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1 Basic

1.1 .vimrc

```
set ru nu cin cul sc so=3 ts=4 sw=4 bs=2 ls=2 mouse=a
inoremap {<CR> {<CR>}<C-o>0
map <F7> :w<CR>:!g++
      "%\" -std=c++17 -Wall -Wextra -Wshadow -Wconversion
      -fsanitize=address,undefined -g && ./a.out<CR>
```

1.2 PBDS

```
#include <bits/extc++.h>
using namespace __gnu_pbds;

#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/tree_policy.hpp>
tree<int, null_type, less<int>, rb_tree_tag,
    tree_order_statistics_node_update> bst;
// order_of_key(n): # of elements <= n
// find_by_order(n): 0-indexed

#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/priority_queue.hpp>
__gnu_pbds::priority_queue<int, greater<int>, thin_heap_tag> pq;
```

1.3 pargma

```
#pragma GCC optimize("Ofast,unroll-loops")
#pragma GCC target("avx,avx2,sse,sse2,
    ,sse3,ssse3,sse4,popcnt,abm,mmx,fma,tune=native")
// chrono
::steady_clock::now().time_since_epoch().count()
```

2 Graph

2.1 2SAT/SCC

```
struct SAT { // 0-base
    int low[N], dfn[N], bln[N], n, Time, nScc;
    bool instack[N], istrue[N];
    stack<int> st;
    vector<int> G[N], SCC[N];
    void init(int _n) {
        n = _n; // assert(n * 2 <= N);
        for (int i = 0; i < n + n; ++i) G[i].clear();
    }
    void add_edge(int a, int b) { G[a].emplace_back(b); }
    int rv(int a) {
        if (a >= n) return a - n;
        return a + n;
    }
    void add_clause(int a, int b) {
        add_edge(rv(a), b), add_edge(rv(b), a);
    }
    void dfs(int u) {
        dfn[u] = low[u] = ++Time;
        instack[u] = 1, st.push(u);
        for (int i : G[u])
            if (!dfn[i])
                dfs(i), low[u] = min(low[i], low[u]);
            else if (instack[i] && dfn[i] < dfn[u])
                low[u] = min(low[u], dfn[i]);
        if (low[u] == dfn[u]) {
            int tmp;
            do {
                tmp = st.top(), st.pop();
                instack[tmp] = 0, bln[tmp] = nScc;
            } while (tmp != u);
            ++nScc;
        }
    }
    bool solve() {
        Time = nScc = 0;
        for (int i = 0; i < n + n; ++i)
            SCC[i].clear(), low[i] = dfn[i] = bln[i] = 0;
        for (int i = 0; i < n + n; ++i)
            if (!dfn[i]) dfs(i);
        for (int i = 0; i < n + n; ++i) SCC[bln[i]].emplace_back(i);
        for (int i = 0; i < n; ++i) {
            if (bln[i] == bln[i + n]) return false;
            istrue[i] = bln[i] < bln[i + n];
            istrue[i + n] = !istrue[i];
        }
        return true;
    }
};
```

2.2 BCC Vertex

```
int n, m, dfn[N], low[N], is_cut[N], nbcc = 0, t = 0;
vector<int> g[N], bcc[N], G[2 * N];
stack<int> st;
void tarjan(int p, int lp) {
    dfn[p] = low[p] = ++t;
    st.push(p);
    for (auto i : g[p]) {
        if (!dfn[i]) {
            tarjan(i, p);
            low[p] = min(low[p], low[i]);
            if (dfn[p] <= low[i]) {
                nbcc++;
                is_cut[p] = 1;
                for (int x = 0; x != i; st.pop()) {
                    x = st.top();
                    bcc[nbcc].push_back(x);
                }
                bcc[nbcc].push_back(p);
            }
        } else low[p] = min(low[p], dfn[i]);
    }
}
```

```

}
}
void build() { // [n+1,n+nbcc] cycle, [1,n] vertex
    for (int i = 1; i <= nbcc; i++) {
        for (auto j : bcc[i]) {
            G[i + n].push_back(j);
            G[j].push_back(i + n);
        }
    }
}
}

```

2.3 MinimumMeanCycle

```

/*  $O(V^3)$ 
let dp[i][j] = min length from 1 to j exactly i edges
ans = min (dp[n + 1][u] - dp[i][u]) / (n + 1 - i) */

```

2.4 MaximumCliqueDyn

```

struct MaxClique { // fast when N <= 100
    bitset<N> G[N], cs[N];
    int ans, sol[N], q, cur[N], d[N], n;
    void init(int _n) {
        n = _n;
        for (int i = 0; i < n; ++i) G[i].reset();
    }
    void add_edge(int u, int v) {
        G[u][v] = G[v][u] = 1;
    }
    void pre_dfs(vector<int> &r, int l, bitset<N> mask) {
        if (l < 4) {
            for (int i : r) d[i] = (G[i] & mask).count();
            sort(all(r), [&](int x, int y) { return d[x] > d[y]; });
        }
        vector<int> c(r.size());
        int lft = max(ans - q + 1, 1), rgt = 1, tp = 0;
        cs[1].reset(), cs[2].reset();
        for (int p : r) {
            int k = 1;
            while ((cs[k] & G[p]).any()) ++k;
            if (k > rgt) cs[++rgt + 1].reset();
            cs[k][p] = 1;
            if (k < lft) r[tp++] = p;
        }
        for (int k = lft; k <= rgt; ++k)
            for (int p = cs[k]._Find_first(); p < N; p = cs[k]._Find_next(p))
                r[tp] = p, c[tp] = k, ++tp;
        dfs(r, c, l + 1, mask);
    }
    void dfs(vector<int> &r, vector<int> &c, int l, bitset<N> mask) {
        while (!r.empty()) {
            int p = r.back();
            r.pop_back(), mask[p] = 0;
            if (q + c.back() <= ans) return;
            cur[q++] = p;
            vector<int> nr;
            for (int i : r) if (G[p][i]) nr.emplace_back(i);
            if (!nr.empty()) pre_dfs(nr, l, mask & G[p]);
            else if (q > ans) ans = q, copy_n(cur, q, sol);
            c.pop_back(), --q;
        }
    }
    int solve() {
        vector<int> r(n);
        ans = q = 0, iota(all(r), 0);
        pre_dfs(r, 0, bitset<N>(string(n, '1')));
        return ans;
    }
};

```

2.5 DMST(slow)

```

struct zhu_liu { //  $O(VE)$ 
    struct edge {

```

```

        int u, v;
        ll w;
    };
    vector<edge> E; // 0-base
    int pe[N], id[N], vis[N];
    ll in[N];
    void init() { E.clear(); }
    void add_edge(int u, int v, ll w) {
        if (u != v) E.emplace_back(edge{u, v, w});
    }
    ll build(int root, int n) {
        ll ans = 0;
        for (;;) {
            fill_n(in, n, INF);
            for (int i = 0; i < E.size(); ++i)
                if (E[i].u != E[i].v && E[i].w < in[E[i].v])
                    pe[E[i].v] = i, in[E[i].v] = E[i].w;
            for (int u = 0; u < n; ++u) // no solution
                if (u != root && in[u] == INF) return -INF;
            int cntnode = 0;
            fill_n(id, n, -1), fill_n(vis, n, -1);
            for (int u = 0; u < n; ++u) {
                if (u != root) ans += in[u];
                int v = u;
                while (vis[v] != u && !~id[v] && v != root)
                    vis[v] = u, v = E[pe[v]].u;
                if (v != root && !~id[v]) {
                    for (int x = E[pe[v]].u; x != v;
                        x = E[pe[x]].u)
                        id[x] = cntnode;
                    id[v] = cntnode++;
                }
            }
            if (!cntnode) break; // no cycle
            for (int u = 0; u < n; ++u)
                if (!~id[u]) id[u] = cntnode++;
            for (int i = 0; i < E.size(); ++i) {
                int v = E[i].v;
                E[i].u = id[E[i].u], E[i].v = id[E[i].v];
                if (E[i].u != E[i].v) E[i].w -= in[v];
            }
            n = cntnode, root = id[root];
        }
        return ans;
    }
};

```

2.6 DMST

```

#define rep(i, a, b) for (int i = a; i < (b); ++i)
#define all(x) begin(x), end(x)
#define sz(x) (int)(x).size()
typedef vector<int> vi;
struct RollbackUF {
    vi e;
    vector<pii> st;
    RollbackUF(int n) : e(n, -1) {}
    int size(int x) { return -e[find(x)]; }
    int find(int x) { return e[x] < 0 ? x : find(e[x]); }
    int time() { return sz(st); }
    void rollback(int t) {
        for (int i = time(); i-- > t;)
            e[st[i].first] = st[i].second;
        st.resize(t);
    }
    bool join(int a, int b) {
        a = find(a), b = find(b);
        if (a == b) return false;
        if (e[a] > e[b]) swap(a, b);
        st.push_back({a, e[a]});
        st.push_back({b, e[b]});
        e[a] += e[b];
        e[b] = a;
        return true;
    }
};
struct Edge {

```

```

int a, b;
ll w;
};
struct Node { /// lazy skew heap node
    Edge key;
    Node *l, *r;
    ll delta;
    void prop() {
        key.w += delta;
        if (l) l->delta += delta;
        if (r) r->delta += delta;
        delta = 0;
    }
    Edge top() {
        prop();
        return key;
    }
};
Node *merge(Node *a, Node *b) {
    if (!a || !b) return a ? b;
    a->prop(), b->prop();
    if (a->key.w > b->key.w) swap(a, b);
    swap(a->l, (a->r = merge(b, a->r)));
    return a;
}
void pop(Node *&a) {
    a->prop();
    a = merge(a->l, a->r);
}
pair<ll, vi> dmst(int n, int r, vector<Edge> &g) {
    RollbackUF uf(n);
    vector<Node *> heap(n);
    for (Edge e : g)
        heap[e.b] = merge(heap[e.b], new Node{e});
    ll res = 0;
    vi seen(n, -1), path(n), par(n);
    seen[r] = r;
    vector<Edge> Q(n), in(n, {-1, -1}), comp;
    deque<tuple<int, int, vector<Edge>>> cys;
    rep(s, 0, n) {
        int u = s, qi = 0, w;
        while (seen[u] < 0) {
            if (!heap[u]) return {-1, {}};
            Edge e = heap[u]->top();
            heap[u]->delta -= e.w, pop(heap[u]);
            Q[qi] = e, path[qi++] = u, seen[u] = s;
            res += e.w, u = uf.find(e.a);
            if (seen[u] == s) { /// found cycle, contract
                Node *cyc = 0;
                int end = qi, time = uf.time();
                do cyc = merge(cyc, heap[w = path[--qi]]);
                while (uf.join(u, w));
                u = uf.find(u), heap[u] = cyc, seen[u] = -1;
                cys.push_front({u, time, {&Q[qi], &Q[end]}});
            }
        }
        rep(i, 0, qi) in[uf.find(Q[i].b)] = Q[i];
    }

    for (auto &[u, t, comp] :
        cys) { /// restore sol (optional)
        uf.rollback(t);
        Edge inEdge = in[u];
        for (auto &e : comp) in[uf.find(e.b)] = e;
        in[uf.find(inEdge.b)] = inEdge;
    }
    rep(i, 0, n) par[i] = in[i].a;
    return {res, par};
}

```

2.7 VizingTheorem

```

namespace Vizing { /// Edge coloring
    /// G: coloring adjM
    int C[N][N], G[N][N];
    void clear(int n) {

```

```

        for (int i = 0; i <= n; i++) {
            for (int j = 0; j <= n; j++) C[i][j] = G[i][j] = 0;
        }
    }
    void solve(vector<pii> &E, int n, int m) {
        int X[n] = {}, a;
        auto update = [&](int u) {
            for (X[u] = 1; C[u][X[u]]; X[u]++);
        };
        auto color = [&](int u, int v, int c) {
            int p = G[u][v];
            G[u][v] = G[v][u] = c;
            C[u][c] = v;
            C[v][c] = u;
            C[u][p] = C[v][p] = 0;
            if (p) X[u] = X[v] = p;
            else update(u), update(v);
            return p;
        };
        auto flip = [&](int u, int c1, int c2) {
            int p = C[u][c1];
            swap(C[u][c1], C[u][c2]);
            if (p) G[u][p] = G[p][u] = c2;
            if (!C[u][c1]) X[u] = c1;
            if (!C[u][c2]) X[u] = c2;
            return p;
        };
        for (int i = 1; i <= n; i++) X[i] = 1;
        for (int t = 0; t < E.size(); t++) {
            int u = E[t].first, v0 = E[t].second, v = v0,
                c0 = X[u], c = c0, d;
            vector<pii> L;
            int vst[n] = {};
            while (!G[u][v0]) {
                L.emplace_back(v, d = X[v]);
                if (!C[v][c])
                    for (a = (int)L.size() - 1; a >= 0; a--)
                        c = color(u, L[a].first, c);
                else if (!C[u][d])
                    for (a = (int)L.size() - 1; a >= 0; a--)
                        color(u, L[a].first, L[a].second);
                else if (vst[d]) break;
                else vst[d] = 1, v = C[u][d];
            }
            if (!G[u][v0]) {
                for (; v; v = flip(v, c, d), swap(c, d));
                if (C[u][c0]) {
                    for (a = (int)L.size() - 2;
                        a >= 0 && L[a].second != c; a--)
                        ;
                    for (; a >= 0; a--)
                        color(u, L[a].first, L[a].second);
                } else t--;
            }
        }
    }
} /// namespace Vizing

```

2.8 MinimumCliqueCover

```

struct Clique_Cover { /// 0-base, 0(n2^n)
    int co[1 << N], n, E[N];
    int dp[1 << N];
    void init(int _n) {
        n = _n, fill_n(dp, 1 << n, 0);
        fill_n(E, n, 0), fill_n(co, 1 << n, 0);
    }
    void add_edge(int u, int v) {
        E[u] |= 1 << v, E[v] |= 1 << u;
    }
    int solve() {
        for (int i = 0; i < n; ++i)
            co[1 << i] = E[i] | (1 << i);
        co[0] = (1 << n) - 1;
        dp[0] = (n & 1) * 2 - 1;
        for (int i = 1; i < (1 << n); ++i) {

