[pos][0]);
    }
}
void decompose(int pos, int h){
    id[dfn++] = pos;
    head[pos] = h, loc[pos] = dfn - 1;
    // upd(loc[pos], val[pos]);
    for(auto x : adj[pos]){
        if(x == adj[pos][0]) decompose(x, h);
        else decompose(x, x);
    }
}
void build(){
    dfs(0, -1);
    decompose(0, 0);
    //build_segtree();
}

int solve(int a, int b){
    int ret = 0;
    while(head[a] != head[b]){
        if(dep[head[a]] > dep[head[b]]) swap(a, b);
        ret = max(ret, qry(loc[head[b]], loc[b]));
        b = par[head[b]];
    }
    if(dep[a] > dep[b]) swap(a, b);
    return max(ret, qry(loc[a], loc[b]));
}
```

2.2 Centroid Decomposition

```
vector<pll> adj[maxn];
ll dist[20][maxn]; // distance to kth-layer-parent
int sz[maxn], del[maxn], par[maxn], cdep[maxn];
ll cnt[maxn], sum[maxn], re[maxn]; // re: subtree->par
int n, q;

void dfssz(int pos, int prev){
    sz[pos] = 1;
    for(auto [x, w] : adj[pos]){
        if(del[x] || x == prev) continue;
        dfssz(x, pos);
        sz[pos] += sz[x];
    }
}
int get_centroid(int pos, int prev, int siz){
    for(auto [x, w] : adj[pos]){
        if(!del[x] && x != prev && sz[x] >
           siz / 2) return get_centroid(x, pos, siz);
    }
    return pos;
}
void get_dist(int pos, int prev, int layer){
    for(auto [x, w] : adj[pos]){

    }
}
```

```

        if(del[x] || x == prev) continue;
        dist[layer][x] = dist[layer][pos] + w;
        get_dist(x, pos, layer);
    }
}

void cd(int pos, int layer = 1, int p = 0){
    dfssz(pos, -1);
    int cen = get_centroid(pos, -1, sz[pos]);
    del[cen] = 1;
    dist[layer][cen] = 0;
    cdep[cen] = layer;
    par[cen] = p;
    get_dist(cen, -1, layer);
    for(auto [x, w] : adj[cen]){
        if(!del[x]){
            cd(x, layer + 1, cen);
        }
    }
}
void upd(int p){
    for(int x = p, d = cdep[x]; d; x = par[x], d--){
        sum[x] += dist[d][p];
        re[x] += dist[d - 1][p];
        cnt[x]++;
    }
}
ll qry(int p){
    ll pre = 0, ans = 0;
    for(int x = p, d = cdep[x]; d; x = par[x], d--){
        ans += sum[x] - re[x] + (cnt[x] - pre) * dist[d][p];
        pre = cnt[x];
    }
    return ans;
}

```

2.3 Link Cut Tree

```

struct LCT{
    int ch[maxn][2], par[maxn], rev[maxn], xr[maxn], val[maxn];
    int get(int x){ return ch[par[x]][1] == x; }
    int isroot(int x){
        return ch[par[x]][0] != x && ch[par[x]][1] != x;
    }
    void push(int x){
        if(rev[x]){
            if(rs) swap(ch[rs][0], ch[rs][1]), rev[rs] ^= 1;
            if(ls) swap(ch[ls][0], ch[ls][1]), rev[ls] ^= 1;
            rev[x] = 0;
        }
    }
    void pull(int x){
        xr[x] = xr[ls] ^ xr[rs] ^ val[x];
    }
    void rotate(int x){
        int y = par[x], z = par[y], k = get(x);
        if(!isroot(y)) ch[z][ch[z][1] == y] = x;
        ch[y][k] = ch[x][!k], par[ch[x][!k]] = y;
        ch[x][!k] = y, par[y] = x;
        par[x] = z;
        pull(y), pull(x);
    }
    void update(int x){
        if(!isroot(x)) update(par[x]);
        push(x);
    }
    void splay(int x){
        update(x);
        for(int p = par[x]; !isroot(x); rotate(x), p = par[x]){
            if(!isroot(p)) rotate(get(p) == get(x) ? p : x);
        }
    }
    void access(int x){
        for(int p = 0; x != 0; p = x, x = par[x]){
            splay(x);
            ch[x][1] = p;
            pull(x);
        }
    }
    void make_root(int x){
        access(x);
        splay(x);
        swap(ls, rs);
        rev[x] ^= 1;
    }
    void link(int x, int y){

```

```

        make_root(x);
        splay(x);
        if(find_root(y) == x) return;
        par[x] = y;
    }
    void cut(int x, int y){
        make_root(x);
        access(y);
        splay(x);
        if(par[y] != x || ch[y][0]) return;
        ch[x][1] = par[y] = 0;
    }
    int find_root(int x){
        access(x);
        splay(x);
        push(x);
        while(ls x = ls, push(x));
        splay(x);
        return x;
    }
    void split(int x, int y){
        make_root(x);
        access(y);
        splay(y);
    }
    void upd(int x, int y){
        access(x);
        splay(x);
        val[x] = y;
        pull(x);
    }
} st;

```

2.4 LiChaoST

```

struct line{
    ll m, k;
    line(){}
    line(ll _m, ll _k) : m(_m), k(_k){}
    ll val(ll x){ return m * x + k; }
};

struct node{
    line ans;
    node *l, *r;
    int siz;
    node(){}
    node(line l) : ans(l), l(nullptr), r(nullptr){}
};
node sgt[maxn];

int root[maxn], cnt = 0;

struct segtree{
    node *rt;
    int n, siz;
    segtree() : n(maxc * 2), siz(0), rt(nullptr){}
    void insert(node* &k, int l, int r, line cur){
        if(!k){
            k = new node(cur);
            siz++;
            return;
        }
        if(l == r){
            if(k->ans.val(l) > cur.val(l)) k->ans = cur;
            return;
        }
        int m = (l + r) / 2;
        if(k->ans.val(m) > cur.val(m)) swap(k->ans, cur);
        if(cur.m > k->ans.m) insert(k->l, l, m, cur);
        else insert(k->r, m + 1, r, cur);
    }
    void insert
        (ll m, ll k) { insert(rt, 0, n, line(m, k)); }
    void insert(line l) { insert(rt, 0, n, l); }
    ll qry(node *k, int l, int r, int pos){
        if(!k) return INF;
        if(l == r) return k->ans.val(pos);
        int m = (l + r) / 2;
        return min(k->ans.val(pos), pos <= m ? qry
            (k->l, l, m, pos) : qry(k->r, m + 1, r, pos));
    }
    ll qry(int pos) { return qry(rt, 0, n, pos); }
};

```

2.5 Leftist Heap

```

struct LeftistTree{
    int cnt, rt[maxn];
    int, lc[maxn * 20], rc[maxn * 20], d[maxn * 20];
    int v[maxn * 20];
    LeftistTree(){}
    int newnode(pll nd){
        cnt++;
        v[cnt] = nd;
        return cnt;
    }
    int merge(int x, int y){
        if(!x || !y) return x + y;
        if(v[x] > v[y]) swap(x, y);
        int p = ++cnt;
        lc[p] = lc[x], v[p] = v[x];
        rc[p] = merge(rc[x], y);
        if(d[lc[p]] < d[rc[p]]) swap(lc[p], rc[p]);
        d[p] = d[rc[p]] + 1;
        return p;
    }
} st;

```

2.6 Treap

```

struct node{
    int val, pri, c = 1;
    node *l, *r;
    node(int _val) :
        val(_val), pri(rand()), l(nullptr), r(nullptr){}
    void recalc();
} *rt;
int cnt(node *t){ return t ? t->c : 0;}
void node::recalc(){
    c = cnt(l) + cnt(r) + 1;
}
pair<node*, node*> split(node *t, int val){
    if(!t) return {nullptr, nullptr};
    if(cnt(t->l) < val){
        auto p = split(t->r, val - cnt(t->l) - 1);
        t->r = p.first;
        t->recalc();
        return {t, p.second};
    }
    else{
        auto p = split(t->l, val);
        t->l = p.second;
        t->recalc();
        return {p.first, t};
    }
}
node* merge(node *a, node *b){
    if(!a || !b) return a ? a : b;
    if(a->pri > b->pri){
        a->r = merge(a->r, b);
        a->recalc();
        return a;
    }
    else{
        b->l = merge(a, b->l);
        b->recalc();
        return b;
    }
}
node *insert(node *t, int k){
    auto [a, b] = split(t, k);
    return merge(merge(a, new node(k)), b);
}
node* remove(node *t, int k){
    auto [a, b] = split(t, k - 1);
    auto [b, c] = split(b, k);
    return merge(a, c);
}

```

2.7 Chtholly Tree

```

struct ChthollyTree {
    struct interval {
        int l, r;
        ll v;
        interval(
            int _l, int _r, ll _v) : l(_l), r(_r), v(_v) {}
    };
    struct cmp {
        bool operator ()(
            const interval &a, const interval& b) const {
            return a.l < b.l;
        }
    };
}

```

```

};

set<interval, cmp> s;
vector<interval> split(int l, int r) {
    // split
    // into [0, l), [l, r), [r, n) and return [l, r)
    vector<interval> del, ans, re;
    auto it = s.lower_bound(interval(l, -1, 0));
    if (it != s.begin() && (it == s.end() || l < it->l)) {
        --it;
        del.pb(*it);
        if (r < it->r) {
            re.pb(interval(it->l, l, it->v));
            ans.pb(interval(l, r, it->v));
            re.pb(interval(r, it->r, it->v));
        } else {
            re.pb(interval(it->l, l, it->v));
            ans.pb(interval(l, it->r, it->v));
        }
        ++it;
    }
    for (; it != s.end() && it->r <= r; ++it) {
        ans.pb(*it);
        del.pb(*it);
    }
    if (it != s.end() && it->l < r) {
        del.pb(*it);
        ans.pb(interval(it->l, r, it->v));
        re.pb(interval(r, it->r, it->v));
    }
    for (interval &i : del)
        s.erase(i);
    for (interval &i : re)
        s.insert(i);
    return ans;
}
void merge(vector<interval> a) {
    for (interval &i : a)
        s.insert(i);
}

```

2.8 Persistent Segment Tree

```

struct Seg {
    // Persistent Segment
    // Tree, single point modify, range query sum
    // 0-indexed, [l, r)
    static Seg mem[M], *pt;
    int l, r, m, val;
    Seg* ch[2];
    Seg () = default;
    Seg (int _l
        , int _r) : l(_l), r(_r), m(l + r >> 1), val(0) {
        if (r - l > 1) {
            ch[0] = new (pt++) Seg(l, m);
            ch[1] = new (pt++) Seg(m, r);
        }
    }
    void pull() {val = ch[0]->val + ch[1]->val;}
    Seg* modify(int p, int v) {
        Seg *now = new (pt++) Seg(*this);
        if (r - l == 1) {
            now->val = v;
        } else {
            now->ch[p >= m] = ch[p >= m]->modify(p, v);
            now->pull();
        }
        return now;
    }
    int query(int a, int b) {
        if (a <= l && r <= b) return val;
        int ans = 0;
        if (a < m) ans += ch[0]->query(a, b);
        if (m < b) ans += ch[1]->query(a, b);
        return ans;
    }
} Seg::mem[M], *Seg::pt = mem;
// Init Tree
Seg *root = new (Seg::pt++) Seg(0, n);

```

2.9 Range Chmin Chmax Add Range Sum

```

#include <algorithm>
#include <iostream>
using namespace std;
typedef long long ll;

```

```

const int MAXC = 200005;
const ll INF = 1e18;

struct node {
    ll sum;
    ll mx, mxcnt, smx;
    ll mi, micnt, smi;
    ll lazymax, lazymin, lazyadd;
    node(ll k = 0)
        : sum(k), mx(k), mxcnt(1), smx(-INF), mi(k),
          micnt(1), smi(INF), lazymax(-INF), lazymin(INF),
          lazyadd(0) {}
    node operator+(const node &a) const {
        node rt;
        rt.sum = sum + a.sum;
        rt.mx = max(mx, a.mx);
        rt.mi = min(mi, a.mi);
        if (mx == a.mx) {
            rt.mxcnt = mxcnt + a.mxcnt;
            rt.smx = max(smx, a.smx);
        } else if (mx > a.mx) {
            rt.mxcnt = mxcnt;
            rt.smx = max(smx, a.mx);
        } else {
            rt.mxcnt = a.mxcnt;
            rt.smx = max(mx, a.smx);
        }
        if (mi == a.mi) {
            rt.micnt = micnt + a.micnt;
            rt.smi = min(smi, a.smi);
        } else if (mi < a.mi) {
            rt.micnt = micnt;
            rt.smi = min(smi, a.mi);
        } else {
            rt.micnt = a.micnt;
            rt.smi = min(mi, a.smi);
        }
        rt.lazymax = -INF;
        rt.lazymin = INF;
        rt.lazyadd = 0;
        return rt;
    }
} seg[MAXC << 2];

ll a[MAXC];

void give_tag_min(int rt, ll t) {
    if (t >= seg[rt].mx) return;
    seg[rt].lazymin = t;
    seg[rt].lazymax = min(seg[rt].lazymax, t);
    seg[rt].sum -= seg[rt].mxcnt * (seg[rt].mx - t);
    if (seg[rt].mx == seg[rt].smi) seg[rt].smi = t;
    if (seg[rt].mx == seg[rt].mi) seg[rt].mi = t;
    seg[rt].mx = t;
}

void give_tag_max(int rt, ll t) {
    if (t <= seg[rt].mi) return;
    seg[rt].lazymax = t;
    seg[rt].sum += seg[rt].micnt * (t - seg[rt].mi);
    if (seg[rt].mi == seg[rt].smx) seg[rt].smx = t;
    if (seg[rt].mi == seg[rt].mx) seg[rt].mx = t;
    seg[rt].mi = t;
}

void give_tag_add(int l, int r, int rt, ll t) {
    seg[rt].lazyadd += t;
    if (seg[rt].lazymax != -INF) seg[rt].lazymax += t;
    if (seg[rt].lazymin != INF) seg[rt].lazymin += t;
    seg[rt].mx += t;
    if (seg[rt].smx != -INF) seg[rt].smx += t;
    seg[rt].mi += t;
    if (seg[rt].smi != INF) seg[rt].smi += t;
    seg[rt].sum += (ll)(r - l + 1) * t;
}

void tag_down(int l, int r, int rt) {
    if (seg[rt].lazyadd != 0) {
        int mid = (l + r) >> 1;
        give_tag_add(l, mid, rt << 1, seg[rt].lazyadd);
        give_tag_add(
            mid + 1, r, rt << 1 | 1, seg[rt].lazyadd);
        seg[rt].lazyadd = 0;
    }
    if (seg[rt].lazymin != INF) {
        give_tag_min(rt << 1, seg[rt].lazymin);
        give_tag_min(rt << 1 | 1, seg[rt].lazymin);
        seg[rt].lazymin = INF;
    }
    if (seg[rt].lazymax != -INF) {
        give_tag_max(rt << 1, seg[rt].lazymax);
        give_tag_max(rt << 1 | 1, seg[rt].lazymax);
        seg[rt].lazymax = -INF;
    }
}

void build(int l, int r, int rt) {
    if (l == r) return seg[rt] = node(a[l]), void();
    int mid = (l + r) >> 1;
    build(l, mid, rt << 1);
    build(mid + 1, r, rt << 1 | 1);
    seg[rt] = seg[rt << 1] + seg[rt << 1 | 1];
}

void modifymax(
    int L, int R, int l, int r, int rt, ll t) {
    if (L <= l && R >= r && t < seg[rt].smx)
        return give_tag_max(rt, t);
    if (l != r) tag_down(l, r, rt);
    int mid = (l + r) >> 1;
    if (L <= mid) modifymax(L, R, l, mid, rt << 1, t);
    if (R > mid)
        modifymax(L, R, mid + 1, r, rt << 1 | 1, t);
    seg[rt] = seg[rt << 1] + seg[rt << 1 | 1];
}

void modifymin(
    int L, int R, int l, int r, int rt, ll t) {
    if (L <= l && R >= r && t > seg[rt].smx)
        return give_tag_min(rt, t);
    if (l != r) tag_down(l, r, rt);
    int mid = (l + r) >> 1;
    if (L <= mid) modifymin(L, R, l, mid, rt << 1, t);
    if (R > mid)
        modifymin(L, R, mid + 1, r, rt << 1 | 1, t);
    seg[rt] = seg[rt << 1] + seg[rt << 1 | 1];
}

void modifyadd(
    int L, int R, int l, int r, int rt, ll t) {
    if (L <= l && R >= r)
        return give_tag_add(l, r, rt, t);
    if (l != r) tag_down(l, r, rt);
    int mid = (l + r) >> 1;
    if (L <= mid) modifyadd(L, R, l, mid, rt << 1, t);
    if (R > mid)
        modifyadd(L, R, mid + 1, r, rt << 1 | 1, t);
    seg[rt] = seg[rt << 1] + seg[rt << 1 | 1];
}

ll query(int L, int R, int l, int r, int rt) {
    if (L <= l && R >= r) return seg[rt].sum;
    if (l != r) tag_down(l, r, rt);
    int mid = (l + r) >> 1;
    if (R <= mid) return query(L, R, l, mid, rt << 1);
    if (L > mid)
        return query(L, R, mid + 1, r, rt << 1 | 1);
    return query(L, R, l, mid, rt << 1) +
        query(L, R, mid + 1, r, rt << 1 | 1);
}

int main() {
    ios::sync_with_stdio(0), cin.tie(0);
    int n, m;
    cin >> n >> m;
    for (int i = 1; i <= n; ++i) cin >> a[i];
    build(1, n, 1);
    while (m--) {
        int k, x, y;
        ll t;
        cin >> k >> x >> y, ++x;
        if (k == 0) cin >> t, modifymin(x, y, 1, n, 1, t);
        else if (k == 1)
            cin >> t, modifymax(x, y, 1, n, 1, t);
        else if (k == 2)
            cin >> t, modifyadd(x, y, 1, n, 1, t);
        else cout << query(x, y, 1, n, 1) << "\n";
    }
}

```

2.10 Range Set

```

struct RangeSet { // [l, r)
    set <pii> S;
    void cut(int x) {
        auto it = S.lower_bound({x + 1, -1});
        if (it == S.begin()) return;
        auto [l, r] = *prev(it);
        if (l >= x || x >= r) return;
        S.erase(prev(it));
        S.insert({l, x});
        S.insert({x, r});
    }
    vector <pii> split(int l, int r) {
        // remove and return ranges in [l, r)
        cut(l), cut(r);
        vector <pii> res;
        while (true) {
            auto it = S.lower_bound({l, -1});
            if (it == S.end() || r <= it->first) break;
            res.pb(*it), S.erase(it);
        }
        return res;
    }
    void insert(int l, int r) {
        // add a range [l, r), [l, r) not in S
        auto it = S.lower_bound({l, r});
        if (it != S.begin() && prev(it)->second == l)
            l = prev(it)->first, S.erase(prev(it));
        if (it != S.end() && r == it->first)
            r = it->second, S.erase(it);
        S.insert({l, r});
    }
    bool count(int x) {
        auto it = S.lower_bound({x + 1, -1});
        return it != S.begin() && prev(it)->first <= x
            && x < prev(it)->second;
    }
}

```

2.11 KD Tree

