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## 1.4 Pragma Optimization

```
#pragma GCC optimize("Ofast,no-stack-protector")
#pragma GCC optimize("no-math-errno,unroll-loops")
#pragma GCC target("sse,sse2,sse3,ssse3,sse4")
#pragma GCC target("popcnt,abm,mmx,avx,tune=native")
__builtin_ia32_ldmxcsr(__builtin_ia32_stmxcsr()|0x8000)
```

## 1.5 IO Optimization

```
static inline int gc() {
    constexpr int B = 1<<20;
    static char buf[B], *p, *q;
    if(p == q &&
        (q=(p=buf)+fread(buf,1,B,stdin)) == buf)
        return EOF;
    return *p++;
}
```

# 2 Data Structure

## 2.1 Dark Magic

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

## 2.2 Link-Cut Tree [7ce2b4]

```
template <typename Val, typename SVal> class LCT {
    struct node {
        int pa, ch[2];
        bool rev;
        Val v, prod, rprod;
        SVal sv, sub, vir;
        node() : pa{0}, ch{0, 0}, rev{false}, v{}, prod{},
            rprod{}, sv{}, sub{}, vir{} {};
    };
    #define cur o[u]
    #define lc cur.ch[0]
    #define rc cur.ch[1]
    vector<node> o;
    bool is_root(int u) const {
        return o[cur.pa].ch[0]!=u && o[cur.pa].ch[1]!=u;
    }
    bool is_rch(int u) const {
        return o[cur.pa].ch[1] == u && !is_root(u);
    }
    void down(int u) {
        if (not cur.rev) return;
        if (lc) set_rev(lc);
        if (rc) set_rev(rc);
        cur.rev = false;
    }
    void up(int u) {
        cur.prod = o[lc].prod * cur.v * o[rc].prod;
        cur.rprod = o[rc].rprod * cur.v * o[lc].rprod;
        cur.sub = cur.vir + o[lc].sub + o[rc].sub + cur.sv;
    }
    void set_rev(int u) {
        swap(lc, rc);
        swap(cur.prod, cur.rprod);
        cur.rev ^= 1;
    }
    void rotate(int u) {
        int f=cur.pa, g=o[f].pa, l=is_rch(u);
        if (cur.ch[l ^ 1]) o[cur.ch[l ^ 1]].pa = f;
        if (not is_root(f)) o[g].ch[is_rch(f)] = u;
        o[f].ch[l] = cur.ch[l ^ 1];
        cur.ch[l ^ 1] = f;
        cur.pa = g, o[f].pa = u;
        up(f);
    }
}
```

```
void splay(int u) {
    vector<int> stk = {u};
    while (not is_root(stk.back()))
        stk.push_back(o[stk.back()].pa);
    while (not stk.empty()) {
        down(stk.back());
        stk.pop_back();
    }
    for (int f = cur.pa; not is_root(u); f = cur.pa) {
        if (!is_root(f)) rotate(is_rch(u)==is_rch(f)?f:u);
        rotate(u);
    }
    up(u);
}
void access(int x) {
    for (int u = x, last = 0; u; u = cur.pa) {
        splay(u);
        cur.vir = cur.vir + o[rc].sub - o[last].sub;
        rc = last; up(last = u);
    }
    splay(x);
}
int find_root(int u) {
    int la = 0;
    for (access(u); u; u = lc) down(la = u);
    return la;
}
void split(int x, int y) {change_root(x);access(y);}
void change_root(int u) { access(u); set_rev(u); }
public:
    LCT(int n = 0) : o(n + 1) {}
    int add(const Val &v = {}) {
        o.push_back(v);
        return int(o.size()) - 2;
    }
    int add(Val &&v) {
        o.emplace_back(move(v));
        return int(o.size()) - 2;
    }
    void set_val(int u, const Val &v) {
        splay(++u); cur.v = v; up(u);
    }
    void set_sval(int u, const SVal &v) {
        splay(++u); cur.sv = v; up(u);
    }
    Val query(int x, int y) {
        split(++x, ++y); return o[y].prod;
    }
    SVal subtree(int p, int u) {
        change_root(++p); access(++u);
        return cur.vir + cur.sv;
    }
    bool connected(int u, int v) {
        return find_root(++u) == find_root(++v);
    }
    void link(int x, int y) {
        change_root(++x); access(++y);
        o[y].vir = o[y].vir + o[x].sub;
        up(o[x].pa = y);
    }
    void cut(int x, int y) {
        split(++x, ++y);
        o[y].ch[0] = o[x].pa = 0; up(y);
    }
    #undef cur
    #undef lc
    #undef rc
};
```

## 2.3 LiChao Segment Tree [c45c03]

```
struct L {
    int m, k, id;
    L() : id(-1) {}
    L(int a, int b, int c) : m(a), k(b), id(c) {}
    int at(int x) { return m * x + k; }
};
class LiChao {
private:
    int n; vector<L> nodes;
    static int lc(int x) { return 2 * x + 1; }
    static int rc(int x) { return 2 * x + 2; }
    void insert(int l, int r, int id, L ln) {
        int m = (l + r) >> 1;
```

```

if (nodes[id].id == -1) {
    nodes[id] = ln;
    return;
}
bool atLeft = nodes[id].at(l) < ln.at(l);
if (nodes[id].at(m) < ln.at(m)) {
    atLeft ^= 1;
    swap(nodes[id], ln);
}
if (r - l == 1) return;
if (atLeft) insert(l, m, lc(id), ln);
else insert(m, r, rc(id), ln);
}
int query(int l, int r, int id, int x) {
    int ret = 0, m = (l + r) >> 1;
    if (nodes[id].id != -1)
        ret = nodes[id].at(x);
    if (r - l == 1) return ret;
    if (x < m) return max(ret, query(l, m, lc(id), x));
    return max(ret, query(m, r, rc(id), x));
}

public:
LiChao(int n_) : n(n_), nodes(n * 4) {}
void insert(L ln) { insert(0, n, 0, ln); }
int query(int x) { return query(0, n, 0, x); }
};

```

## 2.4 Treap [82fac7]

```

__gnu_cxx::sfmt19937 rnd(7122);
namespace Treap{
#define sz(x) ( (x) ? ( (x)->size ) : 0 )
struct node{
    int size; uint32_t pri;
    node *lc, *rc, *pa;
    node():size(0),pri(rnd()),lc(0),rc(0),pa(0){}
    void pull() {
        size = 1; pa = nullptr;
        if ( lc ) { size += lc->size; lc->pa = this; }
        if ( rc ) { size += rc->size; rc->pa = this; }
    }
};
node* merge( node* L, node* R ) {
    if ( not L or not R ) return L ? L : R;
    if ( L->pri > R->pri ) {
        L->rc = merge( L->rc, R ); L->pull();
        return L;
    } else {
        R->lc = merge( L, R->lc ); R->pull();
        return R;
    }
}
void split_by_size( node*rt,int k,node*&L,node*&R ) {
    if ( not rt ) L = R = nullptr;
    else if( sz( rt->lc ) + 1 <= k ) {
        L = rt;
        split_by_size( rt->rc,k-sz(rt->lc)-1,L->rc,R );
        L->pull();
    } else {
        R = rt;
        split_by_size( rt->lc, k, L, R->lc );
        R->pull();
    }
} // sz(L) == k
int getRank(node *o) { // 1-base
    int r = sz(o->lc) + 1;
    for (;o->pa != nullptr; o = o->pa)
        if (o->pa->rc == o) r += sz(o->pa->lc) + 1;
    return r;
}
#undef sz
}

```

## 2.5 Linear Basis

```

template <int BITS, typename S = int> struct Basis {
    static constexpr auto MIN = numeric_limits<S>::min();
    array<pair<uint64_t, S>, BITS> b;
    Basis() { b.fill({0, MIN}); }
    void add(uint64_t x, S p) {
        for (int i = BITS-1; i>=0; i--) if ((x >> i) & 1) {
            if (b[i].first == 0) return b[i]={x, p}, void();
            if (b[i].second < p)

```

```

                swap(b[i].first, x), swap(b[i].second, p);
                x ^= b[i].first;
            }
        }
        optional<uint64_t> query_kth(uint64_t v, uint64_t k){
            vector<pair<uint64_t, int>> o;
            for (int i = 0; i < BITS; i++)
                if (b[i].first < o.empty()) o.emplace_back(b[i].first, i);
            if (k >= (1ULL << o.size())) return {};
            for (int i = int(o.size()) - 1; i >= 0; i--)
                if ((k >> i & 1) ^ (v >> o[i].second & 1))
                    v ^= o[i].first;
            return v;
        }
        Basis filter(S l) {
            Basis res = *this;
            for (int i = 0; i < BITS; i++)
                if (res.b[i].second < l) res.b[i] = {0, MIN};
            return res;
        }
};

```

## 2.6 Binary Search On Segment Tree

```

// find_first = x -> minimal x s.t. check( [a, x) )
// find_last = x -> maximal x s.t. check( [x, b) )
template <typename C>
int find_first(int l, const C &check) {
    if (l >= n) return n + 1;
    l += sz;
    for (int i = height; i > 0; i--)
        propagate(l >> i);
    Monoid sum = identity;
    do {
        while ((l & 1) == 0) l >>= 1;
        if (check(f(sum, data[l]))) {
            while (l < sz) {
                propagate(l);
                l <<= 1;
                auto nxt = f(sum, data[l]);
                if (not check(nxt)) {
                    sum = nxt;
                    l++;
                }
            }
            return l + 1 - sz;
        }
        sum = f(sum, data[l++]);
    } while ((l & -l) != l);
    return n + 1;
}

template <typename C>
int find_last(int r, const C &check) {
    if (r <= 0) return -1;
    r += sz;
    for (int i = height; i > 0; i--)
        propagate((r - 1) >> i);
    Monoid sum = identity;
    do {
        r--;
        while (r > 1 and (r & 1)) r >>= 1;
        if (check(f(data[r], sum))) {
            while (r < sz) {
                propagate(r);
                r = (r << 1) + 1;
                auto nxt = f(data[r], sum);
                if (not check(nxt)) {
                    sum = nxt;
                    r--;
                }
            }
            return r - sz;
        }
        sum = f(data[r], sum);
    } while ((r & -r) != r);
    return -1;
}

```

## 3 Graph

### 3.1 2-SAT (SCC) [3cc0b4]

```

class TwoSat{

```

```

private:
    int n;
    vector<vector<int>> rG,G,sccs;
    vector<int> ord,idx;
    vector<bool> vis,result;
    void dfs(int u){
        vis[u]=true;
        for(int v:G[u])
            if(!vis[v]) dfs(v);
        ord.push_back(u);
    }
    void rdfs(int u){
        vis[u]=false;idx[u]=sccs.size()-1;
        sccs.back().push_back(u);
        for(int v:rG[u])
            if(vis[v])rdfs(v);
    }
public:
    void init(int n_){
        G.clear();G.resize(n=n_);
        rG.clear();rG.resize(n);
        sccs.clear();ord.clear();
        idx.resize(n);result.resize(n);
    }
    void add_edge(int u,int v){
        G[u].push_back(v);rG[v].push_back(u);
    }
    void orr(int x,int y){
        if ((x^y)==1)return;
        add_edge(x^1,y); add_edge(y^1,x);
    }
    bool solve(){
        vis.clear();vis.resize(n);
        for(int i=0;i<n;++i)
            if(not vis[i])dfs(i);
        reverse(ord.begin(),ord.end());
        for (int u:ord){
            if(!vis[u])continue;
            sccs.push_back(vector<int>());
            rdfs(u);
        }
        for(int i=0;i<n;i+=2)
            if(idx[i]==idx[i+1])
                return false;
        vector<bool> c(sccs.size());
        for(size_t i=0;i<sccs.size();++i){
            for(auto sij : sccs[i]){
                result[sij]=c[i];
                c[idx[sij^1]]=!c[i];
            }
        }
        return true;
    }
    bool get(int x){return result[x];}
    int get_id(int x){return idx[x];}
    int count(){return sccs.size();}
} sat2;

```

### 3.2 BCC [e50549]

```

class BCC {
private:
    int n, ecnt;
    vector<vector<pair<int, int>>> g;
    vector<int> dfn, low;
    vector<bool> ap, bridge;
    void dfs(int u, int f) {
        dfn[u] = low[u] = dfn[f] + 1;
        int ch = 0;
        for (auto [v, t] : g[u]) if (v != f) {
            if (dfn[v]) {
                low[u] = min(low[u], dfn[v]);
            } else {
                ++ch, dfs(v, u);
                low[u] = min(low[u], low[v]);
                if (low[v] > dfn[u])
                    bridge[t] = true;
                if (low[v] >= dfn[u])
                    ap[u] = true;
            }
        }
        ap[u] &= (ch != 1 or u != f);
    }
}

```

```

public:
    void init(int n_) {
        g.assign(n = n_, vector<pair<int, int>>());
        low.assign(n, ecnt = 0);
        dfn.assign(n, 0);
        ap.assign(n, false);
    }
    void add_edge(int u, int v) {
        g[u].emplace_back(v, ecnt);
        g[v].emplace_back(u, ecnt++);
    }
    void solve() {
        bridge.assign(ecnt, false);
        for (int i = 0; i < n; ++i)
            if (not dfn[i]) dfs(i, i);
    }
    bool is_ap(int x) { return ap[x]; }
    bool is_bridge(int x) { return bridge[x]; }
};

```

### 3.3 Round Square Tree [df7723]

```

int N, M, cnt;
std::vector<int> G[maxn], T[maxn * 2];

int dfn[maxn], low[maxn], dfc;
int stk[maxn], tp;

void Tarjan(int u) {
    low[u] = dfn[u] = ++dfc;
    stk[++tp] = u;
    for (int v : G[u]) {
        if (!dfn[v]) {
            Tarjan(v);
            low[u] = std::min(low[u], low[v]);
            if (low[v] == dfn[u]) {
                ++cnt;
                for (int x = 0; x != v; --tp) {
                    x = stk[tp];
                    T[cnt].push_back(x);
                    T[x].push_back(cnt);
                }
                T[cnt].push_back(u);
                T[u].push_back(cnt);
            }
        } else
            low[u] = std::min(low[u], dfn[v]);
    }
}

int main() { // ...
    cnt = N;
    for (int u = 1; u <= N; ++u)
        if (!dfn[u]) Tarjan(u), --tp;
}

```

### 3.4 Centroid Decomposition [63b2fb]

```

struct Centroid {
    using G = vector<vector<pair<int, int>>>;
    vector<vector<int64_t>> Dist;
    vector<int> Pa, Dep;
    vector<int64_t> Sub, Sub2;
    vector<int> Cnt, Cnt2;
    vector<int> vis, sz, mx, tmp;
    void DfsSz(const G &g, int x) {
        vis[x] = true, sz[x] = 1, mx[x] = 0;
        for (auto [u, w] : g[x]) if (not vis[u]) {
            DfsSz(g, u); sz[x] += sz[u];
            mx[x] = max(mx[x], sz[u]);
        }
        tmp.push_back(x);
    }
    void DfsDist(const G &g, int x, int64_t D = 0) {
        Dist[x].push_back(D); vis[x] = true;
        for (auto [u, w] : g[x])
            if (not vis[u]) DfsDist(g, u, D + w);
    }
    void DfsCen(const G &g, int x, int D = 0, int p = -1) {
        tmp.clear(); DfsSz(g, x);
        int M = tmp.size(), C = -1;
        for (int u : tmp) {
            if (max(M - sz[u], mx[u]) * 2 <= M) C = u;
        }
    }
}