```

```

    int t = i & -i;
    dp[i] = -dp[i ^ t];
    co[i] = co[i ^ t] & co[t];
}
for (int i = 0; i < (1 << n); ++i)
    co[i] = (co[i] & i) == i;
fwt(co, 1 << n, 1);
for (int ans = 1; ans < n; ++ans) {
    int sum = 0; // probabilistic
    for (int i = 0; i < (1 << n); ++i)
        sum += (dp[i] * co[i]);
    if (sum) return ans;
}
return n;
}
};

```

2.9 CountMaximalClique

```

struct BronKerbosch { // 1-base
    int n, a[N], g[N][N];
    int S, all[N][N], some[N][N], none[N][N];
    void init(int _n) {
        n = _n;
        for (int i = 1; i <= n; ++i)
            for (int j = 1; j <= n; ++j) g[i][j] = 0;
    }
    void add_edge(int u, int v) {
        g[u][v] = g[v][u] = 1;
    }
    void dfs(int d, int an, int sn, int nn) {
        if (S > 1000) return; // pruning
        if (sn == 0 && nn == 0) ++S;
        int u = some[d][0];
        for (int i = 0; i < sn; ++i) {
            int v = some[d][i];
            if (g[u][v]) continue;
            int tsu = 0, tnn = 0;
            copy_n(all[d], an, all[d + 1]);
            all[d + 1][an] = v;
            for (int j = 0; j < sn; ++j)
                if (g[v][some[d][j]])
                    some[d + 1][tsu++] = some[d][j];
            for (int j = 0; j < nn; ++j)
                if (g[v][none[d][j]])
                    none[d + 1][tnn++] = none[d][j];
            dfs(d + 1, an + 1, tsu, tnn);
            some[d][i] = 0, none[d][nn++] = v;
        }
    }
    int solve() {
        iota(some[0], some[0] + n, 1);
        S = 0, dfs(0, 0, n, 0);
        return S;
    }
};

```

2.10 Theorems

$|\text{max independent edge set}| = |V| - |\text{min edge cover}|$
 $|\text{max independent set}| = |V| - |\text{min vertex cover}|$

3 Flow-Matching

3.1 HopcroftKarp

```

struct hopcroftKarp { // 0-based
    bool dfs(int a, int L, vector<vector<int>> &g,
        vector<int> &btoa, vector<int> &A,
        vector<int> &B) {
        if (A[a] != L) return 0;
        A[a] = -1;
        for (int b : g[a])
            if (B[b] == L + 1) {
                B[b] = 0;
                if (btoa[b] == -1 ||
                    dfs(btoa[b], L + 1, g, btoa, A, B))
                    return btoa[b] = a, 1;
            }
    }
};

```

```

return 0;
}

int solve(vector<vector<int>> &g, int m) {
    int res = 0;
    vector<int> btoa(-1, m), A(g.size()),
        B(btoa.size()), cur, next;
    for (;;) {
        fill(all(A), 0), fill(all(B), 0);
        cur.clear();
        for (int a : btoa)
            if (a != -1) A[a] = -1;
        for (int a = 0; a < g.size(); a++)
            if (A[a] == 0) cur.push_back(a);
        /// Find all layers using bfs.
        for (int lay = 1;; lay++) {
            bool islast = 0;
            next.clear();
            for (int a : cur)
                for (int b : g[a]) {
                    if (btoa[b] == -1) {
                        B[b] = lay;
                        islast = 1;
                    } else if (btoa[b] != a && !B[b]) {
                        B[b] = lay;
                        next.push_back(btoa[b]);
                    }
                }
            if (islast) break;
            if (next.empty()) return res;
            for (int a : next) A[a] = lay;
            cur.swap(next);
        }
        /// Use DFS to scan for augmenting paths.
        for (int a = 0; a < g.size(); a++)
            res += dfs(a, 0, g, btoa, A, B);
    }
};

```

3.2 KM

```

struct KM { // 0-base
    ll w[N][N], hl[N], hr[N], slk[N];
    int fl[N], fr[N], pre[N], qu[N], ql, qr, n;
    bool vl[N], vr[N];
    void init(int _n) {
        n = _n;
        for (int i = 0; i < n; ++i)
            fill_n(w[i], n, -INF);
    }
    void add_edge(int a, int b, ll wei) {
        w[a][b] = wei;
    }
    bool Check(int x) {
        if (vl[x] = 1, ~fl[x])
            return vr[qu[qr++]] = fl[x] = 1;
        while (~x) swap(x, fr[fl[x] = pre[x]]);
        return 0;
    }
    void bfs(int s) {
        fill_n(slk,
            , n, INF), fill_n(vl, n, 0), fill_n(vr, n, 0);
        ql = qr = 0, qu[qr++] = s, vr[s] = 1;
        for (ll d;;) {
            while (ql < qr)
                for (int x = 0, y = qu[ql++]; x < n; ++x)
                    if (!vl[x] && slk
                        [x] >= (d = hl[x] + hr[y] - w[x][y])) {
                        if (pre[x] = y, d) slk[x] = d;
                        else if (!Check(x)) return;
                    }
            d = INF;
            for (int x = 0; x < n; ++x)
                if (!vl[x] && d > slk[x]) d = slk[x];
            for (int x = 0; x < n; ++x) {

```

```

    if (vl[x]) hl[x] += d;
    else slk[x] -= d;
    if (vr[x]) hr[x] -= d;
}
for (int x = 0; x < n; ++x)
    if (!vl[x] && !slk[x] && !Check(x)) return;
}
ll solve() {
    fill_n(fl,
        , n, -1), fill_n(fr, n, -1), fill_n(hr, n, 0);
    for (int i = 0; i < n; ++i)
        hl[i] = *max_element(w[i], w[i] + n);
    for (int i = 0; i < n; ++i) bfs(i);
    ll res = 0;
    for (int i = 0; i < n; ++i) res += w[i][fl[i]];
    return res;
}
};

```

3.3 MCMF

```

struct MinCostMaxFlow { // 0-base
    struct Edge {
        ll from, to, cap, flow, cost, rev;
    } *past[N];
    vector<Edge> G[N];
    int inq[N], n, s, t;
    ll dis[N], up[N], pot[N];
    bool BellmanFord() {
        fill_n(dis, n, INF), fill_n(inq, n, 0);
        queue<int> q;
        auto relax = [&](int u, ll d, ll cap, Edge *e) {
            if (cap > 0 && dis[u] > d) {
                dis[u] = d, up[u] = cap, past[u] = e;
                if (!inq[u]) inq[u] = 1, q.push(u);
            }
        };
        relax(s, 0, INF, 0);
        while (!q.empty()) {
            int u = q.front();
            q.pop(), inq[u] = 0;
            for (auto &e : G[u]) {
                ll d2 = dis[u] + e.cost + pot[u] - pot[e.to];
                relax(e.to, d2, min(up[u], e.cap - e.flow), &e);
            }
        }
        return dis[t] != INF;
    }
    void solve(int _s
        , int _t, ll &flow, ll &cost, bool neg = true) {
        s = _s, t = _t, flow = 0, cost = 0;
        if (neg) BellmanFord(), copy_n(dis, n, pot);
        for (; BellmanFord(); copy_n(dis, n, pot)) {
            for (int
                i = 0; i < n; ++i) dis[i] += pot[i] - pot[s];
            flow += up[t], cost += up[t] * dis[t];
            for (int i = t; past[i]; i = past[i]->from) {
                auto &e = *past[i];
                e.flow += up[t], G[e.to][e.rev].flow -= up[t];
            }
        }
    }
    void init(int _n) {
        n = _n, fill_n(pot, n, 0);
        for (int i = 0; i < n; ++i) G[i].clear();
    }
    void add_edge(ll a, ll b, ll cap, ll cost) {
        G[a].emplace_back
            (Edge{a, b, cap, 0, cost, (ll)G[b].size()});
        G[b].emplace_back
            (Edge{b, a, 0, 0, -cost, (ll)G[a].size() - 1});
    }
};

```

3.4 GeneralGraphMatching

```

struct Matching { // 0-base
    queue<int> q; int n;
    vector<int> fa, s, vis, pre, match;
    vector<vector<int>> G;
    int Find(int u)
    { return u == fa[u] ? u : fa[u] = Find(fa[u]); }
    int LCA(int x, int y) {
        static int tk = 0; tk++; x = Find(x); y = Find(y);
        for (; swap(x, y)) if (x != n) {
            if (vis[x] == tk) return x;
            vis[x] = tk;
            x = Find(pre[match[x]]);
        }
    }
    void Blossom(int x, int y, int l) {
        for (; Find(x) != l; x = pre[y]) {
            pre[x] = y, y = match[x];
            if (s[y] == 1) q.push(y), s[y] = 0;
            for (int z: {x, y}) if (fa[z] == z) fa[z] = l;
        }
    }
    bool Bfs(int r) {
        iota(all(fa), 0); fill(all(s), -1);
        q = queue<int>(); q.push(r); s[r] = 0;
        for (; !q.empty(); q.pop()) {
            for (int x = q.front(); int u : G[x])
                if (s[u] == -1) {
                    if (pre[u] = x, s[u] = 1, 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;
    }
    Matching(int _n) : n(_n), fa(n + 1), s(n + 1), vis
        (n + 1), pre(n + 1, n), match(n + 1, n), G(n) {}
    void add_edge(int u, int v)
    { G[u].emplace_back(v), G[v].emplace_back(u); }
    int solve() {
        int ans = 0;
        for (int x = 0; x < n; ++x)
            if (match[x] == n) ans += Bfs(x);
        return ans;
    } // match[x] == n means not matched
};

```

3.5 MaxWeightMaching

```

#define rep(i, l, r) for (int i = (l); i <= (r); ++i)
struct WeightGraph { // 1-based
    struct edge {
        int u, v, w;
    };
    int n, nx;
    vector<int> lab;
    vector<vector<edge>> g;
    vector<int> slack, match, st, pa, S, vis;
    vector<vector<int>> flo, flo_from;
    queue<int> q;
    WeightGraph(int n_)
        : n(n_), nx(n * 2), lab(nx + 1),
          g(nx + 1, vector<edge>(nx + 1)), slack(nx + 1),
          flo(nx + 1), flo_from(nx + 1, vector(n + 1, 0)) {
        match = st = pa = S = vis = slack;
        rep(u, 1, n) rep(v, 1, n) g[u][v] = {u, v, 0};
    }
    int ED(edge e) {
        return lab[e.u] + lab[e.v] - g[e.u][e.v].w * 2;
    }
};

```

```

}
void update_slack(int u, int x, int &s) {
    if (!s || ED(g[u][x]) < ED(g[s][x])) s = 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, slack[x]);
}
void q_push(int x) {
    if (x <= n) q.push(x);
    else
        for (int y : flo[x]) q.push(y);
}
void set_st(int x, int b) {
    st[x] = b;
    if (x > n)
        for (int y : flo[x]) set_st(y, b);
}
vector<int> split_flo(auto &f, int xr) {
    auto it = find(ALL(f), xr);
    if (auto pr = it - f.begin(); pr % 2 == 1)
        reverse(1 + ALL(f), it = f.end() - pr);
    auto res = vector(f.begin(), it);
    return f.erase(f.begin(), it), res;
}
void set_match(int u, int v) {
    match[u] = g[u][v].v;
    if (u <= n) return;
    int xr = flo_from[u][g[u][v].u];
    auto &f = flo[u], z = split_flo(f, xr);
    rep(i, 0, (int)z.size() - 1)
        set_match(z[i], z[i ^ 1]);
    set_match(xr, v);
    f.insert(f.end(), all(z));
}
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 lca(int u, int v) {
    static int t = 0;
    ++t;
    for (++t; u || v; swap(u, v))
        if (u) {
            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 o, int v) {
    int b = find(n + 1 + all(st), 0) - begin(st);
    lab[b] = 0, S[b] = 0;
    match[b] = match[o];
    vector<int> f = {o};
    for (int x = u, y; x != o; x = st[pa[y]])
        f.emplace_back(x),
        f.emplace_back(y = st[match[x]]), q_push(y);
    reverse(1 + all(f));
    for (int x = v, y; x != o; x = st[pa[y]])
        f.emplace_back(x),
        f.emplace_back(y = st[match[x]]), q_push(y);
    flo[b] = f;
    set_st(b, b);
    for (int x = 1; x <= nx; ++x)
        g[b][x].w = g[x][b].w = 0;
    fill(all(flo_from[b]), 0);

    for (int xs : flo[b]) {
        for (int x = 1; x <= nx; ++x)
            if (g[b][x].w == 0 ||
                ED(g[xs][x]) < ED(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 (int x : flo[b]) set_st(x, x);
    int xr = flo_from[b][g[b][pa[b]].u], xs = -1;
    for (int x : split_flo(flo[b], xr)) {
        if (xs == -1) {
            xs = x;
            continue;
        }
        pa[xs] = g[x][xs].u;
        S[xs] = 1, S[x] = 0;
        slack[xs] = 0;
        set_slack(x);
        q_push(x);
        xs = -1;
    }
    for (int x : flo[b])
        if (x == xr) S[x] = 1, pa[x] = pa[b];
        else S[x] = -1, set_slack(x);
    st[b] = 0;
}
bool on_found_edge(const edge &e) {
    if (int u = st[e.u], v = st[e.v]; S[v] == -1) {
        int nu = st[match[v]];
        pa[v] = e.u;
        S[v] = 1;
        slack[v] = slack[nu] = 0;
        S[nu] = 0;
        q_push(nu);
    } else if (S[v] == 0) {
        if (int o = lca(u, v)) add_blossom(u, o, v);
        else return augment(u, v), augment(v, u), true;
    }
    return false;
}
bool matching() {
    fill(all(S), -1), fill(all(slack), 0);
    q = queue<int>();
    for (int x = 1; x <= nx; ++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 (ED(g[u][v]) != 0)
                        update_slack(u, st[v], slack[st[v]]);
                    else if (on_found_edge(g[u][v]))
                        return true;
                }
        }
        int d = INF;
        for (int b = n + 1; b <= nx; ++b)
            if (st[b] == b && S[b] == 1)
                d = min(d, lab[b] / 2);
        for (int x = 1; x <= nx; ++x)
            if (int s = slack[x];
                st[x] == x && s && S[x] <= 0)
                d = min(d, ED(g[s][x]) / (S[x] + 2));
        for (int u = 1; u <= n; ++u)
            if (S[st[u]] == 1) lab[u] += d;
            else if (S[st[u]] == 0) {

