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5.8 DiscreteLog	14	cerr << "\e[1;32m(" << s << ")" = (";	
5.9 Extended Euler	14	<b>int</b> cnt = <b>sizeof</b> ...(T);	
5.10 ExtendedFloorSum	14	(..., (cerr << a << (--cnt ? ", " : ") \e[0m\n"));	
5.11 Fast Fourier Transform	14	}	
5.12 FloorSum	15	<b>template</b> <typename Iter>	
5.13 FWT	15	<b>void</b> dvorak(const char *s, Iter L, Iter R) {	
5.14 Miller Rabin	15	cerr << "\e[1;32m[ " << s << " ] = [ ";	
5.15 NTT	15	<b>for</b> ( <b>int</b> f = 0; L != R; ++L)	
5.16 Partition Number	15	cerr << (f++ ? ", " : "") << *L;	
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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++;
}

template < typename T >
static inline bool gn( T &x ) {
    int c = gc(); T sgn = 1; x = 0;
    while(('0'>c||c>'9') && c!=EOF && c!='-') c = gc();
    if(c == '-') sgn = -1, c = gc();
    if(c == EOF) return false;
    while('0'<=c&&c<='9') x = x*10 + c - '0', c = gc();
    return x *= sgn, true;
}
```

# 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

```
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

```
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

```

__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.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)

```

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

```

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

```

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

```

struct Centroid {
    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(int x) {
        vis[x] = true; sz[x] = 1; mx[x] = 0;
        for (auto [u, w] : g[x]) {
            if (vis[u]) continue;
            DfsSz(u);
            sz[x] += sz[u];
            mx[x] = max(mx[x], sz[u]);
        }
        tmp.push_back(x);
    }
}

```

```

void DfsDist(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(u, D + w);
}
void DfsCen(int x, int D = 0, int p = -1) {
    tmp.clear(); DfsSz(x);
    int M = tmp.size();
    int C = -1;
    for (int u : tmp) {
        if (max(M - sz[u], mx[u]) * 2 <= M) C = u;
        vis[u] = false;
    }
    DfsDist(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(u, D + 1, C);
}
Centroid(int N, vector<vector<pair<int,int>>> g)
: Sub(N), Sub2(N), Cnt(N), Cnt2(N), Dist(N),
  Pa(N), Dep(N), vis(N), sz(N), mx(N)
{ DfsCen(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]++;
        }
        z = x; x = Pa[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];
        z = x; x = Pa[x];
    }
    return res;
}
};

```

### 3.5 Directed Minimum Spanning Tree

```

struct Edge { int u, v, w; };
struct DirectedMST { // find maximum
    int solve(vector<Edge> E, int root, int n) {
        int ans = 0;
        while (true) {
            // find best in edge
            vector<int> in(n, -inf), prv(n, -1);
            for (auto e : E)
                if (e.u != e.v && e.w > in[e.v]) {
                    in[e.v] = e.w;
                    prv[e.v] = e.u;
                }
            in[root] = 0; prv[root] = -1;
            for (int i = 0; i < n; i++)
                if (in[i] == -inf) return -inf;
            // find cycle
            int tot = 0;
            vector<int> id(n, -1), vis(n, -1);
            for (int i = 0; i < n; i++) {
                ans += in[i];
                for (int x = i; x != -1 && id[x] == -1; x = prv[x])
                    if (vis[x] == i) {
                        for (int y = prv[x]; y != x; y = prv[y])
                            id[y] = tot;
                        id[x] = tot++;
                        break;
                    }
                vis[x] = i;
            }
            if (!tot) return ans;
            for (int i = 0; i < n; i++)
                if (id[i] == -1) id[i] = tot++;
            for (auto &e : E) {

```

```

                if (id[e.u] != id[e.v]) e.w -= in[e.v];
                e.u = id[e.u], e.v = id[e.v];
            }
            n = tot; root = id[root];
        }
    } DMST;
}

```

### 3.6 Dominator Tree

```

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

```

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
    // chian[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

