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## 1 Basic

### 1.1 Template

```
#include <bits/stdc++.h>
using namespace std;
typedef long long ll;
typedef unsigned long long ull;
typedef long double ld;
typedef pair<int,int> pii;
typedef pair<ll,ll> pll;
typedef pair<double,double> pdd;
template<typename T> void _do(T x){cerr<<x<<"\n";}
template<typename T,typename ...U> void _do(T x,U ...y)
{cerr<<x<<" ";_do(y...);}
#define dbg(...) cerr<<__VA_ARGS__<<" = ";_do(
__VA_ARGS__);
#define MottoHayaku ios::sync_with_stdio(false);cin.tie
(0);
// #define int ll
#define rep(i,n) for(int i=0;i<n;i++)
#define repl(i,n) for(int i=1;i<=n;i++)
#define F first
#define S second
#define pb push_back
#define uni(c) c.resize(distance(c.begin(),unique(c.
begin(),c.end())))
#define unisort(c) sort(c.begin(),c.end()),uni(c)
```

## 1.2 Fast IO

```
#pragma GCC optimize("Ofast,inline,unroll-loops")
#pragma GCC target("bmi,bmi2,lzcnt,popcnt,avx2")
#pragma GCC target("sse,sse2,sse3,ssse3,sse4,popcnt,abm
,mmx,avx,tune=native")
#include<unistd.h>
char OB[65536]; int OP;
inline char RC() {
    static char buf[65536], *p = buf, *q = buf;
    return p == q && (q = (p = buf) + read(0, buf, 65536)
) == buf ? -1 : *p++;
}
inline int R() {
    static char c;
    while((c = RC()) < '0'); int a = c ^ '0';
    while((c = RC()) >= '0') a *= 10, a += c ^ '0';
    return a;
}
inline void W(int n) {
    static char buf[12], p;
    if (n == 0) OB[OP++] = '0'; p = 0;
    while (n) buf[p++] = '0' + (n % 10), n /= 10;
    for (--p; p >= 0; --p) OB[OP++] = buf[p];
    if (OP > 65520) write(1, OB, OP), OP = 0;
}
```

## 1.3 vimrc

```
sy on
set ru nu rnu cul cin et bs=2 ls=2 so=8 sw=4 sts=4
mouse=a
inoremap {<CR>{<CR>}<Esc>O
noremap <F9> <Esc>:w<CR>:!lg++ "%:p" -o "%:p:r".out -std
=c++14 -O2 -Wall -Wextra -Wshadow -Wconversion -
fsanitize=address,undefined<CR>
noremap <F10> <Esc>:!"%:p:r".out<CR>
map <F11> <F9><F10>
```

## 2 Graph

### 2.1 2SAT

```
struct TwoSAT {
    // 0-indexed
    // idx i * 2 -> +i, i * 2 + 1 -> -i
    vector<vector<int>> adj, radj;
    vector<int> dfs_ord, idx, solution;
    vector<bool> vis;
    int n, nsc;
    TwoSAT() = default;
    TwoSAT(int _n) : n(_n), nsc(0) {
        adj.resize(n * 2), radj.resize(n * 2);
    }
    void add_clause(int x, int y) {
        // (x or y) = true
        int nx = x ^ 1, ny = y ^ 1;
        adj[nx].push_back(y), radj[y].push_back(nx);
        adj[ny].push_back(x), radj[x].push_back(ny);
    }
    void add_ifthen(int x, int y) {
        // if x = true then y = true
        add_clause(x ^ 1, y);
    }
    void add_must(int x) {
        // x = true
        int nx = x ^ 1;
        adj[nx].pb(x), radj[x].pb(nx);
    }
    void dfs(int v) {
        vis[v] = true;
        for (int u : adj[v]) if (!vis[u])
            dfs(u);
        dfs_ord.push_back(v);
    }
    void rdfs(int v) {
        idx[v] = nsc;
        for (int u : radj[v]) if (idx[u] == -1)
            rdfs(u);
    }
    bool find_sol() {
```

```

vis.assign(n * 2, false), idx.assign(n * 2, -1),
    solution.assign(n, -1);
for (int i = 0; i < n * 2; ++i) if (!vis[i])
    dfs(i);
reverse(dfs_ord.begin(), dfs_ord.end());
for (int i : dfs_ord) if (idx[i] == -1)
    rdfs(i), nsc++;;
for (int i = 0; i < n; i++) {
    if (idx[i << 1] == idx[i << 1 | 1])
        return false;
    if (idx[i << 1] < idx[i << 1 | 1])
        solution[i] = 0;
    else
        solution[i] = 1;
}
return true;
}
};

```

## 2.2 VertexBCC

```

vector<int> adj[N];
struct VertexBCC {
    vector<int> newadj[N << 1];
    vector<vector<int>> idx;
    vector<int> low, dep, par, stk;
    vector<bool> cut;
    int n, nbcc;
    VertexBCC () = default;
    VertexBCC (int _n) : n(_n), nbcc(0) {
        low.assign(n, -1), dep.assign(n, -1), idx.assign(n,
            vector<int> ());
        par.assign(n, -1), cut.assign(n, false);
        for (int i = 0; i < n; ++i) if (dep[i] == -1)
            dfs(i, -1);
        // idx < n -> bcc
        // idx >= n -> cut point
        for (int i = 0; i < n; ++i) if (cut[i]) {
            for (int j : idx[i]) {
                newadj[j].push_back(i + n);
                newadj[i + n].push_back(j);
            }
        }
    }
    void dfs(int v, int pa) {
        low[v] = dep[v] = ~pa ? dep[pa] + 1 : 0;
        stk.push_back(v);
        par[v] = pa;
        int ch = 0;
        for (int u : adj[v]) if (u != pa) {
            if (dep[u] == -1) {
                dfs(u, v);
                low[v] = min(low[v], low[u]);
                ch++;
                if (low[u] >= dep[v]) {
                    // v is a cut point
                    cut[v] = true;
                    int x;
                    do {
                        x = stk.back(), stk.pop_back();
                        idx[x].push_back(nbcc);
                    } while (x != u);
                    idx[v].push_back(nbcc++);
                }
            } else {
                low[v] = min(low[v], dep[u]);
            }
        }
        if (pa == -1 && ch < 2)
            cut[v] = false;
    }
};

```

## 2.3 EdgeBCC

```

vector<int> adj[N];
struct EdgeBCC {
    // 0-indexed
    vector<int> newadj[N];
    vector<int> low, dep, idx, stk, par;
    vector<bool> bridge; // edge i -> pa[i] is bridge ?
    int n, nbcc;

```

```

EdgeBCC () = default;
EdgeBCC (int _n) : n(_n), nbcc(0) {
    low.assign(n, -1), dep.assign(n, -1), idx.assign(n,
        -1);
    par.assign(n, -1), bridge.assign(n, false);
    for (int i = 0; i < n; ++i) if (dep[i] == -1) {
        dfs(i, -1);
    }
    for (int i = 1; i < n; ++i) if (bridge[i]) {
        newadj[idx[i]].pb(idx[par[i]]);
        newadj[idx[par[i]]].pb(idx[i]);
    }
}
void dfs(int v, int pa) {
    low[v] = dep[v] = ~pa ? dep[pa] + 1 : 0;
    par[v] = pa;
    stk.push_back(v);
    for (int u : adj[v]) if (u != pa) {
        if (dep[u] == -1) {
            dfs(u, v);
            low[v] = min(low[v], low[u]);
        } else {
            low[v] = min(low[v], low[u]);
        }
    }
    if (low[v] == dep[v]) {
        if (~pa) bridge[v] = true;
        int x;
        do {
            x = stk.back(), stk.pop_back();
            idx[x] = nbcc;
        } while (x != v);
        nbcc++;
    }
}
};

```

## 2.4 Centroid Decomposition

```

vector<int> adj[N];
struct CentroidDecomposition {
    // 0-index
    vector<int> sz, cd_pa;
    int n;
    CentroidDecomposition () = default;
    CentroidDecomposition (int _n) : n(_n) {
        sz.assign(n, 0), cd_pa.assign(n, -2);
        dfs_cd(0, -1);
    }
    void dfs_sz(int v, int pa) {
        sz[v] = 1;
        for (int u : adj[v]) if (u != pa && cd_pa[u] == -2)
            dfs_sz(u, v), sz[v] += sz[u];
    }
    int dfs_cen(int v, int pa, int s) {
        for (int u : adj[v]) if (u != pa && cd_pa[u] == -2)
            if (sz[u] * 2 > s)
                return dfs_cen(u, v, s);
        return v;
    }
    vector<int> block;
    void dfs_cd(int v, int pa) {
        dfs_sz(v, pa);
        int c = dfs_cen(v, pa, sz[v]);
        // centroid D&C
        for (int u : adj[c]) if (cd_pa[u] == -2) {
            dfs_ans(u, c);
            // do something
        }
        for (int u : adj[c]) if (cd_pa[u] == -2) {
            dfs_cd(u, c);
        }
    }
    void dfs_ans(int v, int pa) {
        // calculate path through centroid
        // do something
        // remember delete path from the same size
        for (int u : adj[v]) if (u != pa && cd_pa[u] == -2)
            dfs_ans(u, v);
    }
}

```

```
// Centroid Tree Property:
// let k = lca(u, v) in Centroid Tree, then dis(u, v)
// = dis(u, k) + dis(k, v)
};
```

## 2.5 Count Cycles

```
// ord = sort by deg decreasing, rk[ord[i]] = i
// D[i] = edge point from rk small to rk big
for (int x : ord) { // c3
    for (int y : D[x]) vis[y] = 1;
    for (int y : D[x]) for (int z : D[y]) c3 += vis[z];
    for (int y : D[x]) vis[y] = 0;
}
for (int x : ord) { // c4
    for (int y : D[x]) for (int z : adj[y])
        if (rk[z] > rk[x]) c4 += vis[z]++;
    for (int y : D[x]) for (int z : adj[y])
        if (rk[z] > rk[x]) --vis[z];
} // both are O(M*sqrt(M)), test @ 2022 CCPC guangzhou
```

## 2.6 DirectedMST

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

```
return ans;
}
```

## 2.7 Dominator Tree

```
struct Dominator_tree {
    int n, id;
    vector<vector<int>> adj, radj, bucket;
    vector<int> sdom, dom, vis, rev, par, rt, mn;
    Dominator_tree(int _n) : n(_n), id(0) {
        adj.resize(n), radj.resize(n), bucket.resize(n);
        sdom.resize(n), dom.resize(n, -1), vis.resize(n,
            -1);
        rev.resize(n), rt.resize(n), mn.resize(n), par.
            resize(n);
    }
    void add_edge(int u, int v) {adj[u].pb(v);}
    int query(int v, bool x) {
        if (rt[v] == v) return x ? -1 : v;
        int p = query(rt[v], true);
        if (p == -1) return x ? rt[v] : mn[v];
        if (sdom[mn[v]] > sdom[mn[rt[v]]]) mn[v] = mn[rt[
            v]];
        rt[v] = p;
        return x ? p : mn[v];
    }
    void dfs(int v) {
        vis[v] = id, rev[id] = v;
        rt[id] = mn[id] = sdom[id] = id, id++;
        for (int u : adj[v]) {
            if (vis[u] == -1) dfs(u, par[vis[u]] = vis[v];
            radj[vis[u]].pb(vis[v]);
        }
    }
    void build(int s) {
        dfs(s);
        for (int i = id - 1; ~i; --i) {
            for (int u : radj[i]) {
                sdom[i] = min(sdom[i], sdom[query(u, false)]);
            }
            if (i) bucket[sdom[i]].pb(i);
            for (int u : bucket[i]) {
                int p = query(u, false);
                dom[u] = sdom[p] == i ? i : p;
            }
            if (i) rt[i] = par[i];
        }
        vector<int> res(n, -1);
        for (int i = 1; i < id; ++i) {
            if (dom[i] != sdom[i]) dom[i] = dom[dom[i]];
        }
        for (int i = 1; i < id; ++i) res[rev[i]] = rev[dom[
            i]];
        res[s] = s;
        dom = res;
    }
};
```

## 2.8 Heavy Light Decomposition

```
vector<int> adj[N];
struct HLD {
    // 0-index
    vector<int> dep, pt, hd, idx, sz, par, vis;
    int n, _t;
    HLD() = default;
    HLD(int _n) : n(_n) {
        pt.assign(n, -1), hd.assign(n, -1), par.assign(n,
            -1);
        idx.assign(n, 0), sz.assign(n, 0), dep.assign(n, 0)
            , vis.assign(n, 0);
        _t = 0;
        for (int i = 0; i < n; ++i) if (!vis[i]) {
            dfs1(i, -1);
            dfs2(i, -1, 0);
        }
    }
    void dfs1(int v, int pa) {
        par[v] = pa;
        dep[v] = ~pa ? dep[pa] + 1 : 0;
        sz[v] = vis[v] = 1;
        for (int u : adj[v]) if (u != pa) {
```

```

    dfs1(u, v);
    if (pt[v] == -1 || sz[pt[v]] < sz[u])
        pt[v] = u;
    sz[v] += sz[u];
}
}
void dfs2(int v, int pa, int h) {
    if (v == -1)
        return;
    idx[v] = _t++, hd[v] = h;
    dfs2(pt[v], v, h);
    for (int u : adj[v]) if (u != pa && u != pt[v]) {
        dfs2(u, v, u);
    }
}
void modify(int u, int v) {
    while (hd[u] != hd[v]) {
        if (dep[hd[u]] < dep[hd[v]])
            swap(u, v);
        // range [idx[hd[u]], idx[u] + 1)
        u = par[hd[u]];
    }
    if (dep[u] < dep[v])
        swap(u, v);
    // range [idx[v], idx[u] + 1)
}
int query(int u, int v) {
    int ans = 0;
    while (hd[u] != hd[v]) {
        if (dep[hd[u]] < dep[hd[v]])
            swap(u, v);
        // range [idx[hd[u]], idx[u] + 1)
        u = par[hd[u]];
    }
    if (dep[u] < dep[v])
        swap(u, v);
    // range [idx[v], idx[u] + 1)
    return ans;
}
};

```

## 2.9 Matroid Intersection

```

/*
Each matroid needs:
vector<bool> build_X(vector<bool> &I)
void build_exchange_graph(vector<vector<int>> &adj,
    vector<bool> &I)
exchange graph has to be opposite. i.e. one i->j one j
->i from two matroids
*/
template <typename M1, typename M2>
struct MatroidIntersection {
    M1 m1;
    M2 m2;
    MatroidIntersection (M1 _m1, M2 _m2) : m1(_m1), m2(
        _m2) {}
    /* 1. build X1, X2
    2. If e \in X1 and e \in X2, add e
    3. Else build exchange graph
        m1 -> add edge from I to E \ I
        m2 -> add edge from E \ I to I
        weight: I -> w, E \ I -> -w
    4. find a minimum path (weight, number) from X1 to
        X2 (use bfs or SPFA) */
    vector<vector<int>> adj;
    vector<int> bfs(vector<bool> &X1, vector<bool> &X2) {
        int n = X1.size();
        queue<int> q;
        vector<int> dis(n, -1), rt(n, -1);
        for (int i = 0; i < n; ++i) if (X1[i])
            q.push(i), dis[i] = 0;
        while (!q.empty()) {
            int v = q.front(); q.pop();
            for (int u : adj[v]) if (dis[u] == -1) {
                dis[u] = dis[v] + 1, rt[u] = v;
                q.push(u);
            }
        }
        pair<int, int> mn = make_pair(1 << 30, -1);