```

namespace kdt {
    int root, lc[maxn], rc[maxn], xl[maxn], xr[maxn],
    yl[maxn], yr[maxn];
    point p[maxn];
    int build(int l, int r, int dep = 0) {
        if (l == r) return -1;
        function<bool(const point &, const point &)> f =
            [dep](const point &a, const point &b) {
                if (dep & 1) return a.x < b.x;
                else return a.y < b.y;
            };
        int m = (l + r) >> 1;
        nth_element(p + l, p + m, p + r, f);
        xl[m] = xr[m] = p[m].x;
        yl[m] = yr[m] = p[m].y;
        lc[m] = build(l, m, dep + 1);
        if (~lc[m]) {
            xl[m] = min(xl[m], xl[lc[m]]);
            xr[m] = max(xr[m], xr[lc[m]]);
            yl[m] = min(yl[m], yl[lc[m]]);
            yr[m] = max(yr[m], yr[lc[m]]);
        }
        rc[m] = build(m + 1, r, dep + 1);
        if (~rc[m]) {
            xl[m] = min(xl[m], xl[rc[m]]);
            xr[m] = max(xr[m], xr[rc[m]]);
            yl[m] = min(yl[m], yl[rc[m]]);
            yr[m] = max(yr[m], yr[rc[m]]);
        }
        return m;
    }
    bool bound(const point &q, int o, long long d) {
        double ds = sqrt(d + 1.0);
        if (q.x < xl[o] - ds || q.x > xr[o] + ds ||
            q.y < yl[o] - ds || q.y > yr[o] + ds)
            return false;
        return true;
    }
    long long dist(const point &a, const point &b) {
        return (a.x - b.x) * 1ll * (a.x - b.x) +
            (a.y - b.y) * 1ll * (a.y - b.y);
    }
    void dfs(
        const point &q, long long &d, int o, int dep = 0) {
        if (!bound(q, o, d)) return;
        long long cd = dist(p[o], q);
        if (cd != 0) d = min(d, cd);
    }
}

```

```

if ((dep & 1) && q.x < p[o].x ||
    !(dep & 1) && q.y < p[o].y) {
    if (~lc[o]) dfs(q, d, lc[o], dep + 1);
    if (~rc[o]) dfs(q, d, rc[o], dep + 1);
} else {
    if (~rc[o]) dfs(q, d, rc[o], dep + 1);
    if (~lc[o]) dfs(q, d, lc[o], dep + 1);
}
void init(const vector<point> &v) {
    for (int i = 0; i < v.size(); ++i) p[i] = v[i];
    root = build(0, v.size());
}
long long nearest(const point &q) {
    long long res = 1e18;
    dfs(q, res, root);
    return res;
}
} // namespace kdt

```

2.12 pbds

```

#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/priority_queue.hpp>
using namespace __gnu_pbds;
// heap tags: paring/binary/binomial/rc_binomial/thin
template<typename T>
using pbds_heap=__gnu_pbds::priority_queue<T,less<T>, \
pairing_heap_tag>;
// pbds_heap::point_iterator
// x = pq.push(10); pq.modify(x, 87); a.join(b);
// tree tags: rb_tree_tag/ov_tree_tag/splay_tree_tag
template<typename T>
using ordered_set = tree<T, null_type, less<T>,
rb_tree_tag, tree_order_statistics_node_update>;
// find_by_order, order_of_key
// hash tables: cc_hash_table/gp_hash_table

```

3 Graph

3.1 SCC

```

struct SCC {
    int n, nscc, _id;
    vector<vector<int>> g;
    vector<int> dep, low, scc_id, stk;
    void dfs(int v) {
        dep[v] = low[v] = _id++, stk.pb(v);
        for (int u : g[v]) if (scc_id[u] == -1) {
            if (low[u] == -1) dfs(u);
            low[v] = min(low[v], low[u]);
        }
        if (low[v] == dep[v]) {
            int id = nscc++, x;
            do {
                x = stk.back(), stk.pop_back(), scc_id[x] = id;
            } while (x != v);
        }
    }
    void build() {
        for (int i = 0; i < n; ++i) if (low[i] == -1)
            dfs(i);
    }
    void add_edge(int u, int v) { g[u].pb(v); }
    SCC (int _n) : n(_n), nscc(0), _id(0), g(n), dep(n),
    low(n, -1), scc_id(n, -1), stk() {}
};

```

3.2 BCC Vertex

```

struct BCC { // 0-base
    int n, dft, nbcc;
    vector<int> low, dfn, bln, stk, is_ap, cir;
    vector<vector<int>> G, bcc, nG;
    void make_bcc(int u) {
        bcc.emplace_back(1, u);
        for (; stk.back() != u; stk.pop_back())
            bln[stk.back()] = nbcc, bcc[nbcc].pb(stk.back());
        stk.pop_back(), bln[u] = nbcc++;
    }
    void dfs(int u, int f) {
        int child = 0;
        low[u] = dfn[u] = ++dft, stk.pb(u);
        for (int v : G[u])
            if (!dfn[v]) {
                dfs(v, u), ++child;
                low[u] = min(low[u], low[v]);
            }
    }
}

```

```

    if (dfn[u] <= low[v]) {
        is_ap[u] = 1, bln[u] = nbcc;
        make_bcc(v), bcc.back().pb(u);
    }
} else if (dfn[v] < dfn[u] && v != f) {
    low[u] = min(low[u], dfn[v]);
    if (f == -1 && child < 2) is_ap[u] = 0;
    if (f == -1 && child == 0) make_bcc(u);
}
BCC(int _n): n(_n), dft(),
    nbcc(), low(n), dfn(n), bln(n), is_ap(n), G(n) {}
void add_edge(int u, int v) {
    G[u].pb(v), G[v].pb(u);
}
void solve() {
    for (int i = 0; i < n; ++i)
        if (!dfn[i]) dfs(i, -1);
}
void block_cut_tree() {
    cir.resize(nbcc);
    for (int i = 0; i < n; ++i)
        if (is_ap[i])
            bln[i] = nbcc++;
    cir.resize(nbcc, 1), nG.resize(nbcc);
    for (int i = 0; i < nbcc && !cir[i]; ++i)
        for (int j : bcc[i])
            if (is_ap[j])
                nG[i].pb(bln[j]), nG[bln[j]].pb(i);
} // up to 2 * n - 2 nodes!! bln[i] for id
};

```

3.3 Directed MST

```

using D = int;
struct edge { int u, v; D w; };
// 0-based, return index of edges
vector<int> dmst(vector<edge> &e, int n, int root) {
    using T = pair <D, int>;
    using PQ = pair
        <priority_queue <T, vector <T>, greater <T>>, D>;
    auto push = [] (PQ &pq, T v) {
        pq.first.emplace(v.first - pq.second, v.second);
    };
    auto top = [] (const PQ &pq) -> T {
        auto r = pq.first.top();
        return {r.first + pq.second, r.second};
    };
    auto join = [&push, &top](PQ &a, PQ &b) {
        if (a.first.size() < b.first.size()) swap(a, b);
        while (!b.first.empty())
            push(a, top(b)), b.first.pop();
    };
    vector<PQ> h(n * 2);
    for (int i = 0; i < e.size(); ++i)
        push(h[e[i].v], {e[i].w, i});
    vector<int>
        a(n * 2), v(n * 2, -1), pa(n * 2, -1), r(n * 2);
    iota(all(a), 0);
    auto o = [&]()& (int x) { int y;
        for (y = x; a[y] != y; y = a[y]);
        for (int ox = x; x != y; ox = x)
            x = a[x], a[ox] = y;
        return y;
    };
    v[root] = n + 1;
    int pc = n;
    for (int i = 0; i < n; ++i) if (v[i] == -1) {
        for (int p =
            i; v[p] == -1 || v[p] == i; p = o(e[r[p]].u)) {
            if (v[p] == i) {
                int q = p; p = pc++;
                do {
                    h[q].second = -h[q].first.top().first;
                    join(h[pa[q]] = a[q] = p, h[q]);
                } while ((q = o(e[r[q]].u)) != p);
            }
            v[p] = i;
            while (!h[p].first
                .empty() && o(e[top(h[p]).second].u) == p)
                h[p].first.pop();
            r[p] = top(h[p]).second;
        }
    }
    vector<int> ans;
    for (int i = pc - 1; i >= 0; i--) {
        if (i != root && v[i] != n) {

```

```

            for (int f = e[r[i]].
                v; f != -1 && v[f] != n; f = pa[f]) v[f] = n;
            ans.pb(r[i]);
        }
    }
    return ans;
}

```

3.4 Negative Cycle

```

vector<pll> adj[maxn];
template <typename T>
struct NegativeCycle {
    vector <T> dis;
    vector <int> rt;
    int n; T INF;
    vector <int> cycle;
    NegativeCycle () = default;
    NegativeCycle
        (int _n) : n(_n), INF(numeric_limits<T>::max()) {
        dis.assign(n, 0), rt.assign(n, -1);
        int relax = -1;
        for (int t = 0; t < n; ++t) {
            relax = -1;
            for (int i = 0; i < n; ++i) {
                for (auto
                    [j, w] : adj[i]) if (dis[j] > dis[i] + w) {
                    dis[j] = dis[i] + w, rt[j] = i;
                    relax = j;
                }
            }
        }
        if (relax != -1) {
            int s = relax;
            for (int i = 0; i < n; ++i) s = rt[s];
            vector <bool> vis(n, false);
            while (!vis[s]) {
                cycle.push_back(s), vis[s] = true;
                s = rt[s];
            }
            reverse(cycle.begin(), cycle.end());
        }
    }
};

```

3.5 Dominator Tree

```

int in[maxn], id[maxn], par[maxn], dfn = 0;
int mn[maxn], idom[maxn], sdom[maxn], ans[maxn];
int fa[maxn]; // dsu
int n, m;
vector<int> adj[3][maxn];

void dfs(int pos){
    in[pos] = ++dfn;
    id[dfn] = pos;
    for(auto x : adj[0][pos]){
        if(in[x]) continue;
        par[x] = pos;
        dfs(x);
    }
}

int find(int x){
    if(fa[x] == x) return x;
    int tmp = fa[x];
    fa[x] = find(fa[x]);
    if(in[sdom[mn[tmp]]] < in[sdom[mn[x]]]) {
        mn[x] = mn[tmp];
    }
    return fa[x];
}

void tar(int st){
    dfs(st);
    idom[st] = st;
    for(int i = 0; i < n; i++){
        if(!in[i]) idom[i] = -1;
        else mn[i] = sdom[i] = fa[i] = i;
    }
    for(int i = dfn; i >= 2; i--){
        int pos = id[i], res = INF; // res : in(x) of sdom
        for(auto x : adj[1][pos]){
            if(!in[x]) continue;
            find(x);
            if(in[pos] > in[x]) res = min(res, in[x]);
            else res = min(res, in[sdom[mn[x]]]);
        }
    }
}

```

```

    sdom[pos] = id[res];
    fa[pos] = par[pos];
    adj[2][sdom[pos]].pb(pos);
    pos = par[pos];
    for(auto x : adj[2][pos]){
        find(x);
        if(sdom[mn[x]] == pos){
            idom[x] = pos;
        } else{
            idom[x] = mn[x];
        }
    }
    adj[2][pos].clear();
}
for(int i = 2; i <= dfn; i++){
    int x = id[i];
    if(idom[x] != sdom[x]) idom[x] = idom[idom[x]];
}
}

```

3.6 Maximum Clique

```

struct MaximumClique{
    typedef bitset<maxn> bst;
    bst adj[maxn], empt;
    int p[maxn], n, ans;
    void init(int _n){
        n = _n;
        for(int i = 0; i < n; i++) adj[i].reset();
    }
    void BronKerbosch(bst R, bst P, bst X){
        if(P == empt && X == empt){
            ans = max(ans, (int)R.count());
            return;
        }
        bst tmp = P | X;
        if((R | P | X).count() <= ans) return;
        int u;
        for(int i = 0; i < n; i++){
            if(tmp[u = p[i]]) break;
        }
        bst lim = P & ~adj[u];
        for(int i = 0; i < n; i++){
            int v = p[i];
            if(lim[v]){
                R[v] = 1;
                BronKerbosch
                    (R, P & adj[v], X & adj[v]);
                R[v] = 0, P[v] = 0, X[v] = 1;
            }
        }
        void add_edge(int a, int b){
            adj[a][b] = adj[b][a] = 1;
        }
        int solve(){
            bst R, P, X;
            ans = 0, P.flip();
            iota(p, p + n, 0);
            random_shuffle
                (p, p + n), BronKerbosch(R, P, X);
            return ans;
        }
    }
}

```

3.7 Virtual Tree

```

// need lca, in, out
vector<pll> virtual_tree(vector<int> &v) {
    auto cmp = [&](int x, int y) {return in[x] < in[y];};
    sort(all(v), cmp);
    int sz = (int)v.size();
    for (int i = 0; i + 1 < sz; ++i)
        v.pb(lca(v[i], v[i + 1]));
    sort(all(v), cmp);
    v.resize(unique(all(v)) - v.begin());
    vector <int> stk(1, v[0]);
    vector <pll> res;
    for (int i = 1; i < (int)v.size(); ++i) {
        int x = v[i];
        while (out[stk.back()] < out[x]) stk.pop_back();
        res.emplace_back(stk.back(), x), stk.pb(x);
    }
    return res;
}

```

3.8 Minimum Steiner Tree

```

struct SteinerTree { // 0-base
    int n, dst[N][N], dp[1 << T][N], tdst[N];
    int vcst[N]; // the cost of vertexs
    void init(int _n) {
        n = _n;
        for (int i = 0; i < n; ++i) {
            fill_n(dst[i], n, INF);
            dst[i][i] = vcst[i] = 0;
        }
    }
    void chmin(int &x, int val) {
        x = min(x, val);
    }
    void add_edge(int ui, int vi, int wi) {
        chmin(dst[ui][vi], wi);
    }
    void shortest_path() {
        for (int k = 0; k < n; ++k)
            for (int i = 0; i < n; ++i)
                for (int j = 0; j < n; ++j)
                    chmin(dst[i][j], dst[i][k] + dst[k][j]);
    }
    int solve(const vector<int>& ter) {
        shortest_path();
        int t = SZ(ter), full = (1 << t) - 1;
        for (int i = 0; i <= full; ++i)
            fill_n(dp[i], n, INF);
        copy_n(vcst, n, dp[0]);
        for (int msk = 1; msk <= full; ++msk) {
            if (!(msk & (msk - 1))) {
                int who = __lg(msk);
                for (int i = 0; i < n; ++i)
                    dp[msk]
                        [i] = vcst[ter[who]] + dst[ter[who]][i];
            }
            for (int i = 0; i < n; ++i)
                for (int sub = (
                    msk - 1) & msk; sub; sub = (sub - 1) & msk)
                    chmin(dp[msk][i],
                        dp[sub][i] + dp[msk ^ sub][i] - vcst[i]);
            for (int i = 0; i < n; ++i) {
                tdst[i] = INF;
                for (int j = 0; j < n; ++j)
                    chmin(tdst[i], dp[msk][j] + dst[j][i]);
            }
            copy_n(tdst, n, dp[msk]);
        }
        return *min_element(dp[full], dp[full] + n);
    }
}; // O(V 3^T + V^2 2^T)

```

4 Flow / Matching

4.1 Dinic

```

struct Dinic{
    struct edge{
        ll to, cap;
        edge(){}
        edge(int _to, ll _cap) : to(_to), cap(_cap){}
    };
    vector<edge> e;
    vector<vector<int>> adj;
    vector<int> iter, level;
    int n, s, t;
    void init(int _n, int _s, int _t){
        n = _n, s = _s, t = _t;
        adj = vector<vector<int>>(n);
        iter = vector<int>(n);
        level = vector<int>(n);
        e.clear();
    }
    void add_edge(int from, int to, ll cap){
        adj[from].pb(e.size()), adj[to].pb(e.size() + 1);
        e.pb(edge(to, cap)), e.pb(edge(from, 0));
    }
    void bfs(){
        fill(level.begin(), level.end(), -1);
        level[s] = 0;
        queue<int> q;
        q.push(s);
        while(!q.empty()){
            int cur = q.front(); q.pop();
            for(auto id : adj[cur]){
                auto [to, cap] = e[id];

```

```

        if(level[to] == -1 && cap){
            level[to] = level[cur] + 1;
            q.push(to);
        }
    }
    ll dfs(int pos, ll flow){
        if(pos == t) return flow;
        for(int &i = iter[pos]; i < adj[pos].size(); i++){
            auto [to, cap] = e[adj[pos][i]];
            if(level[to] == level[pos] + 1 && cap){
                ll tmp = dfs(to, min(flow, cap));
                if(tmp){
                    e[adj[pos][i]].cap -= tmp;
                    e[adj[pos][i] ^ 1].cap += tmp;
                    return tmp;
                }
            }
        }
        return 0;
    }
} flow;

```

4.2 Min Cost Max Flow

```

struct MCMF{
    using T = ll;
    struct edge{
        int to;
        T cap, cost;
        edge(){}
        edge(int _to, T _cap, T _cost) : to(_to), cap(_cap), cost(_cost){}
    };
    vector<edge> e;
    vector<vector<int>> adj;
    vector<int> iter, inq;
    vector<T> dist;
    int n, s, t;
    void init(int _n, int _s, int _t){
        n = _n, s = _s, t = _t;
        adj = vector<vector<int>>(n);
        iter = vector<int>(n);
        dist = vector<T>(n);
        inq = vector<int>(n);
        e.clear();
    }
    void add_edge(int from, int to, T cap, T cost = 0){
        adj[from]
            .pb(e.size()), adj[to].pb(e.size() + 1);
        e.pb(edge(to
            , cap, cost)), e.pb(edge(from, 0, -cost));
    }
    bool spfa(){
        fill(dist.begin(), dist.end(), INF);
        queue<int> q;
        q.push(s);
        dist[s] = 0, inq[s] = 1;
        while(!q.empty()){
            int pos = q.front(); q.pop();
            inq[pos] = 0;
            for(auto id : adj[pos]){
                auto [to, cap, cost] = e[id];
                if(cap && dist[to] > dist[pos] + cost){
                    dist[to] = dist[pos] + cost;
                    if(!inq
                        [to]) q.push(to), inq[to] = 1;
                }
            }
        }
        return dist[t] != INF;
    }
    T dfs(int pos, T flow){
        if(pos == t) return flow;
        inq[pos] = 1;
        for(int
            &i = iter[pos]; i < adj[pos].size(); i++){
            auto [to, cap, cost] = e[adj[pos][i]];
            if(!inq[to] &&
                dist[to] == dist[pos] + cost && cap){
                T tmp = dfs(to, min(flow, cap));
                if(tmp){
                    inq[pos] = 0;
                    e[adj[pos][i]].cap -= tmp;
                    e[adj[pos][i] ^ 1].cap += tmp;
                    return tmp;
                }
            }
        }
    }
}

```