```

// 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 MaxCliqueDyn

```

constexpr int kN = 150;
struct MaxClique { // Maximum Clique
    bitset<kN> a[kN], cs[kN];
    int ans, sol[kN], q, cur[kN], d[kN], n;
    void init(int _n) {
        n = _n, ans = q = 0;
        for (int i = 0; i < n; i++) a[i].reset();
    }
    void addEdge(int u, int v) { a[u][v] = a[v][u] = 1; }
    void csort(vector<int> &r, vector<int> &c) {
        int mx = 1, km = max(ans - q + 1, 1), t = 0,
            m = int(r.size());
        cs[1].reset(); cs[2].reset();
        for (int i = 0; i < m; i++) {
            int p = r[i], k = 1;
            while ((cs[k] & a[p]).count()) k++;
            if (k > mx) cs[++mx + 1].reset();
            cs[k][p] = 1;
            if (k < km) r[t++] = p;
        }
        c.resize(m);
        if (t) c[t - 1] = 0;
        for (int k = km; k <= mx; k++) {
            for (int p = int(cs[k]._Find_first());
                p < kN; p = int(cs[k]._Find_next(p))) {
                r[t] = p; c[t++] = k;
            }
        }
    }
    void dfs(vector<int> &r, vector<int> &c, int l,
        bitset<kN> mask) {
        while (!r.empty()) {
            int p = r.back(); r.pop_back();
            mask[p] = 0;
            if (q + c.back() <= ans) return;
            cur[q++] = p;
            vector<int> nr, nc;
            bitset<kN> nmask = mask & a[p];
            for (int i : r)
                if (a[p][i]) nr.push_back(i);
            if (!nr.empty()) {
                if (l < 4) {
                    for (int i : nr)
                        d[i] = int((a[i] & nmask).count());
                    sort(nr.begin(), nr.end(),
                        [&](int x, int y) {
                            return d[x] > d[y];
                        });
                }
                csort(nr, nc); dfs(nr, nc, l + 1, nmask);
            } else if (q > ans) {
                ans = q; copy(cur, cur + q, sol);
            }
            c.pop_back(); q--;
        }
    }
    int solve(bitset<kN> mask) { // vertex mask
        vector<int> r, c;

```

```

        for (int i = 0; i < n; i++)
            if (mask[i]) r.push_back(i);
        for (int i = 0; i < n; i++)
            d[i] = int((a[i] & mask).count());
        sort(r.begin(), r.end(),
            [&](int i, int j) { return d[i] > d[j]; });
        csort(r, c);
        dfs(r, c, 1, mask);
        return ans; // sol[0 ~ ans-1]
    }
} graph;

```

### 3.12 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;

```

### 3.13 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)]

```

### 3.14 Virtual Tree

```
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

```
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

```
// 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

```
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 Construct VC

```

vi cover(vector<vi>& g, int n, int m) {
    vi match(m, -1);
    int res = dfsMatching(g, match);
    vector<bool> lfound(n, true), seen(m);
    for (int it : match) if (it != -1) lfound[it] = false;
    vi q, cover;
    rep(i, 0, n) if (lfound[i]) q.push_back(i);
    while (!q.empty()) {
        int i = q.back(); q.pop_back();
        lfound[i] = 1;
        for (int e : g[i]) if (!seen[e] && match[e] != -1) {
            seen[e] = true;
            q.push_back(match[e]);
        }
    }
    rep(i, 0, n) if (!lfound[i]) cover.push_back(i);
    rep(i, 0, m) if (seen[i]) cover.push_back(n+i);
    assert(sz(cover) == res);
    return cover;
}

```

## 4.5 Flow Models

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

- For each vertex  $v$  with  $d(v) < 0$ , connect  $v \rightarrow T$  with  $(cost, cap) = (0, -d(v))$
- Flow from  $S$  to  $T$ , the answer is the cost of the flow  $C + K$