```



```

    if (lab[u] <= d) return false;
    lab[u] -= d;
}
rep(b, n + 1, nx) if (st[b] == b && S[b] >= 0)
    lab[b] += d * (2 - 4 * S[b]);
for (int x = 1; x <= nx; ++x)
    if (int s = slack[x]; st[x] == x && s &&
        st[s] != x && ED(g[s][x]) == 0)
        if (on_found_edge(g[s][x])) return true;
for (int b = n + 1; b <= nx; ++b)
    if (st[b] == b && S[b] == 1 && lab[b] == 0)
        expand_blossom(b);
}
return false;
}
pair<ll, int> solve() {
    fill(all(match), 0);
    rep(u, 0, n) st[u] = u, flo[u].clear();
    int w_max = 0;
    rep(u, 1, n) rep(v, 1, n) {
        flo_from[u][v] = (u == v ? u : 0);
        w_max = max(w_max, g[u][v].w);
    }
    fill(all(lab), w_max);
    int n_matches = 0;
    ll tot_weight = 0;
    while (matching()) ++n_matches;
    rep(u, 1, n) if (match[u] && match[u] < u)
        tot_weight += g[u][match[u]].w;
    return make_pair(tot_weight, n_matches);
}
void add_edge(int u, int v, int w) {
    g[u][v].w = g[v][u].w = w;
}
};

```

3.6 GlobalMinCut

```

#undef INF
struct SW{ // global min cut,  $O(V^3)$ 
    #define REP for (int i = 0; i < n; ++i)
    static const int MXN = 514, INF = 2147483647;
    int vst[MXN], edge[MXN][MXN], wei[MXN];
    void init(int n) {
        REP fill_n(edge[i], n, 0);
    }
    void addEdge(int u, int v, int w){
        edge[u][v] += w; edge[v][u] += w;
    }
    int search(int &s, int &t, int n){
        fill_n(vst, n, 0), fill_n(wei, n, 0);
        s = t = -1;
        int mx, cur;
        for (int j = 0; j < n; ++j) {
            mx = -1, cur = 0;
            REP if (wei[i] > mx) cur = i, mx = wei[i];
            vst[cur] = 1, wei[cur] = -1;
            s = t; t = cur;
            REP if (!vst[i]) wei[i] += edge[cur][i];
        }
        return mx;
    }
    int solve(int n) {
        int res = INF;
        for (int x, y; n > 1; n--){
            res = min(res, search(x, y, n));
            REP edge[i][x] = (edge[x][i] += edge[y][i]);
            REP {
                edge[y][i] = edge[n - 1][i];
                edge[i][y] = edge[i][n - 1];
            } // edge[y][y] = 0;
        }
        return res;
    }
}
}

```

3.7 BoundedFlow(Dinic)

```

struct BoundedFlow { //  $\Theta$ -base
    struct edge {
        int to, cap, flow, rev;
    };
    vector<edge> G[N];
    int n, s, t, dis[N], cur[N], cnt[N];
    void init(int _n) {
        n = _n;
        for (int i = 0; i < n + 2; ++i)
            G[i].clear(), cnt[i] = 0;
    }
    void add_edge(int u, int v, int lcap, int rcap) {
        cnt[u] -= lcap, cnt[v] += lcap;
        G[u].emplace_back
            (edge{v, rcap, lcap, (int)G[v].size()});
        G[v].emplace_back
            (edge{u, 0, 0, (int)G[u].size() - 1});
    }
    void add_edge(int u, int v, int cap) {
        G[u].emplace_back
            (edge{v, cap, 0, (int)G[v].size()});
        G[v].emplace_back
            (edge{u, 0, 0, (int)G[u].size() - 1});
    }
    int dfs(int u, int cap) {
        if (u == t || !cap) return cap;
        for (int &i = cur[u]; i < G[u].size(); ++i) {
            edge &e = G[u][i];
            if (dis[e.to] == dis[u] + 1 && e.cap != e.flow) {
                int df = dfs(e.to, min(e.cap - e.flow, cap));
                if (df) {
                    e.flow += df, G[e.to][e.rev].flow -= df;
                    return df;
                }
            }
        }
        dis[u] = -1;
        return 0;
    }
    bool bfs() {
        fill_n(dis, n + 3, -1);
        queue<int> q;
        q.push(s), dis[s] = 0;
        while (!q.empty()) {
            int u = q.front();
            q.pop();
            for (edge &e : G[u])
                if (!dis[e.to] && e.flow != e.cap)
                    q.push(e.to), dis[e.to] = dis[u] + 1;
        }
        return dis[t] != -1;
    }
    int maxflow(int _s, int _t) {
        s = _s, t = _t;
        int flow = 0, df;
        while (bfs()) {
            fill_n(cur, n + 3, 0);
            while ((df = dfs(s, INF))) flow += df;
        }
        return flow;
    }
    bool solve() {
        int sum = 0;
        for (int i = 0; i < n; ++i)
            if (cnt[i] > 0)
                add_edge(n + 1, i, cnt[i]), sum += cnt[i];
            else if (cnt[i] < 0) add_edge(i, n + 2, -cnt[i]);
        if (sum != maxflow(n + 1, n + 2)) sum = -1;
        for (int i = 0; i < n; ++i)
            if (cnt[i] > 0)
                G[n + 1].pop_back(), G[i].pop_back();
            else if (cnt[i] < 0)
                G[i].pop_back(), G[n + 2].pop_back();
        return sum != -1;
    }
}

```

```

int solve(int _s, int _t) {
    add_edge(_t, _s, INF);
    if (!solve()) return -1; // invalid flow
    int x = G[_t].back().flow;
    return G[_t].pop_back(), G[_s].pop_back(), x;
}
};

```

3.8 GomoryHuTree

```

MaxFlow Dinic;
int g[N];
void GomoryHu(int n) { // 0-base
    fill_n(g, n, 0);
    for (int i = 1; i < n; ++i) {
        Dinic.reset();
        add_edge(i, g[i], Dinic.maxflow(i, g[i]));
        for (int j = i + 1; j <= n; ++j)
            if (g[j] == g[i] && ~Dinic.dis[j])
                g[j] = i;
    }
}

```

3.9 MinCostCirculation

```

struct MinCostCirculation { // 0-base
    struct Edge {
        ll from, to, cap, fcap, flow, cost, rev;
    } *past[N];
    vector<Edge> G[N];
    ll dis[N], inq[N], n;
    void BellmanFord(int s) {
        fill_n(dis, n, INF), fill_n(inq, n, 0);
        queue<int> q;
        auto relax = [&](int u, ll d, Edge *e) {
            if (dis[u] > d) {
                dis[u] = d, past[u] = e;
                if (!inq[u]) inq[u] = 1, q.push(u);
            }
        };
        relax(s, 0, 0);
        while (!q.empty()) {
            int u = q.front();
            q.pop(), inq[u] = 0;
            for (auto &e : G[u])
                if (e.cap > e.flow)
                    relax(e.to, dis[u] + e.cost, &e);
        }
    }
    void try_edge(Edge &cur) {
        if (cur.cap > cur.flow) return ++cur.cap, void();
        BellmanFord(cur.to);
        if (dis[cur.from] + cur.cost < 0) {
            ++cur.flow, --G[cur.to][cur.rev].flow;
            for (int i = cur.from; past[i]; i = past[i]->from) {
                auto &e = *past[i];
                ++e.flow, --G[e.to][e.rev].flow;
            }
        }
        ++cur.cap;
    }
    void solve(int mxlg) {
        for (int b = mxlg; b >= 0; --b) {
            for (int i = 0; i < n; ++i)
                for (auto &e : G[i])
                    e.cap *= 2, e.fcap *= 2;
            for (int i = 0; i < n; ++i)
                for (auto &e : G[i])
                    if (e.fcap >> b & 1)
                        try_edge(e);
        }
    }
    void init(int _n) { n = _n;
        for (int i = 0; i < n; ++i) G[i].clear();
    }
    void add_edge(ll a, ll b, ll cap, ll cost) {

```

```

        G[a].emplace_back(Edge{a, b,
            0, cap, 0, cost, (ll)G[b].size() + (a == b)});
        G[b].emplace_back(Edge
            {b, a, 0, 0, 0, -cost, (ll)G[a].size() - 1});
    }
} mcmf; // O(VE * ElogC)

```

3.10 FlowModelsBuilding

- 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 with 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.

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

4 Data Structure

4.1 LCT

```
#define ls(x) Tree[x].son[0]
#define rs(x) Tree[x].son[1]
#define fa(x) Tree[x].fa
const int maxn = 600010;
struct node {
    int son[2], Min, id, fa, lazy;
} Tree[maxn];
int n, m, q, w[maxn], Min;
struct Node {
    int u, v, w;
} a[maxn];
inline bool IsRoot(int x) {
    return (ls(fa(x)) == x || rs(fa(x)) == x) ? false : true;
}
inline void PushUp(int x) {
    Tree[x].Min = w[x], Tree[x].id = x;
    if (ls(x) && Tree[ls(x)].Min < Tree[x].Min) {
        Tree[x].Min = Tree[ls(x)].Min;
        Tree[x].id = Tree[ls(x)].id;
    }
    if (rs(x) && Tree[rs(x)].Min < Tree[x].Min) {
        Tree[x].Min = Tree[rs(x)].Min;
        Tree[x].id = Tree[rs(x)].id;
    }
}
inline void Update(int x) {
    Tree[x].lazy ^= 1;
    swap(ls(x), rs(x));
}
inline void PushDown(int x) {
    if (!Tree[x].lazy) return;
    if (ls(x)) Update(ls(x));
    if (rs(x)) Update(rs(x));
    Tree[x].lazy = 0;
}
inline void Rotate(int x) {
    int y = fa(x), z = fa(y), k = rs(y) == x,
        w = Tree[x].son[!k];
    if (!IsRoot(y)) Tree[z].son[rs(z) == y] = x;
    fa(x) = z, fa(y) = x;
    if (w) fa(w) = y;
    Tree[x].son[!k] = y, Tree[y].son[k] = w;
    PushUp(y);
}
inline void Splay(int x) {
    stack<int> Stack;
    int y = x, z;
    Stack.push(y);
    while (!IsRoot(y)) Stack.push(y = fa(y));
    while (!Stack.empty())
        PushDown(Stack.top()), Stack.pop();
    while (!IsRoot(x)) {
        y = fa(x), z = fa(y);
        if (!IsRoot(y))
            Rotate((ls(y) == x) ^ (ls(z) == y) ? x : y);
        Rotate(x);
    }
    PushUp(x);
}
inline void Access(int root) {
    for (int x = 0; root; x = root, root = fa(root))
        Splay(root), rs(root) = x, PushUp(root);
}
inline void MakeRoot(int x) {
    Access(x), Splay(x), Update(x);
}
inline int FindRoot(int x) {
    Access(x), Splay(x);
    while (ls(x)) x = ls(x);
    return Splay(x), x;
}
```

```
inline void Link(int u, int v) {
    MakeRoot(u);
    if (FindRoot(v) != u) fa(u) = v;
}
inline void Cut(int u, int v) {
    MakeRoot(u);
    if (FindRoot(v) != u || fa(v) != u || ls(v)) return;
    fa(v) = rs(u) = 0;
}
inline void Split(int u, int v) {
    MakeRoot(u), Access(v), Splay(v);
}
inline bool Check(int u, int v) {
    return MakeRoot(u), FindRoot(v) == u;
}
inline int LCA(int root, int u, int v) {
    MakeRoot(root), Access(u), Access(v), Splay(u);
    if (!fa(u)) {
        Access(u), Splay(v);
        return fa(v);
    }
    return fa(u);
}
/* ETT
每次進入節點和走邊都放入一次共 3n - 2
node(u) 表示進入節點 u 放入 treap 的位置
edge(u, v) 表示 u -> v 的邊放入 treap 的位置 (push v)
Makeroot u :
    L1 = [begin, node(u) - 1], L2 = [node(u), end]
    -> L2 + L1
Insert u, v :
    Tu -> L1 = [begin, node(u) - 1], L2 = [node(u), end]
    Tv -> L3 = [begin, node(v) - 1], L4 = [node(v), end]
    -> L2 + L1 + edge(u, v) + L4 + L3 + edge(v, u)
Delete u, v :
    maybe need swap u, v
    T -> L1 + edge(u, v) + L2 + edge(v, u) + L3
    -> L1 + L3, L2
*/
```

5 String

5.1 KMP

```
int KMP(string s, string t) {
    t = " " + t; // consistency with ACa
    int n = t.size(), ans = 0;
    vector<int> f(t.size(), 0);
    f[0] = -1;
    for (int i = 1, j = -1; i < t.size(); i++) {
        while (j >= 0 && t[j + 1] != t[i])
            j = f[j];
        f[i] = ++j;
    }
    for (int i = 0, j = 0; i < s.size(); i++) {
        while (j >= 0 && t[j + 1] != s[i])
            j = f[j];
        if (++j + 1 == t.size()) ans++, j = f[j];
    }
    return ans;
}
```

5.2 Z

```
int Z[1000006];
void z(string s) {
    for (int i = 1, mx = 0; i < s.size(); i++) {
        if (i < Z[mx] + mx)
            Z[i] = min(Z[mx] - i + mx, Z[i - mx]);
        while (
            Z[i] + i < s.size() && s[i + Z[i]] == s[Z[i]])
            Z[i]++;
        if (Z[i] + i > Z[mx] + mx) mx = i;
    }
}
```