```

```

    vis[u] = false;
}
DfsDist(g, C);
for (int u : tmp) vis[u] = false;
Pa[C] = p, vis[C] = true, Dep[C] = D;
for (auto [u, w] : g[C])
    if (not vis[u]) DfsCen(g, u, D + 1, C);
}
Centroid(int N, G g)
: Sub(N), Sub2(N), Cnt(N), Cnt2(N), Dist(N), Pa(N),
  Dep(N), vis(N), sz(N), mx(N) { DfsCen(g, 0); }
void Mark(int v) {
    int x = v, z = -1;
    for (int i = Dep[v]; i >= 0; --i) {
        Sub[x] += Dist[v][i], Cnt[x]++;
        if (z != -1)
            Sub2[z] += Dist[v][i], Cnt2[z]++;
        x = Pa[z = x];
    }
}
int64_t Query(int v) {
    int64_t res = 0;
    int x = v, z = -1;
    for (int i = Dep[v]; i >= 0; --i) {
        res += Sub[x] + 1LL * Cnt[x] * Dist[v][i];
        if (z != -1)
            res -= Sub2[z] + 1LL * Cnt2[z] * Dist[v][i];
        x = Pa[z = x];
    }
    return res;
}
};

```

### 3.5 Directed Minimum Spanning Tree

```

using D = int64_t;
struct E {
    int s, t; // 0-base
    D w;
};
vector<int> dmst(const vector<E> &e, int n, int root) {
    using PQ = pair<min_heap<pair<D, int>>, D>;
    auto push = [](PQ &pq, pair<D, int> v) {
        pq.first.emplace(v.first - pq.second, v.second);
    };
    auto top = [](const PQ &pq) -> pair<D, int> {
        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 (size_t i = 0; i < e.size(); ++i)
        push(h[e[i].t], {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]].s)) {
            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]].s)) != p);
            }
            v[p] = i;
            while (!h[p].first.empty() && o(e[top(h[p]).second].s) == p)
                s == 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]].t; f != -1 && v[f] != n; f = pa[f])
        v[f] = n;
    ans.push_back(r[i]);
}
return ans;
}
}

```

### 3.6 Dominator Tree [0631b2]

```

namespace dominator {
vector<int> g[maxn], r[maxn], rdom[maxn];
int dfn[maxn], rev[maxn], fa[maxn], sdom[maxn];
int dom[maxn], val[maxn], rp[maxn], tk;
void init(int n) {
    // vertices are numbered from 0 to n - 1
    fill(dfn, dfn + n, -1); fill(rev, rev + n, -1);
    fill(fa, fa + n, -1); fill(val, val + n, -1);
    fill(sdom, sdom + n, -1); fill(rp, rp + n, -1);
    fill(dom, dom + n, -1); tk = 0;
    for (int i = 0; i < n; ++i) {
        g[i].clear(); r[i].clear(); rdom[i].clear();
    }
}
void add_edge(int x, int y) { g[x].push_back(y); }
void dfs(int x) {
    rev[dfn[x] = tk] = x;
    fa[tk] = sdom[tk] = val[tk] = tk; tk++;
    for (int u : g[x]) {
        if (dfn[u] == -1) dfs(u), rp[dfn[u]] = dfn[x];
        r[dfn[u]].push_back(dfn[x]);
    }
}
void merge(int x, int y) { fa[x] = y; }
int find(int x, int c = 0) {
    if (fa[x] == x) return c ? -1 : x;
    int p = find(fa[x], 1);
    if (p == -1) return c ? fa[x] : val[x];
    if (sdom[val[x]] > sdom[val[fa[x]]]) val[x] = val[fa[x]];
    fa[x] = p;
    return c ? p : val[x];
}
vector<int> build(int s, int n) {
    // return the father of each node in the dominator tree
    // p[i] = -2 if i is unreachable from s
    dfs(s);
    for (int i = tk - 1; i >= 0; --i) {
        for (int u : r[i]) sdom[i] = min(sdom[i], sdom[find(u)]);
        if (i) rdom[sdom[i]].push_back(i);
        for (int &u : rdom[i]) {
            int p = find(u);
            if (sdom[p] == i) dom[u] = i;
            else dom[u] = p;
        }
        if (i) merge(i, rp[i]);
    }
    vector<int> p(n, -2); p[s] = -1;
    for (int i = 1; i < tk; ++i)
        if (sdom[i] != dom[i]) dom[i] = dom[dom[i]];
    for (int i = 1; i < tk; ++i) p[rev[i]] = rev[dom[i]];
    return p;
}
}

```

### 3.7 Edge Coloring

```

// max(d_u) + 1 edge coloring, time: O(NM)
int C[kN][kN], G[kN][kN]; // 1-based, G: ans
void clear(int N) {
    for (int i = 0; i <= N; i++)
        for (int j = 0; j <= N; j++)
            C[i][j] = G[i][j] = 0;
}
void solve(vector<pair<int, int>> &E, int N) {
    int X[kN] = {}, a;
    auto update = [&](int u) {
        for (X[u] = 1; C[u][X[u]]; X[u]++);
    };
}

```



```

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

```

### 3.8 Lowbit Decomposition [aa3f57]

```

class LBD {
    int timer, chains;
    vector<vector<int>> G;
    vector<int> tl, tr, chain, head, dep, pa;
    // chains : number of chain
    // tl, tr[u] : subtree interval in the seq. of u
    // head[i] : head of the chain i
    // chain[u] : chain id of the chain u is on
    void predfs(int u, int f) {
        dep[u] = dep[pa[u] = f] + 1;
        for (int v : G[u]) if (v != f) {
            predfs(v, u);
            if (lowbit(chain[u]) < lowbit(chain[v]))
                chain[u] = chain[v];
        }
        if (chain[u] == 0) chain[u] = ++chains;
    }
    void dfschain(int u, int f) {
        tl[u] = timer++;
        if (head[chain[u]] == -1)
            head[chain[u]] = u;
        for (int v : G[u])
            if (v != f and chain[v] == chain[u])
                dfschain(v, u);
        for (int v : G[u])
            if (v != f and chain[v] != chain[u])
                dfschain(v, u);
        tr[u] = timer;
    }
public:
    LBD(int n) : timer(0), chains(0), G(n), tl(n), tr(n),
        chain(n), head(n, -1), dep(n), pa(n) {}
    void add_edge(int u, int v) {
        G[u].push_back(v); G[v].push_back(u);
    }
    void decompose() { predfs(0, 0); dfschain(0, 0); }
    PII get_subtree(int u) { return {tl[u], tr[u]}; }
    vector<PII> get_path(int u, int v) {
        vector<PII> res;
        while (chain[u] != chain[v]) {

```

```

            if (dep[head[chain[u]]] < dep[head[chain[v]]])
                swap(u, v);
            int s = head[chain[u]];
            res.emplace_back(tl[s], tl[u] + 1);
            u = pa[s];
        }
        if (dep[u] < dep[v]) swap(u, v);
        res.emplace_back(tl[v], tl[u] + 1);
        return res;
    }
};

```

### 3.9 Manhattan Minimum Spanning Tree

```

typedef Point<int> P;
vector<array<int, 3>> manhattanMST(vector<P> ps) {
    vi id(sz(ps));
    iota(all(id), 0);
    vector<array<int, 3>> edges;
    rep(k, 0, 4) {
        sort(all(id), [&](int i, int j) {
            return (ps[i] - ps[j]).x < (ps[j] - ps[i]).y;
        });
        map<int, int> sweep;
        for (int i : id) {
            for (auto it = sweep.lower_bound(-ps[i].y);
                it != sweep.end(); sweep.erase(it++)) {
                int j = it->second;
                P d = ps[i] - ps[j];
                if (d.y > d.x) break;
                edges.push_back({d.y + d.x, i, j});
            }
            sweep[-ps[i].y] = i;
        }
        for (P &p : ps)
            if (k & 1) p.x = -p.x;
            else swap(p.x, p.y);
    }
    return edges; // [{w, i, j}, ...]
}

```

### 3.10 MaxClique [293730]

```

// contain a self loop u to u, than u won't in clique
template <size_t maxn> class MaxClique {
private:
    using bits = bitset<maxn>;
    bits popped, G[maxn], ans;
    size_t deg[maxn], deo[maxn], n;
    void sort_by_degree() {
        popped.reset();
        for (size_t i = 0; i < n; ++i)
            deg[i] = G[i].count();
        for (size_t i = 0; i < n; ++i) {
            size_t mi = maxn, id = 0;
            for (size_t j = 0; j < n; ++j)
                if (not popped[j] and deg[j] < mi)
                    mi = deg[id = j];
            popped[deo[i] = id] = 1;
            for (size_t u = G[i]._Find_first(); u < n;
                u = G[i]._Find_next(u))
                --deg[u];
        }
    }
    void BK(bits R, bits P, bits X) {
        if (R.count() + P.count() <= ans.count()) return;
        if (not P.count() and not X.count()) {
            if (R.count() > ans.count()) ans = R;
            return;
        }
        /* greedily choose max degree as pivot
        bits cur = P | X; size_t pivot = 0, sz = 0;
        for (size_t u = cur._Find_first();
            u < n; u = cur._Find_next(u))
            if (deg[u] > sz) sz = deg[pivot = u];
        cur = P & (~G[pivot]);
        */ // or simply choose first
        bits cur = P & (~G[P | X]._Find_first());
        for (size_t u = cur._Find_first(); u < n;
            u = cur._Find_next(u)) {
            if (R[u]) continue;
            R[u] = 1;
            BK(R, P & G[u], X & G[u]);
            R[u] = P[u] = 0, X[u] = 1;
        }
    }
};

```

```

}
}
public:
void init(size_t n_) {
    n = n_;
    for (size_t i = 0; i < n; ++i) G[i].reset();
    ans.reset();
}
void add_edges(int u, bits S) { G[u] = S; }
void add_edge(int u, int v) { G[u][v] = G[v][u] = 1; }
int solve() {
    sort_by_degree(); // or simply iota( deo... )
    for (size_t i = 0; i < n; ++i)
        deg[i] = G[i].count();
    bits pob, nob = 0; pob.set();
    for (size_t i = n; i < maxn; ++i) pob[i] = 0;
    for (size_t i = 0; i < n; ++i) {
        size_t v = deo[i];
        bits tmp;
        tmp[v] = 1;
        BK(tmp, pob & G[v], nob & G[v]);
        pob[v] = 0, nob[v] = 1;
    }
    return static_cast<int>(ans.count());
}
};

```

### 3.11 Minimum Mean Cycle

```

/* minimum mean cycle O(VE) */
struct MMC{
#define FZ(n) memset((n),0,sizeof(n))
#define E 101010
#define V 1021
#define inf 1e9
    struct Edge { int v,u; double c; };
    int n, m, prv[V][V], prve[V][V], vst[V];
    Edge e[E];
    vector<int> edgeID, cycle, rho;
    double d[V][V];
    void init( int _n ) { n = _n; m = 0; }
    // WARNING: TYPE matters
    void add_edge( int vi , int ui , double ci )
    { e[ m ++ ] = { vi , ui , ci }; }
    void bellman_ford() {
        for(int i=0; i<n; i++) d[0][i]=0;
        for(int i=0; i<n; i++) {
            fill(d[i+1], d[i+1]+n, inf);
            for(int j=0; j<m; j++) {
                int v = e[j].v, u = e[j].u;
                if(d[i][v]<inf && d[i+1][u]>d[i][v]+e[j].c) {
                    d[i+1][u] = d[i][v]+e[j].c;
                    prv[i+1][u] = v;
                    prve[i+1][u] = j;
                }
            }
        }
    }
    double solve(){
        // returns inf if no cycle, mmc otherwise
        double mmc=inf;
        int st = -1;
        bellman_ford();
        for(int i=0; i<n; i++) {
            double avg=-inf;
            for(int k=0; k<n; k++) {
                if(d[n][i]<inf-eps)
                    avg=max(avg,(d[n][i]-d[k][i])/(n-k));
                else avg=max(avg,inf);
            }
            if (avg < mmc) tie(mmc, st) = tie(avg, i);
        }
        FZ(vst);edgeID.clear();cycle.clear();rho.clear();
        for (int i=n; !vst[st]; st=prv[i--][st]) {
            vst[st]++;
            edgeID.PB(prve[i][st]);
            rho.PB(st);
        }
        while (vst[st] != 2) {
            int v = rho.back(); rho.pop_back();
            cycle.PB(v);
            vst[v]++;
        }
    }
};

```

```

reverse(ALL(edgeID));
edgeID.resize(SZ(cycle));
return mmc;
}
} mmc;

```

### 3.12 Mo's Algorithm on Tree

```

dfs u:
    push u
    iterate subtree
    push u
Let P = LCA(u, v) with St(u)<=St(v)
if (P == u) query[St(u), St(v)]
else query[Ed(u), St(v)], query[St(P), St(P)]

```

### 3.13 Virtual Tree [ad5cf5]

```

vector<pair<int, int>> build(vector<int> vs, int r) {
    vector<pair<int, int>> res;
    sort(vs.begin(), vs.end(), [](int i, int j) {
        return dfn[i] < dfn[j]; });
    vector<int> s = {r};
    for (int v : vs) if (v != r) {
        if (int o = lca(v, s.back()); o != s.back()) {
            while (s.size() >= 2) {
                if (dfn[s[s.size() - 2]] < dfn[o]) break;
                res.emplace_back(s[s.size() - 2], s.back());
                s.pop_back();
            }
            if (s.back() != o) {
                res.emplace_back(o, s.back());
                s.back() = o;
            }
        }
        s.push_back(v);
    }
    for (size_t i = 1; i < s.size(); ++i)
        res.emplace_back(s[i - 1], s[i]);
    return res; // (x, y): x->y
}

```

## 4 Matching & Flow

### 4.1 Bipartite Matching [2fc9c7]

```

struct BipartiteMatching {
    vector<int> X[N];
    int fX[N], fY[N], n;
    bitset<N> vis;
    bool dfs(int x) {
        for (auto i : X[x]) if (not vis[i]) {
            vis[i] = true;
            if (fY[i] == -1 || dfs(fY[i])) {
                fY[fX[x] = i] = x;
                return true;
            }
        }
        return false;
    }
    void init(int n_, int m) {
        fill_n(X, n = n_, vector<int>());
        memset(fX, -1, sizeof(int) * n);
        memset(fY, -1, sizeof(int) * m);
    }
    void add_edge(int x, int y) { X[x].push_back(y); }
    int solve() { // return how many pair matched
        int cnt = 0;
        for (int i = 0; i < n; i++) {
            vis.reset();
            cnt += dfs(i);
        }
        return cnt;
    }
};

```

### 4.2 Dijkstra Cost Flow [d4f7c1]

```

// kN = #(vertices)
// MCMF.{Init, AddEdge, MincostMaxflow}
// MincostMaxflow(source, sink, flow_limit, &cost)
// => flow
using Pii = pair<int, int>;
constexpr int kInf = 0x3f3f3f3f, kN = 500;

```

```

struct Edge {
    int to, rev, cost, flow;
};
struct MCMF { // 0-based
    int n, m, s, t;
    vector<Edge> graph[kN];
    // Larger range for relabeling
    int64_t dis[kN] = {}, h[kN] = {};
    int p[kN] = {};
    void Init(int nn) {
        n = nn;
        for (int i = 0; i < n; i++) graph[i].clear();
    }
    void AddEdge(int u, int v, int f, int c) {
        graph[u].push_back({v,
            static_cast<int>(graph[v].size()), c, f});
        graph[v].push_back(
            {u, static_cast<int>(graph[u].size()) - 1,
            -c, 0});
    }
    bool Dijkstra(int &max_flow, int64_t &cost) {
        priority_queue<Pii, vector<Pii>, greater<>> pq;
        fill_n(dis, n, kInf);
        dis[s] = 0;
        pq.emplace(0, s);
        while (!pq.empty()) {
            auto u = pq.top();
            pq.pop();
            int v = u.second;
            if (dis[v] < u.first) continue;
            for (auto &e : graph[v]) {
                auto new_dis =
                    dis[v] + e.cost + h[v] - h[e.to];
                if (e.flow > 0 && dis[e.to] > new_dis) {
                    dis[e.to] = new_dis;
                    p[e.to] = e.rev;
                    pq.emplace(dis[e.to], e.to);
                }
            }
        }
        if (dis[t] == kInf) return false;
        for (int i = 0; i < n; i++) h[i] += dis[i];
        int d = max_flow;
        for (int u = t; u != s;
            u = graph[u][p[u]].to) {
            auto &e = graph[u][p[u]];
            d = min(d, graph[e.to][e.rev].flow);
        }
        max_flow -= d;
        cost += int64_t(d) * h[t];
        for (int u = t; u != s;
            u = graph[u][p[u]].to) {
            auto &e = graph[u][p[u]];
            e.flow += d;
            graph[e.to][e.rev].flow -= d;
        }
        return true;
    }
    int MincostMaxflow(
        int ss, int tt, int max_flow, int64_t &cost) {
        this->s = ss, this->t = tt;
        cost = 0;
        fill_n(h, n, 0);
        auto orig_max_flow = max_flow;
        while (Dijkstra(max_flow, cost) && max_flow) {}
        return orig_max_flow - max_flow;
    }
};