```

```

        for (int i = 0; i < n; ++i) if (X2[i] && dis[i] != -1)
            mn = min(mn, make_pair(dis[i], i));
        int now = mn.second;
        if (now == -1)
            return {};
        vector<int> path = {now};
        while (rt[now] != -1) {
            now = rt[now], path.push_back(now);
        }
        reverse(path.begin(), path.end());
        return path;
    }
    vector<bool> solve(int n) {
        vector<bool> I(n, false);
        while (true) {
            vector<bool> X1 = m1.build_X(I), X2 = m2.build_X(
                I);
            if (count(X1.begin(), X1.end(), 0) == n || count(
                X2.begin(), X2.end(), 0) == n)
                break;
            int add = -1;
            for (int i = 0; i < n; ++i) if (X1[i] && X2[i]) {
                add = i;
                break;
            }
            if (add != -1) {
                I[add] = true;
                continue;
            }
            adj.assign(n, vector<int>());
            m1.build_exchange_graph(adj, I);
            m2.build_exchange_graph(adj, I);
            vector<int> path = bfs(X1, X2);
            if (path.empty())
                break;
            for (int i : path)
                I[i] = !I[i];
        }
        return I;
    }
    vector<int> SPFA(vector<bool> &X1, vector<bool> &
        X2, vector<bool> &I, vector<int> &weight) {
        int n = X1.size();
        queue<int> q;
        vector<pair<int, int>> dis(n, make_pair(1 << 30,
            -1));
        vector<int> rt(n, -1);
        vector<bool> vis(n, false);
        for (int i = 0; i < n; ++i) if (X1[i])
            q.push(i), dis[i] = make_pair(-weight[i], 0), vis[
                i] = true;
        while (!q.empty()) {
            int v = q.front(); q.pop();
            vis[v] = false;
            for (int u : adj[v]) {
                pair<int, int> nxt = make_pair(dis[v].first +
                    (I[u] ? weight[u] : -weight[u]), dis[v].
                    second + 1);
                if (dis[u] > nxt) {
                    dis[u] = nxt, rt[u] = v;
                    if (!vis[u])
                        q.push(u), vis[u] = true;
                }
            }
        }
        pair<pair<int, int>, int> mn = make_pair(
            make_pair(1 << 30, -1), -1);
        for (int i = 0; i < n; ++i) if (X2[i])
            mn = min(mn, make_pair(dis[i], i));
        int now = mn.second;
        if (now == -1)
            return {};
        vector<int> path = {now};
        while (rt[now] != -1) {
            now = rt[now], path.push_back(now);
        }
        reverse(path.begin(), path.end());
        return path;
    }
    vector<bool> solve_max_weight(vector<int> weight) {
        int n = weight.size();

```

```

vector<bool> I(n, false);
while (true) {
    vector<bool> X1 = m1.build_X(I), X2 = m2.build_X(I);
    if (count(X1.begin(), X1.end(), 0) == n || count(X2.begin(), X2.end(), 0) == n)
        break;
    adj.assign(n, vector<int>());
    m1.build_exchange_graph(adj, I);
    m2.build_exchange_graph(adj, I);
    vector<int> path = SPFA(X1, X2, I, weight);
    if (path.empty())
        break;
    for (int i : path)
        I[i] = !I[i];
}
return I;
}
};

```

## 2.10 SCC

```

vector<int> adj[N], radj[N];
struct SCC {
    // 0-indexed
    vector<int> newadj[N];
    vector<int> dfs_ord, idx;
    vector<bool> vis;
    int n, nsc;
    SCC() = default;
    SCC(int _n) : n(_n), nsc(0) {
        vis.assign(n, false), idx.assign(n, -1);
        for (int i = 0; i < n; ++i) if (!vis[i])
            dfs(i);
        reverse(dfs_ord.begin(), dfs_ord.end());
        for (int i : dfs_ord) if (idx[i] == -1)
            rdfs(i), nsc++;
        for (int i = 0; i < n; ++i) for (int j : adj[i]) if (idx[i] != idx[j]) {
            newadj[idx[i]].pb(idx[j]);
        }
        for (int i = 0; i < nsc; ++i) {
            sort(newadj[i].begin(), newadj[i].end());
            newadj[i].resize(unique(newadj[i].begin(), newadj[i].end()) - newadj[i].begin());
        }
    }
    void dfs(int v) {
        vis[v] = true;
        for (int u : adj[v]) if (!vis[u])
            dfs(u);
        dfs_ord.push_back(v);
    }
    void rdfs(int v) {
        idx[v] = nsc;
        for (int u : radj[v]) if (idx[u] == -1)
            rdfs(u);
    }
};

```

## 2.11 Virtual Tree

```

// need lca
vector<int> _g[N], stk;
int st[N], ed[N];
void solve(vector<int> v) {
    auto cmp = [&](int x, int y) {return st[x] < st[y];};
    sort(all(v), cmp);
    int sz = v.size();
    for (int i = 0; i < sz - 1; ++i)
        v.pb(lca(v[i], v[i + 1]));
    sort(all(v), cmp);
    v.resize(unique(all(v)) - v.begin());
    stk.clear(), stk.pb(v[0]);
    for (int i = 1; i < v.size(); ++i) {
        int x = v[i];
        while (ed[stk.back()] < ed[x]) stk.pop_back();
        _g[stk.back()].pb(x), stk.pb(x);
    }
    // do something
    for (int i : v) _g[i].clear();
}

```

## 2.12 Vizing

```

namespace vizing { // returns edge coloring in adjacent
    matrix G, 1 - based
    const int N = 105;
    int C[N][N], G[N][N], X[N], vst[N], n;
    void init(int _n) { n = _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) {
        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;
        };
        fill_n(X + 1, n, 1);
        for (int t = 0; t < E.size(); ++t) {
            int u = E[t].F, v0 = E[t].S, v = v0, c0 = X[u], c = c0, d;
            vector<pii> L;
            fill_n(vst + 1, n, 0);
            while (!G[u][v0]) {
                L.emplace_back(v, d = X[v]);
                if (!C[v][c]) for (int a = (int)L.size() - 1; a >= 0; --a) c = color(u, L[a].F, c);
                else if (!C[u][d]) for (int a = (int)L.size() - 1; a >= 0; --a) color(u, L[a].F, L[a].S);
                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 (int a; C[u][c0]) {
                    for (a = (int)L.size() - 2; a >= 0 && L[a].S != c; --a);
                    for (; a >= 0; --a) color(u, L[a].F, L[a].S);
                }
                else --t;
            }
        }
    }
} // namespace vizing

```

## 2.13 Maximum Clique Dynamic

```

const int N = 150;
struct MaxClique { // Maximum Clique
    bitset<N> a[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++) a[i].reset();
    }
    void addEdge(int u, int v) { a[u][v] = a[v][u] = 1; }
    void csort(vector<int> &r, vector<int> &c) {
        int mx = 1, km = max(ans - q + 1, 1), t = 0, m = r.size();
        cs[1].reset(), cs[2].reset();
        for (int i = 0; i < m; i++) {
            int p = r[i], k = 1;
            while ((cs[k] & a[p]).count()) k++;
            if (k > mx) mx++, cs[mx + 1].reset();
            cs[k][p] = 1;
            if (k < km) r[t++] = p;
        }
        c.resize(m);
    }
};

```

```

    if (t) c[t - 1] = 0;
    for (int k = km; k <= mx; k++)
        for (int p = cs[k]._Find_first(); p < N;
             p = cs[k]._Find_next(p))
            r[t] = p, c[t] = k, t++;
}
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, nc;
        bitset<N> nmask = mask & a[p];
        for (int i : r)
            if (a[p][i]) nr.push_back(i);
        if (!nr.empty()) {
            if (l < 4) {
                for (int i : nr)
                    d[i] = (a[i] & nmask).count();
                sort(nr.begin(), nr.end(),
                    [&](int x, int y) { return d[x] > d[y]; });
            }
            csort(nr, nc), dfs(nr, nc, l + 1, nmask);
        } else if (q > ans) ans = q, copy_n(cur, q, sol);
        c.pop_back(), q--;
    }
}
int solve(bitset<N> mask = bitset<N>(
    string(N, '1'))) { // vertex mask
    vector<int> r, c;
    ans = q = 0;
    for (int i = 0; i < n; i++)
        if (mask[i]) r.push_back(i);
    for (int i = 0; i < n; i++)
        d[i] = (a[i] & mask).count();
    sort(r.begin(), r.end(),
        [&](int i, int j) { return d[i] > d[j]; });
    csort(r, c), dfs(r, c, 1, mask);
    return ans; // sol[0 ~ ans-1]
}
} graph;

```

## 2.14 Theory

$|\text{Maximum independent edge set}| = |V| - |\text{Minimum edge cover}|$   
 $|\text{Maximum independent set}| = |V| - |\text{Minimum vertex cover}|$

# 3 Data Structure

## 3.1 LiChao Tree

```

//C is range of x
//INF is big enough integer
struct Line {
    ll m, k;
    Line(ll _m=0, ll _k=0): m(_m), k(_k){}
    ll val(ll x){return m*x+k;}
};
struct LiChaoTree { //max y value
    Line st[C<<2];
    void init(int l, int r, int id) {
        st[id] = Line(0, 0);
        if (l == r) return;
        int mid = (l + r) / 2;
        init(l, mid, id << 1);
        init(mid + 1, r, id << 1 | 1);
    }
    void upd(int l, int r, Line seg, int id) {
        if (l == r) {
            if (seg.val(l) > st[id].val(l)) st[id] = seg;
            return;
        }
        int mid = (l + r) / 2;
        if (st[id].m > seg.m) swap(st[id], seg);
        if (st[id].val(mid) < seg.val(mid)) {
            swap(st[id], seg);
            upd(l, mid, seg, id << 1);
        } else upd(mid + 1, r, seg, id << 1 | 1);
    }
};

```

```

}
ll qry(int l, int r, ll x, int id) {
    if (l == r) return st[id].val(x);
    int mid = (l + r) / 2;
    if (x <= mid) return max(qry(l, mid, x, id << 1), st[id].val(x));
    else return max(qry(mid + 1, r, x, id << 1 | 1), st[id].val(x));
}
};

```

## 3.2 Dynamic Line Hull

```

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<>> {
    static const ll inf = LLONG_MAX;
    ll div(ll a, ll b) {
        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;
    }
};

```

## 3.3 Leftist Tree

```

struct node {
    ll rk, data, sz, sum;
    node *l, *r;
    node(ll k) : rk(0), data(k), sz(1), l(0), r(0), sum(k) {}
};
ll sz(node *p) { return p ? p->sz : 0; }
ll rk(node *p) { return p ? p->rk : -1; }
ll sum(node *p) { return p ? p->sum : 0; }
node *merge(node *a, node *b) {
    if (!a || !b) return a ? a : b;
    if (a->data < b->data) swap(a, b);
    a->r = merge(a->r, b);
    if (rk(a->r) > rk(a->l)) swap(a->r, a->l);
    a->rk = rk(a->r) + 1, a->sz = sz(a->l) + sz(a->r) + 1;
    a->sum = sum(a->l) + sum(a->r) + a->data;
    return a;
}
void pop(node *&o) {
    node *tmp = o;
    o = merge(o->l, o->r);
    delete tmp;
}

```

## 3.4 Link Cut Tree

```

// weighted subtree size, weighted path max
struct LCT {
    int ch[N][2], pa[N], v[N], sz[N], sz2[N], w[N], mx[N], _id;
    // sz := sum of v in splay, sz2 := sum of v in virtual subtree
    // mx := max w in splay
    bool rev[N];
};

```



```

LCT() : _id(1) {}
int newnode(int _v, int _w) {
    int x = _id++;
    ch[x][0] = ch[x][1] = pa[x] = 0;
    v[x] = sz[x] = _v;
    sz2[x] = 0;
    w[x] = mx[x] = _w;
    rev[x] = false;
    return x;
}
void pull(int i) {
    sz[i] = v[i] + sz2[i];
    mx[i] = w[i];
    if (ch[i][0])
        sz[i] += sz[ch[i][0]], mx[i] = max(mx[i], mx[ch[i][0]]);
    if (ch[i][1])
        sz[i] += sz[ch[i][1]], mx[i] = max(mx[i], mx[ch[i][1]]);
}
void push(int i) {
    if (rev[i]) reverse(ch[i][0]), reverse(ch[i][1]),
        rev[i] = false;
}
void reverse(int i) {
    if (!i) return;
    swap(ch[i][0], ch[i][1]);
    rev[i] ^= true;
}
bool isrt(int i) { // rt of splay
    if (!pa[i]) return true;
    return ch[pa[i]][0] != i && ch[pa[i]][1] != i;
}
void rotate(int i) {
    int p = pa[i], x = ch[p][1] == i, c = ch[i][!x], gp = pa[p];
    if (ch[gp][0] == p) ch[gp][0] = i;
    else if (ch[gp][1] == p) ch[gp][1] = i;
    pa[i] = gp, ch[i][!x] = p, pa[p] = i;
    ch[p][x] = c, pa[c] = p;
    pull(p), pull(i);
}
void splay(int i) {
    vector<int> anc;
    anc.push_back(i);
    while (!isrt(anc.back())) anc.push_back(pa[anc.back()]);
    while (!anc.empty()) push(anc.back()), anc.pop_back();
    while (!isrt(i)) {
        int p = pa[i];
        if (!isrt(p)) rotate(ch[p][1] == i ^ ch[pa[p]][1] == p ? i : p);
        rotate(i);
    }
}
void access(int i) {
    int last = 0;
    while (i) {
        splay(i);
        if (ch[i][1])
            sz2[i] += sz[ch[i][1]];
        sz2[i] -= sz[last];
        ch[i][1] = last;
        pull(i), last = i, i = pa[i];
    }
}
void makert(int i) {
    access(i), splay(i), reverse(i);
}
void link(int i, int j) {
    // assert(findrt(i) != findrt(j));
    makert(i);
    makert(j);
    pa[i] = j;
    sz2[j] += sz[i];
    pull(j);
}
void cut(int i, int j) {
    makert(i), access(j), splay(i);
    // assert(sz[i] == 2 && ch[i][1] == j);
    ch[i][1] = pa[j] = 0, pull(i);
}

```

```

}
int findrt(int i) {
    access(i), splay(i);
    while (ch[i][0]) push(i), i = ch[i][0];
    splay(i);
    return i;
}
};

```

### 3.5 Sparse Table

```

template <typename T>
struct SparseTableMin {
    // 0-indexed, [l, r)
    vector<vector<T>> table;
    SparseTableMin() = default;
    SparseTableMin(vector<T> a) {
        int n = a.size();
        int m = __lg(n) + 1;
        table.resize(n, vector<T>(m, 0));
        for (int i = 0; i < n; ++i)
            table[i][0] = a[i];
        for (int j = 1; j < m; ++j) {
            for (int i = 0; i + (1 << j) <= n; ++i) {
                table[i][j] = min(table[i][j - 1], table[i + (1 << j - 1)][j - 1]);
            }
        }
    }
    T query(int l, int r) {
        if (l >= r)
            return 1 << 30;
        int g = __lg(r - l);
        return min(table[l][g], table[r - (1 << g)][g]);
    }
};

