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4.7 Directed MST	10	1.2 Default Code	
4.8 Dominator Tree	10	#include <bits/stdc++.h>	
		using namespace std;	
5 String	10	typedef long long ll;	
5.1 Aho-Corasick Automaton	10	#define pb push_back	
5.2 KMP Algorithm	11	#define pii pair<int, int>	
5.3 Z Algorithm	11	#define all(a) a.begin(), a.end()	
5.4 Manacher	11	#define sz(a) ((int)a.size())	
5.5 Suffix Array	11		
5.6 SAIS	11	1.3 Increase Stack Size	
5.7 Suffix Automaton	12	const int size = 256 << 20;	
5.8 Minimum Rotation	12	register long rsp asm("rsp");	
5.9 Palindrome Tree	12	char *p = (char*)malloc(size) + size, *bak = (char*)rsp	
5.10Main Lorentz	12	;	
6 Math	13	__asm__("movq %0, %%rsp\n"::"r"(p));	
6.1 Miller Rabin / Pollard Rho	13	// main	
6.2 Ext GCD	13	__asm__("movq %0, %%rsp\n"::"r"(bak));	
6.3 PiCount	13		
6.4 Linear Function Mod Min	13	1.4 Debug Macro	
6.5 Determinant	14	void db() {cout << endl;}	
6.6 Floor Sum	14	template <typename T, typename ...U> void db(T i, U ...	
6.7 Quadratic Residue	14	j) {	
6.8 Simplex	14	cout << i << ' ', db(j...);	
6.9 Berlekamp Massey	15	}	
6.10Linear Programming Construction	15	#define test(x...) db("[" + string(x) + "]", x)	
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7 Polynomial	16	char OB[65536]; int OP;	
7.1 Number Theoretic Transform	16	inline char RC() {	
7.2 Fast Fourier Transform	16	static char buf[65536], *p = buf, *q = buf;	
7.3 Primes	16	return p == q && (q = (p = buf) + read(0, buf, 65536)	
7.4 Polynomial Operations	16) == buf ? -1 : *p++;	
7.5 Fast Linear Recursion	18	}	
7.6 Fast Walsh Transform	18	inline int R() {	
8 Geometry	18	static char c;	
8.1 Basic	18	while((c = RC()) < '0'); int a = c ^ '0';	
8.2 Heart	18	while((c = RC()) >= '0') a *= 10, a += c ^ '0';	
8.3 External Bisector	19	return a;	
8.4 Intersection of Segments	19	}	
8.5 Intersection of Circle and Line	19	inline void W(int n) {	
8.6 Intersection of Circles	19	static char buf[12], p;	
8.7 Intersection of Polygon and Circle	19	if (n == 0) OB[OP++]='0'; p = 0;	
8.8 Tangent Lines of Circle and Point	19	while (n) buf[p++] = '0' + (n % 10), n /= 10;	
8.9 Tangent Lines of Circles	19	for (--p; p >= 0; --p) OB[OP++] = buf[p];	
8.10Point In Convex	19	if (OP > 65520) write(1, OB, OP), OP = 0;	
8.11Point Segment Distance	19	}	
8.12Convex Hull	19		
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8.14Minimum Enclosing Circle	20		
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1.6 Divide*

```

11 divdown(11 a, 11 b) {
    return a / b - (a < 0 && a % b);
}
11 divup(11 a, 11 b) {
    return a / b + (a > 0 && a % b);
}
a / b < x -> divdown(a, b) + 1 <= x
a / b <= x -> divup(a, b) <= x
x < a / b -> x <= divup(a, b) - 1
x <= a / b -> x <= divdown(a, b)

```

2 Data Structure

2.1 Leftist Tree

```

struct node {
    11 rk, data, sz, sum;
    node *l, *r;
    node(11 k) : rk(0), data(k), sz(1), l(0), r(0), sum(k) {}
};
11 sz(node *p) { return p ? p->sz : 0; }
11 rk(node *p) { return p ? p->rk : -1; }
11 sum(node *p) { return p ? p->sum : 0; }
node *merge(node *a, node *b) {
    if (!a || !b) return a ? a : b;
    if (a->data < b->data) swap(a, b);
    a->r = merge(a->r, b);
    if (rk(a->r) > rk(a->l)) swap(a->r, a->l);
    a->rk = rk(a->r) + 1, a->sz = sz(a->l) + sz(a->r) + 1;
    a->sum = sum(a->l) + sum(a->r) + a->data;
    return a;
}
void pop(node *&o) {
    node *tmp = o;
    o = merge(o->l, o->r);
    delete tmp;
}

```

2.2 Splay Tree

```

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

```

```

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

```

2.3 Link Cut Tree

```

// weighted subtree size, weighted path max
struct LCT {
    int ch[N][2], pa[N], v[N], sz[N], sz2[N], w[N], mx[N], _id;
    // sz := sum of v in splay, sz2 := sum of v in virtual subtree
    // mx := max w in splay
    bool rev[N];
    LCT() : _id(1) {}
    int newnode(int _v, int _w) {
        int x = _id++;
        ch[x][0] = ch[x][1] = pa[x] = 0;
        v[x] = sz[x] = _v;
        sz2[x] = 0;
        w[x] = mx[x] = _w;
        rev[x] = false;
        return x;
    }
    void pull(int i) {
        sz[i] = v[i] + sz2[i];
        mx[i] = w[i];
        if (ch[i][0])
            sz[i] += sz[ch[i][0]], mx[i] = max(mx[i], mx[ch[i][0]]);
        if (ch[i][1])
            sz[i] += sz[ch[i][1]], mx[i] = max(mx[i], mx[ch[i][1]]);
    }
    void push(int i) {
        if (rev[i]) reverse(ch[i][0]), reverse(ch[i][1]), rev[i] = false;
    }
    void reverse(int i) {
        if (!i) return;
        swap(ch[i][0], ch[i][1]);
        rev[i] ^= true;
    }
    bool isrt(int i) { // rt of splay
        if (!pa[i]) return true;
        return ch[pa[i]][0] != i && ch[pa[i]][1] != i;
    }
    void rotate(int i) {
        int p = pa[i], x = ch[p][1] == i, c = ch[i][!x], gp = pa[p];
        if (ch[gp][0] == p) ch[gp][0] = i;
        else if (ch[gp][1] == p) ch[gp][1] = i;
        pa[i] = gp, ch[i][!x] = p, pa[p] = i;
        ch[p][x] = c, pa[c] = p;

