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1 Basic

1.1 Template [30a783]

```
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 uni(c) c.resize(distance(c.begin(),unique(c.
begin(),c.end())))
#define unisort(c) sort(c.begin(),c.end()),uni(c)
auto SEED = chrono::steady_clock::now().
time_since_epoch().count();
mt19937 rng(SEED);
// cpp $1 -DDEBUG -fpreprocessed | tr -d '[:space:]' |
md5sum | cut -c-6
```

1.2 Fast IO [b7f4fb]

```
#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;
}
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>0
noremap <F9> <Esc>:w<CR>:!g++ "%: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 (SCC) [1aebd0]

```
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, nscc;
  TwoSAT () = default;
  TwoSAT (int _n) : n(_n), nscc(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] = nscc;
    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), nscc++;
```

```

    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 [d04ebe]

```

struct BCC{ // 0-based, allow multi edges but not allow loops
    int n, m, cnt = 0;
    // n:|V|, m:|E|, cnt:#bcc
    // bcc i : vertices bcc_v[i] and edges bcc_e[i]
    vector<vector<int>> bcc_v, bcc_e;
    vector<vector<pii>> g; // original graph
    vector<pii> edges; // 0-based
    BCC(int _n, vector<pii> _edges):
        n(_n), m(SZ(_edges)), g(_n), edges(_edges){
            for(int i = 0; i < m; i++){
                auto [u, v] = edges[i];
                g[u].pb(pii(v, i)); g[v].pb(pii(u, i));
            }
        }
    void make_bcc(){ bcc_v.pb(); bcc_e.pb(); cnt++; }
    // modify these if you need more information
    void add_v(int v){ bcc_v.back().pb(v); }
    void add_e(int e){ bcc_e.back().pb(e); }
    void build(){
        vector<int> in(n, -1), low(n, -1), stk;
        vector<vector<int>> up(n);
        int ts = 0;
        auto _dfs = [&](auto dfs, int now, int par, int pe
            -> void{
            if(pe != -1) up[now].pb(pe);
            in[now] = low[now] = ts++;
            stk.pb(now);
            for(auto [v, e] : g[now]){
                if(e == pe) continue;
                if(in[v] != -1){
                    if(in[v] < in[now]) up[now].pb(e);
                    low[now] = min(low[now], in[v]);
                    continue;
                }
                dfs(dfs, v, now, e);
                low[now] = min(low[now], low[v]);
            }
            if((now != par && low[now] >= in[par]) || (now == par && SZ(g[now]) == 0)){
                make_bcc();
                for(int v = stk.back(); v = stk.back()){
                    stk.pop_back(), add_v(v);
                    for(int e : up[v]) add_e(e);
                    if(v == now) break;
                }
                if(now != par) add_v(par);
            }
        });
        for(int i = 0; i < n; i++)
            if(in[i] == -1) _dfs(_dfs, i, i, -1);
    }
};

```

2.3 EdgeBCC [8a9523]

```

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);
    bool visp = false;
    for (int u : adj[v]) {
        if (!visp && u == pa) {
            visp = true;
        } else 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 [2356be]

```

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]);
        cd_pa[c] = pa;
        // 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 [c7e8f2]

```
// 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 [d3eb5f]

```
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 [6378d5]

```
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;
} // dom[]: parent on dom. tree, -1 if not reachable
};
```

2.8 Heavy Light Decomposition [372958]

```
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)
u = par[hd[u]];
}
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 Virtual Tree [dcbe4f]

```

// 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();
}

```

2.10 Vizing [fa4b32]

```

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

```

2.11 Maximum Clique Dynamic [6dde09]

```

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;

```

2.12 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 [90f481]

```

//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 [8ec1c7]

```

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 [473c12]

```

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 [87ade4]

```

// 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 Splay Tree [e9029a]

```

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);
        }
    };
};


```

3.6 Treap [9dc91b]

```

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();
    } else {
        b->tl = merge(a, b->tl);
        b->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 [4b930f]

```

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 [8898fb]

```
template <typename T>
```

```

struct Dinic { // 0-based
    const T INF = numeric_limits<T>::max() / 2;
    struct edge { int to, rev; T cap, flow; };
    int n, s, t;
    vector <vector <edge>> g;
    vector <int> dis, cur;
    T dfs(int u, T cap) {
        if (u == t || !cap) return cap;
        for (int &i = cur[u]; i < (int)g[u].size(); ++i) {
            edge &e = g[u][i];
            if (dis[e.to] == dis[u] + 1 && e.flow != e.cap) {
                T df = dfs(e.to, min(e.cap - e.flow, cap));
                if (df) {
                    e.flow += df;
                    g[e.to][e.rev].flow -= df;
                    return df;
                }
            }
        }
        dis[u] = -1;
        return 0;
    }
    bool bfs() {
        fill(all(dis), -1);
        queue<int> q;
        q.push(s), dis[s] = 0;
        while (!q.empty()) {
            int v = q.front(); q.pop();
            for (auto &u : g[v])
                if (!~dis[u.to] && u.flow != u.cap) {
                    q.push(u.to);
                    dis[u.to] = dis[v] + 1;
                }
        }
        return dis[t] != -1;
    }
    T solve(int _s, int _t) {
        s = _s, t = _t;
        T flow = 0, df;
        while (bfs()) {
            fill(all(cur), 0);
            while ((df = dfs(s, INF))) flow += df;
        }
        return flow;
    }
    void reset() {
        for (int i = 0; i < n; ++i)
            for (auto &j : g[i]) j.flow = 0;
    }
    void add_edge(int u, int v, T cap) {
        g[u].pb(edge{v, (int)g[v].size(), cap, 0});
        g[v].pb(edge{u, (int)g[u].size() - 1, 0, 0});
    }
    Dinic (int _n) : n(_n), g(n), dis(n), cur(n) {};
}

```

4.3 Min Cost Max Flow [e18ab8]