```

### 4.3 Dinic [ebd802]

```

template <typename Cap = int64_t>
class Dinic {
private:
    struct E {
        int to, rev;
        Cap cap;
    };
    int n, st, ed;
    vector<vector<E>> G;
    vector<int> lv, idx;
    bool BFS() {
        lv.assign(n, -1);

```

```

        queue<int> bfs;
        bfs.push(st); lv[st] = 0;
        while (not bfs.empty()) {
            int u = bfs.front(); bfs.pop();
            for (auto e : G[u]) {
                if (e.cap <= 0 or lv[e.to] != -1) continue;
                bfs.push(e.to); lv[e.to] = lv[u] + 1;
            }
        }
        return lv[ed] != -1;
    }
    Cap DFS(int u, Cap f) {
        if (u == ed) return f;
        Cap ret = 0;
        for (int &i = idx[u]; i < int(G[u].size()); ++i) {
            auto &e = G[u][i];
            if (e.cap <= 0 or lv[e.to] != lv[u] + 1) continue;
            Cap nf = DFS(e.to, min(f, e.cap));
            ret += nf; e.cap -= nf; f -= nf;
            G[e.to][e.rev].cap += nf;
            if (f == 0) return ret;
        }
        if (ret == 0) lv[u] = -1;
        return ret;
    }
public:
    void init(int n_) { G.assign(n = n_, vector<E>()); }
    void add_edge(int u, int v, Cap c) {
        G[u].push_back({v, int(G[v].size()), c});
        G[v].push_back({u, int(G[u].size())-1, 0});
    }
    Cap max_flow(int st_, int ed_) {
        st = st_, ed = ed_; Cap ret = 0;
        while (BFS()) {
            idx.assign(n, 0);
            Cap f = DFS(st, numeric_limits<Cap>::max());
            ret += f;
            if (f == 0) break;
        }
        return ret;
    }
};

```

### 4.4 Flow Models

- Maximum/Minimum flow with lower bound / Circulation problem
  1. Construct super source  $S$  and sink  $T$ .
  2. For each edge  $(x, y, l, u)$ , connect  $x \rightarrow y$  with capacity  $u - l$ .
  3. For each vertex  $v$ , denote by  $in(v)$  the difference between the sum of incoming lower bounds and the sum of outgoing lower bounds.
  4. If  $in(v) > 0$ , connect  $S \rightarrow v$  with capacity  $in(v)$ , otherwise, connect  $v \rightarrow T$  with capacity  $-in(v)$ .
    - To maximize, connect  $t \rightarrow s$  with capacity  $\infty$  (skip this in circulation problem), and let  $f$  be the maximum flow from  $S$  to  $T$ . If  $f \neq \sum_{v \in V, in(v) > 0} in(v)$ , there's no solution. Otherwise, the maximum flow from  $s$  to  $t$  is the answer.
    - To minimize, let  $f$  be the maximum flow from  $S$  to  $T$ . Connect  $t \rightarrow s$  with capacity  $\infty$  and let the flow from  $S$  to  $T$  be  $f'$ . If  $f + f' \neq \sum_{v \in V, in(v) > 0} in(v)$ , there's no solution. Otherwise,  $f'$  is the answer.
  5. The solution of each edge  $e$  is  $l_e + f_e$ , where  $f_e$  corresponds to the flow of edge  $e$  on the graph.
- Construct minimum vertex cover from maximum matching  $M$  on bipartite graph  $(X, Y)$ 
  1. Redirect every edge:  $y \rightarrow x$  if  $(x, y) \in M$ ,  $x \rightarrow y$  otherwise.
  2. DFS from unmatched vertices in  $X$ .
  3.  $x \in X$  is chosen iff  $x$  is unvisited.
  4.  $y \in Y$  is chosen iff  $y$  is visited.
- Minimum cost cyclic flow
  1. Construct super source  $S$  and sink  $T$
  2. For each edge  $(x, y, c)$ , connect  $x \rightarrow y$  with  $(cost, cap) = (c, 1)$  if  $c > 0$ , otherwise connect  $y \rightarrow x$  with  $(cost, cap) = (-c, 1)$
  3. For each edge with  $c < 0$ , sum these cost as  $K$ , then increase  $d(y)$  by 1, decrease  $d(x)$  by 1
  4. For each vertex  $v$  with  $d(v) > 0$ , connect  $S \rightarrow v$  with  $(cost, cap) = (0, d(v))$
  5. For each vertex  $v$  with  $d(v) < 0$ , connect  $v \rightarrow T$  with  $(cost, cap) = (0, -d(v))$
  6. Flow from  $S$  to  $T$ , the answer is the cost of the flow  $C + K$
- Maximum density induced subgraph
  1. Binary search on answer, suppose we're checking answer  $T$
  2. Construct a max flow model, let  $K$  be the sum of all weights
  3. Connect source  $s \rightarrow v, v \in G$  with capacity  $K$
  4. For each edge  $(u, v, w)$  in  $G$ , connect  $u \rightarrow v$  and  $v \rightarrow u$  with capacity  $w$



- For  $v \in G$ , connect it with sink  $v \rightarrow t$  with capacity  $K + 2T - (\sum_{e \in E(v)} w(e)) - 2w(v)$
- $T$  is a valid answer if the maximum flow  $f < K|V|$

- Minimum weight edge cover

- For each  $v \in V$  create a copy  $v'$ , and connect  $u' \rightarrow v'$  with weight  $w(u, v)$ .
- Connect  $v \rightarrow v'$  with weight  $2\mu(v)$ , where  $\mu(v)$  is the cost of the cheapest edge incident to  $v$ .
- Find the minimum weight perfect matching on  $G'$ .

- Project selection problem

- If  $p_v > 0$ , create edge  $(s, v)$  with capacity  $p_v$ ; otherwise, create edge  $(v, t)$  with capacity  $-p_v$ .
- Create edge  $(u, v)$  with capacity  $w$  with  $w$  being the cost of choosing  $u$  without choosing  $v$ .
- The mincut is equivalent to the maximum profit of a subset of projects.

- 0/1 quadratic programming

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

can be minimized by the mincut of the following graph:

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

## 4.5 General Graph Matching [00732c]

```
namespace matching {
int fa[kn], pre[kn], match[kn], s[kn], v[kn];
vector<int> g[kn];
queue<int> q;
void Init(int n) {
    for (int i = 0; i <= n; ++i) match[i] = pre[i] = n;
    for (int i = 0; i < n; ++i) g[i].clear();
}
void AddEdge(int u, int v) {
    g[u].push_back(v);
    g[v].push_back(u);
}
int Find(int u) {
    return u == fa[u] ? u : fa[u] = Find(fa[u]);
}
int LCA(int x, int y, int n) {
    static int tk = 0; 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, int n) {
    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, n);
```

```
Blossom(x, u, l);
Blossom(u, x, l);
}
}
return false;
}
int Solve(int n) {
    int res = 0;
    for (int x = 0; x < n; ++x) {
        if (match[x] == n) res += Bfs(x, n);
    }
    return res;
}
```

## 4.6 Global Min-Cut

```
const int maxn = 500 + 5;
int w[maxn][maxn], g[maxn];
bool v[maxn], del[maxn];
void add_edge(int x, int y, int c) {
    w[x][y] += c; w[y][x] += c;
}
pair<int, int> phase(int n) {
    memset(v, false, sizeof(v));
    memset(g, 0, sizeof(g));
    int s = -1, t = -1;
    while (true) {
        int c = -1;
        for (int i = 0; i < n; ++i) {
            if (del[i] || v[i]) continue;
            if (c == -1 || g[i] > g[c]) c = i;
        }
        if (c == -1) break;
        v[s = t, t = c] = true;
        for (int i = 0; i < n; ++i) {
            if (del[i] || v[i]) continue;
            g[i] += w[c][i];
        }
    }
    return make_pair(s, t);
}
int mincut(int n) {
    int cut = 1e9;
    memset(del, false, sizeof(del));
    for (int i = 0; i < n - 1; ++i) {
        int s, t; tie(s, t) = phase(n);
        del[t] = true; cut = min(cut, g[t]);
        for (int j = 0; j < n; ++j) {
            w[s][j] += w[t][j]; w[j][s] += w[j][t];
        }
    }
    return cut;
}
```

## 4.7 GomoryHu Tree

```
int g[maxn];
vector<edge> GomoryHu(int n){
    vector<edge> rt;
    for(int i=1;i<=n;++i)g[i]=1;
    for(int i=2;i<=n;++i){
        int t=g[i];
        flow.reset(); // clear flows on all edge
        rt.push_back({i,t,flow(i,t)});
        flow.walk(i); // bfs points that connected to i (use
                        // edges not fully flow)
        for(int j=i+1;j<=n;++j){
            if(g[j]==t && flow.connect(j))g[j]=i; // check if i
            // can reach j
        }
    }
    return rt;
}
```

## 4.8 Kuhn Munkres [1d3c40]

```
class KM {
private:
    static constexpr lld INF = 1LL << 60;
    vector<lld> hl, hr, slk;
    vector<int> fl, fr, pre, qu;
    vector<vector<lld>> w;
    vector<bool> vl, vr;
```

```

int n, ql, qr;
bool check(int x) {
    if (vl[x] == true, fl[x] != -1)
        return vr[qu[qr++]] = fl[x] == true;
    while (x != -1) swap(x, fr[fl[x] = pre[x]]);
    return false;
}
void bfs(int s) {
    fill(slk.begin(), slk.end(), INF);
    fill(vl.begin(), vl.end(), false);
    fill(vr.begin(), vr.end(), false);
    ql = qr = 0;
    vr[qu[qr++]] = s == true;
    while (true) {
        lld d;
        while (ql < qr) {
            for (int x = 0, y = qu[ql++]; x < n; ++x) {
                if (!vl[x] && slk[x] >= (d = hl[x] + hr[y] - w[x][y])) {
                    if (pre[x] == y, d) slk[x] = d;
                    else if (!check(x)) return;
                }
            }
        }
        d = INF;
        for (int x = 0; x < n; ++x)
            if (!vl[x] && d > slk[x]) d = slk[x];
        for (int x = 0; x < n; ++x) {
            if (vl[x]) hl[x] += d;
            else slk[x] -= d;
            if (vr[x]) hr[x] -= d;
        }
        for (int x = 0; x < n; ++x)
            if (!vl[x] && !slk[x] && !check(x)) return;
    }
}
public:
void init(int n_) {
    qu.resize(n = n_);
    fl.assign(n, -1); fr.assign(n, -1);
    hr.assign(n, 0); hl.resize(n);
    w.assign(n, vector<lld>(n));
    slk.resize(n); pre.resize(n);
    vl.resize(n); vr.resize(n);
}
void set_edge(int u, int v, lld x) {w[u][v] = x;}
lld solve() {
    for (int i = 0; i < n; ++i)
        hl[i] = *max_element(w[i].begin(), w[i].end());
    for (int i = 0; i < n; ++i) bfs(i);
    lld res = 0;
    for (int i = 0; i < n; ++i) res += w[i][fl[i]];
    return res;
}
} km;

```

## 4.9 Minimum Cost Circulation [d99194]

```

struct Edge { int to, cap, rev, cost; };
vector<Edge> g[kN];
int dist[kN], pv[kN], ed[kN];
bool mark[kN];
int NegativeCycle(int n) {
    memset(mark, false, sizeof(mark));
    memset(dist, 0, sizeof(dist));
    int upd = -1;
    for (int i = 0; i <= n; ++i) {
        for (int j = 0; j < n; ++j) {
            int idx = 0;
            for (auto &e : g[j]) {
                if (e.cap > 0 && dist[e.to] > dist[j] + e.cost) {
                    dist[e.to] = dist[j] + e.cost;
                    pv[e.to] = j, ed[e.to] = idx;
                    if (i == n) {
                        upd = j;
                        while (!mark[upd]) mark[upd] = 1, upd = pv[upd];
                        return upd;
                    }
                }
            }
            idx++;
        }
    }
    return -1;
}

```

```

}
int Solve(int n) {
    int rt = -1, ans = 0;
    while ((rt = NegativeCycle(n)) >= 0) {
        memset(mark, false, sizeof(mark));
        vector<pair<int, int>> cyc;
        while (!mark[rt]) {
            cyc.emplace_back(pv[rt], ed[rt]);
            mark[rt] = true;
            rt = pv[rt];
        }
        reverse(cyc.begin(), cyc.end());
        int cap = kInf;
        for (auto &i : cyc) {
            auto &e = g[i.first][i.second];
            cap = min(cap, e.cap);
        }
        for (auto &i : cyc) {
            auto &e = g[i.first][i.second];
            e.cap -= cap;
            g[e.to][e.rev].cap += cap;
            ans += e.cost * cap;
        }
    }
    return ans;
}

```

## 4.10 Minimum Cost Maximum Flow [c76e80]

```

template <typename Cap, typename Wei> class MCMF {
    static constexpr auto INF_CAP = numeric_limits<Cap>::
        max();
    static constexpr auto INF_WEI = numeric_limits<Wei>::
        max();

private:
    struct E {
        int to, rev;
        Cap cap; Wei wei;
        E() {}
        E(int a, int b, Cap c, Wei d) : to(a), rev(b), cap(c),
            wei(d) {}
    };
    int S, T;
    vector<vector<E>> G;
    vector<pair<int, int>> f;
    vector<int> inq;
    vector<Wei> d; vector<Cap> up;
    optional<pair<Cap, Wei>> SPFA() {
        queue<int> q;
        for (q.push(S), d[S] = 0, up[S] = INF_CAP; not q.
            empty(); q.pop()) {
            int u = q.front(); inq[u] = false;
            if (up[u] == 0) continue;
            for (int i = 0; i < int(G[u].size()); ++i) {
                auto e = G[u][i]; int v = e.to;
                if (e.cap <= 0 or d[v] <= d[u] + e.wei)
                    continue;
                d[v] = d[u] + e.wei; f[v] = {u, i};
                up[v] = min(up[u], e.cap);
                if (not inq[v]) q.push(v);
                inq[v] = true;
            }
        }
        if (d[T] == INF_WEI) return nullopt;
        for (int i = T; i != S; i = f[i].first) {
            auto &eg = G[f[i].first][f[i].second];
            eg.cap -= up[T];
            G[eg.to][eg.rev].cap += up[T];
        }
        return pair{up[T], d[T]};
    }

public:
    void init(int n) {
        G.assign(n, vector<E>());
        f.resize(n), up.resize(n);
        inq.assign(n, false), d.assign(n, INF_WEI);
    }
    void add_edge(int s, int t, Cap c, Wei w) {
        G[s].emplace_back(t, int(G[t].size()), c, w);
    }
}

```

```

    G[t].emplace_back(s, int(G[s].size()) - 1, 0, -w);
}
pair<Cap, Wei> solve(int a, int b) {
    S = a, T = b;
    Cap c = 0; Wei w = 0;
    while (auto r = SPFA()) {
        c += r->first, w += r->first * r->second;
        fill(inq.begin(), inq.end(), false);
        fill(d.begin(), d.end(), INF_WEI);
    }
    return {c, w};
}
};