```

```

    pull(p), pull(i);
}
void splay(int i) {
    vector<int> anc;
    anc.push_back(i);
    while (!isrt(anc.back())) anc.push_back(pa[anc.back()]);
    while (!anc.empty()) push(anc.back()), anc.pop_back();
    while (!isrt(i)) {
        int p = pa[i];
        if (!isrt(p)) rotate(ch[p][1] == i ^ ch[pa[p]][1] == p ? i : p);
        rotate(i);
    }
}
void access(int i) {
    int last = 0;
    while (i) {
        splay(i);
        if (ch[i][1])
            sz2[i] += sz[ch[i][1]];
        sz2[i] -= sz[last];
        ch[i][1] = last;
        pull(i), last = i, i = pa[i];
    }
}
void makert(int i) {
    access(i), splay(i), reverse(i);
}
void link(int i, int j) {
    // assert(findrt(i) != findrt(j));
    makert(i);
    makert(j);
    pa[i] = j;
    sz2[j] += sz[i];
    pull(j);
}
void cut(int i, int j) {
    makert(i), access(j), splay(i);
    // assert(sz[i] == 2 && ch[i][1] == j);
    ch[i][1] = pa[j] = 0, pull(i);
}
int findrt(int i) {
    access(i), splay(i);
    while (ch[i][0]) push(i), i = ch[i][0];
    splay(i);
    return i;
}
};

```

2.4 Treap

```

struct node {
    int data, sz;
    node *l, *r;
    node(int k) : data(k), sz(1), l(0), r(0) {}
    void up() {
        sz = 1;
        if (l) sz += l->sz;
        if (r) sz += r->sz;
    }
    void down() {}
};
// delete default code sz
int sz(node *a) { return a ? a->sz : 0; }
node *merge(node *a, node *b) {
    if (!a || !b) return a ? a : b;
    if (rand() % (sz(a) + sz(b)) < sz(a))
        return a->down(), a->r = merge(a->r, b), a->up(), a;
    return b->down(), b->l = merge(a, b->l), b->up(), b;
}
void split(node *o, node *&a, node *&b, int k) {
    if (!o) return a = b = 0, void();
    o->down();
    if (o->data <= k)
        a = o, split(o->r, a->r, b, k), a->up();
    else b = o, split(o->l, a, b->l, k), b->up();
}
void split2(node *o, node *&a, node *&b, int k) {
    if (sz(o) <= k) return a = o, b = 0, void();
}

```

```

    o->down();
    if (sz(o->l) + 1 <= k)
        a = o, split2(o->r, a->r, b, k - sz(o->l) - 1);
    else b = o, split2(o->l, a, b->l, k);
    o->up();
}
node *kth(node *o, int k) {
    if (k <= sz(o->l)) return kth(o->l, k);
    if (k == sz(o->l) + 1) return o;
    return kth(o->r, k - sz(o->l) - 1);
}
int Rank(node *o, int key) {
    if (!o) return 0;
    if (o->data < key)
        return sz(o->l) + 1 + Rank(o->r, key);
    else return Rank(o->l, key);
}
bool erase(node *&o, int k) {
    if (!o) return 0;
    if (o->data == k) {
        node *t = o;
        o->down(), o = merge(o->l, o->r);
        delete t;
        return 1;
    }
    node *&t = k < o->data ? o->l : o->r;
    return erase(t, k) ? o->up(), 1 : 0;
}
void insert(node *&o, int k) {
    node *a, *b;
    o->down(), split(o, a, b, k);
    o = merge(a, merge(new node(k), b));
    o->up();
}
void interval(node *&o, int l, int r) {
    node *a, *b, *c; // [l, r)
    o->down();
    split2(o, a, b, l), split2(b, b, c, r - l);
    // operate
    o = merge(a, merge(b, c)), o->up();
}

```

2.5 2D Segment Tree*

```

// 2D range add, range sum in  $\log^2$ 
struct seg {
    int l, r;
    ll sum, lz;
    seg *ch[2]{};
    seg(int _l, int _r) : l(_l), r(_r), sum(0), lz(0) {}
    void push() {
        if (lz) ch[0]->add(l, r, lz), ch[1]->add(l, r, lz),
            lz = 0;
    }
    void pull() { sum = ch[0]->sum + ch[1]->sum; }
    void add(int _l, int _r, ll d) {
        if (_l <= l && r <= _r) {
            sum += d * (r - l + 1);
            lz += d;
            return;
        }
        if (!ch[0]) ch[0] = new seg(l, l + r >> 1), ch[1] =
            new seg(l + r >> 1, r);
        push();
        if (_l < l + r >> 1) ch[0]->add(_l, _r, d);
        if (l + r >> 1 < _r) ch[1]->add(_l, _r, d);
        pull();
    }
    ll qsum(int _l, int _r) {
        if (_l <= l && r <= _r) return sum;
        if (!ch[0]) return lz * (min(r, _r) - max(l, _l) + 1);
        push();
        ll res = 0;
        if (_l < l + r >> 1) res += ch[0]->qsum(_l, _r);
        if (l + r >> 1 < _r) res += ch[1]->qsum(_l, _r);
        return res;
    }
};
struct seg2 {
    int l, r;
    seg v, lz;
    seg2 *ch[2]{};
}

```

```

seg2(int _l, int _r) : l(_l), r(_r), v(0, N), lz(0, N)
{
    if (1 < r - 1) ch[0] = new seg2(1, 1 + r >> 1), ch
        [1] = new seg2(1 + r >> 1, r);
}
void add(int _l, int _r, int _l2, int _r2, ll d) {
    v.add(_l2, _r2, d * (min(r, _r) - max(1, _l)));
    if (_l <= 1 && r <= _r) {
        lz.add(_l2, _r2, d);
        return;
    }
    if (_l < 1 + r >> 1) ch[0]->add(_l, _r, _l2, _r2, d);
    if (1 + r >> 1 < _r) ch[1]->add(_l, _r, _l2, _r2, d);
}
ll qsum(int _l, int _r, int _l2, int _r2) {
    if (_l <= 1 && r <= _r) return v.qsum(_l2, _r2);
    ll res = lz.qsum(_l2, _r2) * (min(r, _r) - max(1,
        _l));
    if (_l < 1 + r >> 1) res += ch[0]->qsum(_l, _r, _l2,
        _r2);
    if (1 + r >> 1 < _r) res += ch[1]->qsum(_l, _r, _l2,
        _r2);
    return res;
}
};