```

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 [ea0477]

```

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) {
        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 [a138de]

```

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) [ac255a]

```

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 [90ead2]

```

vector<array<int, 3>> GomoryHu(Dinic<int> flow) {
    // Tree edge min = mincut (0-based)
    int n = flow.n;
    vector<array<int, 3>> ans;
    vector<int> rt(n);
    for (int i = 1; i < n; ++i) {
        int t = rt[i];
        flow.reset();
        ans.pb({i, t, flow.solve(i, t)});
        flow.bfs();
        for (int j = i + 1; j < n; ++j)

```

```

            if (rt[j] == t && flow.dis[j] != -1) rt[j] = i;
        }
        return ans;
    }

    4.8 General Graph Matching [2b7f20]

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

```

4.9 Flow notes

- Bipartite Matching Restore Answer
runBfs(); Answer is $\{ \text{vis}[x] | x \in L \} \cup \{ \text{vis}[x] | x \in R \}$

- Bipartite Minimum Weight Vertex Covering

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

For general version, change Dinic to MCMF and:

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

- Useful Lemma

(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 $x \implies$ not choose A cost x , tot+ = x
choose A and choose B cost x : NO!!!
Bipartite: can flip one side

- Min Cut Restore Answer

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

- 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 ∞ (skip this in circulation problem), and let f be the maximum flow from S to T . If $f \neq \sum_{v \in V, in(v) > 0} in(v)$, there's no solution. Otherwise, the maximum flow from s to t is the answer.
 - To minimize, let f be the maximum flow from S to T . Connect $t \rightarrow s$ with capacity ∞ and let the flow from S to T be f' . If $f + f' \neq \sum_{v \in V, in(v) > 0} in(v)$, there's no solution. Otherwise, f' is the answer.
- 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.

- Minimum cost cyclic flow

- Construct super source S and sink T
- For each edge (x, y, c) , connect $x \rightarrow y$ with $(cost, cap) = (c, 1)$ if $c > 0$, otherwise connect $y \rightarrow x$ with $(cost, cap) = (-c, 1)$
- For each edge with $c < 0$, sum these cost as K , then increase $d(y)$ by 1, decrease $d(x)$ by 1
- For each vertex v with $d(v) > 0$, connect $S \rightarrow v$ with $(cost, cap) = (0, d(v))$
- For each vertex v with $d(v) < 0$, connect $v \rightarrow T$ with $(cost, cap) = (0, -d(v))$
- Flow from S to T , the answer is the cost of the flow $C + K$

- 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.

5 String

5.1 AC Automaton [b9fe7c]

```
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'];
            ans += cnt[now];
        }
        return ans;
    }
};
```

5.2 Lyndon Factorization [a9eeb0]

```
// partition s = w[0] + w[1] + ... + w[k-1],
// w[0] >= w[1] >= ... >= w[k-1]
// each w[i] strictly smaller than all its suffix
vector<string> duval(const string &s) {
    vector<string> ans;
    for (int n = (int)s.size(), i = 0, j, k; i < n; ) {
        for (j = i + 1, k = i; j < n && s[k] <= s[j]; j++)
            k = (s[k] < s[j] ? i : k + 1);
        for (; i <= k; i += j - k)
            ans.pb(s.substr(i, j - k)); // s.substr(1, len)
    }
    return ans;
}
```

5.3 KMP [5ac553]

```
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;
}

```

5.4 Manacher [643e55]

```

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;
    }
}

```

5.5 Minimum Rotate [acob8e]

```

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);
}

```

5.6 Palindrome Tree [0518a5]

```

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;
    }
}

```

5.7 Repetition [f3da14]

```

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 = l; i < m; ++i)
        to_right[i] = Z[r - m + 1 + i - l];
    reverse(all(sl));
    Z = buildZ(sl);
    for (int i = l; i < m; ++i)
        to_left[i] = Z[m - i - 1];
    reverse(all(sl));
    for (int i = l; 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(sl)), 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 + "#" + sl);
    for (int i = l; i < m; ++i)
        if (Z[r - m + 1 + i - 1] >= m - i)
            rep.pb({i, i, m - i});
    }
}

```

5.8 Suffix Array [60547e]