```

        }
    }
    inq[pos] = 0;
    return 0;
}
pair<T, T> mcmf(){
    T flow = 0, cost = 0;
    while(true){
        if(!spfa()) break;
        fill(iter.begin(), iter.end(), 0);
        T tmp;
        while((tmp = dfs(s, INF)) > 0){
            flow += tmp, cost += tmp * dist[t];
        }
    }
    return {flow, cost};
}
} flow;

```

4.3 Gomory Hu

```

void Gomory_Hu_Tree(vector<int> st){
    if(st.size() <= 1) return;
    int s = st[0], t = st[1];
    flow.init(n, s, t);
    for(auto [a, b, w] : e) flow.add_edge(a, b, w);
    int cost = flow.flow();
    flow.bfs();
    adj[s].eb(t, cost), adj[t].eb(s, cost);
    vector<int> a, b;
    for(auto x : st){
        if(flow.level[x] == -1) a.pb(x);
        else b.pb(x);
    }
    Gomory_Hu_Tree(a);
    Gomory_Hu_Tree(b);
}

```

4.4 SW Min Cut

```

int edge[maxn][maxn], par[maxn], siz[maxn];
int dist[maxn], vis[maxn], done[maxn];
int n, m;
int root(int x)
{ return x == par[x] ? x : par[x] = root(par[x]); }
int contract(int &s, int &t){
    memset(dist, 0, sizeof(dist));
    memset(vis, 0, sizeof(vis));
    int mincut = INF, id, maxc;
    for(int i = 0; i < n; i++){
        id = maxc = -1;
        for(int j = 0; j < n; j++){
            if(!done[j] && !vis[j] && dist[j] > maxc){
                id = j;
                maxc = dist[j];
            }
        }
        if(id == -1) return mincut;
        s = t, t = id;
        mincut = maxc;
        vis[id] = true;
        for(int j = 0; j < n; j++){
            if(!done[j] && !vis[j]) dist[j] += edge[id][j];
        }
    }
    return mincut;
}
int Stoer_Wagner(){
    int mincut = INF, s, t, tmp;
    for(int i = 1; i < n; i++){
        tmp = contract(s, t);
        done[t] = true;
        mincut = min(mincut, tmp);
        if(!mincut) return 0;
        for(int j = 0; j < n; j++){
            if(!done
                [j]) edge[s][j] = (edge[j][s] += edge[j][t]);
        }
    }
    return mincut;
}

```

4.5 Hopcroft Karp

```

int mx[maxn], my[maxn], dx[maxn], dy[maxn], vis[maxn];
vector<int> adj[maxn];

```

```

int l, r, m;

int dfs(int pos){
    for(auto x : adj[pos]){
        if(!vis[x] && dy[x] == dx[pos] + 1){
            vis[x] = 1;
            if(my[x] != -1 && dy[x] == lim) continue;
            if(my[x] == -1 || dfs(my[x])){
                my[x] = pos, mx[pos] = x;
                return true;
            }
        }
    }
    return false;
}

int bfs(){
    fill(dx, dx + l, -1);
    fill(dy, dy + r, -1);
    queue<int> q;
    for(int i = 0; i < l; i++){
        if(mx[i] == -1) dx[i] = 0, q.push(i);
    }
    lim = INF;
    while(!q.empty()){
        int pos = q.front(); q.pop();
        if(dx[pos] > lim) break;
        for(auto x : adj[pos]){
            if(dy[x] == -1){
                dy[x] = dx[pos] + 1;
                if(my[x] == -1) lim = dy[x];
                else dx[my[x]] = dy[x] + 1, q.push(my[x]);
            }
        }
    }
    return lim != INF;
}

void Hopcroft_Karp(){
    int res = 0;
    for(int i = 0; i < l; i++) mx[i] = -1;
    for(int i = 0; i < r; i++) my[i] = -1;
    while(bfs()){
        fill(vis, vis + l + r, 0);
        for(int i = 0; i < l; i++){
            if(mx[i] == -1 && dfs(i)) res++;
        }
    }
}

```

4.6 Kuhn Munkres

```

struct Hungarian{
    using T = ll;
    vector<T> lx, ly, slack;
    vector<int> vx, vy, match;
    vector<vector<T>> w;
    queue<int> q;
    int n;
    void init(int _n){
        n = _n;
        lx.resize(n), ly.resize(n), slack.resize(n);
        vx.resize(n), vy.resize(n), match.resize(n, -1);
        w.resize(n, vector<T>(n));
    }
    void inp(int x, int y, int val){
        w[x][y] = val;
        lx[x] = max(lx[x], val);
    }
    int dfs(int x){
        if(vx[x]) return false;
        vx[x] = 1;
        for(int i = 0; i < n; i++){
            if(lx[x] + ly[i] == w[x][i] && !vy[i]){
                vy[i] = true;
                if(match[i] == -1 || dfs(match[i])){
                    match[i] = x;
                    return true;
                }
            }
        }
        return false;
    }
    int pdfs(int x){

```

```

        fill(vx.begin(), vx.end(), 0);
        fill(vy.begin(), vy.end(), 0);
        return dfs(x);
    }
    void upd(int x){
        for(int i = 0; i < n; i++){
            if(!slack[i]) continue;
            slack[i] =
                min(slack[i], lx[x] + ly[i] - w[x][i]);
            if(!slack[i] && !vy[i]) q.push(i);
        }
    }
    void relabel(){
        T mn = numeric_limits<T>::max() / 3;
        for(int i = 0; i < n; i++){
            if(!vy[i]) mn = min(mn, slack[i]);
        }
        for(int i = 0; i < n; i++){
            if(vx[i]) lx[i] -= mn;
            if(vy[i]) ly[i] += mn;
            else{
                slack[i] -= mn;
                if(!slack[i]) q.push(i);
            }
        }
    }
    auto solve(){
        for(int i = 0; i < n; i++){
            if(pdfs(i)) continue;
            while(!q.empty()) q.pop();
            fill(slack.begin(), slack.end(), INF);
            for(int j = 0; j < n; j++) if(vx[j]) upd(j);
            int ok = 0;
            while(!ok){
                relabel();
                while(!q.empty()){
                    int j = q.front(); q.pop();
                    if(match[j] == -1){
                        pdfs(i);
                        ok = 1;
                        break;
                    }
                    vy[j] = vx;
                    [match[j]] = 1, upd(match[j]);
                }
            }
            T ans = 0;
            for(int i = 0; i < n; i++) ans += w[match[i]][i];
        }
        for(int i = 0; i < n; i++) lx[match[i]] = i;
        return make_pair(ans, lx);
    }
} h;

```

4.7 General Graph Matching

```

struct Matching { // 0-based
    int n, tk;
    vector<vector<int>> g;
    vector<int> fa, pre, match, s, t;
    queue<int> q;
    int Find(int u) {
        return u == fa[u] ? u : fa[u] = Find(fa[u]);
    }
    int lca(int x, int y) {
        tk++;
        x = Find(x), y = Find(y);
        for(;; swap(x, y)){
            if(x != n){
                if(t[x] == tk) return x;
                t[x] = tk;
                x = Find(pre[match[x]]);
            }
        }
    }
    void blossom(int x, int y, int l) {
        while(Find(x) != l){
            pre[x] = y, y = match[x];
            if(s[y] == 1) q.push(y), s[y] = 0;
            if(fa[x] == x) fa[x] = l;
            if(fa[y] == y) fa[y] = l;
            x = pre[y];
        }
    }
}

```

```

bool bfs(int r) {
    iota(all(fa), 0), fill(all(s), -1);
    while (!q.empty()) q.pop();
    q.push(r);
    s[r] = 0;
    while (!q.empty()) {
        int x = q.front(); q.pop();
        for (int u : g[x]) {
            if (s[u] == -1) {
                pre[u] = x, s[u] = 1;
                if (match[u] == n) {
                    for (int a = u, b =
                        x, last; b != n; a = last, b = pre[a])
                        last =
                            match[b], match[b] = a, match[a] = b;
                    return true;
                }
                q.push(match[u]);
                s[match[u]] = 0;
            } else if (!s[u] && Find(u) != Find(x)) {
                int l = lca(u, x);
                blossom(x, u, l);
                blossom(u, x, l);
            }
        }
    }
    return false;
}
int solve() {
    int res = 0;
    for (int x = 0; x < n; ++x) {
        if (match[x] == n) res += bfs(x);
    }
    return res;
}
void add_edge(int u, int v) {
    g[u].push_back(v), g[v].push_back(u);
}
Matching (int _n) : n(_n), tk(0), g(n), fa(n + 1),
    pre(n + 1, n), match(n + 1, n), s(n + 1), t(n) {}
};

```

4.8 Weighted General Graph Matching

```

struct WeightGraph { // 1-based
    static const int inf = INT_MAX;
    static const int maxn = 514;
    struct edge {
        int u, v, w;
        edge(){}
        edge(int u, int v, int w): u(u), v(v), w(w) {}
    };
    int n, n_x;
    edge g[maxn * 2][maxn * 2];
    int lab[maxn * 2];
    int match[maxn *
              2], slack[maxn * 2], st[maxn * 2], pa[maxn * 2];
    int flo_from
        [maxn * 2][maxn + 1], S[maxn * 2], vis[maxn * 2];
    vector<int> flo[maxn * 2];
    queue<int> q;
    int e_delta(const edge &e) {
        return lab[e.u] + lab[e.v] - g[e.u][e.v].w * 2;
    }
    void update_slack
        (int u, int x) { if (!slack[x] || e_delta(g[
            u][x]) < e_delta(g[slack[x]][x])) slack[x] = u; }
    void set_slack(int x) {
        slack[x] = 0;
        for (int u = 1; u <= n; ++u)
            if (g[u][x].w > 0 && st[u] != x && S[st[u]] == 0)
                update_slack(u, x);
    }
    void q_push(int x) {
        if (x < n) q.push(x);
        else for (size_t i
                  = 0; i < flo[x].size(); i++) q.push(flo[x][i]);
    }
    void set_st(int x, int b) {
        st[x] = b;
        if (x > n) for (size_t i = 0;
                        i < flo[x].size(); ++i) set_st(flo[x][i], b);
    }
    int get_pr(int b, int xr) {
        int pr = find(flo[
            b].begin(), flo[b].end(), xr) - flo[b].begin();
        if (pr % 2 == 1) {
            reverse(flo[b].begin() + 1, flo[b].end());

```

```

            return (int)flo[b].size() - pr;
        }
        return pr;
    }
    void set_match(int u, int v) {
        match[u] = g[u][v].v;
        if (u <= n) return;
        edge e = g[u][v];
        int xr = flo_from[u][e.u], pr = get_pr(u, xr);
        for (int i = 0; i < pr; ++i) set_match(flo[u][i], flo[u][i ^ 1]);
        set_match(xr, v);
        rotate(flo[
            u].begin(), flo[u].begin() + pr, flo[u].end());
    }
    void augment(int u, int v) {
        for (; ; ) {
            int xnv = st[match[u]];
            set_match(u, v);
            if (!xnv) return;
            set_match(xnv, st[pa[xnv]]);
            u = st[pa[xnv]], v = xnv;
        }
    }
    int get_lca(int u, int v) {
        static int t = 0;
        for (++t; u || v; swap(u, v)) {
            if (u == 0) continue;
            if (vis[u] == t) return u;
            vis[u] = t;
            u = st[match[u]];
            if (u) u = st[pa[u]];
        }
        return 0;
    }
    void add_blossom(int u, int lca, int v) {
        int b = n + 1;
        while (b <= n_x && st[b]) ++b;
        if (b > n_x) ++n_x;
        lab[b] = 0, S[b] = 0;
        match[b] = match[lca];
        flo[b].clear();
        flo[b].push_back(lca);
        for (int x = u, y; x != lca; x = st[pa[y]])
            flo[b].push_back(x), flo
                [b].push_back(y = st[match[x]]), q_push(y);
        reverse(flo[b].begin() + 1, flo[b].end());
        for (int x = v, y; x != lca; x = st[pa[y]])
            flo[b].push_back(x), flo
                [b].push_back(y = st[match[x]]), q_push(y);
        set_st(b, b);
        for (int x
            = 1; x <= n_x; ++x) g[b][x].w = g[x][b].w = 0;
        for (int x = 1; x <= n; ++x) flo_from[b][x] = 0;
        for (size_t i = 0; i < flo[b].size(); ++i) {
            int xs = flo[b][i];
            for (int x = 1; x <= n_x; ++x)
                if (g[b][x].w ==
                    0 || e_delta(g[xs][x]) < e_delta(g[b][x]))
                    g[b][x] = g[xs][x], g[x][b] = g[x][xs];
            for (int x = 1; x <= n; ++x)
                if (flo_from[xs][x]) flo_from[b][x] = xs;
        }
        set_slack(b);
    }
    void expand_blossom(int b) {
        for (size_t i = 0; i < flo[b].size(); ++i)
            set_st(flo[b][i], flo[b][i]);
        int xr =
            flo_from[b][g[b][pa[b]].u], pr = get_pr(b, xr);
        for (int i = 0; i < pr; i += 2) {
            int xs = flo[b][i], xns = flo[b][i + 1];
            pa[xs] = g[xns][xs].u;
            S[xs] = 1, S[xns] = 0;
            slack[xs] = 0, set_slack(xns);
            q_push(xns);
        }
        S[xr] = 1, pa[xr] = pa[b];
        for (size_t i = pr + 1; i < flo[b].size(); ++i)
            int xs = flo[b][i];
            S[xs] = -1, set_slack(xs);
        }
        st[b] = 0;
    }
    bool on_found_edge(const edge &e) {
        int u = st[e.u], v = st[e.v];

```

```

if (S[v] == -1) {
    pa[v] = e.u, S[v] = 1;
    int nu = st[match[v]];
    slack[v] = slack[nu] = 0;
    S[nu] = 0, q.push(nu);
} else if (S[v] == 0) {
    int lca = get_lca(u, v);
    if (!
        lca) return augment(u, v), augment(v, u), true;
    else add_blossom(u, lca, v);
}
return false;
}
bool matching() {
memset(S + 1, -1, sizeof(int) * n_x);
memset(slack + 1, 0, sizeof(int) * n_x);
q = queue<int>();
for (int x = 1; x <= n_x; ++x)
    if (st[x] == x
        && !match[x]) pa[x] = 0, S[x] = 0, q.push(x);
if (q.empty()) return false;
for (; ; ) {
    while (q.size()) {
        int u = q.front(); q.pop();
        if (S[st[u]] == 1) continue;
        for (int v = 1; v <= n; ++v)
            if (g[u][v].w > 0 && st[u] != st[v]) {
                if (e_delta(g[u][v]) == 0) {
                    if (on_found_edge(g[u][v])) return true;
                } else update_slack(u, st[v]);
            }
    }
    int d = inf;
    for (int b = n + 1; b <= n_x; ++b)
        if (st[b]
            == b && S[b] == 1) d = min(d, lab[b] / 2);
    for (int x = 1; x <= n_x; ++x)
        if (st[x] == x && slack[x]) {
            if (S[x] ==
                -1) d = min(d, e_delta(g[slack[x]][x]));
            else if (S[x] == 0)
                d = min(d, e_delta(g[slack[x]][x]) / 2);
        }
    for (int u = 1; u <= n; ++u) {
        if (S[st[u]] == 0) {
            if (lab[u] <= d) return 0;
            lab[u] -= d;
        } else if (S[st[u]] == 1) lab[u] += d;
    }
    for (int b = n + 1; b <= n_x; ++b)
        if (st[b] == b) {
            if (S[st[b]] == 0) lab[b] += d * 2;
            else if (S[st[b]] == 1) lab[b] -= d * 2;
        }
    q = queue<int>();
    for (int x = 1; x <= n_x; ++x)
        if (st[x] == x && slack[x] && st[slack
            [x]] != x && e_delta(g[slack[x]][x]) == 0)
            if (on_found_edge
                (g[slack[x]][x])) return true;
    for (int b = n + 1; b <= n_x; ++b)
        if (st[b] == b && S
            [b] == 1 && lab[b] == 0) expand_blossom(b);
    }
    return false;
}
pair<long long, int> solve() {
    memset(match + 1, 0, sizeof(int) * n);
    n_x = n;
    int n_matches = 0;
    long long tot_weight = 0;
    for (int
        u = 0; u <= n; ++u) st[u] = u, flo[u].clear();
    int w_max = 0;
    for (int u = 1; u <= n; ++u)
        for (int v = 1; v <= n; ++v) {
            flo_from[u][v] = (u == v ? u : 0);
            w_max = max(w_max, g[u][v].w);
        }
    for (int u = 1; u <= n; ++u) lab[u] = w_max;
    while (matching()) ++n_matches;
    for (int u = 1; u <= n; ++u)
        if (match[u] && match[u] < u)
            tot_weight += g[u][match[u]].w;
    return make_pair(tot_weight, n_matches);
}

```