```

### 3.6 Splay Tree

```

struct Splay {
    int pa[N], ch[N][2], sz[N], rt, _id;
    ll v[N];
    Splay() {}
    void init() {
        rt = 0, pa[0] = ch[0][0] = ch[0][1] = -1;
        sz[0] = 1, v[0] = inf;
    }
    int newnode(int p, int x) {
        int id = _id++;
        v[id] = x, pa[id] = p;
        ch[id][0] = ch[id][1] = -1, sz[id] = 1;
        return id;
    }
    void rotate(int i) {
        int p = pa[i], x = ch[p][1] == i, gp = pa[p], c = ch[i][!x];
        sz[p] -= sz[i], sz[i] += sz[p];
        if (~c) sz[p] += sz[c], pa[c] = p;
        ch[p][x] = c, pa[p] = i;
        pa[i] = gp, ch[i][!x] = p;
        if (~gp) ch[gp][ch[gp][1] == p] = i;
    }
    void splay(int i) {
        while (~pa[i]) {
            int p = pa[i];
            if (~pa[p]) rotate(ch[pa[p]][1] == p ^ ch[p][1] == i ? i : p);
            rotate(i);
        }
        rt = i;
    }
    int lower_bound(int x) {
        int i = rt, last = -1;
        while (true) {
            if (v[i] == x) return splay(i), i;
            if (v[i] > x) {
                last = i;
                if (ch[i][0] == -1) break;
                i = ch[i][0];
            }
            else {
                if (ch[i][1] == -1) break;
            }
        }
    }
};

```

```

        i = ch[i][1];
    }
}
splay(i);
return last; // -1 if not found
}
void insert(int x) {
    int i = lower_bound(x);
    if (i == -1) {
        // assert(ch[rt][1] == -1);
        int id = newnode(rt, x);
        ch[rt][1] = id, ++sz[rt];
        splay(id);
    }
    else if (v[i] != x) {
        splay(i);
        int id = newnode(rt, x), c = ch[rt][0];
        ch[rt][0] = id;
        ch[id][0] = c;
        if (~c) pa[c] = id, sz[id] += sz[c];
        ++sz[rt];
        splay(id);
    }
}
};

```

### 3.7 Treap

```

struct Treap {
    int pri, sz, val;
    Treap *tl, *tr;
    Treap(int x) : val(x), sz(1), pri(rand()), tl(NULL), tr(NULL) {}
    void pull() {
        sz = (tl ? tl->sz : 0) + 1 + (tr ? tr->sz : 0);
    }
    void out() {
        if (tl) tl->out();
        cout << val << ' ';
        if (tr) tr->out();
    }
};
void print(Treap *t) {
    t->out();
    cout << endl;
}
Treap* merge(Treap *a, Treap *b) {
    if (!a || !b) return a ? a : b;
    if (a->pri < b->pri) {
        a->tr = merge(a->tr, b);
        a->pull();
        return a;
    } else {
        b->tl = merge(a, b->tl);
        b->pull();
        return b;
    }
}
void split(Treap* t, int k, Treap* &a, Treap* &b) {
    if (!t) a = b = NULL;
    else if ((t->tl ? t->tl->sz : 0) + 1 <= k) {
        a = t;
        split(t->tr, k - (t->tl ? t->tl->sz : 0) - 1, a->tr, b);
        a->pull();
    } else {
        b = t;
        split(t->tl, k, a, b->tl);
        b->pull();
    }
}

```

## 4 Flow/Matching

### 4.1 Hopcroft Karp

```

struct HopcroftKarp {
    const int INF = 1 << 30;
    vector<int> adj[N];
    int match[N], dis[N], v, n, m;
    bool matched[N], vis[N];

```

```

    bool dfs(int x) {
        vis[x] = true;
        for (int y : adj[x])
            if (match[y] == -1 || (dis[match[y]] == dis[x] + 1 && !vis[match[y]] && dfs(match[y]))) {
                match[y] = x, matched[x] = true;
                return true;
            }
        return false;
    }
    bool bfs() {
        memset(dis, -1, sizeof(int) * n);
        queue<int> q;
        for (int x = 0; x < n; ++x) if (!matched[x])
            dis[x] = 0, q.push(x);
        int mx = INF;
        while (!q.empty()) {
            int x = q.front(); q.pop();
            for (int y : adj[x]) {
                if (match[y] == -1) {
                    mx = dis[x];
                    break;
                } else if (dis[match[y]] == -1)
                    dis[match[y]] = dis[x] + 1, q.push(match[y]);
            }
        }
        return mx < INF;
    }
    int solve() {
        int res = 0;
        memset(match, -1, sizeof(int) * m);
        memset(matched, 0, sizeof(bool) * n);
        while (bfs()) {
            memset(vis, 0, sizeof(bool) * n);
            for (int x = 0; x < n; ++x) if (!matched[x])
                res += dfs(x);
        }
        return res;
    }
    void init(int _n, int _m) {
        n = _n, m = _m;
        for (int i = 0; i < n; ++i) adj[i].clear();
    }
    void add_edge(int x, int y) {
        adj[x].pb(y);
    }
};

```

### 4.2 Dinic

```

struct Dinic {
    const int INF = 1 << 30;
    struct edge {
        int v, f;
        edge(int _v, int _f) : v(_v), f(_f) {}
    };
    vector<vector<int>> adj;
    vector<edge> E;
    vector<int> level;
    int n, s, t;
    Dinic(int _n, int _s, int _t) : n(_n), s(_s), t(_t) {
        adj.resize(n);
    }
    void add_edge(int u, int v, int f) {
        adj[u].pb(E.size());, E.pb(edge(v, f));
        adj[v].pb(E.size());, E.pb(edge(u, 0));
    }
    bool bfs() {
        level.assign(n, -1);
        queue<int> q;
        level[s] = 0, q.push(s);
        while (!q.empty()) {
            int v = q.front(); q.pop();
            for (int id : adj[v]) if (E[id].f > 0 && level[E[id].v] == -1) {
                level[E[id].v] = level[v] + 1;
                q.push(E[id].v);
            }
        }
        return level[t] != -1;
    }
    int dfs(int v, int minf) {
        if (v == t) return minf;

```



```

    int ans = 0;
    for (int id : adj[v]) if (E[id].f > 0 && level[E[id].v] == level[v] + 1) {
        int nxtf = dfs(E[id].v, min(minf, E[id].f));
        minf -= nxtf, E[id].f -= nxtf;
        ans += nxtf, E[id ^ 1].f += nxtf;
        if (!minf) return ans;
    }
    if (!ans) level[v] = -1;
    return ans;
}
int runFlow() {
    int ans = 0;
    while (bfs()) ans += dfs(s, INF);
    return ans;
}
};

```

### 4.3 Min Cost Max Flow

```

struct MCMF {
    const int INF = 1 << 30;
    struct edge {
        int v, f, c;
        edge(int _v, int _f, int _c) : v(_v), f(_f), c(_c) {}
    };
    vector<edge> E;
    vector<vector<int>> adj;
    vector<int> dis, pot, rt;
    int n, s, t;
    MCMF(int _n, int _s, int _t) : n(_n), s(_s), t(_t) {
        adj.resize(n);
    }
    void add_edge(int u, int v, int f, int c) {
        adj[u].pb(E.size(), E.pb(edge(v, f, c)));
        adj[v].pb(E.size(), E.pb(edge(u, 0, -c)));
    }
    bool SPFA() {
        rt.assign(n, -1), dis.assign(n, INF);
        vector<bool> vis(n, false);
        queue<int> q;
        q.push(s), dis[s] = 0, vis[s] = true;
        while (!q.empty()) {
            int v = q.front(); q.pop();
            vis[v] = false;
            for (int id : adj[v]) if (E[id].f > 0 && dis[E[id].v] > dis[v] + E[id].c + pot[v] - pot[E[id].v]) {
                dis[E[id].v] = dis[v] + E[id].c + pot[v] - pot[E[id].v];
                rt[E[id].v] = id;
                if (!vis[E[id].v]) vis[E[id].v] = true, q.push(E[id].v);
            }
        }
        return dis[t] != INF;
    }
    bool dijkstra() {
        rt.assign(n, -1), dis.assign(n, INF);
        priority_queue<pair<int, int>, vector<pair<int, int>>, greater<pair<int, int>>> pq;
        dis[s] = 0, pq.emplace(dis[s], s);
        while (!pq.empty()) {
            int d, v; tie(d, v) = pq.top(); pq.pop();
            if (dis[v] < d) continue;
            for (int id : adj[v]) if (E[id].f > 0 && dis[E[id].v] > dis[v] + E[id].c + pot[v] - pot[E[id].v]) {
                dis[E[id].v] = dis[v] + E[id].c + pot[v] - pot[E[id].v];
                rt[E[id].v] = id;
                pq.emplace(dis[E[id].v], E[id].v);
            }
        }
        return dis[t] != INF;
    }
    pair<int, int> runFlow() {
        pot.assign(n, 0);
        int cost = 0, flow = 0;
        bool fr = true;
        while ((fr ? SPFA() : dijkstra())) {
            for (int i = 0; i < n; i++) {
                dis[i] += pot[i] - pot[s];
            }
        }
    }
};

```

```

    }
    int add = INF;
    for (int i = t; i != s; i = E[rt[i] ^ 1].v) {
        add = min(add, E[rt[i]].f);
    }
    for (int i = t; i != s; i = E[rt[i] ^ 1].v) {
        E[rt[i]].f -= add, E[rt[i] ^ 1].f += add;
    }
    flow += add, cost += add * dis[t];
    fr = false;
    swap(dis, pot);
}
return make_pair(flow, cost);
}
};

```

### 4.4 Min Cost Circulation

```

template<typename F, typename C>
struct MinCostCirculation {
    struct ep { int to; F flow; C cost; };
    int n; vector<int> vis; int visc;
    vector<int> fa, fae; vector<vector<int>> g;
    vector<ep> e; vector<C> pi;
    MinCostCirculation(int n_) : n(n_), vis(n), visc(0),
        g(n), pi(n) {}
    void add_edge(int u, int v, F fl, C cs) {
        g[u].emplace_back((int)e.size());
        e.emplace_back(v, fl, cs);
        g[v].emplace_back((int)e.size());
        e.emplace_back(u, 0, -cs);
    }
    C phi(int x) {
        if (fa[x] == -1) return 0;
        if (vis[x] == visc) return pi[x];
        vis[x] = visc;
        return pi[x] = phi(fa[x]) - e[fae[x]].cost;
    }
    int lca(int u, int v) {
        for (; u != -1 || v != -1; swap(u, v)) if (u != -1) {
            if (vis[u] == visc) return u;
            vis[u] = visc; u = fa[u];
        }
        return -1;
    }
    void pushflow(int x, C &cost) {
        int v = e[x ^ 1].to, u = e[x].to; ++visc;
        if (int w = lca(u, v); w == -1) {
            while (v != -1)
                swap(x ^ 1, fae[v]), swap(u, fa[v]), swap(u, v);
        } else {
            int z = u, dir = 0; F f = e[x].flow;
            vector<int> cyc = {x};
            for (int d : {0, 1})
                for (int i = (d ? u : v); i != w; i = fa[i]) {
                    cyc.push_back(fae[i] ^ d);
                    if (chmin(f, e[fae[i] ^ d].flow)) z = i, dir = d;
                }
            for (int i : cyc) {
                e[i].flow -= f; e[i ^ 1].flow += f;
                cost += f * e[i].cost;
            }
            if (dir) x ^= 1, swap(u, v);
            while (u != z)
                swap(x ^ 1, fae[v]), swap(u, fa[v]), swap(u, v);
        }
    }
    void dfs(int u) {
        vis[u] = visc;
        for (int i : g[u])
            if (int v = e[i].to; vis[v] != visc and e[i].flow)
                fa[v] = u, fae[v] = i, dfs(v);
    }
    C simplex() {
        fa.assign(g.size(), -1); fae.assign(g.size(), -1);
        C cost = 0; ++visc; dfs(0);
        for (int fail = 0; fail < ssize(e); )

```

```

    for (int i = 0; i < ssize(e); i++)
        if (e[i].flow and e[i].cost < phi(e[i ^ 1].to)
            - phi(e[i].to))
            fail = 0, pushflow(i, cost), ++visc;
        else ++fail;
    return cost;
}
};

```

## 4.5 Kuhn Munkres

```

template <typename T>
struct KM { // 0-based
    const T INF = 1 << 30;
    T w[N][N], hl[N], hr[N], slk[N];
    int fl[N], fr[N], pre[N], n;
    bool vl[N], vr[N];
    queue <int> q;
    KM () {}
    void init(int _n) {
        n = _n;
        for (int i = 0; i < n; ++i)
            for (int j = 0; j < n; ++j) w[i][j] = -INF;
    }
    void add_edge(int a, int b, T wei) { w[a][b] = wei; }
    bool check(int x) {
        if (vl[x] = 1, ~fl[x])
            return q.push(fl[x]), vr[fl[x]] = 1;
        while (~x) swap(x, fr[fl[x] = pre[x]]);
        return 0;
    }
    void bfs(int s) {
        fill(slk, slk + n, INF), fill(vl, vl + n, 0);
        fill(vr, vr + n, 0);
        while (!q.empty()) q.pop();
        q.push(s), vr[s] = 1;
        while (true) {
            T d;
            while (!q.empty()) {
                int y = q.front(); q.pop();
                for (int x = 0; 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;
        }
    }
    T solve() {
        fill(fl, fl + n, -1), fill(fr, fr + n, -1);
        fill(hr, 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);
        T res = 0;
        for (int i = 0; i < n; ++i) res += w[i][fl[i]];
        return res;
    }
};

```

## 4.6 Stoer Wagner (Min-cut)

```

struct SW {
    int g[N][N], sum[N], n;
    bool vis[N], dead[N];
    void init(int _n) {
        n = _n;
        for (int i = 0; i < n; ++i) fill(g[i], g[i] + n, 0);
        fill(dead, dead + n, false);
    }
    void add_edge(int u, int v, int w) {

```

```

        g[u][v] += w, g[v][u] += w;
    }
    int run() {
        int ans = 1 << 30;
        for (int round = 0; round + 1 < n; ++round) {
            fill(vis, vis + n, false), fill(sum, sum + n, 0);
            int num = 0, s = -1, t = -1;
            while (num < n - round) {
                int now = -1;
                for (int i = 0; i < n; ++i) if (!vis[i] && !
                    dead[i]) {
                    if (now == -1 || sum[now] < sum[i]) now = i;
                }
                s = t, t = now;
                vis[now] = true, num++;
                for (int i = 0; i < n; ++i) if (!vis[i] && !
                    dead[i]) {
                    sum[i] += g[now][i];
                }
            }
            ans = min(ans, sum[t]);
            for (int i = 0; i < n; ++i) {
                g[i][s] += g[i][t];
                g[s][i] += g[t][i];
            }
            dead[t] = true;
        }
        return ans;
    }
};