5.3 Manacher

```
int man[2000006];
int manacher(string s) {
    string t;
    for (int i = 0; i < s.size(); i++) {
        if (i) t.push_back('$');
        t.push_back(s[i]);
    }
    int mx = 0, ans = 0;
    for (int i = 0; i < t.size(); i++) {
        man[i] = 1;
        man[i] = min(man[mx] + mx - i, man[2 * mx - i]);
        while (man[i] + i < t.size() && i - man[i] >= 0 &&
            t[i + man[i]] == t[i - man[i]])
            man[i]++;
        if (i + man[i] > mx + man[mx]) mx = i;
    }
    for (int i = 0; i < t.size(); i++)
        ans = max(ans, man[i] - 1);
    return ans;
}
```

5.4 SuffixArray

```
vector<int> sa, cnt, rk, tmp, lcp;
void SA(string s) {
    int n = s.size();
    sa.resize(n), cnt.resize(n), rk.resize(n),
    tmp.resize(n);
    iota(all(sa), 0);
    sort(all(sa),
        [&](int i, int j) { return s[i] < s[j]; });
    rk[0] = 0;
    for (int i = 1; i < n; i++)
        rk[sa[i]] =
            rk[sa[i - 1]] + (s[sa[i - 1]] != s[sa[i]]);
    for (int k = 1; k <= n; k <= 1) {
        fill(all(cnt), 0);
        for (int i = 0; i < n; i++)
            cnt[rk[(sa[i] - k + n) % n]]++;
        for (int i = 1; i < n; i++) cnt[i] += cnt[i - 1];
        for (int i = n - 1; i >= 0; i--)
            tmp[--cnt[rk[(sa[i] - k + n) % n]]] =
                (sa[i] - k + n) % n;
        sa.swap(tmp);
        tmp[sa[0]] = 0;
        for (int i = 1; i < n; i++)
            tmp[sa[i]] = tmp[sa[i - 1]] +
                (rk[sa[i - 1]] != rk[sa[i]] ||
                 rk[(sa[i - 1] + k) % n] !=
                 rk[(sa[i] + k) % n]);
        rk.swap(tmp);
    }
}

void LCP(string s) {
    int n = s.size(), k = 0;
    lcp.resize(n);
    for (int i = 0; i < n; i++)
        if (rk[i] == 0) lcp[rk[i]] = 0;
        else {
            if (k) k--;
            int j = sa[rk[i] - 1];
            while (
                i + k < n && j + k < n && s[i + k] == s[j + k])
                k++;
            lcp[rk[i]] = k;
        }
}
```

5.5 SAIS

```
namespace sfx {
    bool _t[N * 2];
    int SA[N * 2], H[N], RA[N];
    int _s[N * 2], _c[N * 2], x[N], _p[N], _q[N * 2];
}
```

```
// zero based, string content MUST > 0
// SA[i]: SA[i]-th
// suffix is the i-th lexicographically smallest suffix.
// H[i]: longest
// common prefix of suffix SA[i] and suffix SA[i - 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]]++] = 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)
        t[i] = (
            s[i] == s[i + 1] ? t[i + 1] : 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++] = 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(nsa, 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 mkhei(int n) {
    for (int i = 0, j = 0; i < n; ++i) {
        if (RA[i])
            for (; _s[i + j] == _s[SA[RA[i] - 1] + j]; ++j);
        H[RA[i]] = j, j = max(0, j - 1);
    }
}
void build(int *s, int n) {
    copy_n(s, n, _s), _s[n] = 0;
    sais(_s, SA, _p, _q, _t, _c, n + 1, 256);
    copy_n(SA + 1, n, SA);
    for (int i = 0; i < n; ++i) RA[SA[i]] = i;
    mkhei(n);
}
```

5.6 ACAutomaton

```
#define sumS 500005
#define sigma 26
#define base 'a'
struct AhoCorasick {
    int ch[sumS][sigma] = {{}}, f[sumS] = {-1},
        tag[sumS], mv[sumS][sigma], jump[sumS],
        cnt[sumS];
    int idx = 0, t = -1;
    vector<int> E[sumS], q;
}
```

```

pii o[sumS];
int insert(string &s, int t) {
    int j = 0;
    for (int i = 0; i < (int)s.size(); i++) {
        if (!ch[j][s[i] - base])
            ch[j][s[i] - base] = ++idx;
        j = ch[j][s[i] - base];
    }
    tag[j] = 1;
    return j;
}
int next(int u, int c) {
    return u < 0 ? 0 : mv[u][c];
}
void dfs(int u) {
    o[u].F = ++t;
    for (auto v : E[u]) dfs(v);
    o[u].S = t;
}
void build() {
    int k = -1;
    q.emplace_back(0);
    while (++k < q.size()) {
        int u = q[k];
        for (int v = 0; v < sigma; v++) {
            if (ch[u][v]) {
                f[ch[u][v]] = next(f[u], v);
                q.emplace_back(ch[u][v]);
            }
            mv[u][v] =
                (ch[u][v] ? ch[u][v] : next(f[u], v));
        }
        if (u) jump[u] = (tag[f[u]] ? f[u] : jump[f[u]]);
    }
    reverse(q.begin(), q.end());
    for (int i = 1; i <= idx; i++)
        E[f[i]].emplace_back(i);
    dfs(0);
}
void match(string &s) {
    fill(cnt, cnt + idx + 1, 0);
    for (int i = 0, j = 0; i < (int)s.size(); i++)
        cnt[j = next(j, s[i] - base)]++;

    for (int i : q)
        if (f[i] > 0) cnt[f[i]] += cnt[i];
}
} ac;

```

5.7 MinRotation

```

int mincyc(string s) {
    int n = s.size();
    s = s + s;
    int i = 0, ans = 0;
    while (i < n) {
        ans = i;
        int j = i + 1, k = i;
        while (j < s.size() && s[j] >= s[k]) {
            k = (s[j] > s[k] ? i : k + 1);
            ++j;
        }
        while (i <= k) i += j - k;
    }
    return ans;
}

```

5.8 ExtSAM

```

#define CNUM 26
struct exSAM {
    int len[N * 2], link[N * 2]; // maxlength, suflink
    int next[N * 2][CNUM], tot; // [0, tot), root = 0
    int lenSorted[N * 2]; // topo. order
    int cnt[N * 2]; // occurence
    int newnode() {
        fill_n(next[tot], CNUM, 0);
    }
}

```

```

len[tot] = cnt[tot] = link[tot] = 0;
return tot++;
}
void init() { tot = 0, newnode(), link[0] = -1; }
int insertSAM(int last, int c) {
    int cur = next[last][c];
    len[cur] = len[last] + 1;
    int p = link[last];
    while (p != -1 && !next[p][c])
        next[p][c] = cur, p = link[p];
    if (p == -1) return link[cur] = 0, cur;
    int q = next[p][c];
    if (len
        [p] + 1 == len[q]) return link[cur] = q, cur;
    int clone = newnode();
    for (int i = 0; i < CNUM; ++i)
        next[
            clone][i] = len[next[q][i]] ? next[q][i] : 0;
    len[clone] = len[p] + 1;
    while (p != -1 && next[p][c] == q)
        next[p][c] = clone, p = link[p];
    link[link[cur] = clone] = link[q];
    link[q] = clone;
    return cur;
}
void insert(const string &s) {
    int cur = 0;
    for (auto ch : s) {
        int &nxt = next[cur][int(ch - 'a')];
        if (!nxt) nxt = newnode();
        cnt[cur = nxt] += 1;
    }
}
void build() {
    queue<int> q;
    q.push(0);
    while (!q.empty()) {
        int cur = q.front();
        q.pop();
        for (int i = 0; i < CNUM; ++i)
            if (next[cur][i])
                q.push(insertSAM(cur, i));
    }
    vector<int> lc(tot);
    for (int i = 1; i < tot; ++i) ++lc[len[i]];
    partial_sum(all(lc), lc.begin());
    for (int i
        = 1; i < tot; ++i) lenSorted[--lc[len[i]]] = i;
}
void solve() {
    for (int i = tot - 2; i >= 0; --i)
        cnt[link[lenSorted[i]]] += cnt[lenSorted[i]];
}
};

```

5.9 PalindromeTree

```

struct palindromic_tree {
    struct node {
        int next[26], fail, len;
        int cnt, num; // cnt: appear times, num: number of
            // pal. suf.
        node(int l = 0) : fail(0), len(l), cnt(0), num(0) {
            for (int i = 0; i < 26; ++i) next[i] = 0;
        }
    };
    vector<node> St;
    vector<char> s;
    int last, n;
    palindromic_tree() : St(2), last(1), n(0) {
        St[0].fail = 1, St[1].len = -1, s.emplace_back(-1);
    }
    inline void clear() {
        St.clear(), s.clear(), last = 1, n = 0;
        St.emplace_back(0), St.emplace_back(-1);
        St[0].fail = 1, s.emplace_back(-1);
    }
}

```

```

}
inline int get_fail(int x) {
    while (s[n - St[x].len - 1] != s[n])
        x = St[x].fail;
    return x;
}
inline void add(int c) {
    s.push_back(c -> 'a'), ++n;
    int cur = get_fail(last);
    if (!St[cur].next[c]) {
        int now = St.size();
        St.emplace_back(St[cur].len + 2);
        St[now].fail =
            St[get_fail(St[cur].fail)].next[c];
        St[cur].next[c] = now;
        St[now].num = St[St[now].fail].num + 1;
    }
    last = St[cur].next[c], ++St[last].cnt;
}
inline void count() { // counting cnt
    auto i = St.rbegin();
    for (; i != St.rend(); ++i) {
        St[i->fail].cnt += i->cnt;
    }
}
inline int size() { // The number of diff. pal.
    return (int)St.size() - 2;
}
};

```

6 Number Theory

6.1 Primes

```

12721 13331 14341 75577 123457 222557 556679 999983
1097774749 1076767633 100102021 999997771 1001010013
1000512343 987654361 999991231 999888733 98789101
987777733 999991921 1010101333 1010102101 1000000000039
100000000000037 2305843009213693951 4611686018427387847
9223372036854775783 18446744073709551557

```

6.2 ExtGCD

```

// beware of negative numbers!
void extgcd(ll a, ll b, ll c, ll &x, ll &y) {
    if (b == 0) x = c / a, y = 0;
    else {
        extgcd(b, a % b, c, y, x);
        y -= x * (a / b);
    }
}
// |x| <= b/2, |y| <= a/2

```

6.3 FloorCeil

```

int floor(int a, int b)
{ return a / b - (a % b && (a < 0) ^ (b < 0)); }
int ceil(int a, int b)
{ return a / b + (a % b && (a < 0) ^ (b > 0)); }

```

6.4 FloorSum

```

ll floorsum(ll A, ll B, ll C, ll N) {
    if (A == 0) return (N + 1) * (B / C);
    if (A > C || B > C)
        return (N + 1) * (B / C) +
            N * (N + 1) / 2 * (A / C) +
            floorsum(A % C, B % C, C, N);
    ll M = (A * N + B) / C;
    return N * M - floorsum(C, C - B - 1, A, M - 1);
} // \sum_{i=0}^N floor((ai + b) / m)

```

6.5 MillerRabin

```

// n < 4,759,123,141      3 : 2, 7, 61
// n < 1,122,004,669,633  4 : 2, 13, 23, 1662803
// n < 3,474,749,660,383  6 : primes <= 13
// n < 2^64              7 :
// 2, 325, 9375, 28178, 450775, 9780504, 1795265022
bool Miller_Rabin(ll a, ll n) {
    if ((a = a % n) == 0) return 1;

```

```

    if (n % 2 == 0) return n == 2;
    ll tmp = (n - 1) / ((n - 1) & (1 - n));
    ll t = __lg(((n - 1) & (1 - n))), x = 1;
    for (; tmp; tmp >>= 1, a = mul(a, a, n))
        if (tmp & 1) x = mul(x, a, n);
    if (x == 1 || x == n - 1) return 1;
    while (--t)
        if ((x = mul(x, x, n)) == n - 1) return 1;
    return 0;
}

```

6.6 PollardRho

```

map<ll, int> cnt;
void PollardRho(ll n) {
    if (n == 1) return;
    if (prime(n)) return ++cnt[n], void();
    if (n % 2
        == 0) return PollardRho(n / 2), ++cnt[2], void();
    ll x = 2, y = 2, d = 1, p = 1;
    #define f(x, n, p) ((mul(x, x, n) + p) % n)
    while (true) {
        if (d != n && d != 1) {
            PollardRho(n / d);
            PollardRho(d);
            return;
        }
        if (d == n) ++p;
        x = f(x, n, p), y = f(f(y, n, p), n, p);
        d = gcd(abs(x - y), n);
    }
}

```

6.7 Fraction

```

struct fraction {
    ll n, d;
    fraction
        (const ll &n=0, const ll &d=1): n(_n), d(_d) {
        ll t = gcd(n, d);
        n /= t, d /= t;
        if (d < 0) n = -n, d = -d;
    }
    fraction operator-() const
    { return fraction(-n, d); }
    fraction operator+(const fraction &b) const
    { return fraction(n * b.d + b.n * d, d * b.d); }
    fraction operator-(const fraction &b) const
    { return fraction(n * b.d - b.n * d, d * b.d); }
    fraction operator*(const fraction &b) const
    { return fraction(n * b.n, d * b.d); }
    fraction operator/(const fraction &b) const
    { return fraction(n * b.d, d * b.n); }
    void print() {
        cout << n;
        if (d != 1) cout << "/" << d;
    }
};

```

6.8 ChineseRemainder

```

ll solve(ll x1, ll m1, ll x2, ll m2) {
    ll g = gcd(m1, m2);
    if ((x2 - x1) % g) return -1; // no sol
    m1 /= g; m2 /= g;
    ll x, y;
    extgcd(m1, m2, __gcd(m1, m2), x, y);
    ll lcm = m1 * m2 * g;
    ll res = x * (x2 - x1) * m1 + x1;
    // be careful with overflow
    return (res % lcm + lcm) % lcm;
}

```

6.9 FactorialMod p^k

```

//  $O(p^k + \log^2 n)$ ,  $pk = p^k$ 
ll prod[MAXP];
ll fac_no_p(ll n, ll p, ll pk) {

```

```

prod[0] = 1;
for (int i = 1; i <= pk; ++i)
    if (i % p) prod[i] = prod[i - 1] * i % pk;
    else prod[i] = prod[i - 1];
ll rt = 1;
for (; n; n /= p) {
    rt = rt * mpow(prod[pk], n / pk, pk) % pk;
    rt = rt * prod[n % pk] % pk;
}
return rt;
} // (n! without factor p) % p^k