```

2.6 Range Set*

```

struct RangeSet { // [L, r)
    set<pii> S;
    void cut(int x) {
        auto it = S.lower_bound({x + 1, -1});
        if (it == S.begin()) return;
        auto [l, r] = *prev(it);
        if (1 >= x || x >= r) return;
        S.erase(prev(it));
        S.insert({l, x});
        S.insert({x, r});
    }
    vector<pii> split(int l, int r) {
        // remove and return ranges in [L, r)
        cut(l), cut(r);
        vector<pii> res;
        while (true) {
            auto it = S.lower_bound({l, -1});
            if (it == S.end() || r <= it->first) break;
            res.pb(*it), S.erase(it);
        }
        return res;
    }
    void insert(int l, int r) {
        // add a range [L, r), [L, r) not in S
        auto it = S.lower_bound({l, r});
        if (it != S.begin() && prev(it)->second == l)
            l = prev(it)->first, S.erase(prev(it));
        if (it != S.end() && r == it->first)
            r = it->second, S.erase(it);
        S.insert({l, r});
    }
    bool count(int x) {
        auto it = S.lower_bound({x + 1, -1});
        return it != S.begin() && prev(it)->first <= x && x
            < prev(it)->second;
    }
};

```

2.7 vEB Tree*

```

using u64=uint64_t;
constexpr int lsb(u64 x){return x?__builtin_ctzll(x)
    :1<<30;}
constexpr int msb(u64 x){return x?63-__builtin_clzll(x)
    :-1;}
template<int N, class T=void>
struct veb{
    static const int M=N>>1;
    veb<M> ch[1<<N-M];
    veb<N-M> aux;
    int mn,mx;
    veb():mn(1<<30),mx(-1){}

```

```

constexpr int mask(int x){return x&((1<<M)-1);}
bool empty(){return mx==-1;}
int min(){return mn;}
int max(){return mx;}
bool have(int x){
    if(x==mn) return true;
    return ch[x>>M].have(mask(x));
}
void insert_in(int x){
    if(empty()) return mn=mx=x,void();
    if(x<mn) swap(x,mn);
    if(x>mx) mx=x;
    if(ch[x>>M].empty()) aux.insert_in(x>>M);
    ch[x>>M].insert_in(mask(x));
}
void erase_in(int x){
    if(mn==mx) return mn=1<<30,mx=-1,void();
    if(x==mn) mn=x=(aux.min()<<M)^ch[aux.min()].min();
    ch[x>>M].erase_in(mask(x));
    if(ch[x>>M].empty()) aux.erase_in(x>>M);
    if(x==mx){
        if(aux.empty()) mx=mn;
        else mx=(aux.max()<<M)^ch[aux.max()].max();
    }
}
void insert(int x){
    if(have(x)) return;
    insert_in(x);
}
void erase(int x){
    if(!have(x)) return;
    erase_in(x);
}
int next(int x){// >=x
    if(x>mx) return 1<<30;
    if(x<mn) return mn;
    if(mask(x)<=ch[x>>M].max()) return ((x>>M)<<M)^ch[x
        >>M].next(mask(x));
    int y=aux.next((x>>M)+1);
    return (y<<M)^ch[y].min();
}
int prev(int x){// <x
    if(x<mn) return -1;
    if(x>mx) return mx;
    if(x<=(aux.min()<<M)+ch[aux.min()].min()) return mn
        ;
    if(mask(x)>ch[x>>M].min()) return ((x>>M)<<M)^ch[x
        >>M].prev(mask(x));
    int y=aux.prev(x>>M);
    return (y<<M)^ch[y].max();
}
};
template<int N>
struct veb<N,typename enable_if<N<=6>::type>{
    u64 a;
    veb():a(0){}
    void insert_in(int x){a|=1ull<<x;}
    void insert(int x){a|=1ull<<x;}
    void erase_in(int x){a&=~(1ull<<x);}
    void erase(int x){a&=~(1ull<<x);}
    bool have(int x){return a>>x&1;}
    bool empty(){return a==0;}
    int min(){return lsb(a);}
    int max(){return msb(a);}
    int next(int x){return lsb(a&~((1ull<<x)-1));}
    int prev(int x){return msb(a&((1ull<<x)-1));}
};

```

3 Flow / Matching

3.1 Dinic

```

const ll INF = 1ll << 60;
template<typename T>
struct Dinic { // 0-base
    struct edge {
        int to, rev;
        T cap, flow;
    };
    vector<edge> adj[N];
    int s, t, dis[N], cur[N], n;

```

```

T dfs(int u, T cap) {
    if (u == t || !cap) return cap;
    for (int &i = cur[u]; i < (int)adj[u].size(); ++i)
    {
        edge &e = adj[u][i];
        if (dis[e.to] == dis[u] + 1 && e.flow != e.cap) {
            T df = dfs(e.to, min(e.cap - e.flow, cap));
            if (df) {
                e.flow += df;
                adj[e.to][e.rev].flow -= df;
                return df;
            }
        }
    }
    dis[u] = -1;
    return 0;
}

bool bfs() {
    fill_n(dis, n, -1);
    queue<int> q;
    q.push(s), dis[s] = 0;
    while (!q.empty()) {
        int tmp = q.front();
        q.pop();
        for (auto &u : adj[tmp])
            if (!dis[u.to] && u.flow != u.cap) {
                q.push(u.to);
                dis[u.to] = dis[tmp] + 1;
            }
    }
    return dis[t] != -1;
}

T solve(int _s, int _t) {
    s = _s, t = _t;
    T flow = 0, df;
    while (bfs()) {
        fill_n(cur, n, 0);
        while ((df = dfs(s, INF))) flow += df;
    }
    return flow;
}

void init(int _n) {
    n = _n;
    for (int i = 0; i < n; ++i) adj[i].clear();
}

void reset() {
    for (int i = 0; i < n; ++i)
        for (auto &j : adj[i]) j.flow = 0;
}

void add_edge(int u, int v, T cap) {
    adj[u].pb(edge{v, (int)adj[v].size(), cap, 0});
    adj[v].pb(edge{u, (int)adj[u].size() - 1, 0, 0});
}
};