### Maximum density induced subgraph

- Binary search on answer, suppose we're checking answer  $T$
- Construct a max flow model, let  $K$  be the sum of all weights
- Connect source  $s \rightarrow v$ ,  $v \in G$  with capacity  $K$
- For each edge  $(u, v, w)$  in  $G$ , connect  $u \rightarrow v$  and  $v \rightarrow u$  with capacity  $w$
- For  $v \in G$ , connect it with sink  $v \rightarrow t$  with capacity  $K + 2T - (\sum_{e \in E(v)} w(e)) - 2w(v)$
- $T$  is a valid answer if the maximum flow  $f < K|V|$

### Minimum weight edge cover

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

### Project selection problem

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

### 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  $c_{xyx'y'}$ .

## 4.6 General Graph Matching

```

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;
}
}

```

## 4.7 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;
}
}

```

## 4.8 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;
}
}

```

## 4.9 Kuhn Munkres

```

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;

```

## 4.10 Minimum Cost Circulation

```

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;
                    }
                }
            }
        }
    }
    return upd;
}

```

```

        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;
}

```

## 4.11 Minimum Cost Maximum Flow

```

class MiniCostMaxiFlow{
    using Cap = int; using Wei = int64_t;
    using PCW = pair<Cap,Wei>;
    static constexpr Cap INF_CAP = 1 << 30;
    static constexpr Wei INF_WEI = 1LL<<60;
private:
    struct Edge{
        int to, back;
        Cap cap; Wei wei;
        Edge() {}
        Edge(int a,int b, Cap c, Wei d):
            to(a),back(b),cap(c),wei(d) {}
    };
    int ori, edd;
    vector<vector<Edge>> G;
    vector<int> fa, wh;
    vector<bool> inq;
    vector<Wei> dis;
    PCW SPFA(){
        fill(inq.begin(),inq.end(),false);
        fill(dis.begin(),dis.end(),INF_WEI);
        queue<int> qq; qq.push(ori);
        dis[ori] = 0;
        while(not qq.empty()){
            int u=qq.front();qq.pop();
            inq[u] = false;
            for(int i=0;i<SZ(G[u]);++i){
                Edge e=G[u][i];
                int v=e.to; Wei d=e.wei;
                if(e.cap<=0||dis[v]<=dis[u]+d)
                    continue;
                dis[v] = dis[u] + d;
                fa[v] = u, wh[v] = i;
                if (inq[v]) continue;
                qq.push(v);
                inq[v] = true;
            }
        }
        if(dis[edd]==INF_WEI) return {-1, -1};
        Cap mw=INF_CAP;
        for(int i=edd;i!=ori;i=fa[i])
            mw=min(mw,G[fa[i]][wh[i]].cap);
        for (int i=edd;i!=ori;i=fa[i]){
            auto &eg=G[fa[i]][wh[i]];
            eg.cap -= mw;

```

```

            G[eg.to][eg.back].cap+=mw;
        }
        return {mw, dis[edd]};
    }
public:
    void init(int n){
        G.clear();G.resize(n);
        fa.resize(n);wh.resize(n);
        inq.resize(n); dis.resize(n);
    }
    void add_edge(int st, int ed, Cap c, Wei w){
        G[st].emplace_back(ed,SZ(G[ed]),c,w);
        G[ed].emplace_back(st,SZ(G[st])-1,0,-w);
    }
    PCW solve(int a, int b){
        ori = a, edd = b;
        Cap cc=0; Wei ww=0;
        while(true){
            PCW ret=SPFA();
            if(ret.first==-1) break;
            cc+=ret.first;
            ww+=ret.first * ret.second;
        }
        return {cc,ww};
    }
} mcmf;

```

## 4.12 Maximum Weight Graph Matching

```

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

#### 5.1.1 Partition function

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

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

$n$	0	1	2	3	4	5	6	7	8	9	20	50	100
$p(n)$	1	1	2	3	5	7	11	15	22	30	627	$\sim 2e5$	$\sim 2e8$

#### 5.1.2 Divisor function

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

#### 5.1.3 Factorial

$n$	1	2	3	4	5	6	7	8	9	10
$n!$	1	2	6	24	120	720	5040	40320	362880	3628800
$n$	11	12	13	14	15	16	17			
$n!$	4.0e7	4.8e8	6.2e9	8.7e10	1.3e12	2.1e13	3.6e14			
$n$	20	25	30	40	50	100	150	171		
$n!$	2e18	2e25	3e32	8e47	3e64	9e157	6e262	>DBL_MAX		

#### 5.1.4 Binom Coef

$n$	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] + 1LL * 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