```

#define FOR(i, a, b) for(int i = a; i <= b; i++)
#define ROF(i, a, b) for(int i = a; i >= b; i--)
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 = (int)s.size();
    FOR(i, 0, m - 1) c[i] = 0;
    FOR(i, 0, n - 1) c[x[i]] = s[i]++;
    FOR(i, 1, m - 1) c[i] += c[i - 1];
    ROF(i, n - 1, 0) sa[--c[x[i]]] = i;
    for (int k = 1; k < n; k <= 1) {
        FOR(i, 0, m - 1) c[i] = 0;
        FOR(i, 0, n - 1) c[x[i]]++;
        FOR(i, 1, m - 1) c[i] += c[i - 1];
        int p = 0;
        FOR(i, n - k, n - 1) y[p++] = i;
        FOR(i, 0, n - 1) if(sa[i] >= k) y[p++] = sa[i] - k;
        ROF(i, n - 1, 0) sa[--c[x[y[i]]]] = y[i];
        y[sa[0]] = p = 0;
        FOR(i, 1, n - 1) {
            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 = (int)s.size(), val = 0;
    FOR(i, 0, n - 1) rk[sa[i]] = i;
    FOR(i, 0, n - 1) {
        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;
        }
    }
}

```

5.9 SAIS (C++20) [6f26bc]

```

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-- : 0;
        }
    }
};

```

5.10 Suffix Automaton [277d1d]

```

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;

```

5.11 Z Value [a8c33c]

```

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 [c34682]

```

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 [cd559d]

```

#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 Discrete Logarithm [da27bf]

```

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;
}

```

6.4 Extgcd [d8bbd5]

```

// 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)};
}

```

6.5 Floor Sum [49de67]

```

// sum^{n-1}_0 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;
}

```

6.6 Factorial Mod P^k [c324f3]

```

// 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

```

6.7 Gaussian Elimination [fa0977]

```

using VI = vector<int>; // be careful if A.empty()
using VVI = vector<VI>; // ensure that 0 <= x < mod
pair<VI, VVI> gauss(VVI A, VI b) { // solve Ax=b
    const int N = (int)A.size(), M = (int)A[0].size();
    vector<int> devp, free(M, true); int rk = 0;
    for (int i = 0; i < M; i++) {
        int p = -1;
        for (int j = rk; j < N; j++)
            if (p == -1 || abs(A[j][i]) > abs(A[p][i]))
                p = j;
        if (p == -1 || A[p][i] == 0) continue;
        swap(A[p], A[rk]); swap(b[p], b[rk]);
        const int inv = modinv(A[rk][i]);
        for (int &x : A[rk]) x = mul(x, inv);
        b[rk] = mul(b[rk], inv);
        for (int j = 0; j < N; j++) if (j != rk) {
            int z = A[j][i];
            for (int k = 0; k < M; k++)
                A[j][k] = sub(A[j][k], mul(z, A[rk][k]));
            b[j] = sub(b[j], mul(z, b[rk]));
        }
        devp.push_back(i); free[i] = false; ++rk;
    }
    for (int i = rk; i < N; i++)

```

```

    if (b[i] != 0) return {}, {}); // not consistent
VI x(M); VVI h;
for (int i = 0; i < rk; i++) x[depv[i]] = b[i];
for (int i = 0; i < M; i++) if (free[i]) {
    h.emplace_back(M); h.back()[i] = 1;
    for (int j = 0; j < rk; j++)
        h.back()[depv[j]] = sub(0, A[j][i]);
}
return {x, h}; // solution = x + span(h[i])
}

```

6.8 Linear Function Mod Min [5552e3]

```

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
        , 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 [07ddf2]

```

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(l, 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 Quadratic Residue [e0bf30]

```

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; 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;
}

```

6.11 Simplex [ece29e]

```

struct Simplex { // 0-based
    using T = long double;
    static const int N = 410, M = 30010;
    const T eps = 1e-7;
    int n, m;
    int Left[M], Down[N];
    // Ax <= b, max c^T x
    // result : v, xi = sol[i]. 1 based
    T a[M][N], b[M], c[N], v, sol[N];
}

```

```

bool eq(T a, T b) {return fabs(a - b) < eps;}
bool ls(T a, T b) {return a < b && !eq(a, b);}
void init(int _n, int _m) {
    n = _n, m = _m, v = 0;
    for (int i = 0; i < m; ++i) for (int j = 0; j < n;
        ++j) a[i][j] = 0;
    for (int i = 0; i < m; ++i) b[i] = 0;
    for (int i = 0; i < n; ++i) c[i] = sol[i] = 0;
}
void pivot(int x, int y) {
    swap(Left[x], Down[y]);
    T k = a[x][y]; a[x][y] = 1;
    vector<int> nz;
    for (int i = 0; i < n; ++i) {
        a[x][i] /= k;
        if (!eq(a[x][i], 0)) nz.push_back(i);
    }
    b[x] /= k;
    for (int i = 0; i < m; ++i) {
        if (i == x || eq(a[i][y], 0)) continue;
        k = a[i][y], a[i][y] = 0;
        b[i] -= k * b[x];
        for (int j : nz) a[i][j] -= k * a[x][j];
    }
    if (eq(c[y], 0)) return;
    k = c[y], c[y] = 0, v += k * b[x];
    for (int i : nz) c[i] -= k * a[x][i];
}
// 0: found solution, 1: no feasible solution, 2:
// unbounded
int solve() {
    for (int i = 0; i < n; ++i) Down[i] = i;
    for (int i = 0; i < m; ++i) Left[i] = n + i;
    while (1) {
        int x = -1, y = -1;
        for (int i = 0; i < m; ++i) if (ls(b[i], 0) && (x
            == -1 || b[i] < b[x])) x = i;
        if (x == -1) break;
        for (int i = 0; i < n; ++i) if (ls(a[x][i], 0) &&
            (y == -1 || a[x][i] < a[x][y])) y = i;
        if (y == -1) return 1;
        pivot(x, y);
    }
    while (1) {
        int x = -1, y = -1;
        for (int i = 0; i < n; ++i) if (ls(0, c[i]) && (y
            == -1 || c[i] > c[y])) y = i;
        if (y == -1) break;
        for (int i = 0; i < m; ++i) if (ls(0, a[i][y]) &&
            (x == -1 || b[i] / a[i][y] < b[x] / a[x][y])
            ) x = i;
        if (x == -1) return 2;
        pivot(x, y);
    }
    for (int i = 0; i < m; ++i) if (Left[i] < n) sol[
        Left[i]] = b[i];
    return 0;
}