```

3.2 Min Cost Max Flow

```

template <typename T1, typename T2>
struct MCMF { // T1 -> flow, T2 -> cost, 0-based
    const T1 INF1 = 1 << 30;
    const T2 INF2 = 1 << 30;
    struct edge {
        int v; T1 f; T2 c;
    } E[M << 1];
    vector<int> adj[N];
    T2 dis[N], pot[N];
    int rt[N], vis[N], n, m, s, t;
    bool SPFA() {
        fill_n(rt, n, -1), fill_n(dis, n, INF2);
        fill_n(vis, n, false);
        queue<int> q;
        q.push(s), dis[s] = 0, vis[s] = true;
        while (!q.empty()) {
            int v = q.front(); q.pop();
            vis[v] = false;
            for (int id : adj[v]) if (E[id].f > 0 && dis[E[id].v] > dis[v] + E[id].c + pot[v] - pot[E[id].v]) {
                dis[E[id].v] = dis[v] + E[id].c + pot[v] - pot[E[id].v];
                E[id].v, rt[E[id].v] = id;
                if (!vis[E[id].v]) vis[E[id].v] = true, q.push(E[id].v);
            }
        }
    }
};

```

```

    }
}
return dis[t] != INF2;
}

bool dijkstra() {
    fill_n(rt, n, -1), fill_n(dis, n, INF2);
    priority_queue<pair<T2, int>, vector<pair<T2, int>>, greater<pair<T2, int>>> pq;
    dis[s] = 0, pq.emplace(dis[s], s);
    while (!pq.empty()) {
        auto [d, v] = pq.top(); pq.pop();
        if (dis[v] < d) continue;
        for (int id : adj[v]) if (E[id].f > 0 && dis[E[id].v] > dis[v] + E[id].c + pot[v] - pot[E[id].v]) {
            dis[E[id].v] = dis[v] + E[id].c + pot[v] - pot[E[id].v];
            E[id].v, rt[E[id].v] = id;
            pq.emplace(dis[E[id].v], E[id].v);
        }
    }
    return dis[t] != INF2;
}

pair<T1, T2> solve(int _s, int _t) {
    s = _s, t = _t, fill_n(pot, n, 0);
    T1 flow = 0; T2 cost = 0;
    bool fr = true;
    while ((fr ? SPFA() : dijkstra())) {
        for (int i = 0; i < n; ++i) {
            dis[i] += pot[i] - pot[s];
        }
        T1 add = INF1;
        for (int i = t; i != s; i = E[rt[i] ^ 1].v) {
            add = min(add, E[rt[i]].f);
        }
        for (int i = t; i != s; i = E[rt[i] ^ 1].v) {
            E[rt[i]].f -= add, E[rt[i] ^ 1].f += add;
        }
        flow += add, cost += add * dis[t];
        fr = false;
        for (int i = 0; i < n; ++i) swap(dis[i], pot[i]);
    }
    return make_pair(flow, cost);
}

void init(int _n) {
    n = _n, m = 0;
    for (int i = 0; i < n; ++i) adj[i].clear();
}

void reset() {
    for (int i = 0; i < m; ++i) E[i].f = 0;
}

void add_edge(int u, int v, T1 f, T2 c) {
    adj[u].pb(m), E[m++] = {v, f, c};
    adj[v].pb(m), E[m++] = {u, 0, -c};
}
};

```

3.3 Kuhn Munkres

```

template <typename T>
struct KM { // 0-based
    T w[N][N], hl[N], hr[N], slk[N];
    T fl[N], fr[N], pre[N]; int n;
    bool vl[N], vr[N];
    const T INF = 1e9;
    queue<int> q;
    KM(int _n) : n(_n) {
        for (int i = 0; i < n; ++i) for (int j = 0; j < n; ++j)
            w[i][j] = -INF;
    }
    void add_edge(int a, int b, int wei) {
        w[a][b] = wei;
    }
    bool check(int x) {
        if (vl[x] = 1, ~fl[x]) return q.push(fl[x]), vr[fl[x]] = 1;
        while (~x) swap(x, fr[fl[x] = pre[x]]);
        return 0;
    }
    void bfs(int s) {
        fill(slk, slk + n, INF), fill(vl, vl + n, 0), fill(vr, vr + n, 0);
    }
};

```

```

q.push(s), vr[s] = 1;
while (1) {
    T d;
    while (!q.empty()) {
        int y = q.front(); q.pop();
        for (int x = 0; x < n; ++x)
            if (!vl[x] && slk[x] >= (d = hl[x] + hr[y] - w[x][y]))
                if (pre[x] = y, d) slk[x] = d;
                else if (!check(x)) return;
    }
    d = INF;
    for (int x = 0; x < n; ++x)
        if (!vl[x] && d > slk[x]) d = slk[x];
    for (int x = 0; x < n; ++x) {
        if (vl[x]) hl[x] += d;
        else slk[x] -= d;
        if (vr[x]) hr[x] -= d;
    }
    for (int x = 0; x < n; ++x) if (!vl[x] && !slk[x] && !check(x)) return;
}
}
T solve() {
    fill(fl, fl + n, -1), fill(fr, fr + n, -1), fill(hr, hr + n, 0);
    for (int i = 0; i < n; ++i) hl[i] = *max_element(w[i], w[i] + n);
    for (int i = 0; i < n; ++i) bfs(i);
    T res = 0;
    for (int i = 0; i < n; ++i) res += w[i][fl[i]];
    return res;
}
};

```

3.4 SW Min Cut

```

template <typename T>
struct SW { // 0-based
    T g[N][N], sum[N]; int n;
    bool vis[N], dead[N];
    void init(int _n) {
        n = _n;
        for (int i = 0; i < n; ++i) fill(g[i], g[i] + n, 0);
        fill(dead, dead + n, false);
    }
    void add_edge(int u, int v, T w) {
        g[u][v] += w, g[v][u] += w;
    }
    T solve() {
        T ans = 1 << 30;
        for (int round = 0; round + 1 < n; ++round) {
            fill(vis, vis + n, false), fill(sum, sum + n, 0);
            int num = 0, s = -1, t = -1;
            while (num < n - round) {
                int now = -1;
                for (int i = 0; i < n; ++i) if (!vis[i] && !dead[i]) {
                    if (now == -1 || sum[now] < sum[i]) now = i;
                }
                s = t, t = now;
                vis[now] = true, num++;
                for (int i = 0; i < n; ++i) if (!vis[i] && !dead[i]) {
                    sum[i] += g[now][i];
                }
            }
            ans = min(ans, sum[t]);
            for (int i = 0; i < n; ++i) {
                g[i][s] += g[i][t];
                g[s][i] += g[t][i];
            }
            dead[t] = true;
        }
        return ans;
    }
};