```

template<typename Int>
Int BSGS(Int x, Int y, Int M) {
    // x^a ≡ 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

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

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

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

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

## 5.11 Fast Fourier Transform

```

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;
}

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

```

// @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;
}
lld floor_sum(lld n, lld m, lld a, lld 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 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);
}

```

## 5.14 Miller Rabin

```

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(mpows(m % x, odd, x), x, t))
            return false;
    return true;
}

```

## 5.15 NTT

```

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);
        }
    }
};
NTT<2013265921, 31, 1048576> ntt;

```

## 5.16 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]);
}

```

## 5.17 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);
}

```

## 5.18 Pollard Rho

```

// 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;
    }
}

```

## 5.19 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 &rev() { 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();
}

Poly InvMod(int L) { // (to evaluate linear recursion)
    Poly R{1, 0}; // *this * R mod x^L = 1 (*this[0] == 1)
    for (int level = 0; (1 << level) < L; ++level) {
        Poly O = R.Mul(Poly(data(), min<int>(2 << level, size())));
        Poly Q(2 << level); Q[0] = 1;
        for (int j = (1 << level); j < (2 << level); ++j)
            Q[j] = modsub(mod, O[j]);
        R = R.Mul(Q).isz(4 << level);
    }
    return R.isz(L);
}

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}, 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 <> decltpe(Poly_t::ntt) Poly_t::ntt = {};

```

## 5.20 Quadratic residue

```

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 };
    }
};

int get_root(int n, int P) {
    if (P == 2 or n == 0) return n;
    if (qpow(n, (P - 1) / 2, P) != 1) return -1;
    auto check = [&](int x) {
        return qpow(x, (P - 1) / 2, P);
    };
    if (check(n) == P-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;
}

```

## 5.21 Simplex

```

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;
}

```

## 5.22 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

```
#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));
}
bool operator<(const P &a, const P &b) {
    return RE(a) != RE(b) ? RE(a) < RE(b) : IM(a) < IM(b);
}
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) {
    lld 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

```
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(lld p, lld 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;
    lld 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

```
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

```
// return the faces with pt indexes
int flag[MXN][MXN];
struct Point {
    ld x, y, z;
    Point operator * (const ld &b) const {
        return (Point){x*b, y*b, z*b};
    }
    Point operator * (const Point &b) const {
        return (Point){y*b.z - b.y*z, z*b.x - b.z*x, x*b.y - b.x*y};
    }
};
Point ver(Point a, Point b, Point c) {
    return (b - a) * (c - a);
}
vector<Face> convex_hull_3D(const vector<Point> pt) {
    int n = SZ(pt), ftop = 0;
    REP(i, n) REP(j, n) flag[i][j] = 0;
    vector<Face> now;
    now.emplace_back(0, 1, 2);
    now.emplace_back(2, 1, 0);
    for (int i = 3; i < n; i++) {
        ftop++; vector<Face> next;
        REP(j, SZ(now)) {
            Face& f = now[j]; int ff = 0;
            ld d = (pt[i] - pt[f.a]).dot(
                ver(pt[f.a], pt[f.b], pt[f.c]));
            if (d <= 0) next.push_back(f);
            if (d > 0) ff = ftop;
            else if (d < 0) ff = -ftop;
            flag[f.a][f.b] = flag[f.b][f.c] = flag[f.c][f.a] = ff;
        }
        REP(j, SZ(now)) {
            Face& f = now[j];
            if (flag[f.a][f.b] > 0 &&
                flag[f.a][f.b] != flag[f.b][f.a])
                next.emplace_back(f.a, f.b, i);
            if (flag[f.b][f.c] > 0 &&
                flag[f.b][f.c] != flag[f.c][f.b])
                next.emplace_back(f.b, f.c, i);
            if (flag[f.c][f.a] > 0 &&
                flag[f.c][f.a] != flag[f.a][f.c])
                next.emplace_back(f.c, f.a, i);
        }
        now = next;
    }
    return now;
}
```

### 6.5 2D Farthest Pair