```

6.12 FFT [43cc28]

```

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;
        }
    };

```

6.13 NTT [f68103]

```

//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;
        }
    }
}

```

6.14 FWT [af59af]

```

void fwt(vector <int> &a) {
    // and : x += y * (1, -1)
    // or : y += x * (1, -1)
    // xor : x = (x + y) * (1, 1/2)
    //      y = (x - y) * (1, 1/2)
    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
    }
}
vector<int> subs_conv(vector<int> a, vector<int> b) {
    // c_i = sum_{j & k = 0, j | k = i} a_j * b_k
    int n = __lg(a.size());
    vector<vector<int>> ha(n + 1, vector<int>(1 << n));
    vector<vector<int>> hb(n + 1, vector<int>(1 << n));
    vector<vector<int>> c(n + 1, vector<int>(1 << n));
    for (int i = 0; i < 1 << n; ++i) {
        ha[__builtin_popcount(i)][i] = a[i];
        hb[__builtin_popcount(i)][i] = b[i];
    }
    for (int i = 0; i <= n; ++i)
        or_fwt(ha[i]), or_fwt(hb[i]);
    for (int i = 0; i <= n; ++i)
        for (int j = 0; i + j <= n; ++j)
            for (int k = 0; k < 1 << n; ++k)
                // mind overflow
                c[i + j][k] += ha[i][k] * hb[j][k];
    for (int i = 0; i <= n; ++i) or_fwt(c[i], true);
    vector<int> ans(1 << n);
    for (int i = 0; i < 1 << n; ++i)
        ans[i] = c[__builtin_popcount(i)][i];
    return ans;
}

```

6.15 Polynomial [69f2b5]

```

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;
}
// sum_j[x^j]f^i for i=0,1,...,m
vector<ll> power_proj(Poly wt, int m) { // 1e5 2s,
    MAXN >= 4 * n()
    // wt.size() = n(), (*this[0]) == 0
    int sz = 1;
    while (sz < n()) sz <= 1;
    Poly f(*this, sz);
    wt.isz(sz).irev();
    int k = 1, ksz2 = 2 * sz * k, ksz4 = 4 * sz * k;
    Poly _P(2 * sz, 0), _Q(2 * sz, 0);
    rep(i, sz) _P[i] = wt[i], _Q[i] = (P - f[i]) % P;
    while (sz > 1) {
        Poly R(ksz2);
        rep(i, ksz2) R[i] = (i % 2 == 0 ? _Q[i] : (P - _Q
            [i]) % P);
        Poly PQ = _P.Mul(R), QQ = _Q.Mul(R);
        PQ.isz(ksz4), QQ.isz(ksz4);
        rep(i, ksz2) {
            if((PQ[ksz2 + i] += _P[i]) >= P) PQ[ksz2 + i]
                -= P;
            if((QQ[ksz2 + i] += _Q[i] + R[i]) >= P) QQ[ksz2
                + i] -= P;
            if(QQ[ksz2 + i] >= P) QQ[ksz2 + i] -= P;
        }
    }
}