```

void add_edge(int ui, int
    vi, int wi) { g[ui][vi].w = g[vi][ui].w = wi; }
void init(int _n) {
    n = _n;
    for (int u = 1; u <= n; ++u)
        for (int v = 1; v <= n; ++v)
            g[u][v] = edge(u, v, 0);
}

```

4.9 Flow Models

- Maximum/Minimum flow with lower bound / Circulation problem
 1. Construct super source S and sink T .
 2. For each edge (x,y,l,u) , connect $x \rightarrow y$ with capacity $u-l$.
 3. For each vertex v , denote by $in(v)$ the difference between the sum of incoming lower bounds and the sum of outgoing lower bounds.
 4. If $in(v) > 0$, connect $S \rightarrow v$ with capacity $in(v)$, otherwise, connect $v \rightarrow T$ with capacity $-in(v)$.
 - To maximize, connect $t \rightarrow s$ with capacity ∞ (skip this in circulation problem), and let f be the maximum flow from S to T . If $f \neq \sum_{v \in V, in(v) > 0} in(v)$, there's no solution. Otherwise, the maximum flow from s to t is the answer.
 - To minimize, let f be the maximum flow from S to T . Connect $t \rightarrow s$ with capacity ∞ and let the flow from S to T be f' . If $f + f' \neq \sum_{v \in V, in(v) > 0} in(v)$, there's no solution. Otherwise, f' is the answer.
 5. The solution of each edge e is $l_e + f_e$, where f_e corresponds to the flow of edge e on the graph.
- Construct minimum vertex cover from maximum matching M on bipartite graph (X, Y)
 1. Redirect every edge: $y \rightarrow x$ if $(x, y) \in M$, $x \rightarrow y$ otherwise.
 2. DFS from unmatched vertices in X .
 3. $x \in X$ is chosen iff x is unvisited.
 4. $y \in Y$ is chosen iff y is visited.
- Minimum cost cyclic flow
 1. Construct super source S and sink T
 2. For each edge (x, y, c) , connect $x \rightarrow y$ with $(cost, cap) = (c, 1)$ if $c > 0$, otherwise connect $y \rightarrow x$ with $(cost, cap) = (-c, 1)$
 3. For each edge with $c < 0$, sum these cost as K , then increase $d(y)$ by 1, decrease $d(x)$ by 1
 4. For each vertex v with $d(v) > 0$, connect $S \rightarrow v$ with $(cost, cap) = (0, d(v))$
 5. For each vertex v with $d(v) < 0$, connect $v \rightarrow T$ with $(cost, cap) = (0, -d(v))$
 6. Flow from S to T , the answer is the cost of the flow $C+K$
- Maximum density induced subgraph
 1. Binary search on answer, suppose we're checking answer T
 2. Construct a max flow model, let K be the sum of all weights
 3. Connect source $s \rightarrow v, v \in G$ with capacity K
 4. For each edge (u, v, w) in G , connect $u \rightarrow v$ and $v \rightarrow u$ with capacity w
 5. For $v \in G$, connect it with sink $v \rightarrow t$ with capacity $K+2T-(\sum_{e \in E(v)} w(e))-2w(v)$
 6. T is a valid answer if the maximum flow $f < K|V|$
- Minimum weight edge cover
 1. For each $v \in V$ create a copy v' , and connect $u' \rightarrow v'$ with weight $w(u, v)$.
 2. Connect $v \rightarrow v'$ with weight $2\mu(v)$, where $\mu(v)$ is the cost of the cheapest edge incident to v .
 3. Find the minimum weight perfect matching on G' .
- Project selection problem
 1. If $p_v > 0$, create edge (s, v) with capacity p_v ; otherwise, create edge (v, t) with capacity $-p_v$.
 2. Create edge (u, v) with capacity w being the cost of choosing u without choosing v .
 3. The mincut is equivalent to the maximum profit of a subset of projects.
- Dual of minimum cost maximum flow
 1. Capacity c_{uv} , Flow f_{uv} , Cost w_{uv} , Required Flow difference for vertex b_u .
 2. If all w_{uv} are integers, then optimal solution can happen when all p_u are integers.

$$\begin{aligned} \min \sum_{uv} w_{uv} f_{uv} \\ -f_{uv} \geq -c_{uv} \Leftrightarrow \min \sum_u b_u p_u + \sum_{uv} c_{uv} \max(0, p_v - p_u - w_{uv}) \\ \sum_v f_{vu} - \sum_v f_{uv} = -b_u \end{aligned}$$

$p_u \geq 0$

5 String

5.1 Z-Value

```
vector<int> z(string s){
    vector<int> z(s.size());
    int x = 0, y = 0;
    for(int i = 1; i < s.size(); i++){
        z[i] = max(0LL, min(z[i - x], y - i));
        while(i + z[i] < s.size() && s[i + z[i]] == s[z[i]]){
            x = i, y = i + z[i], z[i]++;
        }
    }
    return z;
}
```

5.2 KMP

```
vector<int> KMP(string s){
    vector<int> f(s.size());
    for(int i = 1; i < s.size(); i++){
        f[i] = f[i] - 1;
        while(f[i] && s[i] != s[f[i]]) f[i] = f[f[i] - 1];
        if(s[f[i]] == s[i]) f[i]++;
    }
    return f;
}
```

5.3 Manacher

```
vector<int> manacher(string s){
    int n = 2 * s.size() + 1;
    string ss(n, '#');
    for(int i = 0; i < n / 2; i++) ss[i * 2 + 1] = s[i];
    swap(s, ss);
    vector<int> f(n);
    int m = 0, len = 0;
    for(int i = 0; i < n; i++){
        f[i] = max(0LL, min(f[m + m - i], m + len - i));
        while(i + f[i] < n && i - f[i] >= 0 && s[i + f[i]] == s[i - f[i]]){
            m = i, len = f[i], f[i]++;
        }
    }
    return f;
}
```

5.4 Suffix Array

```
struct SuffixArray{
    int ch[2][maxn], sa[maxn], cnt[maxn], n;
    string s;
    void init(string _s){
        s = _s, n = s.size();
        Get_SA();
        Get_LCP();
    }
    void Get_SA(){
        int *x = ch[0], *y = ch[1], m = 256;
        for(int i = 0; i < m; i++) cnt[i] = 0;
        for(int i = 0; i < n; i++) cnt[x[i]] = s[i]++;
        for(int k = 1;; k <= 1){
            for(int i = 0; i < m; i++) cnt[i] = 0;
            for(int i = 0; i < n; i++) cnt[x[i]]++;
            for(int i = 1; i < m; i++) cnt[i] += cnt[i - 1];
            for(int i = 0; i < n; i++) sa[--cnt[x[i]]] = i;
            for(int i = 0; i < n; i++) y[p++] = i;
            for(int i = 0; i < n; i++)
                if(sa[i] >= k) y[p++] = sa[i] - k;
            for(int i = n - 1;
                i >= 0; i--) sa[--cnt[x[y[i]]]] = y[i];
            y[sa[0]] = p = 0;
            for(int i = 1; i < n; i++){
                int a = sa[i], b = sa[i - 1];
                if(a + k < n && b + k < n && x[a] == x[b] && x[a + k] == x[b + k])
                    else p++;
                y[a] = p;
            }
            if(p == n - 1) break;
        }
    }
    void Get_LCP(){
        int n = s.length();
        for(int i = 0; i < n; i++) _s[i] = s[i];
        _s[n] = 0;
        sais(_s, sa, _p, _q, _t, _c, n + 1, 256);
        for(int i = 1; i <= n; i++) sa[i - 1] = sa[i];
    }
}
```

```
swap(x, y);
m = p + 1;
}
int rnk[maxn], lcp[maxn];
void Get_LCP(){
    for(int i = 0; i < n; i++) rnk[sa[i]] = i;
    int val = 0;
    for(int i = 0; i < n; i++){
        if(val) val--;
        if(!rnk[i]){
            lcp[0] = val = 0;
            continue;
        }
        int b = sa[rnk[i] - 1];
        while(b + val < n && i + val < n && s[b + val] == s[i + val]) val++;
        lcp[rnk[i]] = val;
    }
}
} sa;
```

5.5 SAIS

```
int sa[N << 1], rk[N], lcp[N];
// string ASCII value need > 0
namespace sfx {
bool _t[N << 1];
int _s[N << 1], _c[N << 1], x[N], _p[N], _q[N << 1];
void pre(int *sa, int *c, int n, int z) {
    fill_n(sa, n, 0), copy_n(c, z, x);
}
void induce
    (int *sa, int *c, int *s, bool *t, int n, int z) {
    copy_n(c, z - 1, x + 1);
    for (int i = 0; i < n; ++i)
        if (sa[i] && !t[sa[i] - 1])
            sa[x[s[sa[i] - 1]] + 1] = sa[i] - 1;
    copy_n(c, z, x);
    for (int i = n - 1; i >= 0; --i)
        if (sa[i] && t[sa[i] - 1])
            sa[--x[s[sa[i] - 1]]] = sa[i] - 1;
}
void sais(int *s, int *sa
    , int *p, int *q, bool *t, int *c, int n, int z) {
    bool uniq = t[n - 1] = true;
    int nn = 0,
        nmxz = -1, *nsa = sa + n, *ns = s + n, last = -1;
    fill_n(c, z, 0);
    for (int i = 0; i < n; ++i) uniq &= ++c[s[i]] < 2;
    partial_sum(c, c + z, c);
    if (uniq) {
        for (int i = 0; i < n; ++i) sa[--c[s[i]]] = i;
        return;
    }
    for (int i = n - 2; i >= 0; --i)
        if (s[i] == s[i + 1]) t[i] = t[i + 1];
        else t[i] = s[i] < s[i + 1];
    pre(sa, c, n, z);
    for (int i = 1; i <= n - 1; ++i)
        if (t[i] && !t[i - 1])
            sa[--x[s[i]]] = p[q[i] = nn++ + 1] = i;
    induce(sa, c, s, t, n, z);
    for (int i = 0; i < n; ++i)
        if (sa[i] && t[sa[i]] && !t[sa[i] - 1]) {
            bool neq = last < 0 || !equal
                (s + sa[i], s + p[q[sa[i]] + 1], s + last);
            ns[q[last = sa[i]]] = nmxz + neq;
        }
    sais(ns,
        nsa, p + nn, q + n, t + n, c + z, nn, nmxz + 1);
    pre(sa, c, n, z);
    for (int i = nn - 1; i >= 0; --i)
        sa[--x[s[p[nsa[i]]]]] = p[nsa[i]];
    induce(sa, c, s, t, n, z);
}
void buildSA(string s) {
    int n = s.length();
    for (int i = 0; i < n; ++i) _s[i] = s[i];
    _s[n] = 0;
    sais(_s, sa, _p, _q, _t, _c, n + 1, 256);
    for (int i = 1; i <= n; ++i) sa[i - 1] = sa[i];
    // buildLCP()...
}
```

5.6 Suffix Automaton

```

struct SuffixAutomaton{
    int len[maxn], link[maxn]; // maxn >= 2 * n - 1
    map<char, int> nxt[maxn];
    int cnt[maxn], distinct[maxn];
    bool is_clone[maxn];
    int first_pos[maxn];
    vector<int> inv_link[maxn]; //suffix references
    int sz = 1, last = 0;
    void init(string s){
        link[0] = -1;
        for(auto x : s) sa_extend(x);
    }
    void sa_extend(char c){
        int cur = sz++;
        cnt[cur] = 1;
        len[cur] = len[last] + 1;
        first_pos[cur] = len[cur] - 1;
        int p = last;
        while(p != -1 && !nxt[p].count(c)){
            nxt[p][c] = cur;
            p = link[p];
        }
        if(p == -1) link[cur] = 0;
        else{
            int q = nxt[p][c];
            if(len[q] == len[p] + 1) link[cur] = q;
            else{
                int clone = sz++;
                is_clone[clone] = true;
                first_pos[clone] = q;
                len[clone] = len[p] + 1;
                nxt[clone] = nxt[q];
                link[clone] = link[q];
                while(p != -1 && nxt[p][c] == q) {
                    nxt[p][c] = clone;
                    p = link[p];
                }
                link[cur] = link[q] = clone;
            }
        }
        last = cur;
    }
    ll getDistinct(int pos){ // number
        of distinct substr. starting at pos(inc. empty)
        if(distinct[pos]) return distinct[pos];
        distinct[pos] = 1;
        for(auto [c, next]
            : nxt[pos]) distinct[pos] += getDistinct(next);
        return cnt[pos];
    }
    ll numDistinct(){
        return getDistinct
            (0) - 1; // excluding an empty string
    }
    ll numDistinct2(){
        ll tot = 0;
        for(int i
            = 1; i < sz; i++) tot += len[i] - len[link[i]];
        return tot;
    }
    void compute_cnt(){ // endpos set size
        vector<vector<int>> v(sz);
        for(int i = 1; i < sz; i++) v[len[i]].pb(i);
        for(int
            i = sz - 1; i > 0; i--) for(auto x : v[i]) {
            cnt[link[x]] += cnt[x];
        }
    }
    string distinct_kth(ll k){
        // substring
        kth (not distinct) -> compute_cnt()
        numDistinct();
        string s;
        ll cur = 0, tally = 0;
        while(tally < k){
            for(auto [c, next] : nxt[cur]){
                if(tally + distinct[next] >= k){
                    tally += 1;
                    s += c;
                    cur = next;
                    break;
                }
                tally += distinct[next];
            }
        }
        return s;
    }
}

```

```

    }
    //inverse links
    void genLink(){
        for(int i = 1; i < sz; i++){
            inv_link[link[i]].pb(i);
        }
    }
    void get_all_occur(vector<int>& oc, int v){
        if(!is_clone[v]) oc.pb(first_pos[v]);
        for(auto u : inv_link[v]) get_all_occur(oc, u);
    }
    vector<int> all_occ(string s){ // get all occ of s
        int cur = 0;
        for(auto x : s){
            if(!nxt[cur].count(x)) return {};
            cur = nxt[cur][x];
        }
        vector<int> oc;
        get_all_occur(oc, cur);
        for(auto &x : oc
            ) x += 1 - s.length(); // starting positions
        sort(oc.begin(), oc.end());
        return oc;
    }
    int lcs(string t){
        int v = 0, l = 0, ans = 0;
        for(auto x : t){
            while(v && !nxt[v].count(x)){
                v = link[v];
                l = len[v];
            }
            if(nxt[v].count(x)){
                v = nxt[v][x];
                l++;
            }
            ans = max(ans, l);
        }
        return ans;
    }
}

5.7 Palindrome Tree
struct EERTREE{
    int sz, tot, last;
    int cnt[maxn], ch[maxn][26],
        len[maxn], fail[maxn], dif[maxn], slink[maxn];
    int g[maxn], dp[maxn];
    char s[maxn];
    int node(int l){
        sz++;
        memset(ch[sz], 0, sizeof(ch[sz]));
        len[sz] = l;
        fail[sz] = cnt[sz] = 0;
        return sz;
    }
    void init(){
        sz = -1;
        last = 0;
        s[tot = 0] = '$';
        node(0);
        node(-1);
        fail[0] = 1;
    }
    int getfail(int x){
        while(s[tot - len[x] - 1] != s[tot]) x = fail[x];
        return x;
    }
    void insert(char c){
        s[++tot] = c;
        int now = getfail(last);
        if(!ch[now][c - 'a']){
            int x = node(len[now] + 2);
            fail[x] = ch[getfail(fail[now])][c - 'a'];
            ch[now][c - 'a'] = x;
            dif[x] = len[x] - len[fail[x]];
            if(dif[x] == dif[fail[x]]){
                slink[x] = slink[fail[x]];
            }
            else slink[x] = fail[x];
        }
        last = ch[now][c - 'a'];
        cnt[last]++;
    }
    int process
        (string s){ // minimum palindrome partitioning
        for(int i = 0; i < s.size(); i++){

```

```

    insert(s[i]);
    dp[i] = INF;
    for(int x = last; x > 1; x = slink[x]){
        if(i - len[slink[x]] - dif[x] >=
            0) g[x] = dp[i - len[slink[x]] - dif[x]];
        if(dif[x] ==
            dif[fail[x]]) g[x] = min(g[x], g[fail[x]]);
        dp[i] = min(dp[i], g[x] + 1);
    }
}
return dp[s.size() - 1];
}
};

5.8 AC Automaton
```

```

namespace AC{
    int ch[maxn][26],
        fail[maxn], idx[maxn], last[maxn], pt[maxn];
    int val[maxn], cnt[maxn], tot = 0;
    // val[i] = # of times node
    // (i) is visited, cnt[i] = # of occ. of str(i)
    void init(){
        memset(ch,
            0, sizeof(ch)), memset(fail, 0, sizeof(fail));
        memset(idx,
            0, sizeof(idx)), memset(last, 0, sizeof(last));
        memset(val
            , 0, sizeof(val)), memset(cnt, 0, sizeof(cnt));
        tot = 0;
    }
    void insert(string &s, int id){ // id is 1-based
        int cur = 0;
        for(int i = 0; i < s.size(); i++){
            if(!ch[cur]
                ][s[i] - 'a']) ch[cur][s[i] - 'a'] = ++tot;
            cur = ch[cur][s[i] - 'a'];
        }
        if(idx[cur] == 0) idx[cur] = id;
        else pt[id] = idx[cur];
    }
    void build(){
        queue<int> q;
        for(int i = 0; i < 26; i++){
            if(ch[0][i]) q.push(ch[0][i]);
        }
        while(!q.empty()){
            int u = q.front(); q.pop();
            for(int i = 0; i < 26; i++){
                if(ch[u][i]){
                    fail[ch[u][i]] = ch[fail[u]][i];
                    q.push(ch[u][i]);
                }
                else ch[u][i] = ch[fail[u]][i];
                last[ch[u][i]] = idx[fail[ch[u][i]]]
                    ? fail[ch[u][i]] : last[fail[ch[u][i]]];
            }
        }
        int qry(string &s){
            int u = 0, ret = 0;
            for(int i = 0; i < s.size(); i++){
                u = ch[u][s[i] - 'a'];
                for(int j = u; j; j = last[j]) val[j]++;
            }
            for(int i = 0; i <= tot; i++){
                if(idx[i])
                    ret = max(ret, val[i]), cnt[idx[i]] = val[i];
            }
            return ret;
        }
    };
};

5.9 Lyndon Factorization
```

```

vector<string> duval(string s){
    int n = s.length(), i = 0;
    vector<string> fac;
    while(i < n){
        int j = i + 1, k = i; // i <= k < j
        while(j < n && s[k] <= s[j]){
            if(s[k] < s[j]) k = i;
            else k++;
            j++;
        }
        while(i <= k){
            fac.pb(s.substr(i, j - k));
        }
    }
}
```

```

        i += j - k;
    }
}
return fac;
}
```

6 Math

6.1 Miller Rabin

```

using u64 = uint64_t;
using u128 = __uint128_t;

u64 fpow(u64 a, u64 b, u64 n){
    u64 ret = 1;
    while(b > 0){
        if(b & 1) ret = (u128)ret * a % n;
        a = (u128)a * a % n;
        b >>= 1;
    }
    return ret;
}

bool check_composite(u64 n, u64 a, u64 d, int s){
    u64 x = fpow(a, d, n);
    if(x == 1 || x == n - 1) return false;
    for(int r = 1; r < s; r++){
        x = (u128)x * x % n;
        if(x == n - 1) return false;
    }
    return true;
}

bool MillerRabin(u64 n){
    if(n < 2) return false;
    int s = 0;
    u64 d = n - 1;
    while(!(d & 1)){
        d >>= 1;
        s++;
    }
    for(auto a : {2, 3, 5, 7, 11, 13, 17,
        19, 23, 29, 31, 37}){
        if(n == a) return true;
        if(check_composite(n, a, d, s)) return false;
    }
    return true;
}
```

6.2 Pollard Rho

```

ll f(ll t, ll c, ll n){
    return ((u128)t * t + c) % n;
}
ll Pollard_Rho(ll x){
    ll t = 0;
    ll c = rand() % (x - 1) + 1;
    ll s = t;
    ll val = 1;
    for(int goal = 1;; goal <= 1, s = t, val = 1){
        for(int step = 1; step <= goal; step++){
            t = f(t, c, x);
            val = (u128)val * abs(t - s) % x;
            if(!val) return x;
            if(step % 127 == 0){
                ll d = __gcd(val, x);
                if(d > 1) return d;
            }
            ll d = __gcd(val, x);
            if(d > 1) return d;
        }
        return x;
    }
}

void fac(vector<ll> &ans, ll x){
    if(x <= 1) return;
    if(MillerRabin(x)) ans.pb(x);
    else{
        ll t = Pollard_Rho(x);
        fac(ans, x / t);
        fac(ans, t);
    }
}
```

6.3 EXT GCD