```

3.5 Gomory Hu Tree

```

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

```

3.6 Blossom

```

struct Matching { // 0-based
    int fa[N], pre[N], match[N], s[N], v[N], n, tk;
    vector <int> g[N];
    queue <int> q;
    Matching(int _n) : n(_n), tk(0) {
        for (int i = 0; i <= n; ++i) match[i] = pre[i] = n;
        for (int i = 0; i < n; ++i) g[i].clear();
    }
    void add_edge(int u, int v) {
        g[u].push_back(v), g[v].push_back(u);
    }
    int Find(int u) {
        return u == fa[u] ? u : fa[u] = Find(fa[u]);
    }
    int lca(int x, int y) {
        tk++;
        x = Find(x), y = Find(y);
        for (; ; swap(x, y)) {
            if (x != n) {
                if (v[x] == tk) return x;
                v[x] = tk;
                x = Find(pre[match[x]]);
            }
        }
    }
    void blossom(int x, int y, int l) {
        while (Find(x) != l) {
            pre[x] = y, y = match[x];
            if (s[y] == 1) q.push(y), s[y] = 0;
            if (fa[x] == x) fa[x] = l;
            if (fa[y] == y) fa[y] = l;
            x = pre[y];
        }
    }
    bool bfs(int r) {
        for (int i = 0; i <= n; ++i) fa[i] = i, s[i] = -1;
        while (!q.empty()) q.pop();
        q.push(r);
        s[r] = 0;
        while (!q.empty()) {
            int x = q.front(); q.pop();
            for (int u : g[x]) {
                if (s[u] == -1) {
                    pre[u] = x, s[u] = 1;
                    if (match[u] == n) {
                        for (int a = u, b = x, last; b != n; a = last, b = pre[a])
                            last = match[b], match[b] = a, match[a] = b;
                        return true;
                    }
                }
                q.push(match[u]);
                s[match[u]] = 0;
            }
            else if (!s[u] && Find(u) != Find(x)) {
                int l = lca(u, x);
                blossom(x, u, l);
                blossom(u, x, l);
            }
        }
        return false;
    }
};

```



```

}
int solve() {
    int res = 0;
    for (int x = 0; x < n; ++x) {
        if (match[x] == n) res += bfs(x);
    }
    return res;
}
};

```

3.7 Weighted Blossom

```

struct WeightGraph { // 1-based
    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);
}
};

```

3.8 Flow Model

- Maximum/Minimum flow with lower bound / Circulation problem
 - Construct super source S and sink T .
 - For each edge (x, y, l, u) , connect $x \rightarrow y$ with capacity $u - l$.
 - For each vertex v , denote by $in(v)$ the difference between the sum of incoming lower bounds and the sum of outgoing lower bounds.
 - If $in(v) > 0$, connect $S \rightarrow v$ with capacity $in(v)$, otherwise, connect $v \rightarrow T$ with capacity $-in(v)$.

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

5. The solution of each edge e is $l_e + f_e$, where f_e corresponds to the flow of edge e on the graph.

- Construct minimum vertex cover from maximum matching M on bipartite graph (X, Y)
 - Redirect every edge: $y \rightarrow x$ if $(x, y) \in M$, $x \rightarrow y$ otherwise.
 - DFS from unmatched vertices in X .
 - $x \in X$ is chosen iff x is unvisited.
 - $y \in Y$ is chosen iff y is visited.
- Maximum density induced subgraph
 - Binary search on answer, suppose we're checking answer T
 - Construct a max flow model, let K be the sum of all weights
 - Connect source $s \rightarrow v$, $v \in G$ with capacity K
 - For each edge (u, v, w) in G , connect $u \rightarrow v$ and $v \rightarrow u$ with capacity w
 - For $v \in G$, connect it with sink $v \rightarrow t$ with capacity $K + 2T - (\sum_{e \in E(v)} w(e)) - 2w(v)$
 - T is a valid answer if the maximum flow $f < K|V|$
- Minimum weight edge cover
 - For each $v \in V$ create a copy v' , and connect $u' \rightarrow v'$ with weight $w(u, v)$.
 - Connect $v \rightarrow v'$ with weight $2\mu(v)$, where $\mu(v)$ is the cost of the cheapest edge incident to v .
 - Find the minimum weight perfect matching on G' .
- Project selection problem
 - If $p_v > 0$, create edge (s, v) with capacity p_v ; otherwise, create edge (v, t) with capacity $-p_v$.
 - Create edge (u, v) with capacity w with w being the cost of choosing u without choosing v .
 - The mincut is equivalent to the maximum profit of a subset of projects.
- 0/1 quadratic programming

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

can be minimized by the mincut of the following graph:

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

4 Graph

4.1 Heavy-Light Decomposition

```

vector<int> g[N];
int dep[N], pa[N], sz[N], ch[N], hd[N], id[N], _id;
void dfs(int i, int p) {
    dep[i] = ~p ? dep[p] + 1 : 0;
    pa[i] = p, sz[i] = 1, ch[i] = -1;
    for (int j : g[i]) if (j != p) {
        dfs(j, i);
        if (ch[i] == -1 || sz[ch[i]] < sz[j]) ch[i] = j;
        sz[i] += sz[j];
    }
}
void hld(int i, int p, int h) {
    hd[i] = h;
    id[i] = _id++;
    if (~ch[i]) hld(ch[i], i, h);
    for (int j : g[i]) if (j != p && j != ch[i])
        hld(j, i, j);
}
void query(int i, int j) {
    // query2 -> [l, r)
    while (hd[i] != hd[j]) {
        if (dep[hd[i]] < dep[hd[j]]) swap(i, j);
        query2(id[hd[i]], id[i] + 1, i = pa[hd[i]]);
    }
    if (dep[i] < dep[j]) swap(i, j);
    query2(id[j], id[i] + 1);
}

```

4.2 Centroid Decomposition


```

vector <int> g[N];
int dis[N][logN], pa[N], sz[N], dep[N];
bool vis[N];
void dfs_sz(int i, int p) {
    sz[i] = 1;
    for (int j : g[i]) if (j != p && !vis[j])
        dfs_sz(j, i), sz[i] += sz[j];
}
int cen(int i, int p, int _n) {
    for (int j : g[i]) if (j != p && !vis[j] && sz[j] >
        _n / 2)
        return cen(j, i, _n);
    return i;
}
void dfs_dis(int i, int p, int d) {
    // from i to ancestor with depth d
    dis[i][d] = ~p ? dis[p][d] + 1 : 0;
    for (int j : g[i]) if (j != p && !vis[j])
        dfs_dis(j, i, d);
}
void cd(int i, int p, int d) {
    dfs_sz(i, -1), i = cen(i, -1, sz[i]);
    vis[i] = true, pa[i] = p, dep[i] = d;
    dfs_dis(i, -1, d);
    for (int j : g[i]) if (!vis[j])
        cd(j, i, d + 1);
}
}