```

```

fill(ALL(_P), 0), fill(ALL(_Q), 0);
rep(j, 2 * k) rep(i, sz / 2) {
    _P[sz * j + i] = PQ[(2 * sz) * j + (2 * i + 1)]
    ];
    _Q[sz * j + i] = QQ[(2 * sz) * j + (2 * i + 0)]
    ];
}
sz /= 2, k *= 2;
}
vector<ll> p(k);
rep(i, k) p[i] = _P[2 * i];
reverse(ALL(p));
p.resize(m + 1);
return p;
}
Poly comp_inv() { // (*this)[0] == 0, (*this)[1] != 0
    Poly X(*this, n()), wt(n(), 0);
    ll ic = ntt.minv((*this)[1]);
    for (auto& x: X) x = x * ic % P;
    wt[n() - 1] = 1;
    vector<ll> A = X.power_proj(wt, n() - 1);
    Poly g(n() - 1);
    rep1(i, n() - 1) g[n() - 1 - i] = (n() - 1) * A[i]
        % P * ntt.minv(i) % P;
    g = g.Pow(ntt.minv(P - n() + 1));
    g.insert(g.begin(), 0);
    ll p = 1;
    rep(i, g.n()) g[i] = g[i] * p % P, p = p * ic % P;
    return g;
}
Poly TMul(const Poly &rhs) const { // this[i] - rhs[j]
    ] = k
    return Poly(*this).irev().Mul(rhs).isz(n()).irev();
}
Poly composition(Poly g) { // f(g(x)), 1e5 3s, MAXN
    >= 8n
    auto rec = [&](auto &rec, int n, int k, Poly Q) ->
        Poly {
        if (n == 1) {
            Poly p(2 * k);
            irev();
            fi(0, k) p[2 * i] = (*this)[i];
            return p;
        }
        Poly R(2 * n * k);
        fi(0, 2 * n * k) R[i] = (i % 2 == 0 ? Q[i] : (P -
            Q[i]) % P);
        Poly QQ = Q.Mul(R).isz(4 * n * k);
        fi(0, 2 * n * k) {
            QQ[2 * n * k + i] += Q[i] + R[i];
            QQ[2 * n * k + i] %= P;
        }
        Poly nxt_Q(2 * n * k);
        for(int j = 0; j < 2 * k; j++) fi(0, n / 2) {
            nxt_Q[n * j + i] = QQ[(2 * n) * j + (2 * i + 0)]
            ];
        }
        Poly nxt_p = rec(rec, n / 2, k * 2, nxt_Q);
        Poly pq(4 * n * k);
        for(int j = 0; j < 2 * k; j++) fi(0, n / 2) {
            pq[(2 * n) * j + (2 * i + 1)] += nxt_p[n * j +
                i];
            pq[(2 * n) * j + (2 * i + 1)] %= P;
        }
        Poly p(2 * n * k);
        fi(0, 2 * n * k) p[i] = (p[i] + pq[2 * n * k + i
            ]) % P;
        pq.pop_back();
        Poly x = pq.TMul(R);
        fi(0, 2 * n * k) p[i] = (p[i] + x[i]) % P;
        return p;
    };
    int sz = 1;
    while(sz < n() || sz < g.n()) sz <= 1;
    return isz(sz), rec(rec, sz, 1, g.imul(P-1).isz(2 *
        sz)).isz(sz).irev();
}
#endif
using Poly_t = Poly<131072 * 2, 998244353, 3>;
//template<> decltype(Poly_t::ntt) Poly_t::ntt = {};

```

6.16 Generating Functions

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

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

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

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

- Special Generating Function

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

6.17 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. $\sum_{1 \leq i \leq n} A_{jix_i} \geq b_j \rightarrow \sum_{1 \leq i \leq n} -A_{jix_i} \leq -b_j$
3. $\sum_{1 \leq i \leq n} A_{jix_i} = b_j$
 - $\sum_{1 \leq i \leq n} A_{jix_i} \leq b_j$
 - $\sum_{1 \leq i \leq n} A_{jix_i} \geq b_j$

4. If x_i has no lower bound, replace x_i with $x_i - x'_i$

6.18 Estimation

n	2	3	4	5	6	7	8	9	20	30	40	50	100
$p(n)$	2	3	5	7	11	15	22	30	627	5604	4e4	2e5	2e8
n	100	1e3	1e6	1e9	1e12	1e15	1e18						
$d(i)$	12	32	240	1344	6720	26880	103680						
arg	60	840	720720	735134400	963761198400	866421317361600	897612484786617600						
n	1	2	3	4	5	6	7	8	9	10	11	12	13
$\binom{2n}{n}$	2	6	20	70	252	924	3432	12870	48620	184756	7e5	2e6	1e7
n	2	3	4	5	6	7	8	9	10	11	12	13	1.5e8
B_n	2	5	15	52	203	877	4140	21147	115975	7e5	4e6	3e7	

6.19 Theorem

- Kirchhoff's Theorem

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

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

- Tutte's Matrix

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

- Cayley's Formula

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

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

spanning trees.

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

- Erdős-Gallai Theorem

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

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

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

- Burnside's Lemma

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

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

Then

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

- Gale-Ryser theorem

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

- 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

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

- Spherical cap

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

- Chinese Remainder Theorem

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

6.20 General Purpose Numbers

- Bernoulli numbers

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

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

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

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

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

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

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

- Pentagonal number theorem

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

- Catalan numbers

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

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

- Eulerian numbers

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

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

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

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

6.21 Integral

$$\begin{array}{llll} \frac{d}{dx} f(x) & \sec^2 x & -\csc^2 x & \tan x \sec x \\ f(x) & \tan x & \cot x & \sec x \\ & \ln|\sec x| & -\ln|\csc x| & \ln|\tan x + \sec x| \\ & & & -\ln|\cot x + \csc x| \\ \frac{d}{dx} f(x) & \frac{1}{\sqrt{1-x^2}} & \frac{-1}{\sqrt{1-x^2}} & \frac{1}{x^2+1} \\ & \arcsin x & \arccos x & \arctan x \\ & & & \frac{1}{2}(\sec x \tan x + \ln|\sec x + \tan x|) \end{array}$$