```

## 4.7 GomoryHu Tree

```

vector <array <int, 3>> GomoryHu(vector <vector <pii>>
    adj, int n) {
    // Tree edge min -> mincut (0-based)
    Dinic flow(n);
    for (int i = 0; i < n; ++i) for (auto [j, w] : adj[i]
        ])
        flow.add_edge(i, j, w);
    flow.record();
    vector <array <int, 3>> ans;
    vector <int> rt(n);
    for (int i = 0; i < n; ++i) rt[i] = 0;
    for (int i = 1; i < n; ++i) {
        int t = rt[i];
        flow.reset(); // clear flows on all edge
        ans.push_back({i, t, flow.solve(i, t)});
        flow.runbfs(i);
        for (int j = i + 1; j < n; ++j) if (rt[j] == t &&
            flow.vis[j]) {
            rt[j] = i;
        }
    }
    return ans;
}

```

## 4.8 General Graph Matching

```

struct Matching { // 0-based
    int fa[N], pre[N], match[N], s[N], v[N], n, tk;
    vector <int> g[N];
    queue <int> q;
    Matching (int _n) : n(_n), tk(0) {
        for (int i = 0; i <= n; ++i) match[i] = pre[i] = n;
        for (int i = 0; i < n; ++i) g[i].clear();
    }
    void add_edge(int u, int v) {
        g[u].push_back(v), g[v].push_back(u);
    }
    int Find(int u) {
        return u == fa[u] ? u : fa[u] = Find(fa[u]);
    }
    int lca(int x, int y) {
        tk++;
        x = Find(x), y = Find(y);
        for (; ; swap(x, y)) {
            if (x != n) {
                if (v[x] == tk) return x;
                v[x] = tk;
                x = Find(pre[match[x]]);
            }

```

```

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

```

## 4.9 Flow notes

Bipartite Matching Restore Answer

```

runBfs();
Answer -> {!vis[x] | x \in L} U {vis[x] | x \in R}

```

Bipartite Minimum Weight Vertex Covering

$S \rightarrow \{x \mid x \in L\}$ , cap = weight of vertex  $x$   
 $\{x \mid x \in L\} \rightarrow \{y \mid y \in R\}$ , cap = INF  
 $\{y \mid y \in R\} \rightarrow T$ , cap = weight of vertex  $y$

For general version, change Dinic to MCMF and:

$S \rightarrow \{x \mid x \in L\}$ , cap = weight of vertex  $x$ , cost = 0  
 $\{x \mid x \in L\} \rightarrow \{y \mid y \in R\}$ , cap = INF, cost = -w  
 $\{y \mid y \in R\} \rightarrow T$ , cap = weight of vertex  $y$ , cost = 0

{Bipartite Maximum Weight Independent Set} +  
 {Bipartite Minimum Weight Vertex Covering} = weight sum

Min Cut Model

choose A but **not** choose B cost  $x$   
 $A \rightarrow B$ , cap =  $x$   
 choose A cost  $x$   
 $A \rightarrow T$ , cap =  $x$   
**not** choose A cost  $x$   
 $S \rightarrow A$ , cap =  $x$   
 choose A gain  $x \Rightarrow$  **not** choose A cost  $x$ , tot +=  $x$

choose A **and** choose B cost  $x \rightarrow$  NO!!!  
 Bipartite  $\rightarrow$  can flip one side

Min Cut Restore Answer

```

runBfs();
{vis[x] | x \in V}

```

## 4.10 More Flow Models

- Maximum/Minimum flow with lower bound / Circulation problem
  - Construct super source  $S$  and sink  $T$ .
  - For each edge  $(x, y, l, u)$ , connect  $x \rightarrow y$  with capacity  $u - l$ .
  - For each vertex  $v$ , denote by  $in(v)$  the difference between the sum of incoming lower bounds and the sum of outgoing lower bounds.
  - 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  $\infty$  (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  $\infty$  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.
  - 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  $(X, Y)$ 
  - Redirect every edge:  $y \rightarrow x$  if  $(x, y) \in M$ ,  $x \rightarrow y$  otherwise.
  - DFS from unmatched vertices in  $X$ .
  - $x \in X$  is chosen iff  $x$  is unvisited.
  - $y \in Y$  is chosen iff  $y$  is visited.
- Maximum density induced subgraph
  - Binary search on answer, suppose we're checking answer  $T$
  - Construct a max flow model, let  $K$  be the sum of all weights
  - Connect source  $s \rightarrow v$ ,  $v \in G$  with capacity  $K$
  - For each edge  $(u, v, w)$  in  $G$ , connect  $u \rightarrow v$  and  $v \rightarrow u$  with capacity  $w$
  - For  $v \in G$ , connect it with sink  $v \rightarrow t$  with capacity  $K + 2T - (\sum_{e \in E(v)} w(e)) - 2w(v)$
  - $T$  is a valid answer if the maximum flow  $f < K|V|$
- Minimum weight edge cover
  - For each  $v \in V$  create a copy  $v'$ , and connect  $u \rightarrow v'$  with weight  $w(u, v)$ .
  - Connect  $v \rightarrow v'$  with weight  $2\mu(v)$ , where  $\mu(v)$  is the cost of the cheapest edge incident to  $v$ .
  - Find the minimum weight perfect matching on  $G'$ .
- Project selection problem
  - If  $p_v > 0$ , create edge  $(s, v)$  with capacity  $p_v$ ; otherwise, create edge  $(v, t)$  with capacity  $-p_v$ .
  - Create edge  $(u, v)$  with capacity  $w$  with  $w$  being the cost of choosing  $u$  without choosing  $v$ .
  - The mincut is equivalent to the maximum profit of a subset of projects.

- 0/1 quadratic programming

$$\sum_x c_x x + \sum_y c_y \bar{y} + \sum_{xy} c_{xy} x \bar{y} + \sum_{xyx'y'} c_{xyx'y'} (x \bar{y} + x' \bar{y}')$$

can be minimized by the mincut of the following graph:

- Create edge  $(x, t)$  with capacity  $c_x$  and create edge  $(s, y)$  with capacity  $c_y$ .
- Create edge  $(x, y)$  with capacity  $c_{xy}$ .
- Create edge  $(x, y)$  and edge  $(x', y')$  with capacity  $c_{xyx'y'}$ .

## 5 String

### 5.1 AC Automaton

```

struct AC {
    int ch[N][26], to[N][26], fail[N], sz;
    vector<int> g[N];
    int cnt[N];
    AC () {sz = 0, extend();}
    void extend() {fill(ch[sz], ch[sz] + 26, 0), sz++;}
    int nxt(int u, int v) {
        if (!ch[u][v]) ch[u][v] = sz, extend();
        return ch[u][v];
    }
    int insert(string s) {
        int now = 0;

```

```

for (char c : s) now = nxt(now, c - 'a');
cnt[now]++;
return now;
}
void build_fail() {
    queue<int> q;
    for (int i = 0; i < 26; ++i) if (ch[0][i]) {
        to[0][i] = ch[0][i];
        q.push(ch[0][i]);
        g[0].push_back(ch[0][i]);
    }
    while (!q.empty()) {
        int v = q.front(); q.pop();
        for (int j = 0; j < 26; ++j) {
            to[v][j] = ch[v][j] ? ch[v][j] : to[fail[v]][j];
        }
        for (int i = 0; i < 26; ++i) if (ch[v][i]) {
            int u = ch[v][i], k = fail[v];
            while (k && !ch[k][i]) k = fail[k];
            if (ch[k][i]) k = ch[k][i];
            fail[u] = k;
            cnt[u] += cnt[k], g[k].push_back(u);
            q.push(u);
        }
    }
}
int match(string &s) {
    int now = 0, ans = 0;
    for (char c : s) {
        now = to[now][c - 'a'];
        if (ch[now][c - 'a']) now = ch[now][c - 'a'];
        ans += cnt[now];
    }
    return ans;
}
};

```

## 5.2 KMP

```

vector<int> build_fail(string &s) {
    vector<int> f(s.length() + 1, 0);
    int k = 0;
    for (int i = 1; i < s.length(); ++i) {
        while (k && s[k] != s[i])
            k = f[k];
        if (s[k] == s[i])
            k++;
        f[i + 1] = k;
    }
    return f;
}
int match(string &s, string &t) {
    vector<int> f = build_fail(t);
    int k = 0, ans = 0;
    for (int i = 0; i < s.length(); ++i) {
        while (k && s[i] != t[k])
            k = f[k];
        if (s[i] == t[k])
            k++;
        if (k == t.length())
            ans++, k = f[k];
    }
    return ans;
}

```

## 5.3 Manacher

```

int z[MAXN]; // 0-base
/* center i: radius z[i * 2 + 1] / 2
   center i, i + 1: radius z[i * 2 + 2] / 2
   both aba, abba have radius 2 */
void Manacher(string tmp) {
    string s = "%";
    int l = 0, r = 0;
    for (char c : tmp) s.pb(c), s.pb('%');
    for (int i = 0; i < s.size(); ++i) {
        z[i] = r > i ? min(z[2 * l - i], r - i) : 1;
        while (i - z[i] >= 0 && i + z[i] < s.size()
            && s[i + z[i]] == s[i - z[i]]) ++z[i];
        if (z[i] + i > r) r = z[i] + i, l = i;
    }
}

```

## 5.4 Minimum Rotate

```

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

```

## 5.5 Palindrome Tree

```

struct PAM {
    int ch[N][26], cnt[N], fail[N], len[N], sz;
    string s;
    // 0 -> even root, 1 -> odd root
    PAM() {}
    void init(string s) {
        sz = 0, extend(), extend();
        len[0] = 0, fail[0] = 1, len[1] = -1;
        int lst = 1;
        for (int i = 0; i < s.length(); ++i) {
            while (s[i - len[lst] - 1] != s[i])
                lst = fail[lst];
            if (!ch[lst][s[i] - 'a']) {
                int idx = extend();
                len[idx] = len[lst] + 2;
                int now = fail[lst];
                while (s[i - len[now] - 1] != s[i])
                    now = fail[now];
                fail[idx] = ch[now][s[i] - 'a'];
                ch[lst][s[i] - 'a'] = idx;
            }
            lst = ch[lst][s[i] - 'a'], cnt[lst]++;
        }
    }
    void build_count() {
        for (int i = sz - 1; i > 1; --i)
            cnt[fail[i]] += cnt[i];
    }
    int extend() {
        fill(ch[sz], ch[sz] + 26, 0), sz++;
        return sz - 1;
    }
};

```

## 5.6 Repetition

```

int to_left[N], to_right[N];
vector<array<int, 3>> rep; // l, r, len.
// substr( [l, r], len * 2) are tandem
void findRep(string &s, int l, int r) {
    if (r - l == 1) return;
    int m = l + r >> 1;
    findRep(s, l, m), findRep(s, m, r);
    string sl = s.substr(l, m - l);
    string sr = s.substr(m, r - m);
    vector<int> Z = buildZ(sr + "#" + sl);
    for (int i = 1; i < m; ++i)
        to_right[i] = Z[r - m + 1 + i - 1];
    reverse(all(sl));
    Z = buildZ(sl);
    for (int i = 1; i < m; ++i)
        to_left[i] = Z[m - i - 1];
    reverse(all(sl));
    for (int i = 1; i + 1 < m; ++i) {
        int k1 = to_left[i], k2 = to_right[i + 1];
        int len = m - i - 1;
        if (k1 < 1 || k2 < 1 || len < 2) continue;
        int tl = max(1, len - k2), tr = min(len - 1, k1);
        if (tl <= tr) rep.pb({i + 1 - tr, i + 1 - tl, len});
    }
    Z = buildZ(sr);
    for (int i = m; i < r; ++i) to_right[i] = Z[i - m];
    reverse(all(sl)), reverse(all(sr));
    Z = buildZ(sl + "#" + sr);
}

```

```

for (int i = m; i < r; ++i)
    to_left[i] = Z[m - 1 + 1 + r - i - 1];
reverse(all(s1)), reverse(all(sr));
for (int i = m; i + 1 < r; ++i) {
    int k1 = to_left[i], k2 = to_right[i + 1];
    int len = i - m + 1;
    if (k1 < 1 || k2 < 1 || len < 2) continue;
    int tl = max(len - k2, 1), tr = min(len - 1, k1);
    if (tl <= tr)
        rep.pb({i + 1 - len - tr, i + 1 - len - tl, len});
}
Z = buildZ(sr + "#" + s1);
for (int i = 1; i < m; ++i)
    if (Z[r - m + 1 + i - 1] >= m - i)
        rep.pb({i, i, m - i});
}

```

## 5.7 Suffix Array

```

int sa[N], tmp[2][N], c[N], rk[N], lcp[N];
void buildSA(string s) {
    int *x = tmp[0], *y = tmp[1], m = 256, n = s.length();
    for (int i = 0; i < m; ++i) c[i] = 0;
    for (int i = 0; i < n; ++i) c[x[i]] = s[i]++;
    for (int i = 1; i < m; ++i) c[i] += c[i - 1];
    for (int i = n - 1; ~i; --i) sa[--c[x[i]]] = i;
    for (int k = 1; k < n; k <= 1) {
        for (int i = 0; i < m; ++i) c[i] = 0;
        for (int i = 0; i < n; ++i) c[x[i]]++;
        for (int i = 1; i < m; ++i) c[i] += c[i - 1];
        int p = 0;
        for (int i = n - k; i < n; ++i) y[p++] = i;
        for (int i = 0; i < n; ++i) if (sa[i] >= k) y[p++] = sa[i] - k;
        for (int i = n - 1; ~i; --i) sa[--c[x[y[i]]]] = y[i];
        y[sa[0]] = p = 0;
        for (int i = 1; i < n; ++i) {
            int a = sa[i], b = sa[i - 1];
            if (!(x[a] == x[b] && a + k < n && b + k < n && x[a + k] == x[b + k])) p++;
            y[sa[i]] = p;
        }
        if (n == p + 1) break;
        swap(x, y), m = p + 1;
    }
}
void buildLCP(string s) {
    // lcp[i] = LCP(sa[i - 1], sa[i])
    // lcp(i, j) = min(lcp[rk[i] + 1], lcp[rk[i] + 2], ..., lcp[rk[j]])
    int n = s.length(), val = 0;
    for (int i = 0; i < n; ++i) rk[sa[i]] = i;
    for (int i = 0; i < n; ++i) {
        if (!rk[i]) lcp[rk[i]] = 0;
        else {
            if (val) val--;
            int p = sa[rk[i] - 1];
            while (val + i < n && val + p < n && s[val + i] == s[val + p]) val++;
            lcp[rk[i]] = val;
        }
    }
}

```

## 5.8 SAIS (C++20)

```

auto sais(const auto &s) {
    const int n = SZ(s), z = ranges::max(s) + 1;
    if (n == 1) return vector{0};
    vector<int> c(z); for (int x : s) ++c[x];
    partial_sum(ALL(c), begin(c));
    vector<int> sa(n); auto I = views::iota(0, n);
    vector<bool> t(n, true);
    for (int i = n - 2; i >= 0; --i)
        t[i] = (s[i] == s[i + 1] ? t[i + 1] : s[i] < s[i + 1]);
    auto is_lms = views::filter([&t](int x) {
        return x && t[x] && !t[x - 1];
    });
    auto induce = [&] {