```

6.10 QuadraticResidue

```

// Berlekamp-Rabin, log^2(p)
ll trial(ll y, ll z, ll m) {
    ll a0 = 1, a1 = 0, b0 = z, b1 = 1, p = (m - 1) / 2;
    while (p) {
        if (p & 1)
            tie(a0, a1) =
                make_pair((a1 * b1 % m * y + a0 * b0) % m,
                    (a0 * b1 + a1 * b0) % m);
            tie(b0, b1) =
                make_pair((b1 * b1 % m * y + b0 * b0) % m,
                    (2 * b0 * b1) % m);
            p >>= 1;
    }
    if (a1) return inv(a1, m);
    return -1;
}
mt19937 rd(49);
ll psqrt(ll y, ll p) {
    if (fpow(y, (p - 1) / 2, p) != 1) return -1;
    for (int i = 0; i < 30; ++i) {
        ll z = rd() % p;
        if (z * z % p == y) return z;
        ll x = trial(y, z, p);
        if (x == -1) continue;
        return x;
    }
    return -1;
}

```

6.11 MeisselLehmer

```

ll PrimeCount(ll n) { // n ~ 10^13 => < 2s
    if (n <= 1) return 0;
    int v = sqrt(n), s = (v + 1) / 2, pc = 0;
    vector<int> smalls(v + 1), skip(v + 1), roughs(s);
    vector<ll> larges(s);
    for (int i = 2; i <= v; ++i) smalls[i] = (i + 1) / 2;
    for (int i = 0; i < s; ++i) {
        roughs[i] = 2 * i + 1;
        larges[i] = (n / (2 * i + 1) + 1) / 2;
    }
    for (int p = 3; p <= v; ++p) {
        if (smalls[p] > smalls[p - 1]) {
            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 (int k = 0; k < s; ++k) {
                int i = roughs[k];
                if (skip[i]) continue;
                ll d = 1LL * i * p;
                larges[ns] = larges[k] - (d <= v ? larges
                    [smalls[d] - pc] : smalls[n / d]) + pc;
                roughs[ns++] = i;
            }
            s = 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;
            }
        }
    }
}

```

```

}
}
for (int k = 1; k < s; ++k) {
    const ll m = n / roughs[k];
    ll t = larges[k] - (pc + k - 1);
    for (int l = 1; l < k; ++l) {
        int p = roughs[l];
        if (1LL * p * p > m) break;
        t -= smalls[m / p] - (pc + l - 1);
    }
    larges[0] -= t;
}
return larges[0];
}

```

6.12 DiscreteLog

```

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;
}

```

6.13 Theorems

- Cramer's rule

$$\begin{aligned} ax+by &= e & x &= \frac{ed-bf}{ad-bc} \\ cx+dy &= f & y &= \frac{af-ec}{ad-bc} \end{aligned}$$

- Vandermonde's Identity

$$C(n+m, k) = \sum_{i=0}^k C(n, i) C(m, k-i)$$

- 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 $\frac{(n-2)!}{(d_1-1)!(d_2-1)! \dots (d_n-1)!}$ 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 nonnegative integers $d_1 \geq \dots \geq d_n$ can be represented as the degree sequence of a finite simple graph on n vertices if and only if $d_1 + \dots + d_n$ is even and

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

- 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

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

- 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 $\sum_{i=1}^n a_i = \sum_{i=1}^n b_i$

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

- Pick's theorem

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

- Möbius inversion formula

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

- Spherical cap

- A portion of a sphere cut off by a plane.
- r : sphere radius, a : radius of the base of the cap, h : height of the cap, θ : $\arcsin(a/r)$.
- Volume = $\pi h^2(3r - h)/3 = \pi h(3a^2 + h^2)/6 = \pi r^3(2 + \cos\theta)(1 - \cos\theta)^2/3$.
- Area = $2\pi rh = \pi(a^2 + h^2) = 2\pi r^2(1 - \cos\theta)$.

- Lagrange multiplier

- Optimize $f(x_1, \dots, x_n)$ when k constraints $g_i(x_1, \dots, x_n) = 0$.
- Lagrangian function $\mathcal{L}(x_1, \dots, x_n, \lambda_1, \dots, \lambda_k) = f(x_1, \dots, x_n) + \sum_{i=1}^k \lambda_i g_i(x_1, \dots, x_n)$.
- The solution corresponding to the original constrained optimization is always a saddle point of the Lagrangian function.

- Nearest points of two skew lines

- Line 1: $v_1 = p_1 + t_1 d_1$
- Line 2: $v_2 = p_2 + t_2 d_2$
- $n = d_1 \times d_2$
- $n_1 = d_1 \times n$
- $n_2 = d_2 \times n$
- $c_1 = p_1 + \frac{(p_2 - p_1) \cdot n_2}{d_1 \cdot n_2} d_1$
- $c_2 = p_2 + \frac{(p_1 - p_2) \cdot n_1}{d_2 \cdot n_1} d_2$

6.14 Estimation

- Estimation

- The number of divisors of n is at most around 100 for $n < 5e4$, 500 for $n < 1e7$, 2000 for $n < 1e10$, 200000 for $n < 1e19$.
- The number of ways of writing n as a sum of positive integers, disregarding the order of the summands. 1, 1, 2, 3, 5, 7, 11, 15, 22, 30 for $n = 0 \sim 9$, 627 for $n = 20$, $\sim 2e5$ for $n = 50$, $\sim 2e8$ for $n = 100$.
- Total number of partitions of n distinct elements: $B(n) = 1, 1, 2, 5, 15, 52, 203, 877, 4140, 21147, 115975, 678570, 4213597, 27644437, 190899322, \dots$

6.15 Euclidean Algorithms

- $m = \lfloor \frac{an+b}{c} \rfloor$
- Time complexity: $O(\log n)$

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

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

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

6.16 Numbers

- Bernoulli numbers

$$B_0 = 1, B_1 = \pm \frac{1}{2}, B_2 = \frac{1}{6}, B_3 = 0$$

$$\sum_{j=0}^m \binom{m+1}{j} B_j = 0, \text{ EGF is } B(x) = \frac{x}{e^x - 1} = \sum_{n=0}^{\infty} B_n \frac{x^n}{n!}.$$

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

- Stirling numbers of the second kind Partitions of n distinct elements into exactly k groups.

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

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

$$x^n = \sum_{i=0}^n S(n, i) (x)_i$$

- Pentagonal number theorem

$$\prod_{n=1}^{\infty} (1 - x^n) = 1 + \sum_{k=1}^{\infty} (-1)^k \left(x^{k(3k+1)/2} + x^{k(3k-1)/2} \right)$$

- Catalan numbers

$$C_n^{(k)} = \frac{1}{(k-1)n+1} \binom{kn}{n}$$

$$C^{(k)}(x) = 1 + x[C^{(k)}(x)]^k$$

- Eulerian numbers

Number of permutations $\pi \in S_n$ in which exactly k elements are greater than the previous element. k j 's s.t. $\pi(j) > \pi(j+1)$, $k+1$ j 's s.t. $\pi(j) \geq j$, k j 's s.t. $\pi(j) > j$.

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

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

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

6.17 Generating Functions

- Ordinary Generating Function $A(x) = \sum_{i \geq 0} a_i x^i$

- $A(rx) \Rightarrow r^n a_n$
- $A(x) + B(x) \Rightarrow a_n + b_n$
- $A(x)B(x) \Rightarrow \sum_{i=0}^n a_i b_{n-i}$
- $A(x)^k \Rightarrow \sum_{i_1+i_2+\dots+i_k=n} a_{i_1} a_{i_2} \dots a_{i_k}$
- $x A(x)' \Rightarrow n a_n$
- $\frac{A(x)}{1-x} \Rightarrow \sum_{i=0}^n a_i$

- Exponential Generating Function $A(x) = \sum_{i \geq 0} \frac{a_i}{i!} x^i$

- $A(x) + B(x) \Rightarrow a_n + b_n$
- $A^{(k)}(x) \Rightarrow a_{n+k}$
- $A(x)B(x) \Rightarrow \sum_{i=0}^n \binom{n}{i} a_i b_{n-i}$
- $A(x)^k \Rightarrow \sum_{i_1+i_2+\dots+i_k=n} \binom{n}{i_1, i_2, \dots, i_k} a_{i_1} a_{i_2} \dots a_{i_k}$
- $x A(x) \Rightarrow n a_n$

- Special Generating Function

- $(1+x)^n = \sum_{i \geq 0} \binom{n}{i} x^i$
- $\frac{1}{(1-x)^n} = \sum_{i \geq 0} \binom{n-1}{i} x^i$
- $S_k = \sum_{x=1}^n x^k: S = \sum_{p=0}^{\infty} x^p = \frac{e^x - e^{x(n+1)}}{1 - e^x}$

7 Linear Algebra

7.1 Gaussian Elimination

```
#undef M
struct matrix { //m variables, n equations
    int n, m;
    fraction M[N][N+1], sol[N];
    int solve() { //1: inconsistent, >= 0: rank
        for (int i = 0; i < n; ++i) {
            int piv = 0;
            while (piv < m && !M[i][piv].n) ++piv;
            if (piv == m) continue;
            for (int j = 0; j < n; ++j) {
                if (i == j) continue;
                fraction tmp = -M[j][piv] / M[i][piv];
                for (int k = 0; k <=
                    m; ++k) M[j][k] = tmp * M[i][k] + M[j][k];
            }
        }
    }
}
```



```

    }
    int rank = 0;
    for (int i = 0; i < n; ++i) {
        int piv = 0;
        while (piv < m && !M[i][piv].n) ++piv;
        if (piv == m && M[i][m].n) return -1;
        else if (piv
            < m) ++rank, sol[piv] = M[i][m] / M[i][piv];
    }
    return rank;
}
};

```

7.2 BerlekampMassey

```

template <typename T>
vector<T> BerlekampMassey(const vector<T> &output) {
    vector<T> d(output.size() + 1), me, he;
    for (int f = 0, i = 1; i <= output.size(); ++i) {
        for (int j = 0; j < me.size(); ++j)
            d[i] += output[i - j - 2] * me[j];
        if ((d[i] - output[i - 1]) == 0) continue;
        if (me.empty()) {
            me.resize(f + 1);
            continue;
        }
        vector<T> o(i - f - 1);
        T k = -d[i] / d[f];
        o.emplace_back(-k);
        for (T x : he) o.emplace_back(x * k);
        o.resize(max(o.size(), me.size()));
        for (int j = 0; j < me.size(); ++j) o[j] += me[j];
        if (i - f + (int)
            )he.size() >= (int)me.size() he = me, f = i;
        me = o;
    }
    return me;
}

```

7.3 Simplex

Standard form: maximize $\mathbf{c}^T \mathbf{x}$ subject to $A\mathbf{x} \leq \mathbf{b}$ and $\mathbf{x} \geq 0$.
 Dual LP: minimize $\mathbf{b}^T \mathbf{y}$ subject to $A^T \mathbf{y} \geq \mathbf{c}$ and $\mathbf{y} \geq 0$.
 $\bar{\mathbf{x}}$ and $\bar{\mathbf{y}}$ are optimal if and only if for all $i \in [1, n]$, either $\bar{x}_i = 0$ or $\sum_{j=1}^m A_{ji} \bar{y}_j = c_i$ holds and for all $i \in [1, m]$ either $\bar{y}_i = 0$ or $\sum_{j=1}^n A_{ji} \bar{x}_j = b_j$ holds.

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

```

// using N + 2M variables
const int mxM = 25;
const int mxN = 25 + 2 * mxM;
struct simplex {
    const double inf = 1 / .0, eps = 1e-9;
    int n, m, k, var[mxN], inv[mxN], art[mxN];
    double A[mxM][mxN], B[mxM], x[mxN];
    void init(int _n) { n = _n, m = 0; }
    void equation(vector<double> a, double b) {
        for (int i = 0; i < n; i++) A[m][i] = a[i];
        B[m] = b, var[m] = n + m, ++m;
    }
    void pivot(int r, int c, double bx) {
        for (int i = 0; i <= m + 1; i++)
            if (i != r && abs(A[i][c]) > eps) {
                x[var[i]] -= bx * A[i][c] / A[r][var[i]];
                double f = A[i][c] / A[r][c];
                for (int j = 0; j <= n + m + k; j++)
                    A[i][j] -= A[r][j] * f;
                B[i] -= B[r] * f;
            }
    }
    double phase(int p) {
        while (true) {
            int in = min_element(

```

```

                A[m + p], A[m + p] + n + m + k + 1) -
                A[m + p];
            if (A[m + p][in] >= -eps) break;
            double bx = inf;
            int piv = -1;
            for (int i = 0; i < m; i++)
                if (A[i][in] > eps && B[i] / A[i][in] <= bx)
                    piv = i, bx = B[i] / A[i][in];
            if (piv == -1) return inf;
            int out = var[piv];
            pivot(piv, in, bx);
            x[out] = 0, x[in] = bx, var[piv] = in;
        }
        return x[n + m];
    }
    double solve(vector<double> c) {
        auto invert = [&](int r) {
            for (int j = 0; j <= n + m; j++) A[r][j] *= -1;
            B[r] *= -1;
        };
        k = 1;
        for (int i = 0; i < n; i++) A[m][i] = -c[i];
        fill(A[m + 1], A[m + 1] + mxN, 0.0);
        for (int i = 0; i <= m + 1; i++)
            fill(A[i] + n, A[i] + n + m + 2, 0.0),
                var[i] = n + i, A[i][n + i] = 1;

        for (int i = 0; i < m; i++) {
            if (B[i] < 0) {
                ++k;
                for (int j = 0; j <= n + m; j++)
                    A[m + 1][j] += A[i][j];
                invert(i);
                var[i] = n + m + k, A[i][var[i]] = 1,
                    art[var[i]] = n + i;
            }
            x[var[i]] = B[i];
        }

        phase(1);
        if (*max_element(
            x + (n + m + 2), x + (n + m + k + 1)) > eps)
            return .0 / .0;
        for (int i = 0; i <= m; i++)
            if (var[i] > n + m)
                var[i] = art[var[i]], invert(i);
        k = 0;
        return phase(0);
    }
} lp;