```

ll extgcd(ll a, ll b, ll &x, ll &y){
    if(b == 0){
        x = 1, y = 0;
    }
}
```

```

    return a;
}
int res = extgcd(b, a % b, y, x);
y -= (a / b) * x;
return res;
}

```

6.4 Chinese Remainder Theorem

```

ll CRT(vector<ll> p, vector<ll> a){
    ll n = p.size(), prod = 1, ret = 0;
    for(int i = 0; i < n; i++) prod *= p[i];
    for(int i = 0; i < n; i++){
        ll m = (prod / p[i]);
        ll x, y;
        extgcd(m, p[i], x, y);
        ret = ((ret + a[i] * m * x) % prod + prod) % prod;
    }
    return ret;
}

```

6.5 Powerful Number Sieve

```

void linesarsieve(){
    phi[1] = 1;
    for(int i = 2; i < maxn; i++){
        if(!lp[i]) pr.pb(i), lp[i] = i, phi[i] = i - 1;
        for(auto x : pr){
            if(i * x >= maxn) break;
            lp[i * x] = x;
            if(lp[i] == x){
                phi[i * x] = phi[i] * x;
                break;
            }
            phi[i * x] = phi[i] * (x - 1);
        }
    }
    for(int i = 1; i < maxn
        ; i++) sum[i] = (sum[i - 1] + i * phi[i]) % N;
}

int s2(int n){
    static const int inv6 = inv(6);
    n %= N;
    return n * (n + 1) % N * (2 * n + 1) % N * inv6 % N;
}

```

```

int G(int n){
    static const int inv2 = inv(2);
    if(n < maxn) return sum[n];
    if(mp_G.count(n)) return mp_G[n];
    int ans = s2(n);
    for(int i = 2, j; i <= n; i = j + 1){
        j = n / (n / i);
        (ans -= (i + j) % N * (j -
            i + 1) % N * inv2 % N * G(n / i) % N - N) %= N;
    }
    return mp_G[n] = ans;
}

```

```

void dfs(int d, int hd, int p){ // dfs 出所有 PN
    (ans += hd * G(n / d)) %= N;
    for(int i = p; i < pr.size(); i++){
        if(d > n / pr[i] / pr[i]) break;
        int c = 2;
        for(int x
            = d * pr[i] * pr[i]; x <= n; x *= pr[i], c++){
            if(!vis[i][c]){
                int f = fpow(pr[i], c);
                f = f * (f - 1) % N;
                int g = pr[i] * (pr[i] - 1) % N;
                int t = pr[i] * pr[i] % N;
                for(int j = 1; j <= c; j++){
                    (f -= g * h[i][c - j] % N - N) %= N;
                    (g *= t) %= N;
                }
                h[i][c] = f;
                vis[i][c] = true;
            }
            if(h[i][c]) dfs(x, hd * h[i][c] % N, i + 1);
        }
    }
    linesarsieve();
    for(int i = 0; i < pr.size(); i++) h[i][0] = 1;
    dfs(1, 1, 0);
}

```

6.6 Min25 Sieve

```

template <typename U, typename V> struct min25 {
    make_lld n; int sq;
    vector<U> Ss, Sl, Spre; vector<V> Rs, Rl;
    Sieve sv; vector<lld> quo;
    U &S(lld d) { return d < sq ? Ss[d] : Sl[n / d]; }
    V &R(lld d) { return d < sq ? Rs[d] : Rl[n / d]; }
    min25(lld n_) : n_(n_), sq((int)sqrt(n) + 1),
        Ss(sq), Sl(sq), Spre(sq), Rs(sq), Rl(sq), sv(sq) {
        for (lld i = 1, Q; i <= n; i = n / Q + 1)
            quo.push_back(Q = n / i);
    }
    U F_prime(auto &&f, auto &&F) {
        for (lld p : sv.primes) Spre[p] = f(p);
        for (
            int i = 1; i < sq; i++)
            Spre[i] += Spre[i - 1];
        for (lld i : quo) S(i) = F(i) - F(1);
        for (lld p : sv.primes)
            for (lld i : quo) {
                if (p * p > i) break;
                S(i) -= f(p) * (S(i / p) - Spre[p - 1]);
            }
        return S(n);
    }
    V F_comp(auto &&g) {
        for (lld i : quo) R(i) = V(S(i));
        for (lld p : sv.primes | views::reverse)
            for (lld i : quo) {
                if (p * p > i) break;
                lld prod = p;
                for (
                    int c = 1; prod * p <= i; ++c, prod *= p)
                    R(i) += g(p, c) * (R(i / prod) - V(Spre[p]));
                R(i) += g(p, c + 1);
            }
        return R(n);
    }
    /* F_comp: |sum_{2 <= i <= n} g(i)|;
    // O(n^{3/4}) / log n */
    /* U, V 都是環，記 h: U -> V 代表 U 轉型成 V 的函數。
    要求 h(x + y) = h(x) + h(y); f: lld -> U 是完全積性;
    g 是積性函數且 h(f(p)) = g(p) 對於質數 p。
    呼叫 F_comp 前需要先呼叫 F_prime 得到 S(i)。
    S(i), R(i) 是 F_prime 和 F_comp 在 n/k 點的值。
    F(i) = |sum_{fj <= i} f(j) 和 f(i) 需要快速求值。
    g(p, c) := g(pow(p, c)) 需要快速求值。
    例如若 g(p) 是度數 d 的多項式則可以構造 f(p) 是維護
    pow(p, c) 的 (d+1)-tuple */
}

```

6.7 Floor Sum

```

//f(n, a, b, c) = sum_{0 <= i <= n}{(ai + b)/c},
//g(n, a, b, c) = sum_{0 <= i <= n}{i(ai + b)/c},
//h(n, a, b, c) = sum_{0 <= i <= n}{((ai + b)/c)^2},
const int N = 998244353;
const int i2 = (N + 1) / 2, i6 = 166374059;
struct info{
    ll f, g, h;
    info(){f = g = h = 0;}
};
info calc(ll n, ll a, ll b, ll c){
    ll ac = a / c, bc = b / c,
        m = (a * n + b) / c, n1 = n + 1, n21 = n * 2 + 1;
    info d;
    if(a == 0){
        d.f = bc * n1 % N;
        d.g = bc * n % N * n1 % N * i2 % N;
        d.h = bc * bc % N * n1 % N;
        return d;
    }
    if(a >= c || b >= c){
        d.f = n * n1 % N * i2 % N * ac % N + bc * n1 % N;
        d.g = ac * n % N * n1 % N * n21 % N * i2 % N;
        d.h = ac * ac
            % N * n % N * n1 % N * n21 % N * i6 % N + bc *
            bc % N * n1 % N + ac * bc % N * n % N * n1 % N;
    }
    info e = calc(n, a % c, b % c, c);
    d.h +=
        e.h + 2 * bc * e.f % N + 2 * ac % N * e.g % N;
    d.g += e.g, d.f += e.f;
    d.f %= N, d.g %= N, d.h %= N;
    return d;
}

```

```

}
info e = calc(m - 1, c, c - b - 1, a);
d.f = (n * m % N - e.f + N) % N;
d.g = m * n % N *
    n1 % N - e.h - e.f; d.g = (d.g * i2 % N + N) % N;
d.h = n * m % N * (m + 1) % N -
    2 * e.g - 2 * e.f - d.f; d.h = (d.h % N + N) % N;
return d;
}

```

6.8 Euclidean

$$m = \lfloor \frac{an+b}{c} \rfloor$$

$$g(a,b,c,n) = \sum_{i=0}^n i \lfloor \frac{ai+b}{c} \rfloor$$

$$= \begin{cases} \lfloor \frac{a}{c} \rfloor \cdot \frac{n(n+1)(2n+1)}{6} + \lfloor \frac{b}{c} \rfloor \cdot \frac{n(n+1)}{2} \\ + g(a \bmod c, b \bmod c, c, n), & a \geq c \vee b \geq c \\ 0, & n < 0 \vee a = 0 \\ \frac{1}{2} \cdot (n(n+1)m - f(c, c-b-1, a, m-1)) \\ - h(c, c-b-1, a, m-1), & \text{otherwise} \end{cases}$$

$$h(a,b,c,n) = \sum_{i=0}^n \lfloor \frac{ai+b}{c} \rfloor^2$$

$$= \begin{cases} \lfloor \frac{a}{c} \rfloor^2 \cdot \frac{n(n+1)(2n+1)}{6} + \lfloor \frac{b}{c} \rfloor^2 \cdot (n+1) \\ + \lfloor \frac{a}{c} \rfloor \cdot \lfloor \frac{b}{c} \rfloor \cdot n(n+1) \\ + h(a \bmod c, b \bmod c, c, n) \\ + 2 \lfloor \frac{a}{c} \rfloor \cdot g(a \bmod c, b \bmod c, c, n) \\ + 2 \lfloor \frac{b}{c} \rfloor \cdot f(a \bmod c, b \bmod c, c, n), & a \geq c \vee b \geq c \\ 0, & n < 0 \vee a = 0 \\ nm(m+1) - 2g(c, c-b-1, a, m-1) \\ - 2f(c, c-b-1, a, m-1) - f(a, b, c, n), & \text{otherwise} \end{cases}$$

6.9 Big Number

```

template<typename T>
inline string to_string(const T& x){
    stringstream ss;
    return ss<<x,ss.str();
}

struct bigN:vector<ll>{
    const static int base=1000000000, width=log10(base);
    bool negative;
    bigN(const_iterator a,const_iterator b):vector<ll>(a,b){}
    bigN(string s){
        if(s.empty())return;
        if(s[0]=='-')negative=1,s=s.substr(1);
        else negative=0;
        for(int i=int(s.size())-1;i>=0;i-=width){
            ll t=0;
            for(int j=max(0,i-width+1);j<=i;j++)
                t=t*10+s[j]-'0';
            push_back(t);
        }
        trim();
    }
    template<typename T>
    bigN(const T &x):bigN(to_string(x)){}
    bigN():negative(0){}
    void trim(){
        while(size()&&!back())pop_back();
        if(empty())negative=0;
    }
    void carry(int _base=base){
        for(size_t i=0;i<size();++i){
            if(at(i)>=0&&at(i)<_base)continue;
            if(i+1==size())push_back(0);
            int r=at(i)%_base;
            if(r<0)r+=_base;
            at(i+1)+=(at(i)-r)/_base,at(i)=r;
        }
    }
    int abscmp(const bigN &b)const{
        if(size()>b.size())return 1;
        if(size()<b.size())return -1;
        for(int i=int(size())-1;i>=0;--i){
            if(at(i)>b[i])return 1;
            if(at(i)<b[i])return -1;
        }
        return 0;
    }
}

```

```

int cmp(const bigN &b)const{
    if(negative!=b.negative)return negative?-1:1;
    return negative?-abscmp(b):abscmp(b);
}
bool operator<(const bigN&b)const{return cmp(b)<0;}
bool operator>(const bigN&b)const{return cmp(b)>0;}
bool operator<=(const bigN&b)const{return cmp(b)<=0;}
bool operator>=(const bigN&b)const{return cmp(b)>=0;}
bool operator==(const bigN&b)const{return !cmp(b);}
bool operator!=(const bigN&b)const{return cmp(b)!=0;}
bigN abs()const{
    bigN res=*this;
    return res.negative=0, res;
}
bigN operator-()const{
    bigN res=*this;
    return res.negative=!negative,res.trim(),res;
}
bigN operator+(const bigN &b)const{
    if(negative)return -(-(*this)+(-b));
    if(b.negative)return *this-(-b);
    bigN res=*this;
    if(b.size()>size())res.resize(b.size());
    for(size_t i=0;i<b.size();++i)res[i]=b[i];
    return res.carry(),res.trim(),res;
}
bigN operator-(const bigN &b)const{
    if(negative)return -(-(*this)-(-b));
    if(b.negative)return *this+(-b);
    if(abscmp(b)<0)return -(b-(*this));
    bigN res=*this;
    if(b.size()>size())res.resize(b.size());
    for(size_t i=0;i<b.size();++i)res[i]=-b[i];
    return res.carry(),res.trim(),res;
}
bigN operator*(const bigN &b)const{
    bigN res;
    res.negative=negative!=b.negative;
    res.resize(size()+b.size());
    for(size_t i=0;i<size();++i)
        for(size_t j=0;j<b.size();++j)
            if((res[i+j]+=at(i)*b[j])>=base){
                res[i+j+1]+=res[i+j]/base;
                res[i+j]%=base;
            }
    // %a%k%lcarry . / . / i
    return res.trim(),res;
}
bigN operator/(const bigN &b)const{
    int norm=base/(b.back()+1);
    bigN x=abs()*norm;
    bigN y=b.abs()*norm;
    bigN q,r;
    q.resize(x.size());
    for(int i=int(x.size())-1;i>=0;--i){
        r=r*base+x[i];
        int s1=r.size()<=y.size()?0:r[y.size()];
        int s2=r.size()-y.size()?0:r[y.size()-1];
        int d=(ll(base)*s1+s2)/y.back();
        r=r-y*d;
        while(r.negative)r=r+y,-d;
        q[i]=d;
    }
    q.negative=negative!=b.negative;
    return q.trim(),q;
}
bigN operator%(const bigN &b)const{
    return *this-(*this/b)*b;
}
friend istream& operator>>(istream &ss,bigN &b){
    string s;
    return ss>>s, b=s, ss;
}
friend
    ostream& operator<<(ostream &ss,const bigN &b){
        if(b.negative)ss<<'-';
        ss<<(b.empty()?0:b.back());
        for(int i=int(b.size())-2;i>=0;--i)
            ss<<setw(width)<<setfill('0')<<b[i];
        return ss;
}
template<typename T>
operator T(){
    stringstream ss;
    ss<<*this;
    T res;
    return ss>>res,res;
}

```

```
}
```

6.10 Determinant

```
struct Matrix {
    int n, m;
    ll M[MAXN][MAXN];
    int row_swap(int i, int j) {
        if (i == j) return 0;
        for (int k = 0; k < m; ++k)
            swap(M[i][k], M[j][k]);
        return 1;
    }
    ll det() { // return the number of swaps
        int rt = 0;
        for (int i = 0; i < n; ++i) {
            int piv = i;
            while (piv < n && !M[piv][i]) ++piv;
            if (piv == n) continue;
            rt += row_swap(i, piv);
            for (int j = i + 1; j < n; ++j) {
                while (M[j][i]) {
                    int tmp = P - M[i][i] / M[j][i];
                    for (int k = i; k < m; ++k)
                        M[i][k] = (M[j][k] * tmp + M[i][k]) % P;
                    rt += row_swap(i, j);
                }
            }
        }
        rt = (rt & 1) ? P - 1 : 1;
        for (int i = 0; i < n; ++i)
            rt = rt * M[i][i] % P;
        return rt;
        // round(rt) if using double to cal. int. det
    }
};
```

6.11 Discrete Log

```
int DiscreteLog(int s, int x, int y, int m) {
    constexpr int kStep = 32000;
    unordered_map<int, int> p;
    int b = 1;
    for (int i = 0; i < kStep; ++i) {
        p[y] = i;
        y = 1LL * y * x % m;
        b = 1LL * b * x % m;
    }
    for (int i = 0; i < m + 10; i += kStep) {
        s = 1LL * s * b % m;
        if (p.find(s) != p.end()) return i + kStep - p[s];
    }
    return -1;
}
int DiscreteLog(int x, int y, int m) {
    if (m == 1) return 0;
    int s = 1;
    for (int i = 0; i < 100; ++i) {
        if (s == y) return i;
        s = 1LL * s * x % m;
    }
    if (s == y) return 100;
    int p = 100 + DiscreteLog(s, x, y, m);
    if (fpow(x, p, m) != y) return -1;
    return p;
}
```

6.12 Berlekamp Massey

```
// need add, sub, mul
vector<int> BerlekampMassey(vector<int> a) {
    // find min |c|
    // such that a_n = sum c_j * a_{n - j - 1}, 0-based
    // O(N^2), if |c| = k, |a| >= 2k sure correct
    auto f = [&](vector<int> v, ll c) {
        for (int &x : v) x = mul(x, c);
        return v;
    };
    vector<int> c, best;
    int pos = 0, n = (int)a.size();
    for (int i = 0; i < n; ++i) {
        int error = a[i];
        for (int j = 0; j < (int)c.size(); ++j)
            error = sub(error, mul(c[j], a[i - 1 - j]));
        if (error == 0) continue;
        int inv = Pow(error, mod - 2);
        if (c.empty()) {
            c.resize(i + 1), pos = i, best.pb(inv);
        } else {
            vector<int> fix = f(best, error);
            fix.insert(fix.begin(), i - pos - 1, 0);
            if (fix.size() >= c.size()) {
                best = f(c, sub(0, inv));
                best.insert(best.begin(), inv);
                pos = i, c.resize(fix.size());
            }
            for (int j = 0; j < (int)fix.size(); ++j)
                c[j] = add(c[j], fix[j]);
        }
    }
    return c;
}
```

```
if (c.empty()) {
    c.resize(i + 1), pos = i, best.pb(inv);
} else {
    vector<int> fix = f(best, error);
    fix.insert(fix.begin(), i - pos - 1, 0);
    if (fix.size() >= c.size()) {
        best = f(c, sub(0, inv));
        best.insert(best.begin(), inv);
        pos = i, c.resize(fix.size());
    }
    for (int j = 0; j < (int)fix.size(); ++j)
        c[j] = add(c[j], fix[j]);
}
return c;
}
```

6.13 Gaussian Elimination

```
using VI = vector<int>; // be careful if A.empty()
using VVI = vector<VI>; // ensure that 0 <= x < mod
pair<VI, VVI> gauss(VVI A, VI b) { // solve Ax=b
    const int N = (int)A.size(), M = (int)A[0].size();
    vector<int> devp, freev, free(M, true); int rk = 0;
    for (int i = 0; i < M; i++) {
        int p = -1;
        for (int j = rk; j < N; j++)
            if (p == -1 || abs(A[j][i]) > abs(A[p][i]))
                p = j;
        if (p == -1 || A[p][i] == 0) continue;
        swap(A[p], A[rk]); swap(b[p], b[rk]);
        const int inver = inv(A[rk][i]);
        for (int &x : A[rk]) x = mul(x, inver);
        b[rk] = mul(b[rk], inver);
        for (int j = 0; j < N; j++) if (j != rk) {
            int z = A[j][i];
            for (int k = 0; k < M; k++)
                A[j][k] = sub(A[j][k], mul(z, A[rk][k]));
            b[j] = sub(b[j], mul(z, b[rk]));
        }
        devp.push_back(i); freev[i] = false; ++rk;
    }
    for (int i = rk; i < N; i++)
        if (b[i] != 0) return {{}, {}}; // not consistent
    VI x(M); VVI h;
    for (int i = 0; i < rk; i++) x[devp[i]] = b[i];
    for (int i = 0; i < M; i++) if (freev[i]) {
        h.emplace_back(M); h.back()[i] = 1;
        for (int j = 0; j < rk; j++)
            h.back()[devp[j]] = sub(0, A[j][i]);
    }
    return {x, h}; // solution = x + span(h[i])
}
```

6.14 Golden Search