```

## 4.11 Maximum Weight Graph Matching [60ca53]

```

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

```

```

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

```

```

    if (st[x] == x && !match[x]) pa[x] = 0, S[x] = 0,
        q_push(x);
    if (q.empty()) return false;
    for (; ) {
        while (q.size()) {
            int u = q.front(); q.pop();
            if (S[st[u]] == 1) continue;
            for (int v = 1; v <= n; ++v)
                if (g[u][v].w > 0 && st[u] != st[v]) {
                    if (e_delta(g[u][v]) == 0) {
                        if (on_found_edge(g[u][v])) return true;
                    } else update_slack(u, st[v]);
                }
        }
        int d = inf;
        for (int b = n + 1; b <= n_x; ++b)
            if (st[b] == b && S[b] == 1) d = min(d, lab[b] / 2);
        ;
        for (int x = 1; x <= n_x; ++x)
            if (st[x] == x && slack[x]) {
                if (S[x] == -1) d = min(d, e_delta(g[slack[x]] [x])
                );
                else if (S[x] == 0) d = min(d, e_delta(g[slack[x]
                ][x]) / 2);
            }
        for (int u = 1; u <= n; ++u) {
            if (S[st[u]] == 0) {
                if (lab[u] <= d) return 0;
                lab[u] -= d;
            } else if (S[st[u]] == 1) lab[u] += d;
        }
        for (int b = n + 1; b <= n_x; ++b)
            if (st[b] == b) {
                if (S[st[b]] == 0) lab[b] += d * 2;
                else if (S[st[b]] == 1) lab[b] -= d * 2;
            }
        q = queue<int>();
        for (int x = 1; x <= n_x; ++x)
            if (st[x] == x && slack[x] && st[slack[x]] != x &&
                e_delta(g[slack[x]] [x]) == 0)
                if (on_found_edge(g[slack[x]] [x])) return true;
        for (int b = n + 1; b <= n_x; ++b)
            if (st[b] == b && S[b] == 1 && lab[b] == 0)
                expand_blossom(b);
    }
    return false;
}

pair<long long, int> solve() {
    memset(match + 1, 0, sizeof(int) * n);
    n_x = n;
    int n_matches = 0;
    long long tot_weight = 0;
    for (int u = 0; u <= n; ++u) st[u] = u, flo[u].clear
        ();
    int w_max = 0;
    for (int u = 1; u <= n; ++u)
        for (int v = 1; v <= n; ++v) {
            flo_from[u][v] = (u == v ? u : 0);
            w_max = max(w_max, g[u][v].w);
        }
    for (int u = 1; u <= n; ++u) lab[u] = w_max;
    while (matching()) ++n_matches;
    for (int u = 1; u <= n; ++u)
        if (match[u] && match[u] < u)
            tot_weight += g[u][match[u]].w;
    return make_pair(tot_weight, n_matches);
}

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

```

## 5 Math

### 5.1 Common Bounds

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

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

$n$	100	1e3	1e6	1e9	1e12	1e15	1e18
$\max_{i \leq n} (d(i))$	12	32	240	1344	6720	26880	103680

  

$n$	1	2	3	4	5	6	7	8	9	10
$\binom{2n}{n}$	2	6	20	70	252	924	3432	12870	48620	184756

## 5.2 Strling Number

### 5.2.1 First Kind

$S_1(n, k)$  counts the number of permutations of  $n$  elements with  $k$  disjoint cycles.

$$S_1(n, k) = (n - 1) \cdot S_1(n - 1, k) + S_1(n - 1, k - 1)$$

$$x(x + 1) \dots (x + n - 1) = \sum_{k=0}^n S_1(n, k) x^k$$

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

$$\Rightarrow g(x + n) = \sum_{k=0}^n \frac{b_k}{(n - k)!} x^{n - k},$$

$$b_k = \sum_{i=0}^k ((n - i)! a_{n-i}) \cdot \left( \frac{n^{k-i}}{(k - i)!} \right)$$

### 5.2.2 Second Kind

$S_2(n, k)$  counts the number of ways to partition a set of  $n$  elements into  $k$  nonempty sets.

$$S_2(n, k) = S_2(n - 1, k - 1) + k \cdot S_2(n - 1, k)$$

$$S_2(n, k) = \sum_{i=0}^k \binom{k}{i} i^n (-1)^{k-i} = \sum_{i=0}^k \frac{(-1)^i}{i!} \cdot \frac{(k - i)^n}{(k - i)!}$$

## 5.3 ax+by=gcd

```

// ax+ny = 1, ax+ny == ax == 1 (mod n)
void exgcd(lld x, lld y, lld &g, lld &a, lld &b) {
    if (y == 0) g = x, a = 1, b = 0;
    else exgcd(y, x % y, g, b, a), b -= (x / y) * a;
}

```

## 5.4 Berlekamp Massey

```

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

```

## 5.5 Characteristic Polynomial

```

vector<vector<int>> Hessenberg(const vector<vector<int>
    >> &A) {
    int N = A.size();
    vector<vector<int>> H = A;
    for (int i = 0; i < N - 2; ++i) {
        if (!H[i + 1][i]) {
            for (int j = i + 2; j < N; ++j) {
                if (H[j][i]) {
                    for (int k = i; k < N; ++k) swap(H[i + 1][k], H[j
                    ][k]);
                    for (int k = 0; k < N; ++k) swap(H[k][i + 1], H[k
                    ][j]);
                    break;
                }
            }
        }
    }
}

```

```

    }
    }
}
if (!H[i + 1][i]) continue;
int val = fpow(H[i + 1][i], kP - 2);
for (int j = i + 2; j < N; ++j) {
    int coef = 1LL * val * H[j][i] % kP;
    for (int k = i; k < N; ++k) H[j][k] = (H[j][k] + 1LL
        * H[i + 1][k] * (kP - coef)) % kP;
    for (int k = 0; k < N; ++k) H[k][i + 1] = (H[k][i +
        1] + 1LL * H[k][j] * coef) % kP;
}
}
return H;
}
vector<int> CharacteristicPoly(const vector<vector<int>
    >> &A) {
    int N = A.size();
    auto H = Hessenberg(A);
    for (int i = 0; i < N; ++i) {
        for (int j = 0; j < N; ++j) H[i][j] = kP - H[i][j];
    }
    vector<vector<int>> P(N + 1, vector<int>(N + 1));
    P[0][0] = 1;
    for (int i = 1; i <= N; ++i) {
        P[i][0] = 0;
        for (int j = 1; j <= i; ++j) P[i][j] = P[i - 1][j -
            1];
        int val = 1;
        for (int j = i - 1; j >= 0; --j) {
            int coef = 1LL * val * H[j][i - 1] % kP;
            for (int k = 0; k <= j; ++k) P[i][k] = (P[i][k] + 1
                LL * P[j][k] * coef) % kP;
            if (j) val = 1LL * val * (kP - H[j][j - 1]) % kP;
        }
    }
    if (N & 1) {
        for (int i = 0; i <= N; ++i) P[N][i] = kP - P[N][i];
    }
    return P[N];
}

```

## 5.6 Chinese Remainder

```

x = a1 % m1
x = a2 % m2
g = gcd(m1, m2)
assert((a1-a2)%g==0)
[p, q] = exgcd(m2/g, m1/g)
return a2+m2*(p*(a1-a2)/g)
// 0 <= x < lcm(m1, m2)

```

## 5.7 De-Bruijn

```

int res[maxn], aux[maxn], sz;
void db(int t, int p, int n, int k) {
    if (t > n) {
        if (n % p == 0)
            for (int i = 1; i <= p; ++i)
                res[sz++] = aux[i];
    } else {
        aux[t] = aux[t - p];
        db(t + 1, p, n, k);
        for (int i = aux[t - p] + 1; i < k; ++i) {
            aux[t] = i;
            db(t + 1, t, n, k);
        }
    }
}
int de_bruijn(int k, int n) {
    // return cyclic string of len k^n s.t. every string
    // of len n using k char appears as a substring.
    if (k == 1) {
        res[0] = 0;
        return 1;
    }
    for (int i = 0; i < k * n; i++) aux[i] = 0;
    sz = 0;
    db(1, 1, n, k);
    return sz;
}

```

## 5.8 DiscreteLog [86e463]

```

template<typename Int>
Int BSGS(Int x, Int y, Int M) {
    // x^? \equiv y (mod M)
    Int t = 1, c = 0, g = 1;
    for (Int M_ = M; M_ > 0; M_ >= 1)
        g = g * x % M;
    for (g = gcd(g, M); t % g != 0; ++c) {
        if (t == y) return c;
        t = t * x % M;
    }
    if (y % g != 0) return -1;
    t /= g, y /= g, M /= g;
    Int h = 0, gs = 1;
    for (; h * h < M; ++h) gs = gs * x % M;
    unordered_map<Int, Int> bs;
    for (Int s = 0; s < h; bs[y] = ++s)
        y = y * x % M;
    for (Int s = 0; s < M; s += h) {
        t = t * gs % M;
        if (bs.count(t)) return c + s + h - bs[t];
    }
    return -1;
}

```

## 5.9 Extended Euler

$$a^b \equiv \begin{cases} a^{(b \bmod \varphi(m)) + \varphi(m)} & \text{if } (a, m) \neq 1 \wedge b \geq \varphi(m) \\ a^{b \bmod \varphi(m)} & \text{otherwise} \end{cases} \pmod{m}$$

## 5.10 ExtendedFloorSum

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

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

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

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

## 5.11 Fast Fourier Transform

```

namespace fft {
using VI = vector<int>;
using VL = vector<long long>;
const double pi = acos(-1);
cplx omega[maxn + 1];
void prefft() {
    for (int i = 0; i <= maxn; i++)
        omega[i] = cplx(cos(2 * pi * i / maxn),
            sin(2 * pi * i / maxn));
}
void fft(vector<cplx> &v, int n) {
    int z = __builtin_ctz(n) - 1;
    for (int i = 0; i < n; ++i) {
        int x = 0, j = 0;
        for (; (1 << j) < n; ++j) x^=(i >> j & 1) << (z - j);
        if (x > i) swap(v[x], v[i]);
    }
    for (int s = 2; s <= n; s <= 1) {
        int z = s >> 1;
        for (int i = 0; i < n; i += s) {
            for (int k = 0; k < z; ++k) {
                cplx x = v[i + z + k] * omega[maxn / s * k];
                v[i + z + k] = v[i + k] - x;
                v[i + k] = v[i + k] + x;
            }
        }
    }
}
void ifft(vector<cplx> &v, int n) {

```



```

fft(v, n); reverse(v.begin() + 1, v.end());
for (int i=0; i<n; ++i) v[i] = v[i] * cplx(1. / n, 0);
}
VL convolution(const VI &a, const VI &b) {
    // Should be able to handle N <= 10^5, C <= 10^4
    int sz = 1;
    while (sz < a.size() + b.size() - 1) sz <= 1;
    vector<cplx> v(sz);
    for (int i = 0; i < sz; ++i) {
        double re = i < a.size() ? a[i] : 0;
        double im = i < b.size() ? b[i] : 0;
        v[i] = cplx(re, im);
    }
    fft(v, sz);
    for (int i = 0; i <= sz / 2; ++i) {
        int j = (sz - i) & (sz - 1);
        cplx x = (v[i] + v[j].conj()) * (v[i] - v[j].conj())
            * cplx(0, -0.25);
        if (j != i) v[j] = (v[j] + v[i].conj()) * (v[j] - v[i].conj())
            * cplx(0, -0.25);
        v[i] = x;
    }
    ifft(v, sz);
    VL c(sz);
    for (int i = 0; i < sz; ++i) c[i] = round(v[i].re);
    return c;
}
VI convolution_mod(const VI &a, const VI &b, int p) {
    int sz = 1;
    while (sz + 1 < a.size() + b.size()) sz <= 1;
    vector<cplx> fa(sz), fb(sz);
    for (int i = 0; i < (int)a.size(); ++i)
        fa[i] = cplx(a[i] & ((1 << 15) - 1), a[i] >> 15);
    for (int i = 0; i < (int)b.size(); ++i)
        fb[i] = cplx(b[i] & ((1 << 15) - 1), b[i] >> 15);
    fft(fa, sz), fft(fb, sz);
    double r = 0.25 / sz;
    cplx r2(0, -1), r3(r, 0), r4(0, -r), r5(0, 1);
    for (int i = 0; i <= (sz >> 1); ++i) {
        int j = (sz - i) & (sz - 1);
        cplx a1 = (fa[i] + fa[j].conj());
        cplx a2 = (fa[i] - fa[j].conj()) * r2;
        cplx b1 = (fb[i] + fb[j].conj()) * r3;
        cplx b2 = (fb[i] - fb[j].conj()) * r4;
        if (i != j) {
            cplx c1 = (fa[j] + fa[i].conj());
            cplx c2 = (fa[j] - fa[i].conj()) * r2;
            cplx d1 = (fb[j] + fb[i].conj()) * r3;
            cplx d2 = (fb[j] - fb[i].conj()) * r4;
            fa[i] = c1 * d1 + c2 * d2 * r5;
            fb[i] = c1 * d2 + c2 * d1;
        }
        fa[j] = a1 * b1 + a2 * b2 * r5;
        fb[j] = a1 * b2 + a2 * b1;
    }
    fft(fa, sz), fft(fb, sz);
    vector<int> res(sz);
    for (int i = 0; i < sz; ++i) {
        long long a = round(fa[i].re), b = round(fb[i].re),
            c = round(fa[i].im);
        res[i] = (a + ((b % p) << 15) + ((c % p) << 30)) % p;
    }
    return res;
}
}

```

## 5.12 FloorSum [bda6b2]

```

// @param n `n < 2^32`
// @param m `1 <= m < 2^32`
// @return sum_{i=0}^{n-1} floor((ai + b)/m) mod 2^64
llu floor_sum_unsigned(llu n, llu m, llu a, llu b) {
    llu ans = 0;
    while (true) {
        if (a >= m) {
            ans += n * (n - 1) / 2 * (a / m); a %= m;
        }
        if (b >= m) {
            ans += n * (b / m); b %= m;
        }
        llu y_max = a * n + b;
        if (y_max < m) break;
        // y_max < m * (n + 1)
        // floor(y_max / m) <= n

```

```

n = (llu)(y_max / m), b = (llu)(y_max % m);
swap(m, a);
}
return ans;
}
llu floor_sum(llu n, llu m, llu a, llu b) {
    llu ans = 0;
    if (a < 0) {
        llu a2 = (a % m + m) % m;
        ans -= 1ULL * n * (n - 1) / 2 * ((a2 - a) / m);
        a = a2;
    }
    if (b < 0) {
        llu b2 = (b % m + m) % m;
        ans -= 1ULL * n * ((b2 - b) / m);
        b = b2;
    }
    return ans + floor_sum_unsigned(n, m, a, b);
}

```

## 5.13 FloorSum

```

// min{k | l <= ((ak) mod m) <= r}
optional<uint64_t> mod_min(uint32_t a, uint32_t m,
    uint32_t l, uint32_t r) {
    if (a == 0) return l ? nullopt : 0;
    if (auto k = uint64_t(l + a - 1) / a; k * a <= r)
        return k;
    auto b = m / a, c = m % a;
    if (auto y = mod_min(c, a, a - r % a, a - l % a))
        return (l + *y * c + a - 1) / a + *y * b;
    return nullopt;
}