```
// 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;
    llf 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 = dx + kx;
            if (m.find(nx) == m.end()) continue;
            auto& mm = m[nx];
            for (int dy = -2; dy <= 2; ++dy) {
                const lld ny = dy + ky;
                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

```
// 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]);
        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

```
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

```
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

```
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

```
// 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

```

#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;
        int 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])) {
            if (dnC || !above(P, V[a], V[c]))
                b = c;
            else
                a = c;
        } else {
            if (!dnC || !below(P, V[a], V[c]))
                a = c;
            else
                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;
            int 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])) {
                if (!dnC || !below(P, V[a], V[c]))
                    b = c;
                else
                    a = c;
            } else {

```

```

        if (dnC || !above(P, V[a], V[c]))
            a = c;
        else
            b = c;
    }
}

```

### 6.14 Convex Hulls Tangent

```

// 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) {
    int ix1, ix2; // search indices for polygons 1 and 2

    // first get the initial vertex on each polygon
    ix1 = Rtangent_PointPolyC(W[0], m, V); // right
    // tangent from W[0] to V
    ix2 = Ltangent_PointPolyC(V[ix1], n, W); // left
    // tangent from V[ix1] to W

    // ping-pong linear search until it stabilizes
    int done = false; // flag when done
    while (done == false) {
        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;
    return;
}

```

### 6.15 Tangent line of Two Circle

```

vector<Line>
tanline(const Circle &c1, const Circle &c2, int sign1){
    // sign1 = 1 for outer tang, -1 for inter 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;
}

```

### 6.16 Minimum Covering Circle

```

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;
}

```

## 6.17 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;

```

## 6.18 Rotating Sweep Line

```

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 || 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;
    }
}

```

## 6.19 Circle Cover

```

const int N = 1021;
struct CircleCover {
    int C;
    Cir c[N];
    bool g[N][N], overlap[N][N];
    // Area[i] : area covered by at least i circles
    double Area[ N ];
    void init(int _C){ C = _C; }
    struct Teve {
        PTF p; double ang; int add;
        Teve() {}
        Teve(PTF _a, double _b, int _c):p(_a), ang(_b), add(_c){}
    };
    bool operator<(const Teve &a) const {
        return ang < a.ang; }
    } eve[N * 2];
    // strict: x = 0, otherwise x = -1
    bool disjunct(Cir &a, Cir &b, int x)
    { return sign(abs(a.o - b.o) - a.R - b.R) > x; }
    bool contain(Cir &a, Cir &b, int x)
    { return sign(a.R - b.R - abs(a.o - b.o)) > x; }
    bool contain(int i, int j) {
        /* c[j] is non-strictly in c[i]. */
        return (sign(c[i].R - c[j].R) > 0 || (sign(c[i].R - c[j].R) == 0 && i < j)) && contain(c[i], c[j], -1);
    }
    void solve(){
        fill_n(Area, C + 2, 0);
        for(int i = 0; i < C; ++i)
            for(int j = 0; j < C; ++j)
                overlap[i][j] = contain(i, j);
        for(int i = 0; i < C; ++i)
            for(int j = 0; j < C; ++j)
                g[i][j] = !(overlap[i][j] || overlap[j][i] ||