```

4.3 Edge BCC

```

vector <int> g[N], _g[N];
// Notice Multiple Edges
int pa[N], low[N], dep[N], bcc_id[N], _id;
vector <int> stk, bcc[N];
bool vis[N], is_bridge[N];
void dfs(int i, int p = -1) {
    low[i] = dep[i] = ~p ? dep[p] + 1 : 0;
    stk.pb(i), pa[i] = p, vis[i] = true;
    for (int j : g[i]) if (j != p) {
        if (!vis[j])
            dfs(j, i), low[i] = min(low[i], low[j]);
        else
            low[i] = min(low[i], dep[j]);
    }
    if (low[i] == dep[i]) {
        if (~p) is_bridge[i] = true; // (i, pa[i])
        int id = _id++, x;
        do {
            x = stk.back(), stk.pop_back();
            bcc_id[x] = id, bcc[id].pb(x);
        } while (x != i);
    }
}
void build(int n) {
    for (int i = 0; i < n; ++i) if (!vis[i])
        dfs(i);
    for (int i = 0; i < n; ++i) if (is_bridge[i]) {
        int u = bcc_id[i], v = bcc_id[pa[i]];
        _g[u].pb(v), _g[v].pb(u);
    }
}
}

```

4.4 Vertex BCC / Round Square Tree

```

vector <int> g[N], _g[N << 1];
// _g: index >= N: bcc, index < N: original vertex
int pa[N], dep[N], low[N], _id;
bool vis[N];
vector <int> stk;
void dfs(int i, int p = -1) {
    dep[i] = low[i] = ~p ? dep[p] + 1 : 0;
    stk.pb(i), pa[i] = p, vis[i] = true;
    for (int j : g[i]) if (j != p) {
        if (!vis[j]) {
            dfs(j, i), low[i] = min(low[i], low[j]);
            if (low[j] >= dep[i]) {
                int id = _id++, x;
                do {
                    x = stk.back(), stk.pop_back();
                    _g[id + N].pb(x), _g[x].pb(id + N);
                } while (x != j);
                _g[id + N].pb(i), _g[i].pb(id + N);
            }
        }
    }
}
}

```

```

    }
    } else low[i] = min(low[i], dep[j]);
}
}
bool is_cut(int x) {return _g[x].size() != 1;}
vector <int> bcc(int x) {return _g[x + N];}
int pa2[N << 1], dep2[N << 1];
void dfs2(int i, int p = -1) {
    dep2[i] = ~p ? dep2[p] + 1 : 0, pa2[i] = p;
    for (int j : _g[i]) if (j != p) {
        dfs2(j, i);
    }
}
int bcc_id(int u, int v) {
    if (dep2[u] < dep2[v]) swap(u, v);
    return pa2[u] - N;
}
void build(int n) {
    for (int i = 0; i < n; ++i) if (!vis[i])
        dfs(i), dfs2(i);
}
}

```

4.5 SCC / 2SAT

```

struct SAT {
    vector <int> g[N << 1], stk;
    int dep[N << 1], low[N << 1], scc_id[N << 1];
    int n, _id, _t;
    bool is[N];
    SAT() {}
    void init(int _n) {
        n = _n, _id = _t = 0;
        for (int i = 0; i < 2 * n; ++i)
            g[i].clear(), dep[i] = scc_id[i] = -1;
        stk.clear();
    }
    void add_edge(int x, int y) {g[x].push_back(y);}
    int rev(int i) {return i < n ? i + n : i - n;}
    void add_ifthen(int x, int y) {add_clause(rev(x), y);}
    void add_clause(int x, int y) {
        add_edge(rev(x), y);
        add_edge(rev(y), x);
    }
    void dfs(int i) {
        dep[i] = low[i] = _t++, stk.pb(i);
        for (int j : g[i]) if (scc_id[j] == -1) {
            if (dep[j] == -1) dfs(j);
            low[i] = min(low[i], low[j]);
        }
        if (low[i] == dep[i]) {
            int id = _id++, x;
            do {
                x = stk.back(), stk.pop_back();
                scc_id[x] = id;
            } while (x != i);
        }
    }
    bool solve() {
        // is[i] = true -> i, is[i] = false -> -i
        for (int i = 0; i < 2 * n; ++i) if (dep[i] == -1)
            dfs(i);
        for (int i = 0; i < n; ++i) {
            if (scc_id[i] == scc_id[i + n]) return false;
            if (scc_id[i] < scc_id[i + n]) is[i] = true;
            else is[i] = false;
        }
        return true;
    }
}
}

```

4.6 Virtual Tree

```

vector <int> _g[N], stk;
int st[N], ed[N];
void solve(vector <int> v) {
    sort(all(v), [&](int x, int y) {return st[x] < st[y];});
    int sz = v.size();
    for (int i = 0; i < sz - 1; ++i)
        v.push_back(lca(v[i], v[i + 1]));
    sort(all(v), [&](int x, int y) {return st[x] < st[y];});
}

```

```

v.resize(unique(all(v)) - v.begin());
stk.clear(), stk.push_back(v[0]);
for (int i = 1; i < v.size(); ++i) {
    int x = v[i];
    while (ed[stk.back()] < ed[x]) stk.pop_back();
    _g[stk.back()].pb(x), stk.pb(x);
}
// do something
for (int i : v) _g[i].clear();
}

```

4.7 Directed MST

```

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

```

4.8 Dominator Tree

```

struct Dominator_tree {
    int n, id, sdom[N], dom[N];
    vector<int> adj[N], radj[N], bucket[N];
    int vis[N], rev[N], pa[N], rt[N], mn[N], res[N];
};