```
llf gss(llf a, llf b, auto &&f) {
    llf r = (sqrt(5) - 1) / 2, eps = 1e-7;
    llf x1 = b - r*(b - a), x2 = a + r*(b - a);
    llf f1 = f(x1), f2 = f(x2);
    while (b - a > eps)
        if (f1 < f2) { // change to > to find maximum
            b = x2; x2 = x1; f2 = f1;
            x1 = b - r*(b - a); f1 = f(x1);
        } else {
            a = x1; x1 = x2; f1 = f2;
            x2 = a + r*(b - a); f2 = f(x2);
        }
    return a;
}
```

6.15 Pi Count

```
struct S { int rough; lld large; int id; };
lld PrimeCount(lld n) { // n ~ 10^13 => < 1s
    if (n <= 1) return 0;
    const int v = static_cast<int>(sqrtl(n)); int pc = 0;
    vector<int> smalls(v + 1), skip(v + 1); vector<S> z;
    for (int i = 2; i <= v; ++i) smalls[i] = (i + 1) / 2;
    for (int i : views::iota(0, (v + 1) / 2))
        z.emplace_back(2*i+1, (n / (2*i+1) + 1) / 2, i);
    for (int p = 3; p <= v; ++p)
        if (smalls[p] > smalls[p - 1]) {
            const int q = p * p; ++pc;
            if (1LL * q * q > n) break;
            skip[p] = 1;
            for (int i = q; i <= v; i += 2 * p) skip[i] = 1;
```

```

int ns = 0;
for (auto e : z) if (!skip[e.rough]) {
    lld d = 1LL * e.rough * p;
    e.large += pc - (d <=
        v ? z[smalls[d] - pc].large : smalls[n / d]);
    e.id = ns; z[ns++] = e;
}
z.resize(ns);
for (int j = v / p; j >= p; --j) {
    int c =
        = smalls[j] - pc, e = min(j * p + p, v + 1);
    for (int i = j * p; i < e; ++i) smalls[i] -= c;
}
lld ans = z[0].large; z.erase(z.begin());
for (auto &[rough, large, k] : z) {
    const lld m = n / rough; --k;
    ans -= large - (pc + k);
    for (auto [p, _, l] : z)
        if (l >= k || p * p > m) break;
        else ans += smalls[m / p] - (pc + l);
}
return ans;
} // test @ yosupo library checker w/ n=1e11, 68ms

```

6.16 Quadratic Residue

```

int get_root(int n, int P) { // ensure 0 <= n < p
    if (P == 2 || n == 0) return n;
    auto check = [&](ll x) {
        return fpow(ll(x), (P - 1) / 2, P); };
    if (check(n) != 1) return -1;
    mt19937 rnd(7122); ll z = 1, w;
    while (check(w = (z * z - n + P) % P) != P - 1)
        z = rnd() % P;
    const auto M = [&](auto &u, auto &v) {
        auto [a, b] = u; auto [c, d] = v;
        return make_pair((a * c + b * d % P * w) % P,
            (a * d + b * c) % P);
    };
    pll r(1, 0), e(z, 1);
    for (int q = (P + 1) / 2; q >= 1, e = M(e, e))
        if (q & 1) r = M(r, e);
    return ll(r.first); // sqrt(n) mod P where P is prime
}

```

6.17 Simplex

```

namespace simplex {
// maximize c^T x under Ax <= B and x >= 0
// return VD(n, -inf) if the solution doesn't exist
// return VD(n, +inf) if the solution is unbounded
using VD = vector<llf>;
using VVD = vector<vector<llf>>;
const llf eps = 1e-9, inf = 1e+9;
int n, m; VVD d; vector<int> p, q;
void pivot(int r, int s) {
    llf inv = 1.0 / d[r][s];
    for (int i = 0; i < m + 2; ++i)
        for (int j = 0; j < n + 2; ++j)
            if (i != r && j != s)
                d[i][j] -= d[r][j] * d[i][s] * inv;
    for (int i = 0; i < m + 2; ++i) if (i != r) d[i][s] *= -inv;
    for (int j = 0; j < n + 2; ++j) if (j != s) d[r][j] *= +inv;
    d[r][s] = inv; swap(p[r], q[s]);
}
bool phase(int z) {
    int x = m + z;
    while (true) {
        int s = -1;
        for (int i = 0; i <= n; ++i) {
            if (!z && q[i] == -1) continue;
            if (s == -1 || d[x][i] < d[x][s]) s = i;
        }
        if (s == -1 || d[x][s] > -eps) return true;
        int r = -1;
        for (int i = 0; i < m; ++i) {
            if (d[i][s] < eps) continue;
            if (r == -1 ||
                d[i][n + 1] / d[i][s] < d[r][n + 1] / d[r][s]) r = i;
        }
        if (r == -1) return false;
        pivot(r, s);
    }
}
VD solve(const VVD &a, const VD &b, const VD &c) {
    m = (int)b.size(), n = (int)c.size();
    m = VVD(m + 2, VD(n + 2));
    for (int i = 0; i < m; ++i)
        for (int j = 0; j < n; ++j) d[i][j] = a[i][j];
    p.resize(m), q.resize(n + 1);
    for (int i = 0; i < m; ++i)
        p[i] = n + i, d[i][n] = -1, d[i][n + 1] = b[i];
    for (int i = 0; i < n; ++i) q[i] = i, d[m + 1][i] = -c[i];
    q[n] = -1, d[m + 1][n] = 1;
    int r = 0;
    for (int i = 1; i < m; ++i)
        if (d[i][n + 1] < d[r][n + 1]) r = i;
    if (d[r][n + 1] < -eps) {
        pivot(r, n);
        if (!phase(1) || d[m + 1][n + 1] < -eps)
            return VD(n, -inf);
        for (int i = 0; i < m; ++i) if (p[i] == -1) {
            int s = min_element(d[i].begin(), d[i].end() - 1) -
                d[i].begin();
            pivot(i, s);
        }
    }
    if (!phase(0)) return VD(n, inf);
    VD x(n);
    for (int i = 0; i < m; ++i)
        if (p[i] < n) x[p[i]] = d[i][n + 1];
    return x;
} // use double instead of long double if possible

```

```

d = VVD(m + 2, VD(n + 2));
for (int i = 0; i < m; ++i)
    for (int j = 0; j < n; ++j) d[i][j] = a[i][j];
p.resize(m), q.resize(n + 1);
for (int i = 0; i < m; ++i)
    p[i] = n + i, d[i][n] = -1, d[i][n + 1] = b[i];
for (int i = 0; i < n; ++i) q[i] = i, d[m + 1][i] = -c[i];
q[n] = -1, d[m + 1][n] = 1;
int r = 0;
for (int i = 1; i < m; ++i)
    if (d[i][n + 1] < d[r][n + 1]) r = i;
if (d[r][n + 1] < -eps) {
    pivot(r, n);
    if (!phase(1) || d[m + 1][n + 1] < -eps)
        return VD(n, -inf);
    for (int i = 0; i < m; ++i) if (p[i] == -1) {
        int s = min_element(d[i].begin(), d[i].end() - 1) -
            d[i].begin();
        pivot(i, s);
    }
}
if (!phase(0)) return VD(n, inf);
VD x(n);
for (int i = 0; i < m; ++i)
    if (p[i] < n) x[p[i]] = d[i][n + 1];
return x;
} // use double instead of long double if possible

```

6.18 Simplex Construction

Standard form: maximize $\sum_{1 \leq i \leq n} c_i x_i$ such that $\sum_{1 \leq i \leq n} A_{jix_i} \leq b_j$ for all $1 \leq j \leq m$ and $x_i \geq 0$ for all $1 \leq i \leq n$.

1. In case of minimization, let $c'_i = -c_i$
2. $\sum_{1 \leq i \leq n} A_{jix_i} \geq b_j \rightarrow \sum_{1 \leq i \leq n} -A_{jix_i} \leq -b_j$
3. $\sum_{1 \leq i \leq n} A_{jix_i} = b_j \rightarrow \text{add } \leq \text{ and } \geq.$
4. If x_i has no lower bound, replace x_i with $x_i - x'_i$

6.19 Theorem

- Kirchhoff's Theorem

Denote L be a $n \times n$ matrix as the Laplacian matrix of graph G , where $L_{ii} = d(i)$, $L_{ij} = -c$ where c is the number of edge (i, j) in G .

- The number of undirected spanning in G is $|\det(\tilde{L}_{11})|$.
- The number of directed spanning tree rooted at r in G is $|\det(\tilde{L}_{rr})|$.

- Tutte's Matrix

Let D be a $n \times n$ matrix, where $d_{ij} = x_{ij}$ (x_{ij} is chosen uniformly at random) if $i < j$ and $(i, j) \in E$, otherwise $d_{ij} = -d_{ji}$. $\frac{\text{rank}(D)}{2}$ is the maximum matching on G .

- Cayley's Formula

- Given a degree sequence d_1, d_2, \dots, d_n for each labeled vertices, there are

$$\frac{(n-2)!}{(d_1-1)!(d_2-1)! \cdots (d_n-1)!}$$

spanning trees.

- Let $T_{n,k}$ be the number of labeled forests on n vertices with k components, such that vertex $1, 2, \dots, k$ belong to different components. Then $T_{n,k} = kn^{n-k-1}$.

- Erdős–Gallai Theorem

A sequence of non-negative integers $d_1 \geq d_2 \geq \dots \geq d_n$ can be represented as the degree sequence of a finite simple graph on n vertices if and only if $d_1 + d_2 + \dots + d_n$ is even and

$$\sum_{i=1}^k d_i \leq k(k-1) + \sum_{i=k+1}^n \min(d_i, k)$$

holds for all $1 \leq k \leq n$.

- Burnside's Lemma

Let X be a set and G be a group that acts on X . For $g \in G$, denote by X^g the elements fixed by g :

$$X^g = \{x \in X \mid gx \in X\}$$

Then

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

- Gale–Ryser theorem

A pair of sequences of nonnegative integers $a_1 \geq \dots \geq a_n$ and b_1, \dots, b_n is bigraphic if and only if $\sum_{i=1}^n a_i = \sum_{i=1}^n b_i$ and $\sum_{i=1}^n a_i \leq \sum_{i=1}^n \min(b_i, k)$ holds for every $1 \leq k \leq n$. Sequences a and b called bigraphic if there is a labeled simple bipartite graph such that a and b is the degree sequence of this bipartite graph.

- Fulkerson–Chen–Anstee theorem

A sequence $(a_1, b_1), \dots, (a_n, b_n)$ of nonnegative integer pairs with $a_1 \geq \dots \geq a_n$ is digraphic if and only if $\sum_{i=1}^n a_i = \sum_{i=1}^n b_i$ and

$$\sum_{i=1}^k a_i \leq \sum_{i=1}^k \min(b_i, k-1) + \sum_{i=k+1}^n \min(b_i, k) \text{ holds for every } 1 \leq k \leq n.$$

Sequences a and b called digraphic if there is a labeled simple directed graph such that each vertex v_i has indegree a_i and outdegree b_i .

- Pick's theorem

For simple polygon, when points are all integer, we have $A = \#\{\text{lattice points in the interior}\} + \frac{\#\{\text{lattice points on the boundary}\}}{2} - 1$

- Möbius inversion formula

$$\begin{aligned} f(n) &= \sum_{d|n} g(d) \Leftrightarrow g(n) = \sum_{d|n} \mu(d) f\left(\frac{n}{d}\right) \\ f(n) &= \sum_{d|n} g(d) \Leftrightarrow g(n) = \sum_{d|n} \mu\left(\frac{d}{n}\right) f(d) \end{aligned}$$

7 Polynomial

7.1 NTT

```
const int N = 998244353, g = 3;

void NTT(vector<ll> &a, bool invert = 0){
    int n = a.size();
    int lg_n = __lg(n);
    for(int i = 1, j = 0; i < n; i++){
        int bit = n >> 1;
        for(; j & bit; bit >>= 1) j ^= bit;
        j ^= bit;
        if(i < j) swap(a[i], a[j]);
    }
    for(int len = 2; len <= n; len <= 1){
        ll wn = fpow(g, (N - 1) / len);
        if(invert) wn = inv(wn);
        for(int i = 0; i < n; i += len){
            ll w = 1;
            for(int j = 0; j < len / 2; j++){
                ll u
                    = a[i + j], v = a[i + j + len / 2] * w % N;
                a[i + j] = (u + v) % N;
                a[i + j + len / 2] = (u - v + N) % N;
                (w *= wn) %= N;
            }
        }
        ll n_1 = inv(n);
        if(invert) for(auto &x : a) (x *= n_1) %= N;
    }
}
```

7.2 FFT

```
using cd = complex<double>;
const double PI = acos(-1);

void FFT(vector<cd> &a, bool invert = 0){ // iterative version
    int n = a.size();
    int lg_n = __lg(n);
    for(int i =
        1, j = 0; i < n; i++){ //bit-reversal permutation
        int bit = n >> 1;
        for(; j & bit; bit >>= 1) j ^= bit;
        j ^= bit;
        if(i < j) swap(a[i], a[j]);
    }
    for(int len = 2; len <= n; len <= 1){
        double ang = 2 * PI / len * (invert? -1 : 1);
        cd wlen(cos(ang), sin(ang));
        for(int i = 0; i < n; i += len){
            cd w(1);
            for(int j = 0; j < len / 2; j++){
                cd u = a[i + j], v = a[i + j + len / 2] * w;
                a[i + j] = u + v;
                a[i + j + len / 2] = u - v;
                w *= wlen;
            }
        }
        if(invert) for(auto &x : a) x /= n;
    }
}
```

7.3 Primes

Prime	Root	Prime	Root
7681	17	167772161	3
12289	11	104857601	3
40961	3	985661441	3
65537	3	998244353	3
786433	10	1107296257	10
5767169	3	2013265921	31
7340033	3	2810183681	11
23068673	3	2885681153	3
469762049	3	605028353	3
2061584302081	7	1945555039024054273	5
2748779069441	3	9223372036737335297	3

7.4 Fast Walsh Transform

```
void fwt(vector<int> &a, bool inv){
    int n = 1;
    while(n < a.size()) n *= 2;
    a.resize(n);
    for(int len = 1; 2 * len <= n; len <= 1){
        for(int i = 0; i < n; i += 2 * len){
            for(int j = 0; j < len; j++){
                int &u =
                    a[i + j], &v = a[i + j + len];
                tie(u, v) =
                    inv ? pll(u - v, v) : pll(u + v, v); // and
                    // inv ? pll(u, v - u) : pll(u, u + v); // or
                    pll(u + v, u - v); // xor
            }
        }
        if(inv) for(auto &x : a) x /= n; // xor only
    }
}
```

7.5 Fast Linear Recursion

```
int FastLinearRecursion
    (vector <int> a, vector <int> c, ll k) {
// a_n = sigma c_j * a_{n - j - 1}, 0-based
// O(NlogNlogK), |a| = |c|
int n = a.size();
if (k < n) return a[k];
vector <int> base(n + 1, 1);
for (int i = 0; i < n; ++i)
    base[i] = sub(0, c[n - i - 1]);
vector <int> poly(n);
(n == 1 ? poly[0] = c[n - 1] : poly[1] = 1);
auto calc = [&](vector <int> p1, vector <int> p2) {
    // O(n^2) bruteforce or O(nlogn) NTT
    return Divide(Mul(p1, p2), base).second;
};
vector <int> res(n, 0); res[0] = 1;
for ( ; k; k >= 1, poly = calc(poly, poly)) {
    if (k & 1) res = calc(res, poly);
}
int ans = 0;
for (int i = 0; i < n; ++i)
    ans = add(ans, mul(res[i], a[i]));
return ans;
}
```

7.6 Polynomial Operations

```
typedef vector<int> Poly;
Poly Mul(Poly a, Poly b, int bound = N) { // d02e42
    int m = a.size() + b.size() - 1, n = 1;
    while (n < m) n <= 1;
    a.resize(n), b.resize(n);
    ntt(a), ntt(b);
    Poly out(n);
    for (int i = 0; i < n; ++i) out[i] = mul(a[i], b[i]);
    ntt(out, true), out.resize(min(m, bound));
    return out;
}
Poly Inverse(Poly a) { // b137d5
// O(NlogN), a[0] != 0
int n = a.size();
Poly res(1, inv(a[0]));
for (int m = 1; m < n; m <= 1) {
    if (n < m * 2) a.resize(m * 2);
    Poly v1(a.begin(), a.begin() + m * 2), v2 = res;
    v1.resize(m * 4), v2.resize(m * 4);
    ntt(v1), ntt(v2);
    for (int i = 0; i < m * 4; ++i)
        v1[i] = mul(mul(v1[i], v2[i]), v2[i]);
    ntt(v1, true);
    res.resize(m * 2);
    for (int i = 0; i < m; ++i)
```

```

    res[i] = add(res[i], res[i]);
    for (int i = 0; i < m * 2; ++i)
        res[i] = sub(res[i], v1[i]);
}
res.resize(n);
return res;
}
pair <Poly, Poly> Divide(Poly a, Poly b) {
// a = bQ + R, O(NlogN), b.back() != 0
int n = a.size(), m = b.size(), k = n - m + 1;
if (n < m) return {{}, a};
Poly ra = a, rb = b;
reverse(all(ra)), ra.resize(k);
reverse(all(rb)), rb.resize(k);
Poly Q = Mul(ra, Inverse(rb), k);
reverse(all(Q));
Poly res = Mul(b, Q), R(m - 1);
for (int i = 0; i < m - 1; ++i)
    R[i] = sub(a[i], res[i]);
return {Q, R};
}
Poly SqrtImpl(Poly a) { // a642f6
if (a.empty()) return {};
int z = QuadraticResidue(a[0], mod), n = a.size();
if (z == -1) return {-1};
Poly q(1, z);
const int inv2 = (mod + 1) / 2;
for (int m = 1; m < n; m <= 1) {
    if (n < m * 2) a.resize(m * 2);
    q.resize(m * 2);
    Poly f2 = Mul(q, q, m * 2);
    for (int i = 0; i < m * 2; ++i)
        f2[i] = sub(f2[i], a[i]);
    f2 = Mul(f2, Inverse(q), m * 2);
    for (int i = 0; i < m * 2; ++i)
        q[i] = sub(q[i], mul(f2[i], inv2));
}
q.resize(n);
return q;
}
Poly Sqrt(Poly a) { // 0dae9c
// O(NlogN), return {-1} if not exists
int n = a.size(), m = 0;
while (m < n && a[m] == 0) m++;
if (m == n) return Poly(n);
if (m & 1) return {-1};
Poly s = SqrtImpl(Poly(a.begin() + m, a.end()));
if (s[0] == -1) return {-1};
Poly res(n);
for (int i = 0; i < s.size(); ++i)
    res[i + m / 2] = s[i];
return res;
}
Poly Derivative(Poly a) { // 26f29b
int n = a.size();
Poly res(n - 1);
for (int i = 0; i < n - 1; ++i)
    res[i] = mul(a[i + 1], i + 1);
return res;
}
Poly Integral(Poly a) { // f18ba1
int n = a.size();
Poly res(n + 1);
for (int i = 0; i < n; ++i)
    res[i + 1] = mul(a[i], inv(i + 1));
return res;
}
Poly Ln(Poly a) { // 0c1381
// O(NlogN), a[0] = 1
int n = a.size();
if (n == 1) return {};
Poly d = Derivative(a);
a.pop_back();
return Integral(Mul(d, Inverse(a), n - 1));
}
Poly Exp(Poly a) { // d2b129
// O(NlogN), a[0] = 0
int n = a.size();
Poly q(1, 1);
a[0] = add(a[0], 1);
for (int m = 1; m < n; m <= 1) {
    if (n < m * 2) a.resize(m * 2);
    Poly g(a.begin(), a.begin() + m * 2), h(all(q));
    h.resize(m * 2), h = Ln(h);
    for (int i = 0; i < m * 2; ++i)
        g[i] = sub(g[i], h[i]);
}

```