```

8 Polynomials

8.1 NTT (FFT)

```

// 9223372036737335297, 3
#define base ll // complex<double>
#define N 524288
// const double PI = acos(-1);
const ll mod = 998244353, g = 3;
base omega[4 * N], omega_[4 * N];
int rev[4 * N];

ll fpow(ll b, ll p);

ll inverse(ll a) { return fpow(a, mod - 2); }

void calcW(int n) {
    ll r = fpow(g, (mod - 1) / n), invr = inverse(r);
    omega[0] = omega_[0] = 1;
    for (int i = 1; i < n; i++) {
        omega[i] = omega[i - 1] * r % mod;
        omega_[i] = omega_[i - 1] * invr % mod;
    }
    // double arg = 2.0 * PI / n;
    // for (int i = 0; i < n; i++)
    // {

```

```
// omega[i] = base(cos(i * arg), sin(i * arg));
// omega_[i] = base(cos(-i * arg), sin(-i * arg));
// }
}
```

```
void calcrev(int n) {
    int k = __lg(n);
    for (int i = 0; i < n; i++) rev[i] = 0;
    for (int i = 0; i < n; i++)
        for (int j = 0; j < k; j++)
            if (i & (1 << j)) rev[i] ^= 1 << (k - j - 1);
}
```

```
vector<base> NTT(vector<base> poly, bool inv) {
    base *w = (inv ? omega_ : omega);
    int n = poly.size();
    for (int i = 0; i < n; i++)
        if (rev[i] > i) swap(poly[i], poly[rev[i]]);

    for (int len = 1; len < n; len <= 1) {
        int arg = n / len / 2;
        for (int i = 0; i < n; i += 2 * len)
            for (int j = 0; j < len; j++) {
                base odd =
                    w[j * arg] * poly[i + j + len] % mod;
                poly[i + j + len] =
                    (poly[i + j] - odd + mod) % mod;
                poly[i + j] = (poly[i + j] + odd) % mod;
            }
    }
    if (inv)
        for (auto &a : poly) a = a * inverse(n) % mod;
    return poly;
}
```

```
vector<base> mul(vector<base> f, vector<base> g) {
    int sz = 1 << (__lg(f.size() + g.size() - 1) + 1);
    f.resize(sz), g.resize(sz);
    calcrev(sz);
    calcW(sz);
    f = NTT(f, 0), g = NTT(g, 0);
    for (int i = 0; i < sz; i++)
        f[i] = f[i] * g[i] % mod;
    return NTT(f, 1);
}
```

8.2 FHWT

```
/* x: a[j], y: a[j + (L >> 1)]
or: (y += x * op), and: (x += y * op)
xor: (x, y = (x + y) * op, (x - y) * op)
invop: or, and, xor = -1, -1, 1/2 */
void fwt(int *a, int n, int op) { //or
    for (int L = 2; L <= n; L <= 1)
        for (int i = 0; i < n; i += L)
            for (int j = i; j < i + (L >> 1); ++j)
                a[j + (L >> 1)] += a[j] * op;
}
const int N = 21;
int f[
    N][1 << N], g[N][1 << N], h[N][1 << N], ct[1 << N];
void subset_convolution(int *a, int *b, int *c, int L) {
    // c_k = \sum_{i | j = k, i & j = 0} a_i * b_j
    int n = 1 << L;
    for (int i = 1; i < n; ++i)
        ct[i] = ct[i & (i - 1)] + 1;
    for (int i = 0; i < n; ++i)
        f[ct[i]][i] = a[i], g[ct[i]][i] = b[i];
    for (int i = 0; i <= L; ++i)
        fwt(f[i], n, 1), fwt(g[i], n, 1);
    for (int i = 0; i <= L; ++i)
        for (int j = 0; j <= i; ++j)
            for (int x = 0; x < n; ++x)
                h[i][x] += f[j][x] * g[i - j][x];
    for (int i = 0; i <= L; ++i)
        fwt(h[i], n, -1);
}
```

```
for (int i = 0; i < n; ++i)
    c[i] = h[ct[i]][i];
}
```

8.3 PolynomialOperations

```
#define poly vector<ll>
poly inv(poly A) {
    A.resize(1 << (__lg(A.size() - 1) + 1));
    poly B = {inverse(A[0])};
    for (int n = 1; n < A.size(); n += n) {
        poly pA(A.begin(), A.begin() + 2 * n);
        calcrev(4 * n);
        calcW(4 * n);
        pA.resize(4 * n);
        B.resize(4 * n);
        pA = NTT(pA, 0);
        B = NTT(B, 0);
        for (int i = 0; i < 4 * n; i++)
            B[i] =
                ((B[i] * 2 - pA[i] * B[i] % mod * B[i]) % mod +
                 mod) %
                mod;
        B = NTT(B, 1);
        B.resize(2 * n);
    }
    return B;
}
```

```
pair<poly, poly> div(poly A, poly B) {
    if (A.size() < B.size()) return make_pair(poly(), A);
    int n = A.size(), m = B.size();
    poly revA = A, invrevB = B;
    reverse(revA.begin(), revA.end());
    reverse(invrevB.begin(), invrevB.end());
    revA.resize(n - m + 1);
    invrevB.resize(n - m + 1);
    invrevB = inv(invrevB);

    poly Q = mul(revA, invrevB);
    Q.resize(n - m + 1);
    reverse(Q.begin(), Q.end());
    poly R = mul(Q, B);
    R.resize(m - 1);
    for (int i = 0; i < m - 1; i++)
        R[i] = (A[i] - R[i] + mod) % mod;
    return make_pair(Q, R);
}
```

```
ll fast_kitamasu(ll k, poly A, poly C) {
    int n = A.size();
    C.emplace_back(mod - 1);
    poly Q, R = {0, 1}, F = {1};
    R = div(R, C);
    while (k) {
        if (k & 1) F = div(mul(F, R), C);
        R = div(mul(R, R), C);
        k >>= 1;
    }
    ll ans = 0;
    for (int i = 0; i < F.size(); i++)
        ans = (ans + A[i] * F[i]) % mod;
    return ans;
}
```

```
vector<ll> fpow(vector<ll> f, ll p, ll m) {
    int b = 0;
    while (b < f.size() && f[b] == 0) b++;
    f = vector<ll>(f.begin() + b, f.end());
    int n = f.size();
    f.emplace_back(0);
    vector<ll> q(min(m, b * p), 0);
    q.emplace_back(fpow(f[0], p));
    for (int k = 0; q.size() < m; k++) {
        ll res = 0;
        for (int i = 0; i < min(n, k + 1); i++)
            res = (res +

```

```

        p * (i + 1) % mod * f[i + 1] % mod *
        q[k - i + b * p]) %
    mod;
    for (int i = 1; i < min(n, k + 1); i++)
        res = (res -
            f[i] * (k - i + 1) % mod *
            q[k - i + 1 + b * p]) %
            mod;
    res = (res < 0 ? res + mod : res) *
        inv(f[0] * (k + 1) % mod) % mod;
    q.emplace_back(res);
}
return q;
}

```

8.4 NewtonMethod+MiscGF

Given $F(x)$ where

$$F(x) = \sum_{i=0}^{\infty} \alpha_i (x - \beta)^i$$

for β being some constant. Polynomial P such that $F(P) = 0$ can be found iteratively. Denote by Q_k the polynomial such that $F(Q_k) = 0 \pmod{x^{2^k}}$, then

$$Q_{k+1} = Q_k - \frac{F(Q_k)}{F'(Q_k)} \pmod{x^{2^{k+1}}}$$

- A^{-1} : $B_{k+1} = B_k(2 - AB_k) \pmod{x^{2^{k+1}}}$
- $\ln A$: $(\ln A)' = \frac{A'}{A}$
- $\exp A$: $B_{k+1} = B_k(1 + A - \ln B_k) \pmod{x^{2^{k+1}}}$
- \sqrt{A} : $B_{k+1} = \frac{1}{2}(B_k + AB_k^{-1}) \pmod{x^{2^{k+1}}}$

9 Geometry

9.1 Basic

```

typedef pair<pdd, pdd> Line;
struct Cir{ pdd O; double R; };
const double eps = 1e-8;
pdd operator+(pdd a, pdd b)
{ return pdd(a.F + b.S, a.S + b.S); }
pdd operator-(pdd a, pdd b)
{ return pdd(a.F - b.S, a.S - b.S); }
pdd operator*(pdd a, double b)
{ return pdd(a.F * b, a.S * b); }
pdd operator/(pdd a, double b)
{ return pdd(a.F / b, a.S / b); }
double dot(pdd a, pdd b)
{ return a.F * b.F + a.S * b.S; }
double cross(pdd a, pdd b)
{ return a.F * b.S - a.S * b.F; }
double abs2(pdd a)
{ return dot(a, a); }
double abs(pdd a)
{ return sqrt(dot(a, a)); }
int sign(double a)
{ return fabs(a) < eps ? 0 : a > 0 ? 1 : -1; }
int ori(pdd a, pdd b, pdd c)
{ return sign(cross(b - a, c - a)); }
bool collinearity(pdd p1, pdd p2, pdd p3)
{ return sign(cross(p1 - p3, p2 - p3)) == 0; }
bool btw(pdd p1, pdd p2, pdd p3) {
    if (!collinearity(p1, p2, p3)) return 0;
    return sign(dot(p1 - p3, p2 - p3)) <= 0;
}
bool seg_intersect(pdd p1, pdd p2, pdd p3, pdd p4) {
    int a123 = ori(p1, p2, p3);
    int a124 = ori(p1, p2, p4);
    int a341 = ori(p3, p4, p1);
    int a342 = ori(p3, p4, p2);
    if (a123 == 0 && a124 == 0)
        return btw(p1, p2, p3) || btw(p1, p2, p4) ||
            btw(p3, p4, p1) || btw(p3, p4, p2);
    return a123 * a124 <= 0 && a341 * a342 <= 0;
}
pdd intersect(pdd p1, pdd p2, pdd p3, pdd p4) {
    double a123 = cross(p2 - p1, p3 - p1);

```

```

    double a124 = cross(p2 - p1, p4 - p1);
    return (p4
        * a123 - p3 * a124) / (a123 - a124); // C^3 / C^2
}
pdd perp(pdd p1)
{ return pdd(-p1.S, p1.F); }
pdd projection(pdd p1, pdd p2, pdd p3)
{ return p1 + (
    p2 - p1) * dot(p3 - p1, p2 - p1) / abs2(p2 - p1); }
pdd reflection(pdd p1, pdd p2, pdd p3)
{ return p3 + perp(p2 - p1
    ) * cross(p3 - p1, p2 - p1) / abs2(p2 - p1) * 2; }
pdd linearTransformation
    (pdd p0, pdd p1, pdd q0, pdd q1, pdd r) {
    pdd dp = p1 - p0
        , dq = q1 - q0, num(cross(dp, dq), dot(dp, dq));
    return q0 + pdd(
        cross(r - p0, num), dot(r - p0, num)) / abs2(dp);
} // from line p0--p1 to q0--q1, apply to r

```

9.2 ConvexHull

```

void hull(vector<pll> &dots) { // n=1 => ans = {}
    sort(dots.begin(), dots.end());
    vector<pll> ans(1, dots[0]);
    for (int ct = 0; ct < 2; ++ct, reverse(all(dots)))
        for (int i = 1, t = ans.size()
            ; i < dots.size(); ans.emplace_back(dots[i++]))
            while (ans.size() > t &&
                ori(ans.end()[-2], ans.back(), dots[i]) <= 0)
                ans.pop_back();
    ans.pop_back(), ans.swap(dots);
}

```

9.3 SortByAngle

```

int cmp(pll a, pll b, bool same = true) {
#define is_neg(k) (
    sign(k.S) < 0 || (sign(k.S) == 0 && sign(k.F) < 0))
    int A = is_neg(a), B = is_neg(b);
    if (A != B)
        return A < B;
    if (sign(cross(a, b)) == 0)
        return same ? abs2(a) < abs2(b) : -1;
    return sign(cross(a, b)) > 0;
}

```

9.4 DisPointSegment

```

double PointSegDist(pdd q0, pdd q1, pdd p) {
    if (sign(abs(q0 - q1)) == 0) return abs(q0 - p);
    if (sign(dot(q1 - q0,
        p - q0)) >= 0 && sign(dot(q0 - q1, p - q1)) >= 0)
        return fabs(cross(q1 - q0, p - q0) / abs(q0 - q1));
    return min(abs(p - q0), abs(p - q1));
}

```

9.5 PointInCircle

```

// return q'
// s relation with circumcircle of tri(p[0],p[1],p[2])
bool in_cc(const array<pll, 3> &p, pll q) {
    __int128 det = 0;
    for (int i = 0; i < 3; ++i)
        det += __int128(abs2(p[i]) - abs2(q)) *
            cross(p[(i + 1) % 3] - q, p[(i + 2) % 3] - q);
    return det > 0; // in: >0, on: =0, out: <0
}

```

9.6 PointInConvex

```

bool PointInConvex
    (const vector<pll> &C, pll p, bool strict = true) {
    int a = 1, b = (int)C.size() - 1, r = !strict;
    if ((int)C.size() == 0) return false;
    if ((int)
        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;
}

```

9.7 PointTangentConvex

```

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

```

9.8 CircTangentCirc

```

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.F * c - sign2 * h * v.S,
        v.S * c + sign2 * h * v.F);
    pdd p1 = c1.0 + n * c1.R;
    pdd p2 = c2.0 + n * (c2.R * sign1);
    if (sign(p1.F - p2.F) == 0 and
        sign(p1.S - p2.S) == 0)
        p2 = p1 + perp(c2.0 - c1.0);
    ret.emplace_back(Line(p1, p2));
}
return ret;
}

```

9.9 LineCircleIntersect

```

vector<pdd> circleLine(pdd c, double r, pdd a, pdd b) {
    pdd p
        = a + (b - a) * dot(c - a, b - a) / abs2(b - a);
    double s = cross
        (b - a, c - a), h2 = r * r - s * s / abs2(b - a);
    if (h2 < 0) return {};
    if (h2 == 0) return {p};
    pdd h = (b - a) / abs(b - a) * sqrt(h2);
    return {p - h, p + h};
}