```

```

        for (auto x = c; int y : sa)
            if (y-- if (!t[y]) sa[x[s[y] - 1]++] = y;
        for (auto x = c; int y : sa | views::reverse)
            if (y-- if (t[y]) sa[--x[s[y]]] = y;
    };
    vector<int> lms, q(n); lms.reserve(n);
    for (auto x = c; int i : I | is_lms)
        q[i] = SZ(lms), lms.pb(sa[--x[s[i]]] = i);
    induce(); vector<int> ns(SZ(lms));
    for (int j = -1, nz = 0; int i : sa | is_lms) {
        if (j >= 0) {
            int len = min({n - i, n - j, lms[q[i] + 1] - i});
            ns[q[i]] = nz += lexicographical_compare(
                begin(s) + j, begin(s) + j + len,
                begin(s) + i, begin(s) + i + len);
        }
        j = i;
    }
    fill(ALL(sa), 0); auto nsa = sais(ns);
    for (auto x = c; int y : nsa | views::reverse)
        y = lms[y], sa[--x[s[y]]] = y;
    return induce(), sa;
}
// sa[i]: sa[i]-th suffix is the i-th lexicographically
// smallest suffix.
// hi[i]: LCP of suffix sa[i] and suffix sa[i - 1].
struct Suffix {
    int n; vector<int> sa, hi, ra;
    Suffix(const auto &s, int _n) : n(_n), hi(n), ra(n) {
        vector<int> s(n + 1); // s[n] = 0;
        copy_n(_s, n, begin(s)); // _s shouldn't contain 0
        sa = sais(s); sa.erase(sa.begin());
        for (int i = 0; i < n; ++i) ra[sa[i]] = i;
        for (int i = 0, h = 0; i < n; ++i) {
            if (!ra[i]) { h = 0; continue; }
            for (int j = sa[ra[i] - 1]; max(i, j) + h < n &&
                s[i + h] == s[j + h];) ++h;
            hi[ra[i]] = h ? h - 1 : 0;
        }
    }
};

```

## 5.9 Suffix Automaton

```

struct SAM {
    int ch[N][26], len[N], link[N], pos[N], cnt[N], sz;
    // node -> strings with the same endpos set
    // length in range [len(link) + 1, len]
    // node's endpos set -> pos in the subtree of node
    // link -> longest suffix with different endpos set
    // len -> longest suffix
    // pos -> end position
    // cnt -> size of endpos set
    SAM() { len[0] = 0, link[0] = -1, pos[0] = 0, cnt[0] = 0, sz = 1; }
    void build(string s) {
        int last = 0;
        for (int i = 0; i < s.length(); ++i) {
            char c = s[i];
            int cur = sz++;
            len[cur] = len[last] + 1, pos[cur] = i + 1;
            int p = last;
            while (~p && !ch[p][c - 'a'])
                ch[p][c - 'a'] = cur, p = link[p];
            if (p == -1) link[cur] = 0;
            else {
                int q = ch[p][c - 'a'];
                if (len[p] + 1 == len[q]) {
                    link[cur] = q;
                } else {
                    int nxt = sz++;
                    len[nxt] = len[p] + 1, link[nxt] = link[q];
                    pos[nxt] = pos[q];
                    for (int j = 0; j < 26; ++j)
                        ch[nxt][j] = ch[q][j];
                    while (~p && ch[p][c - 'a'] == q)
                        ch[p][c - 'a'] = nxt, p = link[p];
                    link[q] = link[cur] = nxt;
                }
            }
            cnt[cur]++;

```

```

    last = cur;
}
vector<int> p(sz);
iota(all(p), 0);
sort(all(p),
    [&](int i, int j) {return len[i] > len[j];});
for (int i = 0; i < sz; ++i)
    cnt[link[p[i]]] += cnt[p[i]];
}
} sam;

```

## 5.10 Z Value

```

vector<int> build(string s) {
    int n = s.length();
    vector<int> Z(n);
    int l = 0, r = 0;
    for (int i = 0; i < n; ++i) {
        Z[i] = max(min(Z[i - 1], r - i), 0);
        while (i + Z[i] < s.size() && s[Z[i]] == s[i + Z[i]]) {
            l = i, r = i + Z[i], Z[i]++;
        }
    }
    return Z;
}

```

## 6 Math

### 6.1 Berlekamp Massey

```

const int MOD=998244353;
vector<ll> BerlekampMassey(vector<ll> a) {
    // find min |c| such that a_n = sum c_j * a_{n-j-1}, 0-based
    // O(N^2), if |c| = k, |a| >= 2k sure correct
    auto f = [&](vector<ll> v, ll c) {
        for (ll &x : v) x = x * c % MOD;
        return v;
    };
    vector<ll> c, best;
    int pos = 0, n = a.size();
    for (int i = 0; i < n; ++i) {
        ll error = a[i];
        for (int j = 0; j < c.size(); ++j) error = ((error - c[j] * a[i - 1 - j]) % MOD + MOD) % MOD;
        if (error == 0) continue;
        ll inve = inv(error, MOD);
        if (c.empty()) {
            c.resize(i + 1);
            pos = i;
            best.pb(inve);
        } else {
            vector<ll> fix = f(best, error);
            fix.insert(fix.begin(), i - pos - 1, 0);
            if (fix.size() >= c.size()) {
                best = f(c, inve > 0 ? MOD - inve : 0);
                best.insert(best.begin(), inve);
                pos = i;
                c.resize(fix.size());
            }
            for (int j = 0; j < fix.size(); ++j) c[j] = (c[j] + fix[j]) % MOD;
        }
    }
    return c;
}

```

### 6.2 Characteristic Polynomial

```

#define rep(x, y, z) for (int x=y; x<z; x++)
using VI = vector<int>; using VVI = vector<VI>;
void Hessenberg(VVI &H, int N) {
    for (int i = 0; i < N - 2; ++i) {
        for (int j = i + 1; j < N; ++j) if (H[j][i]) {
            rep(k, i, N) swap(H[i+1][k], H[j][k]);
            rep(k, 0, N) swap(H[k][i+1], H[k][j]);
            break;
        }
        if (!H[i + 1][i]) continue;
        for (int j = i + 2; j < N; ++j) {

```

```

            int co = mul(modinv(H[i + 1][i]), H[j][i]);
            rep(k, i, N) subeq(H[j][k], mul(H[i+1][k], co));
            rep(k, 0, N) addeq(H[k][i+1], mul(H[k][j], co));
        }
    }
}
VI CharacteristicPoly(VVI A) {
    int N = (int)A.size(); Hessenberg(A, N);
    VVI P(N + 1, VI(N + 1)); P[0][0] = 1;
    for (int i = 1; i <= N; ++i) {
        rep(j, 0, i+1) P[i][j] = j ? P[i-1][j-1] : 0;
        for (int j = i - 1, val = 1; j >= 0; --j) {
            int co = mul(val, A[j][i - 1]);
            rep(k, 0, j+1) subeq(P[i][k], mul(P[j][k], co));
            if (j) val = mul(val, A[j][j - 1]);
        }
    }
    if (N & 1) for (int &x: P[N]) x = sub(0, x);
    return P[N]; // test: 2021 PTZ Korea K
}

```

### 6.3 Determinant

```

ll findDet(vector<vector<ll>> a) {
    int n = a.size();
    assert(n == a[0].size());
    ll det = 1;
    for (int i = 0; i < n; ++i) {
        if (!a[i][i]) {
            det = mod - det;
            bool is = false;
            for (int j = i + 1; j < n; ++j) if (a[j][i]) {
                swap(a[j], a[i]);
                is = true;
                break;
            }
            if (!is) return 0;
        }
        det = det * a[i][i] % mod;
        ll mul = fpow(a[i][i], mod - 2, mod);
        for (int j = 0; j < n; ++j)
            a[i][j] = a[i][j] * mul % mod;
        for (int j = 0; j < n; ++j) if (i ^ j) {
            int mul = a[j][i];
            for (int k = 0; k < n; ++k) {
                a[j][k] -= a[i][k] * mul % mod;
                if (a[j][k] < 0) a[j][k] += mod;
            }
        }
    }
    return det;
}

```

### 6.4 Discrete Logarithm

```

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;
}

```



## 6.5 Extgcd

```
//a * p.first + b * p.second = gcd(a, b)
pair<ll, ll> extgcd(ll a, ll b) {
    pair<ll, ll> res;
    if (a < 0) {
        res = extgcd(-a, b);
        res.first *= -1;
        return res;
    }
    if (b < 0) {
        res = extgcd(a, -b);
        res.second *= -1;
        return res;
    }
    if (b == 0) return {1, 0};
    res = extgcd(b, a % b);
    return {res.second, res.first - res.second * (a / b)};
}
```

## 6.6 Floor Sum

```
// sum_{i=0}^{n-1} floor((a * i + b) / m) in log(n + m + a + b)
ll floor_sum(ll n, ll m, ll a, ll b) {
    ll ans = 0;
    if (a >= m) ans += (n - 1) * n * (a / m) / 2, a %= m;
    if (b >= m) ans += n * (b / m), b %= m;
    ll y_max = (a * n + b) / m, x_max = (y_max * m - b);
    if (y_max == 0) return ans;
    ans += (n - (x_max + a - 1) / a) * y_max;
    ans += floor_sum(y_max, a, m, (a - x_max % a) % a);
    return ans;
}
```

## 6.7 Factorial Mod $P^k$

```
// 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
```

## 6.8 Linear Function Mod Min

```
ll topos(ll x, ll m) {x %= m; if (x < 0) x += m; return x;}
//min value of ax + b (mod m) for x \in [0, n - 1]. O(log m)
ll min_rem(ll n, ll m, ll a, ll b) {
    a = topos(a, m), b = topos(b, m);
    for (ll g = __gcd(a, m); g > 1; ) return g * min_rem(n / g, m / g, a / g, b / g) + (b % g);
    for (ll nn, nm, na, nb; a; n = nn, m = nm, a = na, b = nb) {
        if (a <= m - a) {
            nn = (a * (n - 1) + b) / m;
            if (!nn) break;
            nn += (b < a);
            nm = a, na = topos(-m, a);
            nb = b < a ? b : topos(b - m, a);
        } else {
            ll lst = b - (n - 1) * (m - a);
            if (lst >= 0) {b = lst; break;}
            nn = -(lst / m) + (lst % m < -a) + 1;
            nm = m - a, na = m % (m - a), nb = b % (m - a);
        }
    }
    return b;
}
//min value of ax + b (mod m) for x \in [0, n - 1],
//also return min x to get the value. O(log m)
```

```
//{value, x}
pair<ll, ll> min_rem_pos(ll n, ll m, ll a, ll b) {
    a = topos(a, m), b = topos(b, m);
    ll mn = min_rem(n, m, a, b), g = __gcd(a, m);
    //ax = (mn - b) (mod m)
    ll x = (extgcd(a, m).first + m) * ((mn - b + m) / g) % (m / g);
    return {mn, x};
}
```

## 6.9 MillerRabin PollardRho

```
ll mul(ll x, ll y, ll p) {return (x * y - (ll)((long double)x / p * y) * p + p) % p;}
vector<ll> chk = {2, 325, 9375, 28178, 450775, 9780504, 1795265022};
ll Pow(ll a, ll b, ll n) {ll res = 1; for (; b; b >>= 1, a = mul(a, a, n)) if (b & 1) res = mul(res, a, n); return res;}
bool check(ll a, ll d, int s, ll n) {
    a = Pow(a, d, n);
    if (a <= 1) return 1;
    for (int i = 0; i < s; ++i, a = mul(a, a, n)) {
        if (a == 1) return 0;
        if (a == n - 1) return 1;
    }
    return 0;
}
bool IsPrime(ll n) {
    if (n < 2) return 0;
    if (n % 2 == 0) return n == 2;
    ll d = n - 1, s = 0;
    while (d % 2 == 0) d >>= 1, ++s;
    for (ll i : chk) if (!check(i, d, s, n)) return 0;
    return 1;
}
const vector<ll> small = {2, 3, 5, 7, 11, 13, 17, 19};
ll FindFactor(ll n) {
    if (IsPrime(n)) return 1;
    for (ll p : small) if (n % p == 0) return p;
    ll x, y = 2, d, t = 1;
    auto f = [&](ll a) {return (mul(a, a, n) + t) % n;};
    for (int l = 2; ; l <= 1) {
        x = y;
        int m = min(1, 32);
        for (int i = 0; i < l; i += m) {
            d = 1;
            for (int j = 0; j < m; ++j) {
                y = f(y), d = mul(d, abs(x - y), n);
            }
            ll g = __gcd(d, n);
            if (g == n) {
                l = 1, y = 2, ++t;
                break;
            }
            if (g != 1) return g;
        }
    }
}
map<ll, int> PollardRho(ll n) {
    map<ll, int> res;
    if (n == 1) return res;
    if (IsPrime(n)) return ++res[n], res;
    ll d = FindFactor(n);
    res = PollardRho(n / d);
    auto res2 = PollardRho(d);
    for (auto [x, y] : res2) res[x] += y;
    return res;
}
```

## 6.10 Phi

```
const int N=1e6+1;
int phi[N];
void build_phi(int n) {
    for(int i=0;i<=n;i++) phi[i]=i;
    for(int i=2;i<=n;i++) if(phi[i]==i) {
        for(int j=i;j<=n;j+=i)
            phi[j]-=phi[j]/i;
    }
}
```

## 6.11 Quadratic Residue

```
int Jacobi(int a, int m) {
    int s = 1;
    for (; m > 1; ) {
        a %= m;
        if (a == 0) return 0;
        const int r = __builtin_ctz(a);
        if ((r & 1) && ((m + 2) & 4)) s = -s;
        a >>= r;
        if (a & m & 2) s = -s;
        swap(a, m);
    }
    return s;
}

int QuadraticResidue(int a, int p) {
    if (p == 2) return a & 1;
    const int jc = Jacobi(a, p);
    if (jc == 0) return 0;
    if (jc == -1) return -1;
    int b, d;
    for (; ; ) {
        b = rand() % p;
        d = (1LL * b * b + p - a) % p;
        if (Jacobi(d, p) == -1) break;
    }
    int f0 = b, f1 = 1, g0 = 1, g1 = 0, tmp;
    for (int e = (1LL + p) >> 1; e >>= 1) {
        if (e & 1) {
            tmp = (1LL * g0 * f0 + 1LL * d * (1LL * g1 * f1 % p)) % p;
            g1 = (1LL * g0 * f1 + 1LL * g1 * f0) % p;
            g0 = tmp;
        }
        tmp = (1LL * f0 * f0 + 1LL * d * (1LL * f1 * f1 % p)) % p;
        f1 = (2LL * f0 * f1) % p;
        f0 = tmp;
    }
    return g0;
}
```

## 6.12 Sieve (With Mu)

```
const int N=1e6+1;
int lpf[N],mu[N];
vector<int> pr;
void sieve_with_mu() {
    mu[1]=1;
    for(int i=2;i<N;i++) {
        if(lpf[i]==0) {
            lpf[i]=i,mu[i]=-1;
            pr.push_back(i);
        }
        for(int j=0;j<(int)pr.size();j++) {
            if(pr[j]>=lpf[i])break;
            lpf[i*pr[j]]=pr[j];
            mu[i*pr[j]]=mu[i]*(pr[j]==lpf[i]?0:-1);
        }
    }
}
```