```

```

// dom[s] = s, dom[v] = -1 if s -> v not exists
Dominator_tree () {}
void init(int _n) {
    n = _n, id = 0;
    fill_n(dom, n, -1), fill_n(vis, n, -1);
}
void add_edge(int u, int v) {adj[u].pb(v);}
int query(int v, int x) {
    if (rt[v] == v) return x ? -1 : v;
    int p = query(rt[v], 1);
    if (p == -1) return x ? rt[v] : mn[v];
    if (sdom[mn[v]] > sdom[mn[rt[v]]])
        mn[v] = mn[rt[v]];
    rt[v] = p;
    return x ? p : mn[v];
}
void dfs(int v) {
    vis[v] = id, rev[id] = v;
    rt[id] = mn[id] = sdom[id] = id, id++;
    for (int u : adj[v]) {
        if (vis[u] == -1) dfs(u), pa[vis[u]] = vis[v];
        radj[vis[u]].pb(vis[v]);
    }
}
void build(int s) {
    dfs(s);
    for (int i = id - 1; ~i; --i) {
        for (int u : radj[i]) {
            sdom[i] = min(sdom[i], sdom[query(u, 0)]);
        }
        if (i) bucket[sdom[i]].pb(i);
        for (int u : bucket[i]) {
            int p = query(u, 0);
            dom[u] = sdom[p] == i ? i : p;
        }
        if (i) rt[i] = pa[i];
    }
    fill_n(res, n, -1);
    for (int i = 1; i < id; ++i) {
        if (dom[i] != sdom[i]) dom[i] = dom[dom[i]];
    }
    for (int i = 1; i < id; ++i)
        res[rev[i]] = rev[dom[i]];
    res[s] = s;
    for (int i = 0; i < n; ++i) dom[i] = res[i];
}
};

```

5 String

5.1 Aho-Corasick Automaton

```

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

```

```

    while (k && !ch[k][i]) k = fail[k];
    if (ch[k][i]) k = ch[k][i];
    fail[u] = k;
    cnt[u] += cnt[k], g[k].push_back(u);
    q.push(u);
}
}
int match(string &s) {
    int now = 0, ans = 0;
    for (char c : s) {
        now = to[now][c - 'a'];
        if (ch[now][c - 'a']) now = ch[now][c - 'a'];
        ans += cnt[now];
    }
    return ans;
}
};

```

5.2 KMP Algorithm

```

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

```

5.3 Z Algorithm

```

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

```

5.4 Manacher

```

// return value only consider string tmp, not s
vector<int> manacher(string tmp) {
    string s = "&";
    for (char c : tmp) s.pb(c), s.pb('%');
    int l = 0, r = 0, n = s.size();
    vector<int> Z(n);
    for (int i = 0; i < n; ++i) {
        Z[i] = r > i ? min(Z[2 * l - i], r - i) : 1;
        while (s[i + Z[i]] == s[i - Z[i]]) Z[i]++;
        if (Z[i] + i > r) l = i, r = Z[i] + i;
    }
    for (int i = 0; i < n; ++i) {
        Z[i] = (Z[i] - (i & 1)) / 2 * 2 + (i & 1);
    }
    return Z;
}
}

```

5.5 Suffix Array

```

int sa[N], tmp[2][N], c[N], rk[N], lcp[N];
void buildSA(string s) {
    int *x = tmp[0], *y = tmp[1], m = 256, n = s.length();
    ;
}

```

```

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

```

5.6 SAIS

```

int sa[N * 2], rk[N], lcp[N];
// string ASCII value need > 0
namespace sfx {
    bool _t[N * 2];
    int _s[N * 2], _c[N * 2], x[N], _p[N], _q[N * 2];
    void pre(int *sa, int *c, int n, int z) {
        fill_n(sa, n, 0), copy_n(c, z, x);
    }
    void induce(int *sa, int *c, int *s, bool *t, int n, int z) {
        copy_n(c, z - 1, x + 1);
        for (int i = 0; i < n; ++i) if (sa[i] && !t[sa[i] - 1]) sa[x[sa[i] - 1]]++ = sa[i] - 1;
        copy_n(c, z, x);
        for (int i = n - 1; i >= 0; --i) if (sa[i] && t[sa[i] - 1]) sa[--x[sa[i] - 1]] = sa[i] - 1;
    }
    void sais(int *s, int *sa, int *p, int *q, bool *t, int *c, int n, int z) {
        bool uniq = t[n - 1] = true;
        int nn = 0, nmxx = -1, *nsa = sa + n, *ns = s + n, last = -1;
        fill_n(c, z, 0);
        for (int i = 0; i < n; ++i) uniq &= ++c[s[i]] < 2;
        partial_sum(c, c + z, c);
        if (uniq) {
            for (int i = 0; i < n; ++i) sa[--c[s[i]]] = i;
            return;
        }
        for (int i = n - 2; i >= 0; --i)
            t[i] = (s[i] == s[i + 1] ? t[i + 1] : s[i] < s[i + 1]);
        pre(sa, c, n, z);
        for (int i = 1; i <= n - 1; ++i)
            if (t[i] && !t[i - 1])
                sa[--x[s[i]]] = p[q[i] = nn++] = i;
        induce(sa, c, s, t, n, z);
        for (int i = 0; i < n; ++i)

```

```

    if (sa[i] && t[sa[i]] && !t[sa[i] - 1]) {
        bool neq = last < 0 || !equal(s + sa[i], s + p[q[
            sa[i]] + 1], s + last);
        ns[q[last = sa[i]]] = nmzx += neq;
    }
    sais(ns, nsa, p + nn, q + n, t + n, c + z, nn, nmzx +
        1);
    pre(sa, c, n, z);
    for (int i = nn - 1; i >= 0; --i)
        sa[--x[s[p[nsa[i]]]]] = p[nsa[i]];
    induce(sa, c, s, t, n, z);
}

void buildSA(string s) {
    int n = s.length();
    for (int i = 0; i < n; ++i) _s[i] = s[i];
    _s[n] = 0;
    sais(_s, sa, _p, _q, _t, _c, n + 1, 256);
    for (int i = 1; i <= n; ++i) sa[i - 1] = sa[i];
} // buildLCP()...
}

```

5.7 Suffix Automaton

```

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

```

5.8 Minimum Rotation

```

string rotate(const string &s) {
    int n = s.length();
    string t = s + s;
    int i = 0, j = 1;
    while (i < n && j < n) {
        int k = 0;
        while (k < n && t[i + k] == t[j + k]) ++k;
        if (t[i + k] <= t[j + k]) j += k + 1;
    }
}

```

```

    else i += k + 1;
    if (i == j) ++j;
}
int pos = (i < n ? i : j);
return t.substr(pos, n);
}

```

5.9 Palindrome Tree

```

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

```

5.10 Main Lorentz

```

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

```

```

    if (tl <= tr) rep.pb({i + 1 - len - tr, i + 1 - len
        - tl, len});
}
Z = buildZ(sr + "#" + sl);
for (int i = 1; i < m; ++i) {
    if (Z[r - m + 1 + i - 1] >= m - i) {
        rep.pb({i, i, m - i});
    }
}
}
}