- $\int_0^{\frac{\pi}{2}} \sin^{2k} dx = \frac{\pi}{2} \cdot \frac{1 \cdot 3 \cdots (2k-1)}{2 \cdot 4 \cdots (2k)}$
- $\int_0^{\frac{\pi}{2}} \sin^{2k+1} dx = \frac{2 \cdot 4 \cdots (2k)}{3 \cdot 5 \cdots (2k+1)}$
- polar: $\iint r \cdot f(r \cos \theta, r \sin \theta) dr d\theta$
- spherical: $\iiint \rho^2 \sin \phi \cdot f(\rho \sin \phi \cos \theta, \rho \sin \phi \sin \theta, \rho \cos \theta) d\rho d\theta d\phi$

7 Geometry

7.1 Basic [54bb7b]

```
using T = long double; // int
const double eps=1e-9; // 1
T operator*(PT a,PT b){return a.x*b.x+a.y*b.y;}
T operator^(PT a,PT b){return a.x*b.y-a.y*b.x;}
T abs2(PT a){return a*a;}
double abs(PT a){return sqrt(a*a);}
int sign(T a){return abs(a)<eps?0:a>0?1:-1;}
int ori(PT a,PT b,PT c){return sign((b-a)^(c-a));}
bool btw(PT a,PT b,PT c){ //is C between AB
    return ori(a,b,c)?0:sign((a-c)*(b-c))<=0;}
PT proj(PT a,PT b,PT c){ //ac projection on ab
    return (b-a)*(c-a)*(b-a)/abs2(b-a);}
double dist(PT a,PT b,PT c){ //distance from C to AB
    return abs((c-a)^(b-a))/abs(b-a);}
PT ccw90(PT p){return PT(-p.y, p.x);}
struct Line{PT a,b;};
struct Cir{PT o,double r;};
```

7.2 Convex Hull [da4142]

```
#define sz(x) ((int)x.size())
vector<PT> ConvexHull(vector<PT> pt) {
    int n = sz(pt);
    sort(pt.begin(), pt.end(), [&](PT a, PT b) { return
        make_pair(a.x, a.y) < make_pair(b.x, b.y); });
    vector<PT> ans = {pt[0]};
    rep(t, 2) {
        int m = sz(ans);
        rep1(i, n - 1) {
            while (sz(ans) > m && ori(ans[sz(ans) - 2], ans.
                back(), pt[i]) <= 0) ans.pop_back();
            ans.pb(pt[i]);
        }
        reverse(pt.begin(), pt.end());
    }
    if (sz(ans) > 1) ans.pop_back();
    return ans;
}
```

7.3 Dynamic Convex Hull [24359e]

```
struct DynamicConvexHull {
    struct UpCmp {
        bool operator()(const PT a, const PT b) const {
            if (a.x==b.x) return a.y<b.y;
            return a.x<b.x;
        }
    };
    struct DownCmp {
        bool operator()(const PT a, const PT b) const {
            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<UpCmp> up;
    Hull<DownCmp> 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 [9a1f2c]

```
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 [db1576]

```
//is p4 in circumcircle of p1p2p3
using i128 = __int128;
i1 sq(i1 x) { return x * x; }
bool in_cc(const PT &p1, const PT &p2, const PT &p3,
    const PT &p4) {
    i1 u11 = p1.x - p4.x; i1 u12 = p1.y - p4.y;
    i1 u21 = p2.x - p4.x; i1 u22 = p2.y - p4.y;
    i1 u31 = p3.x - p4.x; i1 u32 = p3.y - p4.y;
    i1 u13 = sq(p1.x) - sq(p4.x) + sq(p1.y) - sq(p4.y);
    i1 u23 = sq(p2.x) - sq(p4.x) + sq(p2.y) - sq(p4.y);
    i1 u33 = sq(p3.x) - sq(p4.x) + sq(p3.y) - sq(p4.y);
    i128 det =
        - (i128)u13 * u22 * u31 + (i128)u12 * u23 * u31
        + (i128)u13 * u21 * u32 - (i128)u11 * u23 * u32
        - (i128)u12 * u21 * u33 + (i128)u11 * u22 * u33;
    return det > 0;
}
```

7.6 Half Plane Intersection [b9b059]

```
// depends on polar angle
auto area_pair(Line a, Line b) {
    return make_pair((a.b - a.a) ^ (b.a - a.a),
```

```

        (a.b - a.a) ^ (b.b - a.a));
}
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) a12X *= -1, a12Y *= -1;
    return (_int128) a02Y * a12X > (_int128) a02X *
        a12Y;
}
/* [solution exists] <=> [result.size() > 2] */
/* --^-- Line.a --^--- Line.b --^--- */
#define sz(x) ((int)x.size())
vector<Line> HalfPlaneInter(vector<Line> arr) {
    sort(arr.begin(), arr.end(), [&](Line a, Line b) {
        PT p1 = a.b - a.a, p2 = b.b - b.a;
        if ((p1 <= p2) != 0) return p1 < p2;
        return ori(a.a, a.b, b.b) < 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 (((dq.back().b - dq.back().a) <= (p.b - p.a))
            != 0)
            pop_back(2, p), pop_front(2, p), dq.pb(p);
    pop_back(3, dq[0]), pop_front(3, dq.back());
    return vector<Line>(dq.begin(), dq.end());
}