## 6.13 Simplex

```
// by LittleCube8152. 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][c];
                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;
}
```

## 6.14 FFT

```
const double pi=acos(-1);
typedef complex<double> cp;
const int N=(1<<17);
struct FFT
{
    // n has to be same as a.size()
    int n,rev[N];
    cp omega[N],iomega[N];
    void init(int _n) {
        n=_n;
        for(int i=0;i<n;i++) {
            omega[i]=cp(cos(2*pi/n*i),sin(2*pi/n*i));
            iomega[i]=conj(omega[i]);
        }
        int k=log2(n);
        for(int i=0;i<n;i++) {
            rev[i]=0;
            for(int j=0;j<k;j++) if(i&(1<<j))
                rev[i]|=(1<<(k-j-1));
        }
    }
}
```

```

void tran(vector<cp> &a, cp* xomega)
{
    for(int i=0; i<n; i++) if(i<rev[i])
        swap(a[i], a[rev[i]]);
    for(int len=2; len<=n; len<=1) {
        int mid=len>>1, r=n/len;
        for(int j=0; j<n; j+=len) {
            for(int i=0; i<mid; i++) {
                cp t=xomega[r*i]*a[j+mid+i];
                a[j+mid+i]=a[j+i]-t;
                a[j+i]+=t;
            }
        }
    }
}

void fft(vector<cp> &a) {tran(a, omega);}
void ifft(vector<cp> &a) {
    tran(a, iomega);
    for(int i=0; i<n; i++) a[i]/=n;
}
};

```

## 6.15 NTT

```

//needs fpow
//needs inv

//(2^16)+1, 65537, 3
//7*17*(2^23)+1, 998244353, 3
//1255*(2^20)+1, 1315962881, 3
//51*(2^25)+1, 1711276033, 29
template<int MAXN, ll P, ll RT> //MAXN must be 2^k
struct NTT {
    ll w[MAXN];
    ll mpow(ll a, ll n);
    ll minv(ll a) { return mpow(a, P - 2); }
    NTT() {
        ll dw = mpow(RT, (P - 1) / MAXN);
        w[0] = 1;
        for (int i = 1; i < MAXN; ++i) w[i] = w[i - 1] * dw
            % P;
    }
    void bitrev(ll *a, int n) {
        int i = 0;
        for (int j = 1; j < n - 1; ++j) {
            for (int k = n >> 1; (i ^= k) < k; k >>= 1);
            if (j < i) swap(a[i], a[j]);
        }
    }
    void operator()(ll *a, int n, bool inv = false) { //0
        <= a[i] < P
        bitrev(a, n);
        for (int L = 2; L <= n; L <= 1) {
            int dx = MAXN / L, dl = L >> 1;
            for (int i = 0; i < n; i += L) {
                for (int j = i, x = 0; j < i + dl; ++j, x += dx)
                {
                    ll tmp = a[j + dl] * w[x] % P;
                    if ((a[j + dl] = a[j] - tmp) < 0) a[j + dl]
                        += P;
                    if ((a[j] += tmp) >= P) a[j] -= P;
                }
            }
        }
        if (inv) {
            reverse(a + 1, a + n);
            ll invn = minv(n);
            for (int i = 0; i < n; ++i) a[i] = a[i] * invn %
                P;
        }
    }
};

```

## 6.16 FWT

```

void fwt(vector<int> &a) {
    // and : a[j] += x;
    //      : a[j] -= x;
    // or  : a[j ^ (1 << i)] += y;
    //      : a[j ^ (1 << i)] -= y;
    // xor : a[j] = x - y, a[j ^ (1 << i)] = x + y;
    //      : a[j] = (x - y) / 2, a[j ^ (1 << i)] = (x + y)
        / 2;
}

```

```

int n = __lg(a.size());
for (int i = 0; i < n; ++i) {
    for (int j = 0; j < 1 << n; ++j) if (j >> i & 1) {
        int x = a[j ^ (1 << i)], y = a[j];
        // do something
    }
}
}

```

## 6.17 Polynomial

```

NTT<131072 * 2, 998244353, 3> ntt;
#define fi(s, n) for (int i = (int)(s); i < (int)(n); ++i)
template<int MAXN, ll P, ll RT> // MAXN = 2^k
struct Poly : vector<ll> { // coefficients in [0, P)
    using vector<ll>::vector;
    int n() const { return (int)size(); } // n() >= 1
    Poly(const Poly &p, int m) : vector<ll>(m) {
        copy_n(p.data(), min(p.n(), m), data());
    }
    Poly& irev() { return reverse(data(), data() + n()),
        *this; }
    Poly& isz(int m) { return resize(m), *this; }
    Poly& iadd(const Poly &rhs) { // n() == rhs.n()
        fi(0, n()) if (((*this)[i] += rhs[i]) >= P) (*this)
            [i] -= P;
        return *this;
    }
    Poly& imul(ll k) {
        fi(0, n()) (*this)[i] = (*this)[i] * k % P;
        return *this;
    }
    Poly Mul(const Poly &rhs) const {
        int m = 1;
        while (m < n() + rhs.n() - 1) m <= 1;
        Poly X(*this, m), Y(rhs, m);
        ntt(X.data(), m), ntt(Y.data(), m);
        fi(0, m) X[i] = X[i] * Y[i] % P;
        ntt(X.data(), m, true);
        return X.isz(n() + rhs.n() - 1);
    }
    Poly Inv() const { // (*this)[0] != 0, 1e5/95ms
        if (n() == 1) return {ntt.minv((*this)[0])};
        int m = 1;
        while (m < n() * 2) m <= 1;
        Poly Xi = Poly(*this, (n() + 1) / 2).Inv().isz(m);
        Poly Y(*this, m);
        ntt(Xi.data(), m), ntt(Y.data(), m);
        fi(0, m) {
            Xi[i] *= (2 - Xi[i] * Y[i]) % P;
            if ((Xi[i] %= P) < 0) Xi[i] += P;
        }
        ntt(Xi.data(), m, true);
        return Xi.isz(n());
    }
    Poly Sqrt() const { // Jacobi((*this)[0], P) = 1, 1e5
        /235ms
        if (n() == 1) return {QuadraticResidue((*this)[0],
            P)};
        Poly X = Poly(*this, (n() + 1) / 2).Sqrt().isz(n());
        return X.iadd(Mul(X.Inv()).isz(n())).imul(P / 2 +
            1);
    }
    pair<Poly, Poly> DivMod(const Poly &rhs) const { // (
        rhs.back() != 0
        if (n() < rhs.n()) return {{0}, *this};
        const int m = n() - rhs.n() + 1;
        Poly X(rhs); X.irev().isz(m);
        Poly Y(*this); Y.irev().isz(m);
        Poly Q = Y.Mul(X.Inv()).isz(m).irev();
        X = rhs.Mul(Q), Y = *this;
        fi(0, n()) if ((Y[i] - X[i]) < 0) Y[i] += P;
        return {Q, Y.isz(max(1, rhs.n() - 1))};
    }
    Poly Dx() const {
        Poly ret(n() - 1);
        fi(0, ret.n()) ret[i] = (i + 1) * (*this)[i + 1] %
            P;
        return ret.isz(max(1, ret.n()));
    }
}

```

```

Poly Sx() const {
    Poly ret(n() + 1);
    fi(0, n()) ret[i + 1] = ntt.minv(i + 1) * (*this)[i] % P;
    return ret;
}
Poly _tmul(int nn, const Poly &rhs) const {
    Poly Y = Mul(rhs).isz(n() + nn - 1);
    return Poly(Y.data() + n() - 1, Y.data() + Y.n());
}
vector<ll> _eval(const vector<ll> &x, const vector<
    Poly> &up) const {
    const int m = (int)x.size();
    if (!m) return {};
    vector<Poly> down(m * 2);
    // down[1] = DivMod(up[1]).second;
    // fi(2, m * 2) down[i] = down[i / 2].DivMod(up[i])
    // .second;
    down[1] = Poly(up[1]).irev().isz(n()).Inv().irev().
        _tmul(m, *this);
    fi(2, m * 2) down[i] = up[i ^ 1]._tmul(up[i].n() -
        1, down[i / 2]);
    vector<ll> y(m);
    fi(0, m) y[i] = down[m + i][0];
    return y;
}
static vector<Poly> _tree1(const vector<ll> &x) {
    const int m = (int)x.size();
    vector<Poly> up(m * 2);
    fi(0, m) up[m + i] = {(x[i] ? P - x[i] : 0), 1};
    for (int i = m - 1; i > 0; --i) up[i] = up[i * 2].
        Mul(up[i * 2 + 1]);
    return up;
}
vector<ll> Eval(const vector<ll> &x) const { // 1e5,
    1s
    auto up = _tree1(x); return _eval(x, up);
}
static Poly Interpolate(const vector<ll> &x, const
    vector<ll> &y) { // 1e5, 1.4s
    const int m = (int)x.size();
    vector<Poly> up = _tree1(x), down(m * 2);
    vector<ll> z = up[1].Dx()._eval(x, up);
    fi(0, m) z[i] = y[i] * ntt.minv(z[i]) % P;
    fi(0, m) down[m + i] = {z[i]};
    for (int i = m - 1; i > 0; --i) down[i] = down[i *
        2].Mul(up[i * 2 + 1]).iadd(down[i * 2 + 1].Mul(
        up[i * 2]));
    return down[1];
}
Poly Ln() const { // (*this)[0] == 1, 1e5/170ms
    return Dx().Mul(Inv()).Sx().isz(n());
}
Poly Exp() const { // (*this)[0] == 0, 1e5/360ms
    if (n() == 1) return {1};
    Poly X = Poly(*this, (n() + 1) / 2).Exp().isz(n());
    Poly Y = X.Ln(); Y[0] = P - 1;
    fi(0, n()) if ((Y[i] = (*this)[i] - Y[i]) < 0) Y[i]
        += P;
    return X.Mul(Y).isz(n());
}
// M := P(P - 1). If k >= M, k := k % M + M.
Poly Pow(ll k) const {
    int nz = 0;
    while (nz < n()) && !(*this)[nz] ++nz;
    if (nz * min(k, (ll)n()) >= n()) return Poly(n());
    if (!k) return Poly(Poly{1}, n());
    Poly X(data() + nz, data() + nz + n() - nz * k);
    const ll c = ntt.mpow(X[0], k % (P - 1));
    return X.Ln().imul(k % P).Exp().imul(c).irev().isz(
        n()).irev();
}
static ll LinearRecursion(const vector<ll> &a, const
    vector<ll> &coef, ll n) { // a_n = \sum c_j a_{n-j}
    const int k = (int)a.size();
    assert((int)coef.size() == k + 1);
    Poly C(k + 1), W(Poly{1}, k), M = {0, 1};
    fi(1, k + 1) C[k - i] = coef[i] ? P - coef[i] : 0;
    C[k] = 1;
    while (n) {
        if (n % 2) W = W.Mul(M).DivMod(C).second;

```

```

        n /= 2, M = M.Mul(M).DivMod(C).second;
    }
    ll ret = 0;
    fi(0, k) ret = (ret + W[i] * a[i]) % P;
    return ret;
}
vector<ll> chirp_z(ll c, int m) { // P(c^i) for i=0..m
    -1
    Poly B(*this);
    int sz=max(n(),m);
    vector<ll> res(m);
    Poly C(sz * 2), iC(sz);
    ll ic = ntt.minv(c);
    fi(0, sz * 2) C[i] = ntt.mpow(c, 1LL * i * (i - 1)
        / 2 % (P - 1));
    fi(0, sz) iC[i] = ntt.mpow(ic, 1LL * i * (i - 1) /
        2 % (P - 1));
    fi(0, n()) B[i] = B[i] * iC[i] % P;
    B=B.irev().Mul(C);
    fi(0, m) res[i] = B[n()-1+i] * iC[i] % P;
    return res;
}
Poly shift_c(ll c) { // P(x+c)
    ll tmp = 1;
    Poly A(n()), B(n() + 1);
    fi(0, n()) {
        A[i] = (*this)[i] * fac[i] % P; // fac[i]=i!
        B[i] = tmp * in[i] % P; // in[i]=inv(i!)
        tmp = tmp * c % P;
    }
    B.irev();
    Poly C = A.Mul(B);
    A.isz(n());
    fi(0, n()) A[i] = C[n() + i] * in[i] % P;
    return A;
}
};
#undef fi
using Poly_t = Poly<131072 * 2, 998244353, 3>;
//template<> decltype(Poly_t::ntt) Poly_t::ntt = {};

```

## 6.18 Generating Functions

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

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

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

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

- Special Generating Function

$$\begin{aligned}
 - (1+x)^n &= \sum_{i \geq 0} \binom{n}{i} x^i \\
 - \frac{1}{(1-x)^n} &= \sum_{i \geq 0} \binom{n-1}{i} x^i
 \end{aligned}$$

## 6.19 Linear Programming Construction

Standard form: maximize  $c^T x$  subject to  $Ax \leq b$  and  $x \geq 0$ .  
 Dual LP: minimize  $b^T y$  subject to  $A^T y \geq c$  and  $y \geq 0$ .  
 $\bar{x}$  and  $\bar{y}$  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  $\sum_{j=1}^n A_{ij} \bar{x}_j = b_j$  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  $x_i - x'_i$

## 6.20 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:  $B(n) = 1, 1, 2, 5, 15, 52, 203, 877, 4140, 21147, 115975, 678570, 4213597, 27644437, 190899322, \dots$

## 6.21 Theorem

### • Kirchhoff's Theorem

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

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

### • Tutte's Matrix

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

### • Cayley's Formula

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

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

spanning trees.

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

### • Erdős-Gallai Theorem

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

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

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

### • Burnside's Lemma

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

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

Then

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

### • Gale-Ryser theorem

A pair of sequences of nonnegative integers  $a_1 \geq \dots \geq a_n$  and  $b_1, \dots, b_n$  is bigraphic if and only if  $\sum_{i=1}^n a_i = \sum_{i=1}^n b_i$  and  $\sum_{i=1}^k a_i \leq \sum_{i=1}^n \min(b_i, k)$  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  $\sum_{i=1}^n a_i = \sum_{i=1}^n b_i$  and  $\sum_{i=1}^k a_i \leq \sum_{i=1}^k \min(b_i, k-1) + \sum_{i=k+1}^n \min(b_i, k)$  holds for every  $1 \leq k \leq n$ .

### • Möbius inversion formula

- $f(n) = \sum_{d|n} g(d) \Leftrightarrow g(n) = \sum_{d|n} \mu(d) f(\frac{n}{d})$
- $f(n) = \sum_{n|d} g(d) \Leftrightarrow g(n) = \sum_{n|d} \mu(\frac{d}{n}) f(d)$

### • 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,  $\theta$ :  $\arcsin(a/r)$ .
- 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  $= 2\pi r h = \pi(a^2+h^2) = 2\pi r^2(1-\cos\theta)$ .