```

## 5.14 CRT for arbitrary mod

```

const int mod = 1000000007;
const int M1 = 985661441; // G = 3
const int M2 = 998244353;
const int M3 = 1004535809;
int superBigCRT(int64_t A, int64_t B, int64_t C) {
    static_assert(M1 <= M2 && M2 <= M3);
    constexpr int64_t r12 = modpow(M1, M2-2, M2);
    constexpr int64_t r13 = modpow(M1, M3-2, M3);
    constexpr int64_t r23 = modpow(M2, M3-2, M3);
    constexpr int64_t M1M2 = 1LL * M1 * M2 % mod;
    B = (B - A + M2) * r12 % M2;
    C = (C - A + M3) * r13 % M3;
    C = (C - B + M3) * r23 % M3;
    return (A + B * M1 + C * M1M2) % mod;
}

```

## 5.15 FWT

```

/* or convolution:
 * x = (x0, x0+x1), inv = (x0, x1-x0) w/o final div
 * and convolution:
 * x = (x0+x1, x1), inv = (x0-x1, x1) w/o final div */
void fwt(int x[], int N, bool inv = false) {
    for (int d = 1; d < N; d <= 1) {
        for (int s = 0, d2 = d * 2; s < N; s += d2)
            for (int i = s, j = s + d; i < s + d; i++, j++) {
                int ta = x[i], tb = x[j];
                x[i] = modadd(ta, tb);
                x[j] = modsub(ta, tb);
            }
    }
    if (inv) for (int i = 0, invn = modinv(N); i < N; i++)
        x[i] = modmul(x[i], invn);
}

```

## 5.16 NTT [946e8e]

```

template <int mod, int G, int maxn> struct NTT {
    static_assert(maxn == (maxn & -maxn));
    int roots[maxn];
    NTT() {
        int r = modpow(G, (mod - 1) / maxn);
        for (int i = maxn >> 1; i; i >= 1) {
            roots[i] = 1;
            for (int j = 1; j < i; j++)
                roots[i + j] = modmul(roots[i + j - 1], r);
            r = modmul(r, r);
        }
    }
}

```

```

}
// n must be 2^k, and 0 <= F[i] < mod
void operator()(int F[], int n, bool inv = false) {
    for (int i = 0, j = 0; i < n; i++) {
        if (i < j) swap(F[i], F[j]);
        for (int k = n>>1; (j^=k) < k; k>>=1);
    }
    for (int s = 1; s < n; s *= 2) {
        for (int i = 0; i < n; i += s * 2) {
            for (int j = 0; j < s; j++) {
                int a = F[i+j];
                int b = modmul(F[i+j+s], roots[s+j]);
                F[i+j] = modadd(a, b); // a + b
                F[i+j+s] = modsub(a, b); // a - b
            }
        }
    }
    if (inv) {
        int invn = modinv(n);
        for (int i = 0; i < n; i++)
            F[i] = modmul(F[i], invn);
        reverse(F + 1, F + n);
    }
}
};

```

## 5.17 Partition Number

```

int b = sqrt(n);
ans[0] = tmp[0] = 1;
for (int i = 1; i <= b; i++) {
    for (int rep = 0; rep < 2; rep++)
        for (int j = i; j <= n - i * i; j++)
            modadd(tmp[j], tmp[j-i]);
    for (int j = i * i; j <= n; j++)
        modadd(ans[j], tmp[j - i * i]);
}

```

## 5.18 Pi Count (Linear Sieve)

```

static constexpr int N = 1000000 + 5;
lld pi[N];
vector<int> primes;
bool sieved[N];
lld cube_root(lld x){
    lld s=cbrt(x-static_cast<long double>(0.1));
    while(s*s*s <= x) ++s;
    return s-1;
}
lld square_root(lld x){
    lld s=sqrt(x-static_cast<long double>(0.1));
    while(s*s <= x) ++s;
    return s-1;
}
void init(){
    primes.reserve(N);
    primes.push_back(1);
    for(int i=2;i<N;i++){
        if(!sieved[i]) primes.push_back(i);
        pi[i] = !sieved[i] + pi[i-1];
        for(int p: primes) if(p > 1) {
            if(p * i >= N) break;
            sieved[p * i] = true;
            if(p % i == 0) break;
        }
    }
}
lld phi(lld m, lld n) {
    static constexpr int MM = 80000, NN = 500;
    static lld val[MM][NN];
    if(m<MM&&n<NN&&val[m][n])return val[m][n]-1;
    if(n == 0) return m;
    if(primes[n] >= m) return 1;
    lld ret = phi(m,n-1)-phi(m/primes[n],n-1);
    if(m<MM&&n<NN) val[m][n] = ret+1;
    return ret;
}
lld pi_count(lld);
lld P2(lld m, lld n) {
    lld sm = square_root(m), ret = 0;
    for(lld i = n+1;primes[i]<=sm;i++){
        ret+=pi_count(m/primes[i])-pi_count(primes[i])+1;
    }
    return ret;
}

```

```

lld pi_count(lld m) {
    if(m < N) return pi[m];
    lld n = pi_count(cube_root(m));
    return phi(m, n) + n - 1 - P2(m, n);
}

```

## 5.19 Miller Rabin [0edab2]

```

bool isprime(llu x) {
    static auto witn = [](llu a, llu n, int t) {
        if (!a) return false;
        while (t--) {
            llu a2 = mmul(a, a, n);
            if (a2 == 1 && a != 1 && a != n - 1) return true;
            a = a2;
        }
        return a != 1;
    };
    if (x < 2) return false;
    if (!(x & 1)) return x == 2;
    int t = __builtin_ctzll(x - 1);
    llu odd = (x - 1) >> t;
    for (llu m:
        {2, 325, 9375, 28178, 450775, 9780504, 1795265022})
        if (witn(mpow(m % x, odd, x), x, t))
            return false;
    return true;
}

```

## 5.20 Pollard Rho [2aclad]

```

// does not work when n is prime
// return any non-trivial factor
llu pollard_rho(llu n) {
    static auto f = [](llu x, llu k, llu m) {
        return add(k, mul(x, x, m), m);
    };
    if (!(n & 1)) return 2;
    mt19937 rnd(120821011);
    while (true) {
        llu y = 2, yy = y, x = rnd() % n, t = 1;
        for (llu sz = 2; t == 1; sz <= 1, y = yy) {
            for (llu i = 0; t == 1 && i < sz; ++i) {
                yy = f(yy, x, n);
                t = gcd(yy > y ? yy - y : y - yy, n);
            }
            if (t != 1 && t != n) return t;
        }
    }
}

```

## 5.21 Polynomial Operations

```

using V = vector<int>;
#define fi(l, r) for (int i = int(l); i < int(r); ++i)
template <int mod, int G, int maxn> struct Poly : V {
    static uint32_t n2k(uint32_t n) {
        if (n <= 1) return 1;
        return 1u << (32 - __builtin_clz(n - 1));
    }
    static NTT<mod,G,maxn> ntt; // coefficients in [0, P)
    explicit Poly(int n = 1) : V(n) {}
    Poly(const V &v) : V(v) {}
    Poly(const Poly &p, size_t n) : V(n) {
        copy_n(p.data(), min(p.size(), n), data());
    }
    Poly &irev() { return reverse(data(), data() + size())
        , *this; }
    Poly &isz(int sz) { return resize(sz), *this; }
    Poly &iadd(const Poly &rhs) { // n() == rhs.n()
        fi(0, size())(*this)[i] = modadd((*this)[i], rhs[i]);
        return *this;
    }
    Poly &imul(int k) {
        fi(0, size())(*this)[i] = modmul((*this)[i], k);
        return *this;
    }
    Poly Mul(const Poly &rhs) const {
        const int sz = n2k(size() + rhs.size() - 1);
        Poly X(*this, sz), Y(rhs, sz);
        ntt(X.data(), sz), ntt(Y.data(), sz);
        fi(0, sz) X[i] = modmul(X[i], Y[i]);
        ntt(X.data(), sz, true);
        return X.isz(size() + rhs.size() - 1);
    }
}

```

```

Poly Inv() const { // coef[0] != 0
    if (size() == 1) return V{modinv(*begin())};
    const int sz = n2k(size() * 2);
    Poly X = Poly(*this, (size() + 1) / 2).Inv().isz(sz),
        Y(*this, sz);
    ntt(X.data(), sz), ntt(Y.data(), sz);
    fi(0, sz) X[i] = modmul(X[i], modsub(2, modmul(X[i],
        Y[i])));
    ntt(X.data(), sz, true);
    return X.isz(size());
}

Poly Sqrt() const { // coef[0] \in [1, mod)^2
    if (size() == 1) return V{QuadraticResidue(*this)
        [0], mod};
    Poly X = Poly(*this, (size() + 1) / 2).Sqrt().isz(
        size());
    return X.iadd(Mul(X.Inv()).isz(size())).imul(mod / 2
        + 1);
}

pair<Poly, Poly> DivMod(const Poly &rhs) const {
    if (size() < rhs.size()) return {V{0}, *this};
    const int sz = size() - rhs.size() + 1;
    Poly X(rhs); X.irev().isz(sz);
    Poly Y(*this); Y.irev().isz(sz);
    Poly Q = Y.Mul(X.Inv()).isz(sz).irev();
    X = rhs.Mul(Q), Y = *this;
    fi(0, size()) Y[i] = modsub(Y[i], X[i]);
    return {Q, Y.isz(max<int>(1, rhs.size() - 1))};
}

Poly Dx() const {
    Poly ret(size() - 1);
    fi(0, ret.size()) ret[i] = modmul(i + 1, (*this)[i +
        1]);
    return ret.isz(max<int>(1, ret.size()));
}

Poly Sx() const {
    Poly ret(size() + 1);
    fi(0, size()) ret[i + 1] = modmul(modinv(i + 1), (*
        this)[i]);
    return ret;
}

Poly Ln() const { // coef[0] == 1
    return Dx().Mul(Inv()).Sx().isz(size());
}

Poly Exp() const { // coef[0] == 0
    if (size() == 1) return V{1};
    Poly X = Poly(*this, (size() + 1) / 2).Exp().isz(size
        ());
    Poly Y = X.Ln(); Y[0] = mod - 1;
    fi(0, size()) Y[i] = modsub((*this)[i], Y[i]);
    return X.Mul(Y).isz(size());
}

Poly Pow(const string &K) const {
    int nz = 0;
    while (nz < size() && !(*this)[nz]) ++nz;
    int nk = 0, nk2 = 0;
    for (char c : K) {
        nk = (nk * 10 + c - '0') % mod;
        nk2 = nk2 * 10 + c - '0';
        if (nk2 * nz >= size())
            return Poly(size());
        nk2 %= mod - 1;
    }
    if (!nk && !nk2) return Poly(V{1}, size());
    Poly X = V(data() + nz, data() + size() - nz * (nk2 -
        1));
    int x0 = X[0];
    return X.imul(modinv(x0)).Ln().imul(nk).Exp().imul(
        modpow(x0, nk2)).irev().isz(size()).irev();
}

V Eval(V x) const {
    if (x.empty()) return {};
    const size_t n = max(x.size(), size());
    vector<Poly> t(n * 2, V{1, 0}), f(n * 2);
    for (size_t i = 0; i < x.size(); ++i)
        t[n + i] = V{1, mod-x[i]};
    for (size_t i = n - 1; i > 0; --i)
        t[i] = t[i * 2].Mul(t[i * 2 + 1]);
    f[1] = Poly(*this, n).irev().Mul(t[1].Inv()).isz(n).
        irev();
    for (size_t i = 1; i < n; ++i) {
        auto o = f[i]; auto sz = o.size();

```

```

        f[i*2] = o.irev().Mul(t[i*2+1]).isz(sz).irev().isz(t
            [i*2].size());
        f[i*2+1] = o.Mul(t[i*2]).isz(sz).irev().isz(t[i
            *2+1].size());
    }
    for (size_t i=0; i<x.size(); ++i) x[i] = f[n+i][0];
    return x;
}

static int LinearRecursion(const V &a, const V &c,
    int64_t n) { // a_n = \sum c_j a_{n-j}
    const int k = (int)a.size();
    assert((int)c.size() == k + 1);
    Poly C(k + 1), W({1}, k), M = {0, 1};
    fi(1, k + 1) C[k - i] = modsub(mod, c[i]);
    C[k] = 1;
    while (n) {
        if (n % 2) W = W.Mul(M).DivMod(C).second;
        n /= 2, M = M.Mul(M).DivMod(C).second;
    }
    int ret = 0;
    fi(0, k) ret = modadd(ret, modmul(W[i], a[i]));
    return ret;
}
};
#undef fi
using Poly_t = Poly<998244353, 3, 1 << 20>;
template <> decltype(Poly_t::ntt) Poly_t::ntt = {};

```

## 5.22 Quadratic residue [14d6e4]

```

struct S {
    int MOD, w;
    int64_t x, y;
    S(int m, int w=-1, int64_t x=1, int64_t y=0)
        : MOD(m), w(w), x(x), y(y) {}
    S operator*(const S &rhs) const {
        int w_ = w;
        if (w_ == -1) w_ = rhs.w;
        assert(w_ != -1 and w_ == rhs.w);
        return { MOD, w_,
            (x * rhs.x + y * rhs.y % MOD * w) % MOD,
            (x * rhs.y + y * rhs.x % MOD * w) % MOD };
    }
};

int get_root(int n, int P) {
    if (P == 2 or n == 0) return n;
    auto check = [&](int x) {
        return qpow(x, (P - 1) / 2, P);
    };
    if (check(n) != 1) return -1;
    int64_t a; int w; mt19937 rnd(7122);
    do { a = rnd() % P;
        w = ((a * a - n) % P + P) % P;
    } while (check(w) != P - 1);
    return qpow(S(P, w, a, 1), (P + 1) / 2).x;
}

```

## 5.23 Simplex [e975d5]

```

namespace simplex {
    // maximize c^T x under Ax <= B
    // return VD(n, -inf) if the solution doesn't exist
    // return VD(n, +inf) if the solution is unbounded
    using VD = vector<double>;
    using VVD = vector<vector<double>>;
    const double eps = 1e-9;
    const double inf = 1e+9;
    int n, m;
    VVD d;
    vector<int> p, q;
    void pivot(int r, int s) {
        double inv = 1.0 / d[r][s];
        for (int i = 0; i < m + 2; ++i)
            for (int j = 0; j < n + 2; ++j)
                if (i != r && j != s)
                    d[i][j] -= d[r][j] * d[i][s] * inv;
        for (int i=0; i<m+2; ++i) if (i != r) d[i][s] *= -inv;
        for (int j=0; j<n+2; ++j) if (j != s) d[r][j] *= +inv;
        d[r][s] = inv; swap(p[r], q[s]);
    }
    bool phase(int z) {
        int x = m + z;
        while (true) {
            int s = -1;

```

```

for (int i = 0; i <= n; ++i) {
    if (!z && q[i] == -1) continue;
    if (s == -1 || d[x][i] < d[x][s]) s = i;
}
if (d[x][s] > -eps) return true;
int r = -1;
for (int i = 0; i < m; ++i) {
    if (d[i][s] < eps) continue;
    if (r == -1 || \
        d[i][n+1]/d[i][s] < d[r][n+1]/d[r][s]) r = i;
}
if (r == -1) return false;
pivot(r, s);
}
}
VD solve(const VVD &a, const VD &b, const VD &c) {
    m = b.size(), n = c.size();
    d = VVD(m + 2, VD(n + 2));
    for (int i = 0; i < m; ++i)
        for (int j = 0; j < n; ++j) d[i][j] = a[i][j];
    p.resize(m), q.resize(n + 1);
    for (int i = 0; i < m; ++i)
        p[i] = n + i, d[i][n] = -1, d[i][n + 1] = b[i];
    for (int i = 0; i < n; ++i) q[i] = i, d[m][i] = -c[i];
    q[n] = -1, d[m + 1][n] = 1;
    int r = 0;
    for (int i = 1; i < m; ++i)
        if (d[i][n + 1] < d[r][n + 1]) r = i;
    if (d[r][n + 1] < -eps) {
        pivot(r, n);
        if (!phase(1) || d[m + 1][n + 1] < -eps)
            return VD(n, -inf);
        for (int i = 0; i < m; ++i) if (p[i] == -1) {
            int s = min_element(d[i].begin(), d[i].end() - 1)
                - d[i].begin();
            pivot(i, s);
        }
    }
    if (!phase(0)) return VD(n, inf);
    VD x(n);
    for (int i = 0; i < m; ++i)
        if (p[i] < n) x[p[i]] = d[i][n + 1];
    return x;
}
}