```

    q = Mul(g, q, m * 2);
}
q.resize(n);
return q;
}
Poly PolyPow(Poly a, ll k) { // d50135
int n = a.size(), m = 0;
Poly ans(n, 0);
while (m < n && a[m] == 0) m++;
if (k && m && (k >= n || k * m >= n)) return ans;
if (m == n) return ans[0] = 1, ans;
int lead = m * k;
Poly b(a.begin() + m, a.end());
int base = fpow(b[0], k), inv = fpow(b[0], N - 2);
for (int i = 0; i < n - m; ++i)
    b[i] = mul(b[i], inv);
b = Ln(b);
for (int i = 0; i < n - m; ++i)
    b[i] = mul(b[i], k % mod);
b = Exp(b);
for (int i = lead; i < n; ++i)
    ans[i] = mul(b[i - lead], base);
return ans;
}
vector <int> Evaluate(Poly a, vector <int> x) {
if (x.empty()) return {};
int n = x.size();
vector <Poly> up(n * 2);
for (int i = 0; i < n; ++i)
    up[i + n] = {sub(0, x[i]), 1};
for (int i = n - 1; i > 0; --i)
    up[i] = Mul(up[i * 2], up[i * 2 + 1]);
vector <Poly> down(n * 2);
down[1] = Divide(a, up[1]).second;
for (int i = 2; i < n * 2; ++i)
    down[i] = Divide(down[i - 1], up[i]).second;
Poly y(n);
for (int i = 0; i < n; ++i) y[i] = down[i + n][0];
return y;
}
Poly Interpolate(vector <int> x, vector <int> y) {
int n = x.size(); // 743f56
vector <Poly> up(n * 2);
for (int i = 0; i < n; ++i)
    up[i + n] = {sub(0, x[i]), 1};
for (int i = n - 1; i > 0; --i)
    up[i] = Mul(up[i * 2], up[i * 2 + 1]);
Poly a = Evaluate(Derivative(up[1]), x);
for (int i = 0; i < n; ++i)
    a[i] = mul(y[i], inv(a[i]));
vector <Poly> down(n * 2);
for (int i = 0; i < n; ++i) down[i + n] = {a[i]};
for (int i = n - 1; i > 0; --i) {
    Poly lhs = Mul(down[i * 2], up[i * 2 + 1]);
    Poly rhs = Mul(down[i * 2 + 1], up[i * 2]);
    down[i].resize(lhs.size());
    for (int j = 0; j < lhs.size(); ++j)
        down[i][j] = add(lhs[j], rhs[j]);
}
return down[1];
}

```

8 Geometry

8.1 Basic

```

struct pt{
    double x, y;
    pt(){}
    pt(double _x, double _y) : x(_x), y(_y){}
};
pt operator + (pt a, pt b)
{ return pt(a.x + b.x, a.y + b.y); }
pt operator - (pt a, pt b)
{ return pt(a.x - b.x, a.y - b.y); }
pt operator * (pt a, double p)
{ return pt(a.x * p, a.y * p); }
pt operator / (pt a, double p)
{ return pt(a.x / p, a.y / p); }
bool operator < (const pt &a, const pt &b)
{ return a.x < b.x || (a.x == b.x && a.y < b.y); }
bool operator == (const pt &a, const pt &b)
{ return a.x == b.x && a.y == b.y; }
double dot(pt a, pt b)
{ return a.x * b.x + a.y * b.y; }
double cross(pt a, pt b)
{ return a.x * b.y - a.y * b.x; }

```

```

double len(pt a)
{ return sqrt(dot(a, a)); }
double angle(pt a, pt b)
{ return acos(dot(a, b) / len(a) / len(b)); }
double area2(pt a, pt b, pt c)
{ return cross(b - a, c - a); }

const double eps = 1e-9;
int dcmp(double x){
    if(fabs(x) < eps) return 0;
    return x < 0? -1 : 1;
}

inline int ori(pt a, pt b, pt c){
    double area = cross(b - a, c - a);
    if(area > -eps && area < eps) return 0;
    return area > 0? 1 : -1;
}

inline int btw(pt a, pt b, pt c){ // [a, c, b]
    if(fabs(cross(b - a, c - a)) > eps) return false;
    if(dot(b - a, c - a)
        > -eps && len(c - a) <= len(b - a)) return true;
    return false;
}

bool intersect(pt a, pt b, pt c, pt d){
    if(a == c || a == d || b == c || b == d) return true;
    int a123 = ori(a, b, c), a124 = ori(a,
        b, d), a341 = ori(c, d, a), a342 = ori(c, d, b);
    if(a123 == 0 && a124 == 0){
        if(btw(a, b, c) || btw(a, b, d)
            || btw(c, d, a) || btw(c, d, b)) return true;
        else return false;
    }
    else if(a123
        * a124 <= 0 && a341 * a342 <= 0) return true;
    return false;
}

istream &operator>>(istream &s, pt &a){
    s >> a.x >> a.y;
    return s;
}

```

8.2 Convex Hull

```

vector<pt> ConvexHull(vector<pt> a) {
    int n = a.size();
    sort(a.begin(), a.end());
    vector<pt> ans = {a[0]};
    for (int t : {0, 1}) {
        int m = ans.size();
        for (int i = 1; i < n; i++) {
            while (ans.size() > m && ori(ans[ans.size() - 2],
                ans.back(), a[i]) < 0) ans.pop_back();
            ans.pb(a[i]);
        }
        reverse(all(a));
    }
    if (ans.size() > 1) ans.pop_back();
    return ans;
}

```

8.3 Minkowski Sum

```

void reorder(vector<pt> &a){
    int pos = 0;
    for(int j = 1; j < a.size(); j++){
        if(a[j].x < a[pos].x || (a[j].x
            == a[pos].x && a[j].y < a[pos].y)) pos = j;
    }
    rotate(a.begin(), a.begin() + pos, a.end());
}

vector<pt> minkowski(vector<pt> a, vector<pt> b){
    // for(int i = 0;
    //     i < b.size(); i++) b[i] = {-b[i].x, -b[i].y};
    最短距離：把 Q 鏡像，找凸包到 (0, 0) 的最短距離
    reorder(a), reorder(b);
    a.pb(a[0]), a.pb(a[1]);
    b.pb(b[0]), b.pb(b[1]);
    vector<pt> res;
    int i = 0, j = 0;
    while(i < a.size() - 2 || j < b.size() - 2){
        res.pb(a[i] + b[j]);
        int c
            = cross(a[i + 1] - a[i], b[j + 1] - b[j]);

```

```

        if(c >= 0 && i < a.size() - 2) i++;
        if(c <= 0 && j < b.size() - 2) j++;
    }
    return res;
}

```

8.4 Intersection of Circle and Line

```

vector<Pt> CircleLineInter(Cir c, Line l) {
    Pt p = l.a + (l.b - l.a)
        * ((c.o - l.a) * (l.b - l.a)) / abs2(l.b - l.a);
    double s = (l.b - l.a) ^ (c.o
        - l.a), h2 = c.r * c.r - s * s / abs2(l.b - l.a);
    if (sign(h2) == -1) return {};
    if (sign(h2) == 0) return {p};
    Pt h = (l.b - l.a) / abs(l.b - l.a) * sqrt(h2);
    return {p - h, p + h};
}

```

8.5 Intersection of Circles

```

vector<Pt> CirclesInter(Cir c1, Cir c2) {
    double d2 = abs2(c1.o - c2.o), d = sqrt(d2);
    if (d < max(c1.r, c2.r)
        - min(c1.r, c2.r) || d > c1.r + c2.r) return {};
    Pt u = (c1.o + c2.o) / 2 + (c1.o -
        c2.o) * ((c2.r * c2.r - c1.r * c1.r) / (2 * d2));
    double A = sqrt((c1.r + c2.r + d) * (c1.r - c2.
        r + d) * (c1.r + c2.r - d) * (-c1.r + c2.r + d));
    Pt v = Pt(c1
        .o.y - c2.o.y, -c1.o.x + c2.o.x) * A / (2 * d2);
    if (sign(v.x) == 0 && sign(v.y) == 0) return {u};
    return {u + v, u - v};
}

```

8.6 Point in Convex

```

bool PointInConvex
    (const vector<Pt> &C, Pt p, bool strict = true) {
// only works when no three points are collinear
    int a = 1, b = int(C.size()) - 1, r = !strict;
    if (C.size() == 0) return false;
    if (C.size() < 3) return r && btw(C[0], C.back(), p);
    if (ori(C[0], C[a], C[b]) > 0) swap(a, b);
    if (ori(C[0], C[a], p
        ) >= r || ori(C[0], C[b], p) <= -r) return false;
    while (abs(a - b) > 1) {
        int c = (a + b) / 2;
        (ori(C[0], C[c], p) > 0 ? b : a) = c;
    }
    return ori(C[a], C[b], p) < r;
}

```

8.7 Minimum Enclosing Circle

```

pt circle(pt a, pt b, pt c){
    pt m1 = (a + b) / 2, m2 = (a + c) / 2,
    d1 = (b - a).rot().norm(), d2 = (c - a).norm();
    double tar = dot(m2, d2) - dot(m1, d2);
    double k = tar / dot(d1, d2);
    return m1 + d1 * k;
}

```

```

pair<pt, double> min_enclosing(vector<pt> &a) {
    random_shuffle(a.begin(), a.end());
    pt c = {0, 0};
    double r2 = 0;
    for(int i = 0; i < n; i++){
        if((a[i] - c).len2() <= r2) continue;
        c = a[i], r2 = 0;
        for(int j = 0; j < i; j++){
            if((a[j] - c).len2() <= r2) continue;
            c = (a[i] + a[j]) / 2, r2 = (a[i] - c).len2();
            for(int k = 0; k < j; k++){
                if((a[k] - c).len2() <= r2) continue;
                c = circle
                    (a[i], a[j], a[k]), r2 = (a[k] - c).len2();
            }
        }
    }
    return make_pair(c, sqrt(r2));
}

```

8.8 Rotating Caliper

```

void RotatingCaliper(vector<pt> &pts) {
    int n = pts.size();
    for(int i = 0, j = 2; i < n; ++i) {

```

```

int ni = (i + 1) % n;
while (true) {
    int nj = (j + 1) % n;
    if (area(pts[j], pts[i], pts[ni]) < area(pts[nj], pts[i], pts[ni]))
        j = nj;
    else break;
}
// do something
}

```

8.9 Rotating Sweep Line

```

struct Event {
    Pt d; int u, v;
    bool operator < (const Event &b) const {
        return sign(d ^ b.d) > 0; }
};

Pt ref(Pt o) {return pos(o) == 1 ? Pt(-o.x, -o.y) : o;}
void RotatingSweepLine(vector <Pt> &pt) {
    int n = pt.size();
    vector <int> ord(n), pos(n);
    vector <Event> e;
    for (int i = 0; i < n; ++i)
        for (int j = i + 1; j < n; ++j) if (i ^ j)
            e.pb({ref(pt[i] - pt[j]), i, j});
    sort(all(e));
    iota(all(ord), 0);
    sort(all(ord), [&](int i, int j) {
        return (sign(pt[i].y - pt[j].y) == 0 ?
            pt[i].x < pt[j].x : pt[i].y < pt[j].y); });
    for (int i = 0; i < n; ++i) pos[ord[i]] = i;
    const auto makeReverse = [](&v) {
        sort(all(v)); v.resize(unique(all(v)) - v.begin());
        vector <pii> segs;
        for (int i = 0, j = 0; i < v.size(); i = j) {
            for (; j < v.size() && v[j] - v[i] <= j - i; ++j)
                segs.emplace_back(v[i], v[j - 1] + 1 + 1);
        }
        return segs;
    };
    for (int i = 0, j = 0; i < e.size(); i = j) {
        vector <int> tmp;
        for (; j < e.size() && !(e[i] < e[j]); j++)
            tmp.pb(min(pos[e[j].u], pos[e[j].v]));
        for (auto [l, r] : makeReverse(tmp)) {
            reverse(ord.begin() + l, ord.begin() + r);
            for (int t = l; t < r; ++t) pos[ord[t]] = t;
            // update value here
        }
    }
}

```

8.10 Tangent Line of Two Circles

```

vector<Line>
> go( const Cir& c1 , const Cir& c2 , int sign1 ){
// sign1 = 1 for outer tang, -1 for inter tang
vector<Line> ret;
double d_sq = abs2(c1.0 - c2.0);
if (sign(d_sq) == 0) return ret;
double d = sqrt(d_sq);
pdd v = (c2.0 - c1.0) / d;
double c = (c1.R - sign1 * c2.R) / d;
if (c * c > 1) return ret;
double h = sqrt(max(0.0, 1.0 - c * c));
for (int sign2 = 1; sign2 >= -1; sign2 -= 2) {
    pdd n = pdd(v.X * c - sign2 * h * v.Y,
                 v.Y * c + sign2 * h * v.X);
    pdd p1 = c1.0 + n * c1.R;
    pdd p2 = c2.0 + n * (c2.R * sign1);
    if (sign(p1.X - p2.X) == 0 and
        sign(p1.Y - p2.Y) == 0)
        p2 = p1 + perp(c2.0 - c1.0);
    ret.pb(Line(p1, p2));
}
return ret;
}

```

8.11 Tangent Point to Hull

```

/* The point should be strictly out of hull
return arbitrary point on the tangent line */
pii get_tangent(vector<pll> &C, pll p) {
    auto gao = [&](int s) {

```

```

        return cyc_tsearch(SZ(C), [&](int x, int y) {
            { return ori(p, C[x], C[y]) == s; });
        return pii(gao(1), gao(-1));
    } // return (a, b), ori(p, C[a], C[b]) >= 0
}

```

8.12 3D Point

```

struct Pt {
    double x, y, z;
    Pt(double _x = 0, double _y = 0, double _z = 0): x(_x), y(_y), z(_z){}
    Pt operator + (const Pt &o) const
    { return Pt(x + o.x, y + o.y, z + o.z); }
    Pt operator - (const Pt &o) const
    { return Pt(x - o.x, y - o.y, z - o.z); }
    Pt operator * (const double &k) const
    { return Pt(x * k, y * k, z * k); }
    Pt operator / (const double &k) const
    { return Pt(x / k, y / k, z / k); }
    double operator * (const Pt &o) const
    { return x * o.x + y * o.y + z * o.z; }
    Pt operator ^ (const Pt &o) const
    { return {Pt(y * o.z - z * o.y, z * o.x - x * o.z, x * o.y - y * o.x)}; }
};

double abs2(Pt o) { return o * o; }
double abs(Pt o) { return sqrt(abs2(o)); }
Pt cross3(Pt a, Pt b, Pt c)
{ return (b - a) ^ (c - a); }
double area(Pt a, Pt b, Pt c)
{ return abs(cross3(a, b, c)); }
double volume(Pt a, Pt b, Pt c, Pt d)
{ return cross3(a, b, c) * (d - a); }
bool coplaner(Pt a, Pt b, Pt c, Pt d)
{ return sign(volume(a, b, c, d)) == 0; }
Pt proj(Pt o, Pt a, Pt b, Pt c) // o proj to plane abc
{ Pt n = cross3(a, b, c);
    return o - n * ((o - a) * (n / abs2(n))); }
Pt LinePlaneInter(Pt u, Pt v, Pt a, Pt b, Pt c) {
    // intersection of line uv and plane abc
    Pt n = cross3(a, b, c);
    double s = n * (u - v);
    if (sign(s) == 0) return {-1, -1, -1}; // not found
    return v + (u - v) * ((n * (a - v)) / s);
}

```

8.13 3D Convex Hull

```

struct CH3D {
    struct face{int a, b, c; bool ok;} F[8 * N];
    double dblcmp(Pt &p, face &f)
    {return
        cross3(P[f.a], P[f.b], P[f.c]) * (p - P[f.a]));}
    int g[N][N], num, n;
    Pt P[N];
    void deal(int p, int a, int b) {
        int f = g[a][b];
        face add;
        if (F[f].ok) {
            if (dblcmp(P[p], F[f]) > eps) dfs(p, f);
            else
                add.a =
                    b, add.b = a, add.c = p, add.ok = 1, g[p][
                    b] = g[a][p] = g[b][a] = num, F[num++] = add;
        }
    }
    void dfs(int p, int now) {
        F[now].ok = 0;
        deal(p, F[now].b, F[now].a), deal(p, F[
            now].c, F[now].b), deal(p, F[now].a, F[now].c);
    }
    bool same(int s, int t){
        Pt &a = P[F[s].a];
        Pt &b = P[F[s].b];
        Pt &c = P[F[s].c];
        return fabs(volume(a, b, c, P[F[t].a
            ])) < eps && fabs(volume(a, b, c, P[F[t].b])) <
            eps && fabs(volume(a, b, c, P[F[t].c])) < eps;
    }
    void init(int _n){n = _n, num = 0;}
    void solve() {
        face add;
        num = 0;
        if(n < 4) return;
        if([&](){
            for (int i = 1; i < n; ++i)

```