### • Chinese Remainder Theorem

- $x \equiv a_i \pmod{m_i}$
- $M = \prod m_i, M_i = M/m_i$
- $t_i M_i \equiv 1 \pmod{m_i}$
- $x = \sum a_i t_i M_i \pmod{M}$

## 7 Geometry

### 7.1 Basic

```
#define X first
#define Y second
typedef pair<double,double> Pt;
const double eps=1e-9;
Pt operator+(Pt a,Pt b){return Pt(a.X+b.X,a.Y+b.Y);}
Pt operator-(Pt a,Pt b){return Pt(a.X-b.X,a.Y-b.Y);}
Pt operator*(Pt a,double b){return Pt(a.X*b,a.Y*b);}
Pt operator/(Pt a,double b){return Pt(a.X/b,a.Y/b);}
double operator*(Pt a,Pt b){return a.X*b.X+a.Y*b.Y;}
double operator^(Pt a,Pt b){return a.X*b.Y-a.Y*b.X;}
double abs2(Pt a){return a*a;}
double abs(Pt a){return sqrt(a*a);}
int sign(double a){return fabs(a)>eps?0:a>0?1:-1;}
int ori(Pt a,Pt b,Pt c){return sign((b-a)^(c-a));}
bool collinear(Pt a,Pt b,Pt c){return sign((a-c)^(b-c))==0;}
bool btw(Pt a,Pt b,Pt c){return !collinear(a,b,c)?0:
    sign((a-c)*(b-c))<=0;}//is C between AB
Pt proj(Pt a,Pt b,Pt c){return (b-a)*((c-a)*(b-a)/abs2(
    b-a));} //ac projection on ab
double dist(Pt a,Pt b,Pt c){return abs((c-a)^(b-a))/abs(
    b-a);} //distance from C to AB
Pt perp(Pt p1){return Pt(-p1.Y, p1.X);}
struct Line{Pt a,b;}
struct Cir{Pt o;double r;}
struct Arc{Pt o,a,b;} //cross(oa,ob)>=0
```

### 7.2 Convex Hull

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

### 7.3 Dynamic Convex Hull

```
struct DynamicConvexHull {
    struct Up_cmp {
        bool operator()(const Pt a,const Pt b) {
            if(a.X==b.X) return a.Y<b.Y;
            return a.X<b.X;
        }
    };
    struct Down_cmp {
        bool operator()(const Pt a,const Pt b) {
            if (a.X==b.X) return a.Y>b.Y;
            return a.X>b.X;
        }
    };
    template <typename T>
    struct Hull {
        set<Pt,T> hull;
        bool chk(Pt i,Pt j,Pt k){return ((k-i)^(j-i))>0;}
        void insert(Pt x) {
            if(inside(x)) return;
            hull.insert(x);
            auto it=hull.lower_bound(x);
            if(next(it)!=hull.end()) {
                for(auto it2=next(it);next(it2)!=hull.end();++
                    it2) {
                    if(chk(x,*it2,*next(it2))) break;
                    hull.erase(it2);
                    it2=hull.lower_bound(x);
                }
            }
        }
    };
};
```

```

    }
}
it=hull.lower_bound(x);
if(it!=hull.begin()) {
    for(auto it2=prev(it); it2!=hull.begin(); --it2)
    {
        if(chk(*prev(it2), *it2, x)) break;
        hull.erase(it2);
        it2=hull.lower_bound(x);
        if(it2==hull.begin()) break;
    }
}
}
bool inside(Pt x) {
    if(hull.lower_bound(x)!=hull.end() && *hull.
        lower_bound(x)==x)
        return true;
    auto it=hull.lower_bound(x);
    bool ans=false;
    if(it!=hull.begin() && it!=hull.end()) {
        ans=!chk(*prev(it), x, *it);
    }
    return ans;
}
};
Hull<Up_cmp> up;
Hull<Down_cmp> down;
void insert(Pt x){up.insert(x), down.insert(x);}
bool inside(Pt x){return up.inside(x) && down.inside(x)
};
};

```

## 7.4 Point In Convex Hull

```

bool PointInConvex(const vector<Pt> &C, Pt p, bool
    strict = true) {
    int a = 1, b = int(C.size()) - 1, r = !strict;
    if (C.size() == 0) return false;
    if (C.size() < 3) return r && btw(C[0], C.back(), p);
    if (ori(C[0], C[a], C[b]) > 0) swap(a, b);
    if (ori(C[0], C[a], p) >= r || ori(C[0], C[b], p) <=
        -r)
        return false;
    while (abs(a - b) > 1) {
        int c = (a + b) / 2;
        (ori(C[0], C[c], p) > 0 ? b : a) = c;
    }
    return ori(C[a], C[b], p) < r;
}

```

## 7.5 Point In Circle

```

//is p4 in circumcircle of p1p2p3
ll sqr(ll x) { return x * x; }
bool in_cc(const p1l& p1, const p1l& p2, const p1l& p3,
    const p1l& p4) {
    ll u11 = p1.X - p4.X; ll u12 = p1.Y - p4.Y;
    ll u21 = p2.X - p4.X; ll u22 = p2.Y - p4.Y;
    ll u31 = p3.X - p4.X; ll u32 = p3.Y - p4.Y;
    ll u13 = sqr(p1.X) - sqr(p4.X) + sqr(p1.Y) - sqr(p4.Y)
        );
    ll u23 = sqr(p2.X) - sqr(p4.X) + sqr(p2.Y) - sqr(p4.Y)
        );
    ll u33 = sqr(p3.X) - sqr(p4.X) + sqr(p3.Y) - sqr(p4.Y)
        );
    __int128 det = (__int128)-u13 * u22 * u31 + (__int128)
        u12 * u23 * u31 + (__int128)u13 * u21 * u32 - (
        __int128)u11 * u23 * u32 - (__int128)u12 * u21 *
        u33 + (__int128)u11 * u22 * u33;
    return det > 0;
}

```

## 7.6 Half Plane Intersection

```

p1l area_pair(Line a, Line b)
{ return p1l(cross(a.Y - a.X, b.X - a.X), cross(a.Y - a
    .X, b.Y - a.X)); }
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;
}
/* 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.Y - a.X, b.Y - b.X, 0) != -1)
            return cmp(a.Y - a.X, b.Y - b.X, 0);
        return ori(a.X, a.Y, b.Y) < 0;
    });
    deque<Line> dq(1, arr[0]);
    auto pop_back = [&](int t, Line p) {
        while (SZ(dq) >= t && !isin(p, dq[SZ(dq) - 2], dq.
            back()))
            dq.pop_back();
    };
    auto pop_front = [&](int t, Line p) {
        while (SZ(dq) >= t && !isin(p, dq[0], dq[1]))
            dq.pop_front();
    };
    for (auto p : arr)
        if (cmp(dq.back().Y - dq.back().X, p.Y - p.X, 0) !=
            -1)
            pop_back(2, p), pop_front(2, p), dq.pb(p);
    pop_back(3, dq[0]), pop_front(3, dq.back());
    return vector<Line>(ALL(dq));
}

```

## 7.7 Minkowski Sum

```

vector<Pt> Minkowski(vector<Pt> a, vector<Pt> b) {
    a = ConvexHull(a), b = ConvexHull(b);
    int n = a.size(), m = b.size();
    vector<Pt> c = {a[0] + b[0]}, s1, s2;
    for(int i = 0; i < n; ++i)
        s1.pb(a[(i + 1) % n] - a[i]);
    for(int i = 0; i < m; ++i)
        s2.pb(b[(i + 1) % m] - b[i]);
    for(int p1 = 0, p2 = 0; p1 < n || p2 < m;)
        if (p2 == m || (p1 < n && sign(s1[p1] ^ s2[p2]) >=
            0))
            c.pb(c.back() + s1[p1++]);
        else
            c.pb(c.back() + s2[p2++]);
    return ConvexHull(c);
}

```

## 7.8 Polar Angle

```

int cmp(pdd a, pdd b, bool same=1){ //polar angle sort
#define is_neg(k) (sign(k.Y)<0 || (sign(k.Y)==0 && sign(k
    .X)<0))
    int A=is_neg(a), B=is_neg(b);
    if(A!=B) return A<B;
    if(sign(a^b)==0) return (same?abs2(a)<abs2(b):-1);
    return sign(a^b)>0;
}

```

## 7.9 Rotating Sweep Line

```

void rotatingSweepLine(vector<pii> &ps) {
    int n = SZ(ps), 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.Y] - ps[a.X], ps[b.Y] - ps[b.X]);
    }); // cmp(): polar angle compare
    iota(ALL(id), 0);
    sort(ALL(id), [&](int a, int b) {
        if (ps[a.Y] != ps[b.Y]) return ps[a.Y] < ps[b.Y];
        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.X], pos[l.Y], id[pos[l.X]], id[pos[l.Y]])
            = make_tuple(pos[l.Y], pos[l.X], l.Y, l.X);
    }
}

```



```
}
}
```

## 7.10 Segment Intersect

```
bool seg_sect(Pt p1, Pt p2, Pt p3, Pt p4) { //does p1p2
    intersect p3p4
    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);
    else return a123*a124<=0&&a341*a342<=0;
}
Pt intersect(Pt p1, Pt p2, Pt p3, Pt p4) {
    double a123 = (p2 - p1) ^ (p3 - p1);
    double a124 = (p2 - p1) ^ (p4 - p1);
    return (p4 * a123 - p3 * a124) / (a123 - a124); // C
    ^3 / C^2
}
```

## 7.11 Circle Intersect With Any

```
vector<Pt> CircleLineInter(Cir c, Line l) { //cir-line
    Pt p = l.a + (l.b - l.a) * ((c.o - l.a) * (l.b - l.a)
        ) / abs2(l.b - l.a);
    double s = (l.b - l.a) ^ (c.o - l.a), h2 = c.r * c.r
        - s * s / abs2(l.b - l.a);
    if (sign(h2) == -1) return {};
    if (sign(h2) == 0) return {p};
    Pt h = (l.b - l.a) / abs(l.b - l.a) * sqrt(h2);
    return {p - h, p + h};
}
vector<Pt> CirclesInter(Cir c1, Cir c2) { //cir-cir
    double d2 = abs2(c1.o - c2.o), d = sqrt(d2);
    if (d < max(c1.r, c2.r) - min(c1.r, c2.r) || d > c1.r
        + c2.r) return {};
    Pt u = (c1.o + c2.o) / 2 + (c1.o - c2.o) * ((c2.r *
        c2.r - c1.r * c1.r) / (2 * d2));
    double A = sqrt((c1.r + c2.r + d) * (c1.r - c2.r + d)
        * (c1.r + c2.r - d) * (-c1.r + c2.r + d));
    Pt v = Pt(c1.o.Y - c2.o.Y, -c1.o.X + c2.o.X) * A / (2
        * d2);
    if (sign(v.X) == 0 && sign(v.Y) == 0) return {u};
    return {u + v, u - v};
}
double _area(Pt pa, Pt pb, double r) { //for poly-cir
    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 = pb * (pb - pa) / a / c, B = acos(cosB);
    double cosC = (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(vector<Pt> poly, Pt O, double r
    ) { //poly-cir
    double S = 0; int n = poly.size();
    for (int i = 0; i < n; ++i)
        S += _area(poly[i] - O, poly[(i + 1) % n] - O, r) *
            ori(O, poly[i], poly[(i + 1) % n]);
    return fabs(S);
}
```

## 7.12 Tangents

```
vector<Line> tangent(Cir c, Pt p) {
    vector<Line> z;
    double d = abs(p - c.o);
    if (sign(d - c.r) == 0) {
        Pt i = rot(p - c.o, pi / 2);
```

```
        z.push_back({p, p + i});
    } else if (d > c.r) {
        double o = acos(c.r / d);
        Pt i = unit(p - c.o), j = rot(i, o) * c.r, k = rot(
            i, -o) * c.r;
        z.push_back({c.o + j, p});
        z.push_back({c.o + k, p});
    }
    return z;
}
vector<Line> tangent(Cir c1, Cir c2, int sign1) {
    // sign1 = 1 for outer tang, -1 for inter tang
    vector<Line> ret;
    double d_sq = abs2(c1.o - c2.o);
    if (sign(d_sq) == 0) return ret;
    double d = sqrt(d_sq);
    Pt v = (c2.o - c1.o) / 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) {
        Pt n = Pt(v.X * c - sign2 * h * v.Y, v.Y * c +
            sign2 * h * v.X);
        Pt p1 = c1.o + n * c1.r;
        Pt p2 = c2.o + n * (c2.r * sign1);
        if (sign(p1.X - p2.X) == 0 && sign(p1.Y - p2.Y) ==
            0)
            p2 = p1 + perp(c2.o - c1.o);
        ret.pb({p1, p2});
    }
    return ret;
}
```

## 7.13 Tangent to Convex Hull

```
/* The point should be strictly out of hull
    return arbitrary point on the tangent line */
pii get_tangent(vector<pll> &C, pll p) {
    auto gao = [&](int s) {
        return cyc_tsearch(SZ(C), [&](int x, int y)
            { return ori(p, C[x], C[y]) == s; });
    };
    return pii(gao(1), gao(-1));
} // return (a, b), ori(p, C[a], C[b]) >= 0
```

## 7.14 Minimum Enclosing Circle

```
Cir min_enclosing(vector<Pt> &p) {
    random_shuffle(p.begin(), p.end());
    double r = 0.0;
    Pt cent = p[0];
    for (int i = 1; i < p.size(); ++i) {
        if (abs2(cent - p[i]) <= r) continue;
        cent = p[i];
        r = 0.0;
        for (int j = 0; j < i; ++j) {
            if (abs2(cent - p[j]) <= r) continue;
            cent = (p[i] + p[j]) / 2;
            r = abs2(p[j] - cent);
            for (int k = 0; k < j; ++k) {
                if (abs2(cent - p[k]) <= r) continue;
                cent = circcenter(p[i], p[j], p[k]);
                r = abs2(p[k] - cent);
            }
        }
    }
    return {cent, sqrt(r)};
}
```