```

## 5.24 Simplex Construction

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

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

# 6 Geometry

## 6.1 Basic Geometry [adea5f]

```

#define IM imag
#define RE real
using lld = int64_t;
using llf = long double;
using PT = std::complex<lld>;
using PTF = std::complex<llf>;
using P = PT;
auto toPTF(PT p) { return PTF{RE(p), IM(p)}; }
int sgn(lld x) { return (x > 0) - (x < 0); }
lld dot(P a, P b) { return RE(conj(a) * b); }
lld cross(P a, P b) { return IM(conj(a) * b); }
int ori(P a, P b, P c) {
    return sgn(cross(b - a, c - a));
}
namespace std {
    bool operator<(const P &a, const P &b) {
        return RE(a) != RE(b) ? RE(a) < RE(b) : IM(a) < IM(b);
    }
} // namespace std

```

```

int quad(P p) {
    return (IM(p) == 0) // use sgn for PTF
        ? (RE(p) < 0 ? 3 : 1) : (IM(p) < 0 ? 0 : 2);
}
int argCmp(P a, P b) {
    // -1 / 0 / 1 <-> < / == / > (atan2)
    int qa = quad(a), qb = quad(b);
    if (qa != qb) return sgn(qa - qb);
    return sgn(cross(b, a));
}
template <typename V> llf area(const V &pt) {
    llf ret = 0;
    for (int i = 1; i + 1 < (int)pt.size(); i++)
        ret += cross(pt[i] - pt[0], pt[i+1] - pt[0]);
    return ret / 2.0;
}
P rot90(P p) { return P{-IM(p), RE(p)}; }
PTF project(PTF p, PTF q) { // p onto q
    return dot(p, q) * q / dot(q, q);
}
llf FMOD(llf x) {
    if (x < -PI) x += PI * 2;
    if (x > PI) x -= PI * 2;
    return x;
}

```

## 6.2 Segment & Line Intersection [ba5d3c]

```

struct Segment { // closed segment
    PT st, dir; // represent st + t*dir for 0<=t<=1
    Segment(PT s, PT e) : st(s), dir(e - s) {}
    static bool valid(llf p, llf q) {
        // is there t s.t. 0 <= t <= 1 && qt == p ?
        if (q < 0) q = -q, p = -p;
        return 0 <= p && p <= q;
    }
    vector<PT> ends() const { return { st, st + dir }; }
};
template <typename T> bool isInter(T A, PT P) {
    if (A.dir == PT(0)) return P == A.st; // BE CAREFUL
    return cross(P - A.st, A.dir) == 0 &&
        T::valid(dot(P - A.st, A.dir), norm(A.dir));
}
template <typename U, typename V>
bool isInter(U A, V B) {
    if (cross(A.dir, B.dir) == 0) { // BE CAREFUL
        bool res = false;
        for (PT P: A.ends()) res |= isInter(B, P);
        for (PT P: B.ends()) res |= isInter(A, P);
        return res;
    }
    PT D = B.st - A.st;
    llf C = cross(A.dir, B.dir);
    return U::valid(cross(D, B.dir), C) &&
        V::valid(cross(D, A.dir), C);
}
struct Line {
    PT st, ed, dir;
    Line(PT s, PT e)
        : st(s), ed(e), dir(e - s) {}
};
PTF intersect(const Line &A, const Line &B) {
    llf t = cross(B.st - A.st, B.dir) /
        llf(cross(A.dir, B.dir));
    return toPTF(A.st) + PTF(t) * toPTF(A.dir);
}

```

## 6.3 2D Convex Hull [e4ccde]

```

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

```

## 6.4 3D Convex Hull [93b153]

```
// return the faces with pt indexes
struct P3{
    lld x,y,z;
    P3 operator * (const P3 &b) const {
        return(P3){y*b.z-b.y*z,z*b.x-b.z*x,x*b.y-b.x*y};
    }
};
struct Face {
    int a, b, c;
    Face(int ta,int tb,int tc):a(ta),b(tb),c(tc){}
};
P3 ver(P3 a, P3 b, P3 c) { return (b - a) * (c - a); }
// plz ensure that first 4 points are not coplanar
// all points coplanar case will WA
vector<Face> convex_hull_3D(const vector<P3> &pt) {
    int n = int(pt.size()); vector<Face> now;
    if (n <= 2) return {}; // be careful about edge case
    vector<vector<int>> flag(n, vector<int>(n));
    now.emplace_back(0,1,2); now.emplace_back(2,1,0);
    for (int i = 3; i < n; i++) {
        vector<Face> next;
        for (const auto &f : now) {
            lld d = (pt[i] - pt[f.a]).dot(
                ver(pt[f.a], pt[f.b], pt[f.c]));
            if (d <= 0) next.push_back(f);
            int ff = (d > 0) - (d < 0);
            flag[f.a][f.b]=flag[f.b][f.c]=flag[f.c][f.a]=ff;
        }
        for (const auto &f : now) {
            const 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);
        }
        now = next;
    }
    return now;
}
// delaunay: facets with negative z normal of
// convexhull of (x, y, x^2 + y^2)
```

## 6.5 2D Farthest Pair [83d60a]

```
// stk is from convex hull
n = (int)(stk.size());
int pos = 1, ans = 0; stk.push_back(stk[0]);
for(int i=0;i<n;i++) {
    while(abs(cross(stk[i+1]-stk[i],
        stk[(pos+1)%n]-stk[i])) >
        abs(cross(stk[i+1]-stk[i],
        stk[pos]-stk[i]))) pos = (pos+1)%n;
    ans = max({ans, dis(stk[i], stk[pos]),
        dis(stk[i+1], stk[pos])});
}
```

## 6.6 kD Closest Pair (3D ver.)

```
llf solve(vector<P> v) {
    shuffle(v.begin(), v.end(), mt19937());
    unordered_map<lld, unordered_map<lld,
        unordered_map<lld, int>>> m;
    lld d = dis(v[0], v[1]);
    auto Idx = [&d] (llf x) -> lld {
        return round(x * 2 / d) + 0.1; };
    auto rebuild_m = [&m, &v, &Idx](int k) {
        m.clear();
        for (int i = 0; i < k; ++i)
            m[Idx(v[i].x)][Idx(v[i].y)]
                [Idx(v[i].z)] = i;
    }; rebuild_m(2);
    for (size_t i = 2; i < v.size(); ++i) {
        const lld kx = Idx(v[i].x), ky = Idx(v[i].y),
            kz = Idx(v[i].z); bool found = false;
        for (int dx = -2; dx <= 2; ++dx) {
            const lld nx = kx + dx;
            if (m.find(nx) == m.end()) continue;
            auto& mm = m[nx];
            for (int dy = -2; dy <= 2; ++dy) {
                const lld ny = ky + dy;
                if (mm.find(ny) == mm.end()) continue;
                auto& mmm = mm[ny];
```

```
for (int dz = -2; dz <= 2; ++dz) {
    const lld nz = dz + kz;
    if (mmm.find(nz) == mmm.end()) continue;
    const int p = mmm[nz];
    if (dis(v[p], v[i]) < d) {
        d = dis(v[p], v[i]);
        found = true;
    }
}
}
}
if (found) rebuild_m(i + 1);
else m[kx][ky][kz] = i;
}
return d;
}
```

## 6.7 Simulated Annealing

```
llf anneal() {
    mt19937 rnd_engine( seed );
    uniform_real_distribution< llf > rnd( 0, 1 );
    const llf dT = 0.001;
    // Argument p
    llf S_cur = calc( p ), S_best = S_cur;
    for ( llf T = 2000 ; T > EPS ; T -= dT ) {
        // Modify p to p_prime
        const llf S_prime = calc( p_prime );
        const llf delta_c = S_prime - S_cur;
        llf prob = min( ( llf ) 1, exp( -delta_c / T ) );
        if ( rnd( rnd_engine ) <= prob )
            S_cur = S_prime, p = p_prime;
        if ( S_prime < S_best ) // find min
            S_best = S_prime, p_best = p_prime;
    }
    return S_best;
}
```

## 6.8 Half Plane Intersection [0d6d9f]

```
// cross(pt-line.st, line.dir)<=0 <-> pt in half plane
bool operator<(const Line &lhs, const Line &rhs) {
    if (int cmp = argCmp(lhs.dir, rhs.dir))
        return cmp == -1;
    return ori(lhs.st, lhs.ed, rhs.st) < 0;
}
// intersect function is in "Segment Intersect"
llf HPI(vector<Line> &lines) {
    sort(lines.begin(), lines.end());
    deque<Line> que;
    deque<PTF> pt;
    que.push_back(lines[0]);
    for (int i = 1; i < (int)lines.size(); i++) {
        if (argCmp(lines[i].dir, lines[i-1].dir) == 0)
            continue;
#define POP(L, R) \
        while (pt.size() > 0 \
            && ori(L.st, L.ed, pt.back()) < 0) \
            pt.pop_back(), que.pop_back(); \
        while (pt.size() > 0 \
            && ori(R.st, R.ed, pt.front()) < 0) \
            pt.pop_front(), que.pop_front();
        POP(lines[i], lines[i-1]);
        pt.push_back(intersect(que.back(), lines[i]));
        que.push_back(lines[i]);
    }
    POP(que.front(), que.back())
    if (que.size() <= 1 ||
        argCmp(que.front().dir, que.back().dir) == 0)
        return 0;
    pt.push_back(intersect(que.front(), que.back()));
    return area(pt);
}
```

## 6.9 Minkowski Sum [6a9b21]

```
vector<pll> Minkowski(vector<pll> A, vector<pll> B) {
    hull(A), hull(B);
    vector<pll> C(1, A[0] + B[0]), s1, s2;
    for(int i = 0; i < SZ(A); ++i)
        s1.pb(A[(i + 1) % SZ(A)] - A[i]);
    for(int i = 0; i < SZ(B); ++i)
        s2.pb(B[(i + 1) % SZ(B)] - B[i]);
    for(int p1 = 0, p2 = 0; p1 < SZ(A) || p2 < SZ(B);)
```



```

    if (p2 >= SZ(B)
        || (p1 < SZ(A) && cross(s1[p1], s2[p2]) >= 0))
        C.pb(C.back() + s1[p1++]);
    else
        C.pb(C.back() + s2[p2++]);
    return hull(C), C;
}

```

## 6.10 Circle Class [1df37f]

```

struct Circle { PTF o; llf r; };
vector<llf> intersectAngle(Circle A, Circle B) {
    PTF dir = B.o - A.o; llf d2 = norm(dir);
    if (norm(A.r - B.r) >= d2) // norm(x) := |x|^2
        if (A.r < B.r) return {-PI, PI}; // A in B
        else return {}; // B in A
    if (norm(A.r + B.r) <= d2) return {};
    llf dis = abs(dir), theta = arg(dir);
    llf phi = acos((A.r * A.r + d2 - B.r * B.r) /
        (2 * A.r * dis));
    llf L = FMOD(theta - phi), R = FMOD(theta + phi);
    return { L, R };
}
vector<PTF> intersectPoint(Circle a, Circle b) {
    llf d = abs(a.o - b.o);
    if (d >= b.r + a.r || d <= abs(b.r - a.r)) return {};
    llf dt = (b.r * b.r - a.r * a.r) / d, d1 = (d + dt) / 2;
    PTF dir = (a.o - b.o) / d;
    PTF u = dir * d1 + b.o;
    PTF v = rot90(dir) * sqrt(max<llf>(0, b.r * b.r - d1 * d1));
    return {u + v, u - v};
}

```

## 6.11 Intersection of line and Circle [5c86ef]

```

vector<PTF> line_interCircle(const PTF &p1,
    const PTF &p2, const PTF &c, const double r) {
    PTF ft = p1 + project(c - p1, p2 - p1), vec = p2 - p1;
    llf dis = abs(c - ft);
    if (abs(dis - r) < eps) return {ft};
    if (dis > r) return {};
    vec = vec * sqrt(r * r - dis * dis) / abs(vec);
    return {ft + vec, ft - vec};
}

```

## 6.12 Intersection of Polygon and Circle [1504f9]

```

// Divides into multiple triangle, and sum up
// test by HDU2892
llf _area(PTF pa, PTF pb, llf r) {
    if (abs(pa) < abs(pb)) swap(pa, pb);
    if (abs(pb) < eps) return 0;
    llf S, h, theta;
    llf a = abs(pb), b = abs(pa), c = abs(pb - pa);
    llf cosB = dot(pb, pb - pa) / a / c, B = acos(cosB);
    llf cosC = dot(pa, pb) / a / b, C = acos(cosC);
    if (a > r) {
        S = (C / 2) * r * r;
        h = a * b * sin(C) / c;
        if (h < r && B < PI / 2)
            S -= (acos(h / r) * r * r - h * sqrt(r * r - h * h));
    } else if (b > r) {
        theta = PI - B - asin(sin(B) / r * a);
        S = 0.5 * a * r * sin(theta) + (C - theta) / 2 * r * r;
    } else
        S = 0.5 * sin(C) * a * b;
    return S;
}
llf area_poly_circle(const vector<PTF> &poly,
    const PTF &O, const llf r) {
    llf S = 0;
    for (int i = 0, N = poly.size(); i < N; ++i)
        S += _area(poly[i] - O, poly[(i + 1) % N] - O, r) *
            ori(O, poly[i], poly[(i + 1) % N]);
    return fabs(S);
}

```

## 6.13 Point & Hulls Tangent [5b4fef]

```

#define above(P, Vi, Vj) (ori(P, Vi, Vj) > 0) // true
    if Vi is above Vj
#define below(P, Vi, Vj) (ori(P, Vi, Vj) < 0) // true
    if Vi is below Vj

```

```

// Rtangent_PointPolyC(): binary search for convex
    polygon right tangent
// Input: P = a 2D point (exterior to the polygon)
//      n = number of polygon vertices
//      V = array of vertices for a 2D convex polygon
    with V[n] = V[0]
// Return: index "i" of rightmost tangent point V[i]
int Rtangent_PointPolyC(PT P, int n, PT *V) {
    if (n == 1) return 0;
    if (below(P, V[1], V[0]) && !above(P, V[n - 1], V[0]))
        return 0;
    for (int a = 0, b = n; ; ) {
        int c = (a + b) / 2, dnC = not above(P, V[c + 1], V[c]);
        if (dnC && !above(P, V[c - 1], V[c])) return c;
        if (above(P, V[a + 1], V[a]))
            ((dnC || above(P, V[a], V[c])) ? b : a) = c;
        else
            ((!dnC || !below(P, V[a], V[c])) ? a : b) = c;
    }
}

// Ltangent_PointPolyC(): binary search for convex
    polygon left tangent
// Input: P = a 2D point (exterior to the polygon)
//      n = number of polygon vertices
//      V = array of vertices for a 2D convex polygon
    with V[n]=V[0]
// Return: index "i" of leftmost tangent point V[i]
int Ltangent_PointPolyC(PT P, int n, PT *V) {
    if (n == 1) return 0;
    if (above(P, V[n - 1], V[0]) && !below(P, V[1], V[0]))
        return 0;
    for (int a = 0, b = n; ; ) {
        int c = (a + b) / 2, dnC = below(P, V[c + 1], V[c]);
        if (!below(P, V[c - 1], V[c]) && !dnC) return c;
        if (below(P, V[a + 1], V[a]))
            ((!dnC || below(P, V[a], V[c])) ? b : a) = c;
        else
            ((dnC || !above(P, V[a], V[c])) ? a : b) = c;
    }
}