```

9.10 LineConvexIntersect

```

int TangentDir(vector<pll> &C, pll dir) {
    return cyc_tsearch((int)C.size(), [&](int a, int b) {
        return cross(dir, C[a]) > cross(dir, C[b]);
    });
}
#define cmpL(i) sign(cross(C[i] - a, b - a))
pii lineHull(pll a, pll b, vector<pll> &C) {
    int A = TangentDir(C, a - b);
    int B = TangentDir(C, b - a);
    int n = (int)C.size();
    if (cmpL(A) < 0 || cmpL(B) > 0)
        return pii(-1, -1); // no collision
    auto gao = [&](int l, int r) {
        for (int t = l; (l + 1) % n != r; ) {
            int m = ((l + r + (l < r ? 0 : n)) / 2) % n;
            (cmpL(m) == cmpL(t) ? l : r) = m;
        }
        return (l + !cmpL(r)) % n;
    };
    pii res = pii(gao(B, A), gao(A, B)); // (i, j)
    if (res.F == res.S) // touching the corner i
        return pii(res.F, -1);
    if (!
        cmpL(res.F) && !cmpL(res.S)) // along side i, i+1
        switch ((res.F - res.S + n + 1) % n) {
            case 0: return pii(res.F, res.F);
            case 2: return pii(res.S, res.S);
        }
    /* crossing sides (i, i+1) and (j, j+1)
       crossing corner i is treated as side (i, i+1)
       returned
       in the same order as the line hits the convex */
    return res;
} // convex cut: (r, l]

```

9.11 CircIntersectCirc

```

bool CCinter(Cir &a, Cir &b, pdd &p1, pdd &p2) {
    pdd o1 = a.0, o2 = b.0;
    double r1 =
        a.R, r2 = b.R, d2 = abs2(o1 - o2), d = sqrt(d2);
    if (d < max
        (r1, r2) - min(r1, r2) || d > r1 + r2) return 0;
    pdd u = (o1 + o2) * 0.5
        + (o1 - o2) * ((r2 * r2 - r1 * r1) / (2 * d2));
    double A = sqrt((r1 + r2 + d) *
        (r1 - r2 + d) * (r1 + r2 - d) * (-r1 + r2 + d));
    pdd v
        = pdd(o1.S - o2.S, -o1.F + o2.F) * A / (2 * d2);
    p1 = u + v, p2 = u - v;
    return 1;
}

```

9.12 PolyIntersectCirc

```

// Divides into multiple triangle, and sum up
const double PI = acos(-1);
double _area(pdd pa, pdd pb, double r) {
    if (abs(pa) < abs(pb)) swap(pa, pb);
    if (abs(pb) < eps) return 0;
    double S, h, theta;
    double a = abs(pb), b = abs(pa), c = abs(pb - pa);
    double cosB = dot(pb, pb - pa) / a / c,
        B = acos(cosB);
    double cosC = dot(pa, pb) / a / b, C = acos(cosC);
    if (a > r) {
        S = (C / 2) * r * r;
        h = a * b * sin(C) / c;
        if (h < r && B < PI / 2)
            S -= (acos(h / r) * r * r -
                h * sqrt(r * r - h * h));
    } else if (b > r) {
        theta = PI - B - asin(sin(B) / r * a);
        S = .5 * a * r * sin(theta) +
            (C - theta) / 2 * r * r;
    }
}

```

```

    } else S = .5 * sin(C) * a * b;
    return S;
}

double area_poly_circle(const vector<pdd> poly,
    const pdd &O, const double r) {
    double S = 0;
    for (int i = 0; i < (int)poly.size(); ++i)
        S += _area(poly[i] - O,
            poly[(i + 1) % (int)poly.size()] - O, r) *
            ori(
                O, poly[i], poly[(i + 1) % (int)poly.size()]);
    return fabs(S);
}

```

9.13 MinkowskiSum

```

vector<pll> Minkowski
    (vector<pll> A, vector<pll> B) { // |A|,|B|>=3
    hull(A), hull(B);
    vector<pll> C(1, A[0] + B[0]), s1, s2;
    for (int i = 0; i < A.size(); ++i)
        s1.emplace_back(A[(i + 1) % A.size()] - A[i]);
    for (int i = 0; i < B.size(); ++i)
        s2.emplace_back(B[(i + 1) % B.size()] - B[i]);
    for (int i = 0, j = 0; i < A.size() || j < B.size(); )
        if (j >= B.size()
            || (i < A.size() && cross(s1[i], s2[j]) >= 0))
            C.emplace_back(B[j % B.size()] + A[i++]);
        else
            C.emplace_back(A[i % A.size()] + B[j++]);
    return hull(C), C;
}

```

9.14 MinMaxEnclosingRect

```

const double INF = 1e18, qi = acos(-1) / 2 * 3;
pdd solve(vector<pll> &dots) {
#define diff(u, v) (dots[u] - dots[v])
#define vec(v) (dots[v] - dots[i])
    hull(dots);
    double Max = 0, Min = INF, deg;
    int n = (int)dots.size();
    dots.emplace_back(dots[0]);
    for (int i = 0, u = 1, r = 1, l = 1; i < n; ++i) {
        pll nw = vec(i + 1);
        while (cross(nw, vec(u + 1)) > cross(nw, vec(u)))
            u = (u + 1) % n;
        while (dot(nw, vec(r + 1)) > dot(nw, vec(r)))
            r = (r + 1) % n;
        if (!i) l = (r + 1) % n;
        while (dot(nw, vec(l + 1)) < dot(nw, vec(l)))
            l = (l + 1) % n;
        Min = min(Min, (double)(dot(nw, vec(r)) - dot
            (nw, vec(l))) * cross(nw, vec(u)) / abs2(nw));
        deg = acos(dot(diff(r, l), vec(u)) / abs(vec(u)));
        deg = (qi - deg) / 2;
        Max = max(Max, abs(diff
            (r, l)) * abs(vec(u)) * sin(deg) * sin(deg));
    }
    return pdd(Min, Max);
}

```

9.15 MinEnclosingCircle

```

pdd Minimum_Enclosing_Circle
    (vector<pdd> dots, double &r) {
    pdd cent;
    random_shuffle(all(dots));
    cent = dots[0], r = 0;
    for (int i = 1; i < (int)dots.size(); ++i)
        if (abs(dots[i] - cent) > r) {
            cent = dots[i], r = 0;
            for (int j = 0; j < i; ++j)
                if (abs(dots[j] - cent) > r) {
                    cent = (dots[i] + dots[j]) / 2;
                    r = abs(dots[i] - cent);
                }
        }
    }

```

```

        for(int k = 0; k < j; ++k)
            if(abs(dots[k] - cent) > r)
                cent = excenter
                    (dots[i], dots[j], dots[k], r);
        }
    }
    return cent;
}

```

9.16 CircleCover

```

const int N = 1021;
struct CircleCover {
    int C;
    Cir c[N];
    bool g[N][N], overlap[N][N];
    // Area[i] : area covered by at least i circles
    double Area[ N ];
    void init(int _C){ C = _C; }
    struct Teve {
        pdd p; double ang; int add;
        Teve() {}
        Teve(pdd _a,
            double _b, int _c):p(_a), ang(_b), add(_c){}
        bool operator<(const Teve &a)const {
            return ang < a.ang; }
    }eve[N * 2];
    // strict: x = 0, otherwise x = -1
    bool disjunct(Cir &a, Cir &b, int x)
    {return sign(abs(a.O - b.O) - a.R - b.R) > x;}
    bool contain(Cir &a, Cir &b, int x)
    {return sign(a.R - b.R - abs(a.O - b.O)) > x;}
    bool contain(int i, int j) {
        /* c[j] is non-strictly in c[i]. */
        return (sign
            (c[i].R - c[j].R) > 0 || (sign(c[i].R - c[j].
            R) == 0 && i < j)) && contain(c[i], c[j], -1);
    }
    void solve(){
        fill_n(Area, C + 2, 0);
        for(int i = 0; i < C; ++i)
            for(int j = 0; j < C; ++j)
                overlap[i][j] = contain(i, j);
        for(int i = 0; i < C; ++i)
            for(int j = 0; j < C; ++j)
                g[i][j] = !(overlap[i][j] || overlap[j][i] ||
                    disjunct(c[i], c[j], -1));
        for(int i = 0; i < C; ++i){
            int E = 0, cnt = 1;
            for(int j = 0; j < C; ++j)
                if(j != i && overlap[j][i])
                    ++cnt;
            for(int j = 0; j < C; ++j)
                if(i != j && g[i][j]) {
                    pdd aa, bb;
                    CCinter(c[i], c[j], aa, bb);
                    double A =
                        atan2(aa.Y - c[i].O.Y, aa.X - c[i].O.X);
                    double B =
                        atan2(bb.Y - c[i].O.Y, bb.X - c[i].O.X);
                    eve[E++] = Teve
                        (bb, B, 1), eve[E++] = Teve(aa, A, -1);
                    if(B > A) ++cnt;
                }
            if(E == 0) Area[cnt] += pi * c[i].R * c[i].R;
            else{
                sort(eve, eve + E);
                eve[E] = eve[0];
                for(int j = 0; j < E; ++j){
                    cnt += eve[j].add;
                    Area[cnt]
                        += cross(eve[j].p, eve[j + 1].p) * .5;
                    double theta = eve[j + 1].ang - eve[j].ang;
                    if (theta < 0) theta += 2. * pi;
                    Area[cnt] += (theta
                        - sin(theta)) * c[i].R * c[i].R * .5;
                }
            }
        }
    }
}

```



```

    }
  }
};

```

9.17 LineCmp

```

using Line = pair<pll, pll>;
struct LineCmp {
    bool operator()(Line l1, Line l2) const {
        int X =
            (max(l1.F.F, l2.F.F) + min(l1.S.F, l2.S.F)) / 2;
        ll p1 =
            (X - l1.F.F) * l1.S.S + (l1.S.F - X) * l1.F.S,
        p2 =
            (X - l2.F.F) * l2.S.S + (l2.S.F - X) * l2.F.S,
        q1 = (l1.S.F - l1.F.F), q2 = (l2.S.F - l2.F.F);
        if (q1 == 0) p1 = l1.F.S + l1.S.S, q1 = 2;
        if (q2 == 0) p2 = l2.F.S + l2.S.S, q2 = 2;
        if (l1.F == l2.F || l2.F == l2.S) l1 = l2;
        return make_tuple((__int128)(p1 * q2), l1) <
            make_tuple((__int128)(p2 * q1), l2);
    }
};

```

9.18 Trapezoidalization

```

struct SweepLine {
    struct cmp {
        cmp(const SweepLine &swp): swp(swp) {}
        bool operator()(int a, int b) const {
            if (abs(swp.get_y(a) - swp.get_y(b)) <= swp.eps)
                return swp.slope_cmp(a, b);
            return swp.get_y(a) + swp.eps < swp.get_y(b);
        }
        const SweepLine &swp;
    } _cmp;
    T curTime, eps, curQ;
    vector<Line> base;
    multiset<int, cmp> sweep;
    multiset<pair<T, int>> event;
    vector<typename multiset<int, cmp>::iterator> its;
    vector<typename multiset<pair<T, int>>::iterator> eits;
    bool slope_cmp(int a, int b) const {
        assert(a != -1);
        if (b == -1) return 0;
        return sign(cross(base[a].Y - base[a].X, base[b].Y - base[b].X)) < 0;
    }
    T get_y(int idx) const {
        if (idx == -1) return curQ;
        Line l = base[idx];
        if (l.X.X == l.Y.X) return l.Y.Y;
        return ((curTime - l.X.X) * l.Y.Y
            + (l.Y.X - curTime) * l.X.Y) / (l.Y.X - l.X.X);
    }
    void insert(int idx) {
        its[idx] = sweep.insert(idx);
        if (its[idx] != sweep.begin())
            update_event(*prev(its[idx]));
        update_event(idx);
        event.emplace
            (base[idx].Y.X, idx + 2 * (int)base.size());
    }
    void erase(int idx) {
        assert(eits[idx] != event.end());
        auto p = sweep.erase(its[idx]);
        its[idx] = sweep.end();
        if (p != sweep.begin())
            update_event(*prev(p));
    }
    void update_event(int idx) {
        if (eits[idx] != event.end())
            event.erase(eits[idx]);
        eits[idx] = event.end();
        auto nxt = next(its[idx]);

```

```

        if (nxt ==
            sweep.end() || !slope_cmp(idx, *nxt)) return;
        auto t = intersect(base[idx].
            X, base[idx].Y, base[*nxt].X, base[*nxt].Y).X;
        if (t + eps < curTime || t
            >= min(base[idx].Y.X, base[*nxt].Y.X)) return;
        eits[idx]
            = event.emplace(t, idx + (int)base.size());
    }
    void swp(int idx) {
        assert(eits[idx] != event.end());
        eits[idx] = event.end();
        int nxt = *next(its[idx]);
        swap((int&)*its[idx], (int&)*its[nxt]);
        swap(its[idx], its[nxt]);
        if (its[nxt] != sweep.begin())
            update_event(*prev(its[nxt]));
        update_event(idx);
    }
    // only expected to call the functions below
    SweepLine(T t, T e, vector<Line> vec): _cmp
        (*this), curTime(t), eps(e), curQ(), base(vec),
        sweep(_cmp), event(), its((int)vec.size(), sweep
            .end()), eits((int)vec.size(), event.end()) {
        for (int i = 0; i < (int)base.size(); ++i) {
            auto &[p, q] = base[i];
            if (p > q) swap(p, q);
            if (p.X <= curTime && curTime <= q.X)
                insert(i);
            else if (curTime < p.X)
                event.emplace(p.X, i);
        }
    }
    void setTime(T t, bool ers = false) {
        assert(t >= curTime);
        while (!event.empty() && event.begin()->X <= t) {
            auto [et, idx] = *event.begin();
            int s = idx / (int)base.size();
            idx %= (int)base.size();
            if (abs(et - t) <= eps && s == 2 && !ers) break;
            curTime = et;
            event.erase(event.begin());
            if (s == 2) erase(idx);
            else if (s == 1) swp(idx);
            else insert(idx);
        }
        curTime = t;
    }
    T nextEvent() {
        if (event.empty()) return INF;
        return event.begin()->X;
    }
    int lower_bound(T y) {
        curQ = y;
        auto p = sweep.lower_bound(-1);
        if (p == sweep.end()) return -1;
        return *p;
    }
};