```

```

    disjunct(c[i], c[j], -1));
for(int i = 0; i < C; ++i){
    int E = 0, cnt = 1;
    for(int j = 0; j < C; ++j)
        if(j != i && overlap[j][i])
            ++cnt;
    for(int j = 0; j < C; ++j)
        if(i != j && g[i][j]) {
            auto IP = intersectPoint(c[i], c[j]);
            PTF aa = IP[0], bb = IP[1];
            llf A = arg(aa-c[i].0), B = arg(bb-c[i].0);
            eve[E++] = Teve(bb,B,1), eve[E++] = Teve(aa,A,-1);
            if(B > A) ++cnt;
        }
    if(E == 0) Area[cnt] += pi * c[i].R * c[i].R;
    else{
        sort(eve, eve + E);
        eve[E] = eve[0];
        for(int j = 0; j < E; ++j){
            cnt += eve[j].add;
            Area[cnt] += cross(eve[j].p, eve[j + 1].p) * .5;
            double theta = eve[j + 1].ang - eve[j].ang;
            if (theta < 0) theta += 2. * pi;
            Area[cnt] += (theta - sin(theta)) * c[i].R * c[i].R * .5;
        }
    }
}
};

```

## 7 Stringology

### 7.1 Hash

```

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

```

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]]] = p[q[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

```

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;
                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[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 KMP

```

vector<int> kmp(const string &s) {
    vector<int> f(s.size(), 0);
    /* f[i] = length of the longest prefix
       (excluding s[0:i]) such that it coincides
       with the suffix of s[0:i] of the same length */
    /* i + 1 - f[i] is the length of the
       smallest recurring period of s[0:i] */
    int k = 0;
    for (int i = 1; i < (int)s.size(); ++i) {
        while (k > 0 && s[i] != s[k]) k = f[k - 1];
        if (s[i] == s[k]) ++k;
        f[i] = k;
    }
    return f;
}
vector<int> search(const string &s, const string &t) {
    // return 0-indexed occurrence of t in s
    vector<int> f = kmp(t), r;
    for (int i = 0, k = 0; i < (int)s.size(); ++i) {
        while (k > 0 && (k == (int)t.size() || s[i] != t[k]))
            k = f[k - 1];
        if (s[i] == t[k]) ++k;
        if (k == (int)t.size()) r.push_back(i - t.size() + 1);
    }
    return res;
}

```

## 7.5 Z value

```

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] = i;
    }
    return z;
}

```

## 7.6 Manacher

```

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;
}

```

## 7.7 Lexico Smallest Rotation

```

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);
}

```

## 7.8 Main Lorentz

```

vector<tuple<tuple<size_t, size_t, int, int>>> reps;
void find_repetitions(const string &s, int shift = 0) {
    if (s.size() <= 1)
        return;
    const size_t nu = s.size() / 2, nv = s.size() - nu;
    string u = s.substr(0, nu), v = s.substr(nu);
    string ru(u.rbegin(), u.rend());
    string rv(v.rbegin(), v.rend());
    find_repetitions(u, shift);
    find_repetitions(v, shift + nu);
    auto z1 = Zalgo(ru), z2 = Zalgo(v + '#' + u),
        z3 = Zalgo(ru + '#' + rv), z4 = Zalgo(v);
    for (size_t cntr = 0; cntr < s.size(); cntr++) {
        size_t l; int k1, k2;
        if (cntr < nu) {
            l = nu - cntr;
            k1 = l < z1.size() ? z1[l] : 0;
            k2 = n + 1 - l < z2.size() ? z2[n + 1 - l] : 0;
        } else {
            l = cntr - nu + 1;
            k1 = n + 1 - l < z3.size() ? z3[n + 1 - l] : 0;
            k2 = l < z4.size() ? z4[l] : 0;
        }
        if (k1 + k2 >= l)
            reps.emplace_back(cntr, l, k1, k2);
    }
}

```

## 7.9 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;

```

## 7.10 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  $T_{n,k} = kn^{n-k-1}$ .

#### 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

$$V - E + F = C + 1, E \leq 3V - 6(?)$$

### 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

```

struct L {
    mutable int64_t a, b, p;
    bool operator<(const L &r) const { return a < r.a; }
    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;
        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) {
        auto l = *lower_bound(x);
        return l.a * x + l.b;
    }
};

```

## 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

```

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;
}

```