## 7.15 Union of Stuff

```
//Union of Circles
vector<pair<double, double>> CoverSegment(Cir a, Cir b)
{
    double d = abs(a.o - b.o);
    vector<pair<double, double>> res;
    if (sign(a.r + b.r - d) == 0);
    else if (d <= abs(a.r - b.r) + eps) {
        if (a.r < b.r) res.emplace_back(0, 2 * pi);
    } else if (d < abs(a.r + b.r) - eps) {
        double o = acos((a.r * a.r + d * d - b.r * b.r) /
            (2 * a.r * d)), z = atan2((b.o - a.o).Y, (b.o -
            a.o).X);
```

```

    if (z < 0) z += 2 * pi;
    double l = z - o, r = z + o;
    if (l < 0) l += 2 * pi;
    if (r > 2 * pi) r -= 2 * pi;
    if (l > r) res.emplace_back(l, 2 * pi), res.
        emplace_back(0, r);
    else res.emplace_back(l, r);
}
return res;
}
double CircleUnionArea(vector<Cir> c) { // circle
    should be identical
    int n = c.size();
    double a = 0, w;
    for (int i = 0; w = 0, i < n; ++i) {
        vector<pair<double, double>> s = {{2 * pi, 9}}, z;
        for (int j = 0; j < n; ++j) if (i != j) {
            z = CoverSegment(c[i], c[j]);
            for (auto &e : z) s.push_back(e);
        }
        sort(s.begin(), s.end());
        auto F = [&](double t) { return c[i].r * (c[i].r *
            t + c[i].o.X * sin(t) - c[i].o.Y * cos(t)); };
        for (auto &e : s) {
            if (e.first > w) a += F(e.first) - F(w);
            w = max(w, e.second);
        }
    }
    return a * 0.5;
}
// Union of Polygons
double polyUnion(vector<vector<Pt>> poly) {
    int n = poly.size();
    double ans = 0;
    auto solve = [&](Pt a, Pt b, int cid) {
        vector<pair<Pt, int>> event;
        for (int i = 0; i < n; ++i) {
            int st = 0, sz = poly[i].size();
            while (st < sz && ori(poly[i][st], a, b) != 1) st
                ++;
            if (st == sz) continue;
            for (int j = 0; j < sz; ++j) {
                Pt c = poly[i][(j + st) % sz], d = poly[i][(j +
                    st + 1) % sz];
                if (sign((a - b) ^ (c - d)) != 0) {
                    int ok1 = ori(c, a, b) == 1, ok2 = ori(d, a,
                        b) == 1;
                    if (ok1 ^ ok2) event.emplace_back(LinesInter
                        ({a, b}, {c, d}), ok1 ? 1 : -1);
                } else if (ori(c, a, b) == 0 && sign((a - b) *
                    (c - d)) > 0 && i <= cid) {
                    event.emplace_back(c, -1);
                    event.emplace_back(d, 1);
                }
            }
        }
        sort(all(event), [&](pair<Pt, int> i, pair<Pt,
            int> j) {
            return ((a - i.first) * (a - b)) < ((a - j.first)
                * (a - b));
        });
        int now = 0;
        Pt lst = a;
        for (auto [x, y] : event) {
            if (btw(a, b, lst) && btw(a, b, x) && !now) ans
                += lst ^ x;
            now += y, lst = x;
        }
    };
    for (int i = 0; i < n; ++i) for (int j = 0; j < poly[
        i].size(); ++j) {
        solve(poly[i][j], poly[i][(j + 1) % int(poly[i].
            size())], i);
    }
    return ans / 2;
}
}

```

## 7.16 Delaunay Triangulation

/\* Delaunay Triangulation:  
Given a sets of points on 2D plane, find a  
triangulation such that no points will strictly

```

inside circumcircle of any triangle. */
struct Edge {
    int id; // oidx[id]
    list<Edge>::iterator twin;
    Edge(int _id = 0):id(_id) {}
};
struct Delaunay { // 0-base
    int n, oidx[N];
    list<Edge> head[N]; // result udir. graph
    pll p[N];
    void init(int _n, pll _p[]) {
        n = _n, iota(oidx, oidx + n, 0);
        for (int i = 0; i < n; ++i) head[i].clear();
        sort(oidx, oidx + n, [&](int a, int b)
            { return _p[a] < _p[b]; });
        for (int i = 0; i < n; ++i) p[i] = _p[oidx[i]];
        divide(0, n - 1);
    }
    void addEdge(int u, int v) {
        head[u].push_front(Edge(v));
        head[v].push_front(Edge(u));
        head[u].begin()->twin = head[v].begin();
        head[v].begin()->twin = head[u].begin();
    }
    void divide(int l, int r) {
        if (l == r) return;
        if (l + 1 == r) return addEdge(l, l + 1);
        int mid = (l + r) >> 1, nw[2] = {l, r};
        divide(l, mid), divide(mid + 1, r);
        auto gao = [&](int t) {
            pll pt[2] = {p[nw[0]], p[nw[1]]};
            for (auto it : head[nw[t]]) {
                int v = ori(pt[1], pt[0], p[it.id]);
                if (v > 0 || (v == 0 && abs2(pt[t ^ 1] - p[it.
                    id]) < abs2(pt[1] - pt[0])))
                    return nw[t] = it.id, true;
            }
            return false;
        };
        while (gao(0) || gao(1));
        addEdge(nw[0], nw[1]); // add tangent
        while (true) {
            pll pt[2] = {p[nw[0]], p[nw[1]]};
            int ch = -1, sd = 0;
            for (int t = 0; t < 2; ++t)
                for (auto it : head[nw[t]])
                    if (ori(pt[0], pt[1], p[it.id]) > 0 && (
                        ch == -1 || in_cc({pt[0], pt[1], p[ch]
                            }, p[it.id])))
                        ch = it.id, sd = t;
            if (ch == -1) break; // upper common tangent
            for (auto it = head[nw[sd]].begin(); it != head[
                nw[sd]].end(); )
                if (seg_strict_intersect(pt[sd], p[it->id], pt[
                    sd ^ 1], p[ch]))
                    head[it->id].erase(it->twin), head[nw[sd]].
                        erase(it++);
            else ++it;
            nw[sd] = ch, addEdge(nw[0], nw[1]);
        }
    }
} tool;

```

## 7.17 Voronoi Diagram

```

// 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].pb(Line(m, m + d));
        }
}

```

## 7.18 Trapezoidalization

```

template<class T>
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 * SZ(base));
    }
    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 + SZ(base));
    }
    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(SZ(vec)), sweep.end(), eits(SZ(vec), event.end()) {
        for (int i = 0; i < SZ(base); ++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 / SZ(base);
        idx %= SZ(base);
        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;
}
};

```

## 7.19 3D Basic

```

struct Point {
    double x, y, z;
    Point(double _x = 0, double _y = 0, double _z = 0): x(_x), y(_y), z(_z){}
    Point(pdd p) { x = p.X, y = p.Y, z = abs2(p); }
};
Point operator-(const Point &p1, const Point &p2) {
    return Point(p1.x - p2.x, p1.y - p2.y, p1.z - p2.z);
}
Point operator+(const Point &p1, const Point &p2) {
    return Point(p1.x + p2.x, p1.y + p2.y, p1.z + p2.z);
}
Point operator/(const Point &p1, const double &v) {
    return Point(p1.x / v, p1.y / v, p1.z / v);
}
Point cross(const Point &p1, const Point &p2) {
    return Point(p1.y * p2.z - p1.z * p2.y, p1.z * p2.x - p1.x * p2.z, p1.x * p2.y - p1.y * p2.x);
}
double dot(const Point &p1, const Point &p2) {
    return p1.x * p2.x + p1.y * p2.y + p1.z * p2.z;
}
double abs(const Point &a) {
    return sqrt(dot(a, a));
}
Point cross3(const Point &a, const Point &b, const Point &c) {
    return cross(b - a, c - a);
}
double area(Point a, Point b, Point c) {
    return abs(cross3(a, b, c));
}
double volume(Point a, Point b, Point c, Point d) {
    return dot(cross3(a, b, c), d - a);
}
Point masscenter(Point a, Point b, Point c, Point d) {
    return (a + b + c + d) / 4;
}
pdd proj(Point a, Point b, Point c, Point u) {
    // proj. u to the plane of a, b, and c
    Point e1 = b - a;
    Point e2 = c - a;
    e1 = e1 / abs(e1);
    e2 = e2 - e1 * dot(e2, e1);
    e2 = e2 / abs(e2);
    Point p = u - a;
    return pdd(dot(p, e1), dot(p, e2));
}

```

## 7.20 3D Convex Hull

```

struct convex_hull_3D {
    struct Face {
        int a, b, c;
        Face(int ta, int tb, int tc): a(ta), b(tb), c(tc) {}
    }; // return the faces with pt indexes
    vector<Face> res;
    vector<Point> P;
    convex_hull_3D(const vector<Point> &P): res(), P(P) {
        // all points coplanar case will WA, O(n^2)
        int n = SZ(P);
    }
}

```

```

if (n <= 2) return; // be careful about edge case
// ensure first 4 points are not coplanar
swap(P[1], *find_if(ALL(P), [&](auto p) { return sign
    (abs2(P[0] - p)) != 0; }));
swap(P[2], *find_if(ALL(P), [&](auto p) { return sign
    (abs2(cross3(p, P[0], P[1]))) != 0; }));
swap(P[3], *find_if(ALL(P), [&](auto p) { return sign
    (volume(P[0], P[1], P[2], p)) != 0; }));
vector<vector<int>> flag(n, vector<int>(n));
res.emplace_back(0, 1, 2); res.emplace_back(2, 1, 0);
for (int i = 3; i < n; ++i) {
    vector<Face> next;
    for (auto f : res) {
        int d = sign(volume(P[f.a], P[f.b], P[f.c], P[i]));
        if (d <= 0) next.pb(f);
        int ff = (d > 0) - (d < 0);
        flag[f.a][f.b] = flag[f.b][f.c] = flag[f.c][f.a]
            = ff;
    }
    for (auto f : res) {
        auto F = [&](int x, int y) {
            if (flag[x][y] > 0 && flag[y][x] <= 0)
                next.emplace_back(x, y, i);
        };
        F(f.a, f.b); F(f.b, f.c); F(f.c, f.a);
    }
    res = next;
}
}
bool same(Face s, Face t) {
    if (sign(volume(P[s.a], P[s.b], P[s.c], P[t.a])) != 0) return 0;
    if (sign(volume(P[s.a], P[s.b], P[s.c], P[t.b])) != 0) return 0;
    if (sign(volume(P[s.a], P[s.b], P[s.c], P[t.c])) != 0) return 0;
    return 1;
}
int polygon_face_num() {
    int ans = 0;
    for (int i = 0; i < SZ(res); ++i)
        ans += none_of(res.begin(), res.begin() + i, [&](
            Face g) { return same(res[i], g); });
    return ans;
}
double get_volume() {
    double ans = 0;
    for (auto f : res)
        ans += volume(Point(0, 0, 0), P[f.a], P[f.b], P[f.c]);
    return fabs(ans / 6);
}
double get_dis(Point p, Face f) {
    Point p1 = P[f.a], p2 = P[f.b], p3 = P[f.c];
    double a = (p2.y - p1.y) * (p3.z - p1.z) - (p2.z - p1.z) * (p3.y - p1.y);
    double b = (p2.z - p1.z) * (p3.x - p1.x) - (p2.x - p1.x) * (p3.z - p1.z);
    double c = (p2.x - p1.x) * (p3.y - p1.y) - (p2.y - p1.y) * (p3.x - p1.x);
    double d = 0 - (a * p1.x + b * p1.y + c * p1.z);
    return fabs(a * p.x + b * p.y + c * p.z + d) / sqrt(a * a + b * b + c * c);
}
};

```

## 8 Misc

### 8.1 Cyclic Ternary Search

```

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

```

```

}
return pred(1, r % n) ? l : r % n;
}

```

### 8.2 Mo's Algorithm

```

struct MoAlgorithm {
    struct query {
        int l, r, id;
        bool operator < (const query &o) {
            if (l / C == o.l / C)
                return (l / C & 1 ? r > o.r : r < o.r);
            return l / C < o.l / C;
        }
    };
    int cur_ans;
    vector<int> ans;
    void add(int x) {
        // do something
    }
    void sub(int x) {
        // do something
    }
    vector<query> Q;
    void add_query(int l, int r, int id) {
        // [l, r)
        Q.push_back({l, r, id});
        ans.push_back(0);
    }
    void run() {
        sort(Q.begin(), Q.end());
        int pl = 0, pr = 0;
        cur_ans = 0;
        for (query &i : Q) {
            while (pl > i.l) add(a[--pl]);
            while (pr < i.r) add(a[pr++]);
            while (pl < i.l) sub(a[pl++]);
            while (pr > i.r) sub(a[--pr]);
            ans[i.id] = cur;
        }
    }
};

```

### 8.3 Mo's Algorithm On Tree

```

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

```

## 8.4 PBDS

```

#include <ext/pb_ds/tree_policy.hpp>
#include <ext/pb_ds/assoc_container.hpp>
using namespace __gnu_pbds;
tree<int, null_type, less<int>, rb_tree_tag,
    tree_order_statistics_node_update> oset;
// order_of_key
// find_by_order
cc_hash_table<int, int> m1;
gp_hash_table<int, int> m2;
// like map, but much faster

```

## 8.5 Random

```

auto SEED = chrono::steady_clock::now().
    time_since_epoch().count();
mt19937 rng(SEED);

```

## 8.6 SOS dp

```

//memory optimized, super easy to code.
for(int i = 0; i < (1<<N); ++i)
    F[i] = A[i];
for(int i = 0; i < N; ++i) for(int mask = 0; mask < (1<<N); ++mask){
    if(mask & (1<<i))
        F[mask] += F[mask^(1<<i)];
}

```

## 8.7 SMAWK

```

long long query(int l, int r) {
    // ...
}
struct SMAWK {
    // Condition:
    // If M[1][0] < M[1][1] then M[0][0] < M[0][1]
    // If M[1][0] == M[1][1] then M[0][0] <= M[0][1]
    // For all i, find r_i s.t. M[i][r_i] is maximum ||
    // minimum.
    int ans[N], tmp[N];
    void interpolate(vector<int> l, vector<int> r) {
        int n = l.size(), m = r.size();
        vector<int> nl;
        for (int i = 1; i < n; i += 2) {
            nl.push_back(l[i]);
        }
        run(nl, r);
        for (int i = 1, j = 0; i < n; i += 2) {
            while (j < m && r[j] < ans[l[i]])
                j++;
            assert(j < m && ans[l[i]] == r[j]);
            tmp[l[i]] = j;
        }
        for (int i = 0; i < n; i += 2) {
            int curl = 0, curr = m - 1;
            if (i)
                curl = tmp[l[i - 1]];
            if (i + 1 < n)
                curr = tmp[l[i + 1]];
            long long res = query(l[i], r[curl]);
            ans[l[i]] = r[curl];
            for (int j = curl + 1; j <= curr; ++j) {
                lli nxt = query(l[i], r[j]);
                if (res < nxt)
                    res = nxt, ans[l[i]] = r[j];
            }
        }
    }
    void reduce(vector<int> l, vector<int> r) {
        int n = l.size(), m = r.size();
        vector<int> nr;
        for (int j : r) {
            while (!nr.empty()) {

```

```

                int i = nr.size() - 1;
                if (query(l[i], nr.back()) <= query(l[i], j))
                    nr.pop_back();
                else
                    break;
            }
            if (nr.size() < n)
                nr.push_back(j);
        }
        run(l, nr);
    }
    void run(vector<int> l, vector<int> r) {
        int n = l.size(), m = r.size();
        if (max(n, m) <= 2) {
            for (int i : l) {
                ans[i] = r[0];
                if (m > 1) {
                    if (query(i, r[0]) < query(i, r[1]))
                        ans[i] = r[1];
                }
            }
        } else if (n >= m) {
            interpolate(l, r);
        } else {
            reduce(l, r);
        }
    }
};

```

## 8.8 Tree Hash

```

ull seed;
ull shift(ull x) {
    x ^= x << 13;
    x ^= x >> 7;
    x ^= x << 17;
    return x;
}
ull dfs(int u, int f) {
    ull sum = seed;
    for (int i : G[u])
        if (i != f)
            sum += shift(dfs(i, u));
    return sum;
}

```

## 8.9 Python

```

from [decimal, fractions, math, random] import *
setcontext(Context(prec=10, Emax=MAX_EMAX, rounding=
    ROUND_FLOOR))
Decimal('1.1') / Decimal('0.2')
Fraction(3, 7)
Fraction(Decimal('1.14'))
Fraction('1.2').limit_denominator(4).numerator
Fraction(cos(pi / 3)).limit_denominator()
print(*[randint(1, C) for i in range(0, N)], sep=' ')

```