```

9.19 TriangleHearts

```

pdd circenter(
    pdd p0, pdd p1, pdd p2) { // radius = abs(center)
    p1 = p1 - p0, p2 = p2 - p0;
    double x1 = p1.F, y1 = p1.S, x2 = p2.F, y2 = p2.S;
    double m = 2. * (x1 * y2 - y1 * x2);
    pdd center = pdd((x1 * x1 * y2 - x2 * x2 * y1 +
        y1 * y2 * (y1 - y2)) / m,
        (x1 * x2 * (x2 - x1) - y1 * y1 * x2 +
        x1 * y2 * y2) / m);
    return center + p0;
}
pdd incenter(
    pdd p1, pdd p2, pdd p3) { // radius = area / s * 2
    double a = abs(p2 - p3), b = abs(p1 - p3),

```



```

        c = abs(p1 - p2);
        double s = a + b + c;
        return (a * p1 + b * p2 + c * p3) / s;
    }
    pdd masscenter(pdd p1, pdd p2, pdd p3) {
        return (p1 + p2 + p3) / 3;
    }
    pdd orthcenter(pdd p1, pdd p2, pdd p3) {
        return masscenter(p1, p2, p3) * 3 -
            circenter(p1, p2, p3) * 2;
    }

```

9.20 HalfPlaneIntersect

```

pll area_pair(Line a, Line b)
{ return pll(cross(a.S
    - a.F, b.F - a.F), cross(a.S - a.F, b.S - a.F)); }
bool isin(Line l0, Line l1, Line l2) {
    // Check inter(l1, l2) strictly in l0
    auto [a02X, a02Y] = area_pair(l0, l2);
    auto [a12X, a12Y] = area_pair(l1, l2);
    if (a12X - a12Y < 0) a12X *= -1, a12Y *= -1;
    return (__int128)
        a02Y * a12X - (__int128) a02X * a12Y > 0; // C^4
}
/* Having solution, check size > 2 */
/* ---^--- Line.X ---^--- Line.Y ---^--- */
vector<Line> halfPlaneInter(vector<Line> arr) {
    sort(all(arr), [&](Line a, Line b) -> int {
        if (cmp(a.S - a.F, b.S - b.F, 0) != -1)
            return cmp(a.S - a.F, b.S - b.F, 0);
        return ori(a.F, a.S, b.S) < 0;
    });
    deque<Line> dq(1, arr[0]);
    for (auto p : arr) {
        if (cmp(
            dq.back().S - dq.back().F, p.S - p.F, 0) == -1)
            continue;
        while ((int)dq.size() >= 2
            && !isin(p, dq[(int)dq.size() - 2], dq.back()))
            dq.pop_back();
        while
            ((int)dq.size() >= 2 && !isin(p, dq[0], dq[1]))
            dq.pop_front();
        dq.emplace_back(p);
    }
    while ((int)dq.size() >= 3 &&
        !isin(dq[0], dq[(int)dq.size() - 2], dq.back()))
        dq.pop_back();
    while ((int)
        dq.size() >= 3 && !isin(dq.back(), dq[0], dq[1]))
        dq.pop_front();
    return vector<Line>(all(dq));
}

```

9.21 RotatingSweepLine

```

void rotatingSweepLine(vector<pii> &ps) {
    int n = (int)ps.size(), m = 0;
    vector<int> id(n), pos(n);
    vector<pii> line(n * (n - 1));
    for (int i = 0; i < n; ++i)
        for (int j = 0; j < n; ++j)
            if (i != j) line[m++] = pii(i, j);
    sort(all(line), [&](pii a, pii b) {
        return cmp(ps[a.S] - ps[a.F], ps[b.S] - ps[b.F]);
    }); // cmp(): polar angle compare
    iota(all(id), 0);
    sort(all(id), [&](int a, int b) {
        if (ps[a].S != ps[b].S) return ps[a].S < ps[b].S;
        return ps[a] < ps[b];
    }); // initial order, since (1, 0) is the smallest
    for (int i = 0; i < n; ++i) pos[id[i]] = i;
    for (int i = 0; i < m; ++i) {
        auto l = line[i];
        // do something
    }
}

```

```

        tie(pos[l.F], pos[l.S], id[pos[l.F]], id[pos[l.S]
            ]) = make_tuple(pos[l.S], pos[l.F], l.S, l.F);
    }
}

```

9.22 DelaunayTriangulation

```

/* Delaunay Triangulation:
Given a sets of points on 2D plane, find a
triangulation such that no points will strictly
inside circumcircle of any triangle.
find : return a triangle contain given point
add_point : add a point into triangulation
A Triangle is in triangulation iff. its has_chd is 0.
Region of triangle u: iterate each u.edge[i].tri,
each points are u.p[(i+1)%3], u.p[(i+2)%3]
Voronoi diagram: for each triangle in triangulation,
the bisector of all its edges will split the region.
nearest point will belong to the triangle containing it
*/
const
    ll inf = MAXC * MAXC * 100; // lower_bound unknown
struct Tri;
struct Edge {
    Tri* tri; int side;
    Edge(): tri(0), side(0){}
    Edge(Tri* _tri, int _side): tri(_tri), side(_side){}
};
struct Tri {
    pll p[3];
    Edge edge[3];
    Tri* chd[3];
    Tri() {}
    Tri(const pll& p0, const pll& p1, const pll& p2) {
        p[0] = p0; p[1] = p1; p[2] = p2;
        chd[0] = chd[1] = chd[2] = 0;
    }
    bool has_chd() const { return chd[0] != 0; }
    int num_chd() const {
        return !!chd[0] + !!chd[1] + !!chd[2];
    }
    bool contains(pll const& q) const {
        for (int i = 0; i < 3; ++i)
            if (ori(p[i], p[(i + 1) % 3], q) < 0)
                return 0;
        return 1;
    }
} pool[N * 10], *tris;
void edge(Edge a, Edge b) {
    if(a.tri) a.tri->edge[a.side] = b;
    if(b.tri) b.tri->edge[b.side] = a;
}
struct Trig { // Triangulation
    Trig() {
        the_root
            = // Tri should at least contain all points
            new(tris++) Tri(pll(-inf, -inf),
                pll(inf + inf, -inf), pll(-inf, inf + inf));
    }
    Tri* find(pll p) { return find(the_root, p); }
    void add_point(const
        pll &p) { add_point(find(the_root, p), p); }
    Tri* the_root;
    static Tri* find(Tri* root, const pll &p) {
        while (1) {
            if (!root->has_chd())
                return root;
            for (int i = 0; i < 3 && root->chd[i]; ++i)
                if (root->chd[i]->contains(p)) {
                    root = root->chd[i];
                    break;
                }
        }
        assert(0); // "point not found"
    }
    void add_point(Tri* root, pll const& p) {
        Tri* t[3];
        /* split it into three triangles */
    }
}

```

```

for (int i = 0; i < 3; ++i)
    t[i] = new(tris
        ++ Tri(root->p[i], root->p[(i + 1) % 3], p);
for (int i = 0; i < 3; ++i)
    edge(Edge(t[i], 0), Edge(t[(i + 1) % 3], 1));
for (int i = 0; i < 3; ++i)
    edge(Edge(t[i], 2), root->edge[(i + 2) % 3]);
for (int i = 0; i < 3; ++i)
    root->chd[i] = t[i];
for (int i = 0; i < 3; ++i)
    flip(t[i], 2);
}
void flip(Tri* tri, int pi) {
    Tri* trj = tri->edge[pi].tri;
    int pj = tri->edge[pi].side;
    if (!trj) return;
    if (!in_cc(tri->p
        [0], tri->p[1], tri->p[2], trj->p[pj])) return;
    /* flip edge between tri, trj */
    Tri* trk = new(tris++) Tri
        (tri->p[(pi + 1) % 3], trj->p[pj], tri->p[pi]);
    Tri* trl = new(tris++) Tri
        (trj->p[(pj + 1) % 3], tri->p[pi], trj->p[pj]);
    edge(Edge(trk, 0), Edge(trl, 0));
    edge(Edge(trk, 1), tri->edge[(pi + 2) % 3]);
    edge(Edge(trk, 2), trj->edge[(pj + 1) % 3]);
    edge(Edge(trl, 1), trj->edge[(pj + 2) % 3]);
    edge(Edge(trl, 2), tri->edge[(pi + 1) % 3]);
    tri->chd
        [0] = trk; tri->chd[1] = trl; tri->chd[2] = 0;
    trj->chd
        [0] = trk; trj->chd[1] = trl; trj->chd[2] = 0;
    flip(trk, 1); flip(trk, 2);
    flip(trl, 1); flip(trl, 2);
}
};
vector<Tri*> triang; // vector of all triangle
set<Tri*> vst;
void go(Tri* now) { // store all tri into triang
    if (vst.find(now) != vst.end())
        return;
    vst.insert(now);
    if (!now->has_chd())
        return triang.emplace_back(now);
    for (int i = 0; i < now->num_chd(); ++i)
        go(now->chd[i]);
}
void build(int n, pll* ps) { // build triangulation
    tris = pool; triang.clear(); vst.clear();
    random_shuffle(ps, ps + n);
    Trig tri; // the triangulation structure
    for (int i = 0; i < n; ++i)
        tri.add_point(ps[i]);
    go(tri.the_root);
}

```

9.23 VoronoiDiagram

```

// all coord. is even
// you may want to call halfPlaneInter after then
vector<vector<Line>> vec;
void build_voronoi_line(int n, pll *arr) {
    tool.init(n, arr); // Delaunay
    vec.clear(), vec.resize(n);
    for (int i = 0; i < n; ++i)
        for (auto e : tool.head[i]) {
            int u = tool.oidx[i], v = tool.oidx[e.id];
            pll m = (arr[v]
                + arr[u]) / 2LL, d = perp(arr[v] - arr[u]);
            vec[u].emplace_back(Line(m, m + d));
        }
}

```

10 Misc

10.1 MoAlgoWithModify

```

/*
Mo's Algorithm With modification
Block:  $N^{\frac{2}{3}}$ , Complexity:  $N^{\frac{5}{3}}$ 
*/
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 < q.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
        // answer query
    }
}

```

10.2 MoAlgoOnTree

```

/*
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.R;
    }
};
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]);
    }
}

```

10.3 MoAlgoAdvanced

- Mo's Algorithm With Addition Only
 - Sort queries same as the normal Mo's algorithm.

- For each query $[l, r]$:
- If $l/blk = r/blk$, brute-force.
- If $l/blk \neq r/blk$, initialize $curL := (l/blk + 1) \cdot blk, curR := curL - 1$
- 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: $f([l, r], r+1) = f([l, r], r+1) - f([l, l], r+1)$.
- Part1: Answer all $f([l, r], r+1)$ 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.

10.4 HilbertCurve

```
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
```

10.5 SternBrocotTree

- Construction: Root $\frac{1}{1}$, left/right neighbor $\frac{0}{1}, \frac{1}{0}$, each node is sum of last left/right neighbor: $\frac{a}{b}, \frac{c}{d} \rightarrow \frac{a+c}{b+d}$
- Property: Adjacent (mid-order DFS) $\frac{a}{b}, \frac{c}{d} \Rightarrow bc - ad = 1$.
- Search known $\frac{p}{q}$: keep L-R alternative. Each step can be calculated in $O(1) \Rightarrow$ total $O(\log C)$.
- Search unknown $\frac{p}{q}$: keep L-R alternative. Each step can be calculated in $O(\log C)$ checks \Rightarrow total $O(\log^2 C)$ checks.

10.6 AllLCS

```
void all_lcs(string s, string t) { // 0-base
    vector<int> h((int)t.size());
    iota(all(h), 0);
    for (int a = 0; a < (int)s.size(); ++a) {
        int v = -1;
        for (int c = 0; c < (int)t.size(); ++c)
            if (s[a] == t[c] || h[c] < v)
                swap(h[c], v);
        // LCS(s[0, a], t[b, c]) =
        // c - b + 1 - sum([h[i] >= b] | i <= c)
        // h[i] might become -1 !!
    }
}
```

10.7 SimulatedAnnealing

```
double factor = 1000000;
const int base = 1e9; // remember to run ~ 10 times
for (int it = 1; it <= 1000000; ++it) {
    // ans:
    answer, nw: current value, rnd(): mt19937 rnd()
    if (exp(-(nw - ans) / factor) >= (double)(rnd() % base) / base)
        ans = nw;
    factor *= 0.99995;
}
```

10.8 SMAWK

```
int opt[N];
ll A(int x, int y); // target func
void smawk(vector<int> &r, vector<int> &c);
void interpolate(vector<int> &r, vector<int> &c) {
    int n = (int)r.size();
    vector<int> er;
    for (int i = 1; i < n; i += 2) er.emplace_back(r[i]);
    smawk(er, c);
    for (int i = 0, j = 0; j < c.size(); j++) {
        if (A(r[i], c[j]) < A(r[i], opt[r[i]]))
            opt[r[i]] = c[j];
        if (i + 2 < n && c[j] == opt[r[i + 1]])
            j--, i += 2;
    }
}
void reduce(vector<int> &r, vector<int> &c) {
    int n = (int)r.size();
    vector<int> nc;
    for (int i : c) {
        int j = (int)nc.size();
        while (
            j && A(r[j - 1], nc[j - 1]) > A(r[j - 1], i))
            nc.pop_back(), j--;
        if (nc.size() < n) nc.emplace_back(i);
    }
    smawk(r, nc);
}
void smawk(vector<int> &r, vector<int> &c) {
    if (r.size() == 1 && c.size() == 1) opt[r[0]] = c[0];
    else if (r.size() >= c.size()) interpolate(r, c);
    else reduce(r, c);
}
```

10.9 Python

```
math.isqrt(2) # integer sqrt
```

10.10 LineContainer

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

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