```

7.7 Minkowski Sum [65bf29]

```

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;
    rep(i, n) s1.pb(a[(i + 1) % n] - a[i]);
    rep(i, m) 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 [9d4843]

```

// CCW starting from (1, 0) inclusive, w/o tie-breaking
int halfplane(PT p) {
    if (sign(p * p) == 0) return 0;
    return 1 - 2 * (sign(p.y) > 0 || (sign(p.y) == 0 &&
        sign(p.x) > 0));
} // upper(-1) -> origin(0) -> lower(1)
auto operator<=>(PT a, PT b) {
    int ha = halfplane(a), hb = halfplane(b);
    if (ha != hb) return ha <= hb;
    return 0 <= sign(a ^ b);
} // before c++20: replace <= with <

```

7.9 Rotating Sweep Line [bdd83b]

```

// pts: 0-indexed Pt array
void RotSwpLine(int n, PT* pts) {
    using E = pair<PT, pii>;
    vector<E> ev; // dir, i, j: (i, j)=>(j, i)
    rep(i, n) rep(j, i) {
        PT dir = pts[j] - pts[i];
        halfplane(dir) < 0 ? ev.pb({dir, {i, j}}) :
            ev.pb({PT(0, 0) - dir, {j, i}});
    }
    sort(ev.begin(), ev.end(), [&](E e1, E e2) {
        auto pol = (e1.F <= e2.F);
        return pol < 0 || (pol == 0 &&
            pll(e1.F * pts[e1.S.F], e1.F * pts[e1.S.S])
            < pll(e1.F * pts[e2.S.F], e1.F * pts[e2.S.S])));
    });
}

```

```

});
```

vector<int> ord(n), rk(n);
 iota(ord.begin(), ord.end(), 0);
 sort(ord.begin(), ord.end(), [&](int i, int j) {
 return make_pair(pts[i].y, pts[i].x) < make_pair(pts[j].y, pts[j].x);
 });
 rep(i, n) rk[ord[i]] = i;
 init_order(ord); // ord[*]: point indices
 int ne = (int)ev.size();
 rep(ie, ne) {
 int i, j; tie(i, j) = ev[ie].S;
 update_swap(i, j); // i, j: point indices
 rk[i]++; rk[j]--; // rk[point idx]: rank in ord
 tie(ord[rk[i]], ord[rk[i] - 1]) = tie(i, j);
 if (ie == ne - 1 || (ev[ie + 1].F <= ev[ie].F) != 0) update_ans();
 }
}

7.10 Segment Intersect [3c8feb]

```

bool seg_sect(PT p1, PT p2, PT p3, PT p4) {
    int a123 = ori(p1, p2, p3);
    int a124 = ori(p1, p2, p4);
    int a341 = ori(p3, p4, p1);
    int a342 = ori(p3, p4, p2);
    if (!a123 && !a124) return btw(p1, p2, p3) || btw(p1,
        p2, p4) || btw(p3, p4, p1) || btw(p3, p4, p2);
    return a123 * a124 <= 0 && a341 * a342 <= 0;
} // does p1p2 intersect p3p4
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 [c326f7]

```

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] - 0, poly[(i + 1) % n] - 0, r) *
        ori(0, poly[i], poly[(i + 1) % n]);
return fabs(S);
}

```

7.12 Tangents [44761a]

```

PT unit(PT p) { return p / abs(p); }
PT ccw(PT p, double t) {
    return PT(
        p.x * cos(t) - p.y * sin(t),
        p.x * sin(t) + p.y * cos(t)
    );
}
vector<Line> tangent(Cir c, PT p) {
    vector<Line> z;
    double d = abs(p - c.o);
    if (sign(d - c.r) == 0) {
        z.push_back({p, p + ccw90(p - c.o)});
    } else if (d > c.r) {
        double o = acos(c.r / d);
        PT i = unit(p - c.o), j = ccw(i, o) * c.r, k = ccw(
            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 + ccw90(c2.o - c1.o);
        ret.pb({p1, p2});
    }
    return ret;
}

```

7.13 Tangent to Convex Hull [e374ab]

```

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

```

7.14 Minimum Enclosing Circle [4a08af]

```

PT circenter(PT a, PT b, PT c) {
    PT ab = (a + b) / 2, ac = (a + c) / 2;
    return intersect(
        ab, ab + ccw90(b - a),
        ac, ac + ccw90(c - a)
    );
}
Cir min_enclosing(vector<PT> &p) {
    shuffle(p.begin(), p.end(), mt19937(clock()));
    double r = 0;
    PT cent = p[0];
    rep(i, p.size()) if (abs2(cent - p[i]) > r) {
        cent = p[i]; r = 0;
        rep(j, i) if (abs2(cent - p[j]) > r) {
            cent = (p[i] + p[j]) / 2;

```

```

            r = abs2(p[j] - cent);
            rep(k, j) if (abs2(cent - p[k]) > r) {
                cent = circenter(p[i], p[j], p[k]);
                r = abs2(p[k] - cent);
            }
        }
    }
    return {cent, sqrt(r)};
}