```

## 6.14 Polygon Union [5c0b42]

```

llf rat(P a, P b) { return sgn(RE(b)) ? llf(RE(a)) / RE(b)
    : llf(IM(a)) / IM(b); }
llf polyUnion(vector<vector<P>> &poly) {
    llf ret = 0; // area of poly[i] must be non-negative
    rep(i, 0, sz(poly)) rep(v, 0, sz(poly[i])) {
        P A = poly[i][v], B = poly[i][(v + 1) % sz(poly[i])];
        vector<pair<llf, int>> segs{{0, 0}, {1, 0}};
        rep(j, 0, sz(poly)) if (i != j) {
            rep(u, 0, sz(poly[j])) {
                P C = poly[j][u], D = poly[j][(u + 1) % sz(poly[j])];
                if (int sc = ori(A, B, C), sd = ori(A, B, D); sc !=
                    sd) {
                    llf sa = cross(D - C, A - C), sb = cross(D - C, B - C);
                    if (min(sc, sd) < 0)
                        segs.emplace_back(sa / (sa - sb), sgn(sc - sd));
                    else if (!sc && !sd && j < i && sgn(dot(B - A, D - C))
                        > 0) {
                        segs.emplace_back(rat(C - A, B - A), 1);
                        segs.emplace_back(rat(D - A, B - A), -1);
                    }
                }
            }
        }
    }
    sort(segs.begin(), segs.end());
    for (auto &s : segs) s.first = clamp<llf>(s.first, 0, 1);
    llf sum = 0;
    int cnt = segs[0].second;
    rep(j, 1, sz(segs)) {
        if (!cnt) sum += segs[j].first - segs[j - 1].first;
        cnt += segs[j].second;
    }
    ret += cross(A, B) * sum;
    return ret / 2;
}

```

## 6.15 Convex Hulls Tangent [e9c73c]

```
// RLtangent_PolyPolyC(): get the RL tangent between
// two convex polygons
// Input:
// m = number of vertices in polygon 1
// V = array of vertices for convex polygon 1 with V[m]
//    =V[0]
// n = number of vertices in polygon 2
// W = array of vertices for convex polygon 2 with W[n]
//    =W[0]
// Output:
// *t1 = index of tangent point V[t1] for polygon 1
// *t2 = index of tangent point W[t2] for polygon 2
void RLtangent_PolyPolyC(int m, PT *V, int n, PT *W,
    int *t1, int *t2) {
    // * first get the initial vertex on each polygon
    // right tangent from W[0] to V
    int ix1 = Rtangent_PointPolyC(W[0], m, V);
    // left tangent from V[ix1] to W
    int ix2 = Ltangent_PointPolyC(V[ix1], n, W);
    // * ping-pong linear search until it stabilizes
    for (bool done = false; not done; ) {
        done = true; // assume done until...
        while (ori(W[ix2], V[ix1], V[ix1 + 1]) <= 0)
            ++ix1; // get Rtangent from W[ix2] to V
        while (ori(V[ix1], W[ix2], W[ix2 + 1]) >= 0) {
            --ix2; // get Ltangent from V[ix1] to W
            done = false; // not done if had to adjust this
        }
    }
    *t1 = ix1, *t2 = ix2;
}
```

## 6.16 Tangent line of Two Circle [40c677]

```
vector<Line>
tanline(const Circle &c1, const Circle &c2, int sign1){
    // sign1 = 1 for outer tang, -1 for inner tang
    vector<Line> ret;
    if (norm(c1.o - c2.o) < eps) return ret;
    llf d = abs(c1.o - c2.o);
    PTF v = (c2.o - c1.o) / d;
    llf c = (c1.r - sign1 * c2.r) / d;
    if (c * c > 1) return ret;
    llf h = sqrt(max<llf>(0, 1 - c * c));
    for (int sign2 : {1, -1}) {
        PTF n = c * v + sign2 * h * rot90(v);
        PTF p1 = c1.o + n * c1.r;
        PTF p2 = c2.o + n * (c2.r * sign1);
        if (norm(p2 - p1) < eps)
            p2 = p1 + rot90(c2.o - c1.o);
        ret.push_back({p1, p2});
    }
    return ret;
}
```

## 6.17 Minimum Covering Circle [a26cde]

```
template<typename P>
Circle getCircum(const P &a, const P &b, const P &c){
    Real a1 = a.x-b.x, b1 = a.y-b.y;
    Real c1 = (a.x+b.x)/2 * a1 + (a.y+b.y)/2 * b1;
    Real a2 = a.x-c.x, b2 = a.y-c.y;
    Real c2 = (a.x+c.x)/2 * a2 + (a.y+c.y)/2 * b2;
    Circle cc;
    cc.o.x = (c1*b2-b1*c2)/(a1*b2-b1*a2);
    cc.o.y = (a1*c2-c1*a2)/(a1*b2-b1*a2);
    cc.r = hypot(cc.o.x-a.x, cc.o.y-a.y);
    return cc;
}

template<typename P>
Circle MinCircleCover(const vector<P>& pts){
    random_shuffle(pts.begin(), pts.end());
    Circle c = { pts[0], 0 };
    for(int i=0;i<(int)pts.size();i++){
        if (dist(pts[i], c.o) <= c.r) continue;
        c = { pts[i], 0 };
        for (int j = 0; j < i; j++) {
            if(dist(pts[j], c.o) <= c.r) continue;
            c.o = (pts[i] + pts[j]) / 2;
            c.r = dist(pts[i], c.o);
            for (int k = 0; k < j; k++) {
                if (dist(pts[k], c.o) <= c.r) continue;
                c = getCircum(pts[i], pts[j], pts[k]);
            }
        }
    }
}
```

```
}
}
}
return c;
}
```

## 6.18 KDTree (Nearest Point)

```
const int MXN = 100005;
struct KDTree {
    struct Node {
        int x,y,x1,y1,x2,y2;
        int id,f;
        Node *L, *R;
    } tree[MXN], *root;
    int n;
    LL dis2(int x1, int y1, int x2, int y2) {
        LL dx = x1-x2, dy = y1-y2;
        return dx*dx+dy*dy;
    }
    static bool cmpx(Node& a, Node& b){return a.x<b.x;}
    static bool cmpy(Node& a, Node& b){return a.y<b.y;}
    void init(vector<pair<int,int>> ip) {
        n = ip.size();
        for (int i=0; i<n; i++) {
            tree[i].id = i;
            tree[i].x = ip[i].first;
            tree[i].y = ip[i].second;
        }
        root = build_tree(0, n-1, 0);
    }
    Node* build_tree(int L, int R, int d) {
        if (L>R) return nullptr;
        int M = (L+R)/2; tree[M].f = d%2;
        nth_element(tree+L, tree+M, tree+R+1, d%2?cmpy:cmpx);
        tree[M].x1 = tree[M].x2 = tree[M].x;
        tree[M].y1 = tree[M].y2 = tree[M].y;
        tree[M].L = build_tree(L, M-1, d+1);
        if (tree[M].L) {
            tree[M].x1 = min(tree[M].x1, tree[M].L->x1);
            tree[M].x2 = max(tree[M].x2, tree[M].L->x2);
            tree[M].y1 = min(tree[M].y1, tree[M].L->y1);
            tree[M].y2 = max(tree[M].y2, tree[M].L->y2);
        }
        tree[M].R = build_tree(M+1, R, d+1);
        if (tree[M].R) {
            tree[M].x1 = min(tree[M].x1, tree[M].R->x1);
            tree[M].x2 = max(tree[M].x2, tree[M].R->x2);
            tree[M].y1 = min(tree[M].y1, tree[M].R->y1);
            tree[M].y2 = max(tree[M].y2, tree[M].R->y2);
        }
        return tree+M;
    }
    int touch(Node* r, int x, int y, LL d2){
        LL dis = sqrt(d2)+1;
        if (x<r->x1-dis || x>r->x2+dis ||
            y<r->y1-dis || y>r->y2+dis)
            return 0;
        return 1;
    }
    void nearest(Node* r, int x, int y, int &mID, LL &md2) {
        if (!r || !touch(r, x, y, md2)) return;
        LL d2 = dis2(r->x, r->y, x, y);
        if (d2 < md2 || (d2 == md2 && mID < r->id)) {
            mID = r->id;
            md2 = d2;
        }
        // search order depends on split dim
        if ((r->f == 0 && x < r->x) ||
            (r->f == 1 && y < r->y)) {
            nearest(r->L, x, y, mID, md2);
            nearest(r->R, x, y, mID, md2);
        } else {
            nearest(r->R, x, y, mID, md2);
            nearest(r->L, x, y, mID, md2);
        }
    }
    int query(int x, int y) {
        int id = 1029384756;
        LL d2 = 102938475612345678LL;
        nearest(root, x, y, id, d2);
        return id;
    }
}
```

```
} tree;
```

## 6.19 Rotating Sweep Line [f8c127]

```
void rotatingSweepLine(pair<int, int> a[], int n) {
    vector<pair<int, int>> l;
    l.reserve(n * (n - 1) / 2);
    for (int i = 0; i < n; ++i)
        for (int j = i + 1; j < n; ++j)
            l.emplace_back(i, j);
    sort(l.begin(), l.end(), [&a](auto &u, auto &v){
        lld udx = a[u.first].first - a[u.second].first;
        lld udy = a[u.first].second - a[u.second].second;
        lld vdx = a[v.first].first - a[v.second].first;
        lld vdy = a[v.first].second - a[v.second].second;
        if (udx == 0 or vdx == 0) return not udx == 0;
        int s = sgn(udx * vdx);
        return udy * vdx * s < vdy * udx * s;
    });
    vector<int> idx(n), p(n);
    iota(idx.begin(), idx.end(), 0);
    sort(idx.begin(), idx.end(), [&a](int i, int j){
        return a[i] < a[j]; });
    for (int i = 0; i < n; ++i) p[idx[i]] = i;
    for (auto [i, j]: l) {
        // do here
        swap(p[i], p[j]);
        idx[p[i]] = i, idx[p[j]] = j;
    }
}
```

## 6.20 Circle Cover [7b92c0]

```
#define eb emplace_back
struct CircleCover { // test@SPOJ N=1000, 0.3~0.5s
    struct Teve {
        PTF p; llf ang; int add;
        Teve() {}
        Teve(PTF a, llf b, int c) : p(a), ang(b), add(c) {}
        bool operator<(const Teve &a)
            const { return ang < a.ang; }
    };
    // strict: x = 0, otherwise x = -1
    bool disjunct(Cir &a, Cir &b, int x)
    { return sgn(abs(a.o - b.o) - a.r - b.r) > x; }
    bool contain(Cir &a, Cir &b, int x)
    { return sgn(a.r - b.r - abs(a.o - b.o)) > x; }
    vector<llf> solve(vector<Cir> c) {
        // area[i] : area covered by at least i circles
        int N = c.size(); vector<llf> area(N + 1);
        vector<vector<int>> overlap(N, vector<int>(N));
        auto g = overlap; // use simple 2darray to speedup
        for (int i = 0; i < N; ++i)
            for (int j = 0; j < N; ++j) {
                /* c[j] is non-strictly in c[i]. */
                overlap[i][j] = i != j &&
                    (sgn(c[i].r - c[j].r) > 0 ||
                     (sgn(c[i].r - c[j].r) == 0 && i < j)) &&
                    contain(c[i], c[j], -1);
            }
        for (int i = 0; i < N; ++i)
            for (int j = 0; j < N; ++j)
                g[i][j] = i != j && !(overlap[i][j] ||
                    overlap[j][i] || disjunct(c[i], c[j], -1));
        for (int i = 0; i < N; ++i) {
            vector<Teve> eve; int cnt = 1;
            for (int j = 0; j < N; ++j)
                if (overlap[j][i]) ++cnt;
            // if (cnt > 1) continue; (if only need area[1])
            for (int j = 0; j < N; ++j) if (g[i][j]) {
                auto IP = intersectPoint(c[i], c[j]);
                PTF aa = IP[1], bb = IP[0];
                llf A = arg(aa - c[i].o), B = arg(bb - c[i].o);
                eve.eb(bb, B, 1); eve.eb(aa, A, -1);
                if (B > A) ++cnt;
            }
            if (eve.empty())
                area[cnt] += pi * c[i].r * c[i].r;
            else {
                sort(eve.begin(), eve.end());
                eve.eb(eve[0]); eve.back().ang += 2. * pi;
                for (size_t j = 0; j + 1 < eve.size(); j++) {
                    cnt += eve[j].add;
                    area[cnt] += cross(eve[j].p, eve[j+1].p) * .5;
                }
            }
        }
    }
};
```

```
llf t = eve[j + 1].ang - eve[j].ang;
area[cnt] += (t - sin(t)) * c[i].r * c[i].r * .5;
}
}
return area;
}
} CC0;
```

## 7 Stringology

### 7.1 Hash [7afe3e]

```
class Hash {
private:
    static constexpr int P = 127, Q = 1051762951;
    vector<int> h, p;
public:
    void init(const string &s){
        h.assign(s.size()+1, 0); p.resize(s.size()+1);
        for (size_t i = 0; i < s.size(); ++i)
            h[i + 1] = add(mul(h[i], P), s[i]);
        generate(p.begin(), p.end(), [x=1, y=1, this]()
            mutable { y=x; x=mul(x, P); return y; });
    }
    int query(int l, int r){ // 1-base (l, r)
        return sub(h[r], mul(h[l], p[r-l]));
    }
};
```

### 7.2 Suffix Array [4e7e80]

```
namespace sfx {
    bool _t[maxn * 2];
    int hi[maxn], rev[maxn];
    int _s[maxn * 2], sa[maxn * 2], _c[maxn * 2];
    int x[maxn], _p[maxn], _q[maxn * 2];
    // sa[i]: sa[i]-th suffix is the
    // i-th lexicographically smallest suffix.
    // hi[i]: longest common prefix
    // of suffix sa[i] and suffix sa[i - 1].
    void pre(int *a, int *c, int n, int z) {
        memset(a, 0, sizeof(int) * n);
        memcpy(x, c, sizeof(int) * z);
    }
    void induce(int *a, int *c, int *s, bool *t, int n, int z) {
        memcpy(x + 1, c, sizeof(int) * (z - 1));
        for (int i = 0; i < n; ++i)
            if (a[i] && !t[a[i] - 1])
                a[x[s[a[i] - 1]]++] = a[i] - 1;
        memcpy(x, c, sizeof(int) * z);
        for (int i = n - 1; i >= 0; --i)
            if (a[i] && t[a[i] - 1])
                a[--x[s[a[i] - 1]]] = a[i] - 1;
    }
    void sais(int *s, int *a, int *p, int *q,
        bool *t, int *c, int n, int z) {
        bool uniq = t[n - 1] = true;
        int nn=0, nmzx=-1, *nsa = a+n, *ns=s+n, last=-1;
        memset(c, 0, sizeof(int) * z);
        for (int i = 0; i < n; ++i) uniq &= ++c[s[i]] < 2;
        for (int i = 0; i < z - 1; ++i) c[i + 1] += c[i];
        if (uniq) {
            for (int i = 0; i < n; ++i) a[--c[s[i]]] = i;
            return;
        }
        for (int i = n - 2; i >= 0; --i)
            t[i] = (s[i]==s[i + 1] ? t[i + 1] : s[i]<s[i + 1]);
        pre(a, c, n, z);
        for (int i = 1; i <= n - 1; ++i)
            if (t[i] && !t[i - 1])
                a[--x[s[i]]] = nn++ = i;
        induce(a, c, s, t, n, z);
        for (int i = 0; i < n; ++i) {
            if (a[i] && t[a[i]] && !t[a[i] - 1]) {
                bool neq = last < 0 || \
                    memcmp(s + a[i], s + last,
                        (p[q[a[i]] + 1] - a[i]) * sizeof(int));
                ns[q[last = a[i]]] = nmzx += neq;
            }
        }
        sais(ns, nsa, p+nn, q+n, t+n, c+z, nn, nmzx+1);
        pre(a, c, n, z);
        for (int i = nn - 1; i >= 0; --i)
            a[--x[s[p[nsa[i]]]]] = p[nsa[i]];
    }
};
```

```

induce(a, c, s, t, n, z);
}
void build(const string &s) {
    const int n = int(s.size());
    for (int i = 0; i < n; ++i) _s[i] = s[i];
    _s[n] = 0; // s shouldn't contain 0
    sais(_s, sa, _p, _q, _t, _c, n + 1, 256);
    for(int i = 0; i < n; ++i) rev[sa[i] = sa[i+1]] = i;
    int ind = hi[0] = 0;
    for (int i = 0; i < n; ++i) {
        if (!rev[i]) {
            ind = 0;
            continue;
        }
        while (i + ind < n && \
            s[i + ind] == s[sa[rev[i] - 1] + ind]) ++ind;
        hi[rev[i]] = ind ? ind-- : 0;
    }
}
}