```

if (abs(P[0] - P[i]) > eps)
    return swap(P[1], P[i]), 0;
return 1;
}() || [&]() {
    for (int i = 2; i < n; ++i)
        if (abs(cross3(P[i], P[0], P[1])) > eps)
            return swap(P[2], P[i]), 0;
    return 1;
}() || [&]() {
    for (int i = 3; i < n; ++i)
        if (fabs(((P[0] - P[1])
                  ^ (P[1] - P[2])) * (P[0] - P[i])) > eps)
            return swap(P[3], P[i]), 0;
    return 1;
}(); return;
for (int i = 0; i < 4; ++i) {
    add.a = (i + 1) % 4, add.b = (i
        + 2) % 4, add.c = (i + 3) % 4, add.ok = true;
    if (dblcmp(P[i], add) > 0) swap(add.b, add.c);
    g[add.a][add.b] = g[add.b][add.c] = g[add.c][add.a] = num;
    F[num++] = add;
}
for (int i = 4; i < n; ++i)
    for (int j = 0; j < num; ++j)
        if (F[j].ok && dblcmp(P[i], F[j]) > eps) {
            dfs(i, j);
            break;
        }
    for (int tmp = num, i = (num = 0); i < tmp; ++i)
        if (F[i].ok) F[num++] = F[i];
}
double get_area() {
    double res = 0.0;
    if (n == 3)
        return abs(cross3(P[0], P[1], P[2])) / 2.0;
    for (int i = 0; i < num; ++i)
        res += area(P[F[i].a], P[F[i].b], P[F[i].c]);
    return res / 2.0;
}
double get_volume() {
    double res = 0.0;
    for (int i = 0; i < num; ++i)
        res += volume(Pt
            (0, 0, 0), P[F[i].a], P[F[i].b], P[F[i].c]);
    return fabs(res / 6.0);
}
int triangle() {return num;}
int polygon() {
    int res = 0;
    for (int i = 0,
        flag = 1; i < num; ++i, res += flag, flag = 1)
        for (int j = 0; j < i && flag; ++j)
            flag &= !same(i, j);
    return res;
}
Pt getcent(){
    Pt ans(0, 0, 0), temp = P[F[0].a];
    double v = 0.0, t2;
    for (int i = 0; i < num; ++i)
        if (F[i].ok == true) {
            Pt p1 =
                P[F[i].a], p2 = P[F[i].b], p3 = P[F[i].c];
            t2 = volume(temp, p1, p2, p3) / 6.0;
            if (t2>0)
                ans.x += (p1.x + p2.x + p3.x) * t2, ans.y += (p1.y + p2.y + p3.y) * t2, ans.z += (p1.z + p2.z + p3.z) * t2, v += t2;
        }
    ans.x /= (4 * v), ans.y /= (4 * v), ans.z /= (4 * v);
    return ans;
}
double pointmindis(Pt p) {
    double rt = 99999999;
    for(int i = 0; i < num; ++i)
        if(F[i].ok == true) {
            Pt p1 =
                P[F[i].a], p2 = P[F[i].b], p3 = P[F[i].c];
            double a = (p2.y - p1.y) * (p3.z - p1.z) - (p2.z - p1.z) * (p3.y - p1.y);
            double b = (p2.z - p1.z) * (p3.x - p1.x) - (p2.x - p1.x) * (p3.z - p1.z);
            double c = (p2.x - p1.x) * (p3.y - p1.y) - (p2.y - p1.y) * (p3.x - p1.x);
            double d = 0 - (a * p1.x + b * p1.y + c * p1.z);
            double temp = fabs(a * p.x + b * p.y + c * p.z + d) / sqrt(a * a + b * b + c * c);
            rt = min(rt, temp);
        }
    return rt;
}

```

```

    double
    d = 0 - (a * p1.x + b * p1.y + c * p1.z);
    double temp = fabs(a * p.x + b * p.y +
                      c * p.z + d) / sqrt(a * a + b * b + c * c);
    rt = min(rt, temp);
}
return rt;
}

```

9 Misc

9.1 Cyclic Tenary Search

```

/* bool pred(int a, int b);
f(0) ~ f(n - 1) is a cyclic-shift U-function
return idx s.t. pred(x, idx) is false forall x */
int cyc_tsearch(int n, auto pred) {
    if (n == 1) return 0;
    int l = 0, r = n; bool rv = pred(1, 0);
    while (r - l > 1) {
        int m = (l + r) / 2;
        if (pred(0, m) ? rv : pred(m, (m + 1) % n)) r = m;
        else l = m;
    }
    return pred(l, r % n) ? l : r % n;
}

```

9.2 Binary Search on Fraction

```

struct Q {
    ll p, q;
    Q go(Q b, ll d) { return {p + b.p*d, q + b.q*d}; }
};
bool pred(Q);
// returns smallest p/q in [lo, hi] such that
// pred(p/q) is true, and 0 <= p, q <= N
Q frac_bs(ll N) {
    Q lo{0, 1}, hi{1, 0};
    if (pred(lo)) return lo;
    assert(pred(hi));
    bool dir = 1, L = 1, H = 1;
    for (; L || H; dir = !dir) {
        ll len = 0, step = 1;
        for (int t = 0; t < 2 && (t ? step/=2 : step*=2))
            if (Q mid = hi.go(lo, len + step);
                mid.p > N || mid.q > N || dir ^ pred(mid))
                t++;
            else len += step;
        swap(lo, hi = hi.go(lo, len));
        (dir ? L : H) = !len;
    }
    return dir ? hi : lo;
}

```

9.3 Random

```

struct custom_hash {
    static uint64_t splitmix64(uint64_t x) {
        x += 0x9e3779b97f4a7c15;
        x = (x ^ (x >> 30)) * 0xbff58476d1ce4e5b9;
        x = (x ^ (x >> 27)) * 0x94d049bb13311eb;
        return x ^ (x >> 31);
    }
    size_t operator()(uint64_t a) const {
        static const uint64_t FIXED_RANDOM = chrono::steady_clock::now().time_since_epoch().count();
        return splitmix64(i + FIXED_RANDOM);
    }
    unordered_map <int, int, custom_hash> m1;
    random_device rd; mt19937 rng(rd());
}

```

9.4 Bit Hack

```

ll next_perm(ll v) { ll t = v | (v - 1);
    return (t + 1) | (((~t & -~t) - 1) >> (_builtin_ctz(v) + 1)); }

```

9.5 Dynamic MST

```

int cnt[maxn], cost[maxn], st[maxn], ed[maxn];
pair<int, int> qr[maxn];
// qr[i].first = id of edge to
// be changed, qr[i].second = weight after operation
// cnt[i] = number of operation on edge i
// call solve(0, q - 1, v,
// 0), where v contains edges i such that cnt[i] == 0

```

```

void contract(int l, int r, vector<int> v, vector<int> &x, vector<int> &y) {
    sort(v.begin(), v.end(), [&](int i, int j) {
        if (cost[i] == cost[j]) return i < j;
        return cost[i] < cost[j];
    });
    djs.save();
    for (int i = l; i <= r; ++i) djs.merge(st[qr[i].first], ed[qr[i].first]);
    for (int i = 0; i < (int)v.size(); ++i) {
        if (djs.find(st[v[i]]) != djs.find(ed[v[i]])) {
            x.push_back(v[i]);
            djs.merge(st[v[i]], ed[v[i]]);
        }
    }
    djs.undo();
    djs.save();
    for (int i = 0; i < (int)x.size(); ++i) djs.merge(st[x[i]], ed[x[i]]);
    for (int i = 0; i < (int)v.size(); ++i) {
        if (djs.find(st[v[i]]) != djs.find(ed[v[i]])) {
            y.push_back(v[i]);
            djs.merge(st[v[i]], ed[v[i]]);
        }
    }
    djs.undo();
}

void solve(int l, int r, vector<int> v, long long c) {
    if (l == r) {
        cost[qr[l].first] = qr[l].second;
        if (st[qr[l].first] == ed[qr[l].first]) {
            printf("%lld\n", c);
            return;
        }
        int minv = qr[l].second;
        for (int i = 0; i < (int)v.size(); ++i) minv = min(minv, cost[v[i]]);
        printf("%lld\n", c + minv);
        return;
    }
    int m = (l + r) >> 1;
    vector<int> lv = v, rv = v;
    vector<int> x, y;
    for (int i = m + 1; i <= r; ++i) {
        cnt[qr[i].first]--;
        if (cnt[qr[i].first] == 0) lv.push_back(qr[i].first);
    }
    contract(l, m, lv, x, y);
    long long lc = c, rc = c;
    djs.save();
    for (int i = 0; i < (int)x.size(); ++i) {
        lc += cost[x[i]];
        djs.merge(st[x[i]], ed[x[i]]);
    }
    solve(l, m, y, lc);
    djs.undo();
    x.clear(), y.clear();
    for (int i = m + 1; i <= r; ++i) cnt[qr[i].first]++;
    for (int i = l; i <= m; ++i) {
        cnt[qr[i].first]--;
        if (cnt[qr[i].first] == 0) rv.push_back(qr[i].first);
    }
    contract(m + 1, r, rv, x, y);
    djs.save();
    for (int i = 0; i < (int)x.size(); ++i) {
        rc += cost[x[i]];
        djs.merge(st[x[i]], ed[x[i]]);
    }
    solve(m + 1, r, y, rc);
    djs.undo();
    for (int i = l; i <= m; ++i) cnt[qr[i].first]++;
}

```

9.6 Manhattan MST

```

void solve(Point *a, int n) {
    sort(a, a + n, [](const Point &p, const Point &q) {
        return p.x + p.y < q.x + q.y;
    });
    set<Point> st; // greater<Point::x>
    for (int i = 0; i < n; ++i) {
        for (auto it = st.lower_bound(a[i]); it != st.end(); it = st.erase(it)) {

```

```

            if (it -> x - it -> y < a[i].x - a[i].y) break;
            es.push_back({{it -> u, a[i].u, dist(*it, a[i])}});
        }
        st.insert(a[i]);
    }
}

void MST(Point *a, int n) {
    for (int t = 0; t < 2; ++t) {
        solve(a, n);
        for (int i = 0; i < n; ++i) swap(a[i].x, a[i].y);
        solve(a, n);
        for (int i = 0; i < n; ++i) a[i].x = -a[i].x;
    }
}

```

9.7 DP Optimization Conditions

9.7.1 Totally Monotone (Concave/Convex)

$$\forall i < i', j < j', B[i][j] \leq B[i'][j] \implies B[i][j'] \leq B[i'][j']$$

$$\forall i < i', j < j', B[i][j] \geq B[i'][j] \implies B[i][j'] \geq B[i'][j']$$

9.7.2 Monge Condition (Concave/Convex)

$$\forall i < i', j < j', B[i][j] + B[i'][j'] \geq B[i][j'] + B[i'][j]$$

$$\forall i < i', j < j', B[i][j] + B[i'][j'] \leq B[i][j'] + B[i'][j]$$

9.7.3 Optimal Split Point

$$\text{If } B[i][j] + B[i+1][j+1] \geq B[i][j+1] + B[i+1][j]$$

then

$$H_{i,j-1} \leq H_{i,j} \leq H_{i+1,j}$$

9.8 Mo's Algo With Modification

```

/*
Mo's Algorithm With modification
Block: N^{2/3}, Complexity: N^{5/3}
*/
struct Query {
    int L, R, LBid, RBid, T;
    Query(int l, int r, int t) : L(l), R(r), LBid(l / blk), RBid(r / blk), T(t) {}
    bool operator<(const Query &q) const {
        if (LBid != q.LBid) return LBid < q.LBid;
        if (RBid != q.RBid) return RBid < q.RBid;
        return T < b.T;
    }
};
void solve(vector<Query> query) {
    sort(ALL(query));
    int L = 0, R = 0, T = -1;
    for (auto q : query) {
        while (T < q.T) addTime(L, R, ++T); // TODO
        while (T > q.T) subTime(L, R, T--); // TODO
        while (R < q.R) add(arr[++R]); // TODO
        while (L > q.L) add(arr[--L]); // TODO
        while (R > q.R) sub(arr[R--]); // TODO
        while (L < q.L) sub(arr[L++]); // TODO
    }
}

```

9.9 Mo's Algo On Tree

```

/*
Mo's Algorithm On Tree
Preprocess:
1) LCA
2) dfs with in[u] = dft++, out[u] = dft++
3) ord[in[u]] = ord[out[u]] = u
4) bitset<MAXN> inset
*/
struct Query {
    int L, R, LBid, lca;
    Query(int u, int v) {
        int c = LCA(u, v);
        if (c == u || c == v)
            q.lca = -1, q.L = out[c ^ u ^ v], q.R = out[c];
        else if (out[u] < in[v])
            q.lca = c, q.L = out[u], q.R = in[v];
        else
            q.lca = c, q.L = out[v], q.R = in[u];
        q.Lid = q.L / blk;
    }
    bool operator<(const Query &q) const {
        if (LBid != q.LBid) return LBid < q.LBid;
        return R < q.RB
```

```

    }
};

void flip(int x) {
    if (inset[x]) sub(arr[x]); // TODO
    else add(arr[x]); // TODO
    inset[x] = ~inset[x];
}

void solve(vector<Query> query) {
    sort(ALL(query));
    int L = 0, R = 0;
    for (auto q : query) {
        while (R < q.R) flip(ord[++R]);
        while (L > q.L) flip(ord[--L]);
        while (R > q.R) flip(ord[R--]);
        while (L < q.L) flip(ord[L++]);
        if (~q.lca) add(arr[q.lca]);
        // answer query
        if (~q.lca) sub(arr[q.lca]);
    }
}

```

9.10 Mo's Algorithm

- Mo's Algorithm With Addition Only
 - Sort querys same as the normal Mo's algorithm.
 - For each query $[l, r]$:
 - If $l/bk = r/bk$, brute-force.
 - If $l/bk \neq curL/bk$, initialize $curL := (l/bk+1) \cdot blk, curR := curL-1$
 - If $r > curR$, increase $curR$
 - decrease $curL$ to fit l , and then undo after answering
- Mo's Algorithm With Offline Second Time
 - Require: Changing answer \equiv adding $f([l, r], r+1)$.
 - Require: $f([l, r], r+1) = f([1, r], r+1) - f([1, l], r+1)$.
 - Part1: Answer all $f([1, r], r+1)$ first.
 - Part2: Store $curR \rightarrow R$ for $curL$ (reduce the space to $O(N)$), and then answer them by the second offline algorithm.
 - Note: You must do the above symmetrically for the left boundaries.

9.11 Hilbert Curve

```

ll hilbert(int n, int x, int y) {
    ll res = 0;
    for (int s = n / 2; s; s >>= 1) {
        int rx = (x & s) > 0;
        int ry = (y & s) > 0;
        res += s * 1ll * s * ((3 * rx) ^ ry);
        if (ry == 0) {
            if (rx == 1) x = s - 1 - x, y = s - 1 - y;
            swap(x, y);
        }
    }
    return res;
} // n = 2^k

```

9.12 SMAWK

```

bool select(int r, int u, int v){
    // if f(r, v) is better than f(r, u), return true
    return f(r, u) < f(r, v);
}

// For all 2x2 submatrix: (x < y => y is better than x)
// If M[1][0] < M[1][1], M[0][0] < M[0][1]
// If M[1][0] == M[1][1], M[0][0] <= M[0][1]
// M[i][ans[i]] is the best value in the i-th row
vector<int> solve(vector<int> &r, vector<int> &c){
    if (r.size() == 1){
        vector<int> opt(1, 0);
        for (int i = 1; i < c.size(); i++){
            if (select(r[0], c[opt[0]], c[i])){
                opt[0] = i;
            }
        }
        return opt;
    }
    //reduce
    vector<int> st, rev;
    for (int i = 0; i < c.size(); i++){
        while (!st.empty()
               && select(r[st.size() - 1], st.back(), c[i])){
            st.pop_back();
            rev.pop_back();
        }
        if (st.size() < r.size()){
            st.pb(c[i]);
            rev.pb(i);
        }
    }
    //interpolate
}

```

```

vector<int> half;
for (int i = 0; i < r.size(); i += 2){
    half.pb(r[i]);
}
vector<int> ans(r.size());
auto interp = solve(half, st);
for (int i = 0;
     i < interp.size(); i++) ans[i * 2] = interp[i];
for (int i = 1; i < ans.size(); i += 2){
    int s = ans[i - 1], e = (i + 1) < ans.size() ? ans[i + 1] : st.size() - 1;
    ans[i] = s;
    for (int j = s + 1; j <= e; j++){
        if (select(r[i], st[ans[i]], st[j])) ans[i] = j;
    }
}
for (int i = 0; i < ans.size(); i++) ans[i] = rev[ans[i]];
return ans;
}

vector<int> smawk(int n, int m){
    vector<int> r(n), c(m);
    iota(r.begin(), r.end(), 0);
    iota(c.begin(), c.end(), 0);
    return solve(r, c);
}

```

9.13 Simulate Annealing

```

double anneal() {
    mt19937 rng_engine(time(0));
    uniform_real_distribution<double> rng(0, 1);
    const double dT = 0.001;
    // Argument p
    double S_cur = calc(p), S_best = S_cur;
    for (double T = 2000; T > eps; T -= dT) {
        // Modify p to p_prime
        const double S_prime = calc(p_prime);
        const double delta_c = S_prime - S_cur;
        double prob = min((double)1, exp(-delta_c / T));
        if (rng(rng_engine) <= prob)
            S_cur = S_prime, p = p_prime;
        if (S_prime < S_best) // find min
            S_best = S_prime, p_best = p_prime;
    }
    return S_best;
}

```

9.14 Python

```

from decimal import *
from fractions import *
from math import *
from random import *

arr = list(map(int, input().split())) # input
setcontext(Context(
    prec=10, Emax=MAX_EMAX, rounding=ROUND_FLOOR))
Decimal('1.1') / Decimal('0.2')
Fraction(3, 7)
Fraction(Decimal('1.14'))
Fraction('1.2').limit_denominator(4).numerator
Fraction(cos(pi / 3)).limit_denominator()
S = set(), S.add((a, b)), S.remove((a, b)) # set
if not (a, b) in S:
    D = dict(), D[(a, b)] = 1, del D[(a, b)] # dict
    for (a, b) in D.items():
        arr = [randint(1, C) for i in range(N)]
        choice([8, 6, 4, 1]) # random pick one

```

9.15 Matroid

Start from $S = \emptyset$. In each iteration, let

$$\bullet Y_1 = \{x \notin S \mid S \cup \{x\} \in I_1\}$$

$$\bullet Y_2 = \{x \notin S \mid S \cup \{x\} \in I_2\}$$

If there exists $x \in Y_1 \cap Y_2$, insert x into S . Otherwise for each $x \in S, y \notin S$, create edges

$$\bullet x \rightarrow y \text{ if } S - \{x\} \cup \{y\} \in I_1.$$

$$\bullet y \rightarrow x \text{ if } S - \{x\} \cup \{y\} \in I_2.$$

Find a shortest path (with BFS) starting from a vertex in Y_1 and ending at a vertex in Y_2 which doesn't pass through any other vertices in Y_2 , and alternate the path. The size of S will be incremented by 1 in each iteration. For the weighted case, assign weight $w(x)$ to vertex x if $x \in S$ and $-w(x)$ if $x \notin S$. Find the path with the minimum number of edges among all minimum length paths and alternate it.