```

7.15 Union of Stuff [234a81]

```

//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(intersect(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 [982e64]

```

/* 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].
                            [t]}, 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 [da0c5e]

```

// 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 3D Basic [440428]

```

struct Point {
    double x, y, z;
    Point(double _x = 0, double _y = 0, double _z = 0): x
        (_x), y(_y), z(_z){}
    Point(pld 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; }
pld 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));
}

```

7.19 3D Convex Hull [875f37]

```

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 Binary Search On Fraction [765c5a]

```

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


```

```

        else len += step;
        swap(lo, hi = hi.go(lo, len));
        (dir ? L : H) = !len;
    }
    return dir ? hi : lo;
}

```

8.2 Cyclic Ternary Search [9017cc]

```

/* 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 for all 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 - 1 > 1) {
        int m = (l + r) / 2;
        if (pred(0, m) ? rv : pred(m, (m + 1) % n)) r = m;
        else l = m;
    }
    return pred(l, r % n) ? l : r % n;
}

```

8.3 Matroid Intersection

$M = (E, \mathcal{I})$, where $\mathcal{I} \subseteq 2^E$ is nonempty, is a matroid if:

- If $S \in \mathcal{I}$ and $S' \subsetneq S$, then $S' \in \mathcal{I}$.
- For $S_1, S_2 \in \mathcal{I}$ s.t. $|S_1| < |S_2|$, there exists $e \in S_2 \setminus S_1$ s.t. $S_1 \cup \{e\} \in \mathcal{I}$.

Matroid intersection:

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

- $Y_1 = \{x \notin S \mid S \cup \{x\} \in \mathcal{I}_1\}$
- $Y_2 = \{x \notin S \mid S \cup \{x\} \in \mathcal{I}_2\}$

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

- $x \rightarrow y$ if $S - \{x\} \cup \{y\} \in \mathcal{I}_1$.
- $y \rightarrow x$ if $S - \{x\} \cup \{y\} \in \mathcal{I}_2$.

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

8.4 Min Plus Convolution [09b5c3]

```

// a is convex a[i+1]-a[i] <= a[i+2]-a[i+1]
vector<int> min_plus_convolution(vector<int> &a, vector
    <int> &b) {
    int n = SZ(a), m = SZ(b);
    vector<int> c(n + m - 1, INF);
    auto dc = [&](auto Y, int l, int r, int jl, int jr) {
        if (l > r) return;
        int mid = (l + r) / 2, from = -1, &best = c[mid];
        for (int j = jl; j <= jr; ++j)
            if (int i = mid - j; i >= 0 && i < n)
                if (best > a[i] + b[j])
                    best = a[i] + b[j], from = j;
        Y(Y, l, mid - 1, jl, from), Y(Y, mid + 1, r, from,
            jr);
    };
    return dc(dc, 0, n - 1 + m - 1, 0, m - 1), c;
}

```

8.5 Mo's Algorithm [ea5261]

```

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_ans;
    }
}

```

8.6 Mo's Algorithm On Tree [8331c2]

```

/* 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]);
    }
}

```

8.7 PBDS [d65996]

```

#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

```

8.8 Simulated Annealing [de78c6]

```

double factor = 100000;
const int base = 1e9; // remember to run ~ 10 times
for (int it = 1; it <= 1000000; ++it) {
    // ans: answer, nw: current value, rnd(): mt19937
    if (exp(-(nw - ans) / factor) >= (double)(rnd() %
        base) / base) ans = nw;
}

```

```

    factor *= 0.99995;
}

```

8.9 SOS dp [6aadbl]

```

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

```

8.10 SMAWK [a2a4ce]

```

// For all 2x2 submatrix:
// If M[1][0] < M[1][1], M[0][0] < M[0][1]
// If M[1][0] == M[1][1], M[0][0] <= M[0][1]
// M[i][ans_i] is the best value in the i-th row
// select(int r, int u, int v) return true if f(r, v)
// is better than f(r, u)
vector<int> smawk(int N, int M, auto &&select) {
    auto dc = [&](auto self, const vector<int> &r, const
                  vector<int> &c) {
        if (r.empty()) return vector<int>{};
        const int n = SZ(r); vector<int> ans(n), nr, nc;
        for (int i : c) {
            while (!nc.empty() &&
                   select(r[nc.size() - 1], nc.back(), i))
                nc.pop_back();
            if (int(nc.size()) < n) nc.push_back(i);
        }
        for (int i = 1; i < n; i += 2) nr.push_back(r[i]);
        const auto na = self(self, nr, nc);
        for (int i = 1; i < n; i += 2) ans[i] = na[i >> 1];
        for (int i = 0, j = 0; i < n; i += 2) {
            ans[i] = nc[j];
            const int end = i + 1 == n ? nc.back() : ans[i +
                1];
            while (nc[j] != end)
                if (select(r[i], ans[i], nc[++j])) ans[i] = nc[j];
        }
        return ans;
    };
    vector<int> R(N), C(M); iota(iter(R), 0), iota(iter(C),
                                                    0);
    return dc(dc, R, C);
}

```

8.11 Tree Hash [34aae5]

```

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;
}

```

8.12 Python [ebfb5e]

```

from decimal 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=' ')

```