```

### 7.3 Suffix Automaton [bf53b9]

```

struct SuffixAutomaton {
    struct node {
        int ch[K], len, fail, cnt, indeg;
        node(int L = 0) : ch{}, len(L), fail(0), cnt(0),
            indeg(0) {}
    } st[N];
    int root, last, tot;
    void extend(int c) {
        int cur = ++tot;
        st[cur] = node(st[last].len + 1);
        while (last && !st[last].ch[c]) {
            st[last].ch[c] = cur;
            last = st[last].fail;
        }
        if (!last) {
            st[cur].fail = root;
        } else {
            int q = st[last].ch[c];
            if (st[q].len == st[last].len + 1) {
                st[cur].fail = q;
            } else {
                int clone = ++tot;
                st[clone] = st[q];
                st[clone].len = st[last].len + 1;
                st[st[cur].fail = st[q].fail = clone].cnt = 0;
                while (last && st[last].ch[c] == q) {
                    st[last].ch[c] = clone;
                    last = st[last].fail;
                }
            }
        }
        st[last = cur].cnt += 1;
    }
    void init(const char* s) {
        root = last = tot = 1;
        st[root] = node(0);
        for (char c; c = *s; ++s) extend(c - 'a');
    }
    int q[N];
    void dp() {
        for (int i = 1; i <= tot; i++) ++st[st[i].fail].indeg;
        ;
        int head = 0, tail = 0;
        for (int i = 1; i <= tot; i++)
            if (st[i].indeg == 0) q[tail++] = i;
        while (head != tail) {
            int now = q[head++];
            if (int f = st[now].fail) {
                st[f].cnt += st[now].cnt;
                if (--st[f].indeg == 0) q[tail++] = f;
            }
        }
    }
    int run(const char* s) {
        int now = root;
        for (char c; c = *s; ++s) {
            if (!st[now].ch[c - 'a']) return 0;
            now = st[now].ch[c];
        }
        return st[now].cnt;
    }
}

```

```

} SAM;

```

### 7.4 Z value [6a7fd0]

```

vector<int> Zalgo(const string &s) {
    vector<int> z(s.size(), s.size());
    for (int i = 1, l = 0, r = 0; i < z[0]; ++i) {
        int j = clamp(r - i, 0, z[i - l]);
        for (; i + j < z[0] and s[i + j] == s[j]; ++j);
        if (i + (z[i] = j) > r) r = i + z[i];
    }
    return z;
}

```

### 7.5 Manacher [365720]

```

int z[maxn];
int manacher(const string& s) {
    string t = ".";
    for(char c: s) t += c, t += '.';
    int l = 0, r = 0, ans = 0;
    for (int i = 1; i < t.length(); ++i) {
        z[i] = (r > i ? min(z[2 * l - i], r - i) : 1);
        while (i - z[i] >= 0 && i + z[i] < t.length()) {
            if (t[i - z[i]] == t[i + z[i]]) ++z[i];
            else break;
        }
        if (i + z[i] > r) r = i + z[i], l = i;
    }
    for(int i=1;i<t.length();++i) ans = max(ans, z[i]-1);
    return ans;
}

```

### 7.6 Lexico Smallest Rotation [0e9fb8]

```

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

```

### 7.7 Main Lorentz

```

vector<pair<int, int>> rep[kN]; // 0-base [l, r]
void main_lorentz(const string &s, int sft = 0) {
    const int n = s.size();
    if (n == 1) return;
    const int nu = n / 2, nv = n - nu;
    const string u = s.substr(0, nu), v = s.substr(nu,
        ru(u.rbegin(), u.rend()), rv(v.rbegin(), v.rend()));
    main_lorentz(u, sft), main_lorentz(v, sft + nu);
    const auto z1 = Zalgo(ru), z2 = Zalgo(v + '#' + u),
        z3 = Zalgo(ru + '#' + rv), z4 = Zalgo(v);
    auto get_z = [&](const std::vector<int> &z, int i) {
        return (0 <= i and i < (int)z.size()) ? z[i] : 0;
    };
    auto add_rep = [&](bool left, int c, int l, int k1,
        int k2) {
        const int L = max(1, l - k2), R = std::min(l - left,
            k1);
        if (L > R) return;
        if (left) rep[l].emplace_back(sft + c - R, sft + c -
            L);
        else rep[l].emplace_back(sft + c - R - l + 1, sft + c
            - L - l + 1);
    };
    for (int cntr = 0; cntr < n; cntr++) {
        int l, k1, k2;
        if (cntr < nu) {
            l = nu - cntr;
            k1 = get_z(z1, nu - cntr);
            k2 = get_z(z2, nv + 1 + cntr);
        } else {
            l = cntr - nu + 1;
            k1 = get_z(z3, nu + 1 + nv - 1 - (cntr - nu));
            k2 = get_z(z4, (cntr - nu) + 1);
        }
        if (k1 + k2 >= l)
            add_rep(cntr < nu, cntr, l, k1, k2);
    }
}

```

## 7.8 BWT

```
struct BurrowsWheeler{
#define SIGMA 26
#define BASE 'a'
vector<int> v[ SIGMA ];
void BWT(char* ori, char* res){
    // make ori -> ori + ori
    // then build suffix array
}
void iBWT(char* ori, char* res){
    for( int i = 0 ; i < SIGMA ; i ++ )
        v[ i ].clear();
    int len = strlen( ori );
    for( int i = 0 ; i < len ; i ++ )
        v[ ori[i] - BASE ].push_back( i );
    vector<int> a;
    for( int i = 0 , ptr = 0 ; i < SIGMA ; i ++ )
        for( auto j : v[ i ] ){
            a.push_back( j );
            ori[ ptr ++ ] = BASE + i;
        }
    for( int i = 0 , ptr = 0 ; i < len ; i ++ ){
        res[ i ] = ori[ a[ ptr ] ];
        ptr = a[ ptr ];
    }
    res[ len ] = 0;
}
} bwt;
```

## 7.9 Palindromic Tree

```
struct palindromic_tree{
    struct node{
        int next[26], f, len;
        int cnt, num, st, ed; // num = depth of fail link
        node(int l=0):f(0), len(l), cnt(0), num(0) {
            memset(next, 0, sizeof(next)); }
    };
    vector<node> st;
    vector<char> s;
    int last, n;
    void init(){
        st.clear(); s.clear(); last=1; n=0;
        st.push_back(0); st.push_back(-1);
        st[0].f=1; s.push_back(-1); }
    int getFail(int x){
        while(s[n-st[x].len-1] != s[n]) x=st[x].f;
        return x; }
    void add(int c){
        s.push_back(c-'a'); ++n;
        int cur=getFail(last);
        if(!st[cur].next[c]){
            int now=st.size();
            st.push_back(st[cur].len+2);
            st[now].f=st[getFail(st[cur].f)].next[c];
            st[cur].next[c]=now;
            st[now].num=st[st[now].f].num+1;
        }
        last=st[cur].next[c];
        ++st[last].cnt; }
    void dpCnt() { // cnt = #occurrence in whole str
        for( int i=st.size()-1; i >= 0; i-- )
            st[st[i].f].cnt += st[i].cnt;
    }
    int size(){ return st.size()-2; }
} pt;
int main() {
    string s; cin >> s; pt.init();
    for( int i=0; i<SZ(s); i++ ) {
        int prvsz = pt.size(); pt.add(s[i]);
        if( prvsz != pt.size() ) {
            int r = i, l = r - pt.st[pt.last].len + 1;
            // pal @ [l,r]: s.substr(l, r-l+1)
        }
    }
    return 0;
}
```

## 8 Misc

### 8.1 Theorems

#### 8.1.1 Sherman-Morrison formula

$$(A + uv^T)^{-1} = A^{-1} - \frac{A^{-1}uv^T A^{-1}}{1 + v^T A^{-1}u}$$

#### 8.1.2 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  $|\det(\tilde{L}_{rr})|$ .

#### 8.1.3 Tutte's Matrix

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

#### 8.1.4 Cayley's Formula

- Given a degree sequence  $d_1, d_2, \dots, d_n$  for each labeled vertices, there're  $\frac{(n-2)!}{(d_1-1)!(d_2-1)!\dots(d_n-1)!}$  spanning trees.
- Let  $T_{n,k}$  be the number of labeled forests on  $n$  vertices with  $k$  components, such that vertex  $1, 2, \dots, k$  belong to different components. Then  $T_{n,k} = k n^{n-k-1}$ .

#### 8.1.5 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  $1 \leq k \leq n$ .

#### 8.1.6 Havel–Hakimi algorithm

find the vertex who has greatest degree unused, connect it with other greatest vertex.

#### 8.1.7 Euler's planar graph formula

$$V - E + F = C + 1. \quad E \leq 3V - 6 \quad (\text{when } V \geq 3)$$

#### 8.1.8 Pick's theorem

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

#### 8.1.9 Matroid Intersection

Given matroids  $M_1 = (G, I_1)$ ,  $M_2 = (G, I_2)$ , find maximum  $S \in I_1 \cap I_2$ . For each iteration, build the directed graph and find a shortest path from  $s$  to  $t$ .

- $s \rightarrow x : S \sqcup \{x\} \in I_1$
- $x \rightarrow t : S \sqcup \{x\} \in I_2$
- $y \rightarrow x : S \setminus \{y\} \sqcup \{x\} \in I_1$  ( $y$  is in the unique circuit of  $S \sqcup \{x\}$ )
- $x \rightarrow y : S \setminus \{y\} \sqcup \{x\} \in I_2$  ( $y$  is in the unique circuit of  $S \sqcup \{x\}$ )

Alternate the path, and  $|S|$  will increase by 1. Let  $R = \min(\text{rank}(I_1), \text{rank}(I_2))$ ,  $N = |G|$ . In each iteration,  $|E| = O(RN)$ . For weighted case, assign weight  $-w(x)$  and  $w(x)$  to  $x \in S$  and  $x \notin S$ , resp. Use Bellman-Ford to find the weighted shortest path. The maximum iteration of Bellman-Ford is  $2R + 1$ .

## 8.2 Bitset LCS

```
scanf("%d%d", &n, &m), u = n / 64 + 1;
for( int i = 1, c; i <= n; i++ )
    scanf("%d", &c), p[c].set(i);
for( int i = 1, c; i <= m; i++ ) {
    scanf("%d", &c), (g = f) |= p[c];
    f.shiftLeftByOne(), f.set(0);
    ((f = g - f) ^= g) &= g;
}
printf("%d\n", f.count());
```



### 8.3 Prefix Substring LCS

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

### 8.4 Convex 1D/1D DP

```
struct segment {
    int i, l, r;
    segment() {}
    segment(int a, int b, int c): i(a), l(b), r(c) {}
};
inline lld f(int l, int r){return dp[l] + w(l+1, r);}
void solve() {
    dp[0] = 0;
    deque<segment> dq; dq.push_back(segment(0, 1, n));
    for (int i = 1; i <= n; ++i) {
        dp[i] = f(dq.front().i, i);
        while(dq.size() && dq.front().r < i+1) dq.pop_front();
        dq.front().l = i + 1;
        segment seg = segment(i, i + 1, n);
        while (dq.size() &&
            f(i, dq.back().l) < f(dq.back().i, dq.back().l))
            dq.pop_back();
        if (dq.size()) {
            int d = 1 << 20, c = dq.back().l;
            while (d >= 1) if (c + d <= dq.back().r)
                if (f(i, c+d) > f(dq.back().i, c+d)) c += d;
            dq.back().r = c; seg.l = c + 1;
        }
        if (seg.l <= n) dq.push_back(seg);
    }
}
```

### 8.5 ConvexHull Optimization [bcdcl1a]

```
struct L {
    mutable int64_t a, b, p;
    bool operator<(const L &r) const {
        return a < r.a; /* here */
    }
    bool operator<(int64_t x) const { return p < x; }
};
struct DynamicHull : multiset<L, less<>> {
    static const int64_t kInf = 1e18;
    bool Isect(iterator x, iterator y) {
        auto Div = [] (int64_t a, int64_t b) {
            return a / b - ((a ^ b) < 0 && a % b); };
        if (y == end()) { x->p = kInf; return false; }
        if (x->a == y->a)
            x->p = x->b > y->b ? kInf : -kInf; /* here */
        else x->p = Div(y->b - x->b, x->a - y->a);
        return x->p >= y->p;
    }
    void Insert(int64_t a, int64_t b) {
        auto z = insert({a, b, 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));
    }
    int64_t Query(int64_t x) { // default chmax
        auto l = *lower_bound(x); // to chmin:
        return l.a * x + l.b; // modify the 2 "<>"
    }
};
```

### 8.6 Josephus Problem

```
// n people kill m for each turn
int f(int n, int m) {
    int s = 0;
    for (int i = 2; i <= n; i++)
        s = (s + m) % i;
    return s;
}
```

```
}
// died at kth
int kth(int n, int m, int k){
    if (m == 1) return n-1;
    for (k = k*m+m-1; k >= n; k = k-n+(k-n)/(m-1));
    return k;
}
```

### 8.7 Tree Knapsack

```
int dp[N][K]; PII obj[N];
vector<int> G[N];
void dfs(int u, int mx){
    for(int s: G[u]) {
        if(mx < obj[s].first) continue;
        for(int i=0; i<=mx-obj[s].FF; i++)
            dp[s][i] = dp[u][i];
        dfs(s, mx - obj[s].first);
        for(int i=obj[s].FF; i<=mx; i++)
            dp[u][i] = max(dp[u][i],
                dp[s][i - obj[s].FF] + obj[s].SS);
    }
}
```

### 8.8 N Queens Problem

```
vector<int> solve(int n) {
    // no solution when n=2, 3
    vector<int> ret;
    if (n % 6 == 2) {
        for (int i = 2; i <= n; i += 2)
            ret.push_back(i);
        ret.push_back(3); ret.push_back(1);
        for (int i = 7; i <= n; i += 2)
            ret.push_back(i);
        ret.push_back(5);
    } else if (n % 6 == 3) {
        for (int i = 4; i <= n; i += 2)
            ret.push_back(i);
        ret.push_back(2);
        for (int i = 5; i <= n; i += 2)
            ret.push_back(i);
        ret.push_back(1); ret.push_back(3);
    } else {
        for (int i = 2; i <= n; i += 2)
            ret.push_back(i);
        for (int i = 1; i <= n; i += 2)
            ret.push_back(i);
    }
    return ret;
}
```

### 8.9 Stable Marriage

```
1: Initialize  $m \in M$  and  $w \in W$  to free
2: while  $\exists$  free man  $m$  who has a woman  $w$  to propose to do
3:    $w \leftarrow$  first woman on  $m$ 's list to whom  $m$  has not yet proposed
4:   if  $\exists$  some pair  $(m', w)$  then
5:     if  $w$  prefers  $m$  to  $m'$  then
6:        $m' \leftarrow$  free
7:        $(m, w) \leftarrow$  engaged
8:     end if
9:   else
10:     $(m, w) \leftarrow$  engaged
11:   end if
12: end while
```

### 8.10 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  $0 \leq p, q \leq N$ 
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;  
}
```