```

6 Math

6.1 Miller Rabin / Pollard Rho

```

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

```

6.2 Ext GCD

```

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

```

```

        res = extgcd(a, -b);
        res.second *= -1;
        return res;
    }
    if (b == 0) return {1, 0};
    res = extgcd(b, a % b);
    return {res.second, res.first - res.second * (a / b)
        };
}

```

6.3 PiCount

```

const int V = 10000000, N = 100, M = 100000;
vector<int> primes;
bool isp[V];
int small_pi[V], dp[N][M];
void sieve(int x){
    for(int i = 2; i < x; ++i) isp[i] = true;
    isp[0] = isp[1] = false;
    for(int i = 2; i * i < x; ++i) if(isp[i]) for(int j =
        i * i; j < x; j += i) isp[j] = false;
    for(int i = 2; i < x; ++i) if(isp[i]) primes.
        push_back(i);
}
void init(){
    sieve(V);
    small_pi[0] = 0;
    for(int i = 1; i < V; ++i) small_pi[i] = small_pi[i -
        1] + isp[i];
    for(int i = 0; i < M; ++i) dp[0][i] = i;
    for(int i = 1; i < N; ++i) for(int j = 0; j < M; ++j)
        dp[i][j] = dp[i - 1][j] - dp[i - 1][j / primes[i
            - 1]];
}
ll phi(ll n, int a){
    if(!a) return n;
    if(n < M && a < N) return dp[a][n];
    if(primes[a - 1] > n) return 1;
    if(((ll)primes[a - 1]) * primes[a - 1] >= n && n < V)
        return small_pi[n] - a + 1;
    ll de = phi(n, a - 1) - phi(n / primes[a - 1], a - 1)
        ;
    return de;
}
ll PiCount(ll n){
    if(n < V) return small_pi[n];
    int s = sqrt(n + 0.5), y = cbrt(n + 0.5), a =
        small_pi[y];
    ll res = phi(n, a) + a - 1;
    for(; primes[a] <= s; ++a) res -= max(PiCount(n /
        primes[a]) - PiCount(primes[a]) + 1, 0ll);
    return res;
}

```

6.4 Linear Function Mod Min

```

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

```

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

6.5 Determinant

```
ll Det(vector<vector<ll>> a) {
    int n = a.size();
    ll det = 1;
    for (int i = 0; i < n; ++i) {
        if (!a[i][i]) {
            det = -det;
            if (det < 0) det += mod;
            for (int j = i + 1; j < n; ++j) if (a[j][i]) {
                swap(a[j], a[i]);
                break;
            }
            if (!a[i][i]) return 0;
        }
        det = det * a[i][i] % mod;
        ll mul = mpow(a[i][i], mod - 2);
        for (int j = 0; j < n; ++j) a[i][j] = a[i][j] * mul
            % mod;
        for (int j = 0; j < n; ++j) if (i ^ j) {
            ll mul = a[j][i];
            for (int k = 0; k < n; ++k) {
                a[j][k] -= a[i][k] * mul % mod;
                if (a[j][k] < 0) a[j][k] += mod;
            }
        }
    }
    return det;
}
```

6.6 Floor Sum

```
// sum^{n-1}_0 floor((a * i + b) / m) in Log(n + m + a + b)
ll floor_sum(ll n, ll m, ll a, ll b) {
    ll ans = 0;
    if (a >= m) ans += (n - 1) * n * (a / m) / 2, a %= m;
    if (b >= m) ans += n * (b / m), b %= m;
    ll y_max = (a * n + b) / m, x_max = (y_max * m - b);
    if (y_max == 0) return ans;
    ans += (n - (x_max + a - 1) / a) * y_max;
    ans += floor_sum(y_max, a, m, (a - x_max % a) % a);
    return ans;
}
```

6.7 Quadratic Residue

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

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

```
for (int e = (1LL + p) >> 1; e; e >>= 1) {
    if (e & 1) {
        tmp = (1LL * g0 * f0 + 1LL * d * (1LL * g1 * f1 %
            p)) % p;
        g1 = (1LL * g0 * f1 + 1LL * g1 * f0) % p;
        g0 = tmp;
    }
    tmp = (1LL * f0 * f0 + 1LL * d * (1LL * f1 * f1 % p
        )) % p;
    f1 = (2LL * f0 * f1) % p;
    f0 = tmp;
}
return g0;
}
```

6.8 Simplex

```
struct Simplex { // 0-based
    using T = long double;
    static const int N = 410, M = 30010;
    const T eps = 1e-7;
    int n, m;
    int Left[M], Down[N];
    // Ax <= b, max c^T x
    // result : v, xi = sol[i]
    T a[M][N], b[M], c[N], v, sol[N];
    bool eq(T a, T b) {return fabs(a - b) < eps;}
    bool ls(T a, T b) {return a < b && !eq(a, b);}
    void init(int _n, int _m) {
        n = _n, m = _m, v = 0;
        for (int i = 0; i < m; ++i) for (int j = 0; j < n;
            ++j) a[i][j] = 0;
        for (int i = 0; i < m; ++i) b[i] = 0;
        for (int i = 0; i < n; ++i) c[i] = sol[i] = 0;
    }
    void pivot(int x, int y) {
        swap(Left[x], Down[y]);
        T k = a[x][y]; a[x][y] = 1;
        vector<int> nz;
        for (int i = 0; i < n; ++i) {
            a[x][i] /= k;
            if (!eq(a[x][i], 0)) nz.push_back(i);
        }
        b[x] /= k;
        for (int i = 0; i < m; ++i) {
            if (i == x || eq(a[i][y], 0)) continue;
            k = a[i][y], a[i][y] = 0;
            b[i] -= k * b[x];
            for (int j : nz) a[i][j] -= k * a[x][j];
        }
        if (eq(c[y], 0)) return;
        k = c[y], c[y] = 0, v += k * b[x];
        for (int i : nz) c[i] -= k * a[x][i];
    }
    // 0: found solution, 1: no feasible solution, 2:
    // unbounded
    int solve() {
        for (int i = 0; i < n; ++i) Down[i] = i;
        for (int i = 0; i < m; ++i) Left[i] = n + i;
        while (1) {
            int x = -1, y = -1;
            for (int i = 0; i < m; ++i) if (ls(b[i], 0) && (x
                == -1 || b[i] < b[x])) x = i;
            if (x == -1) break;
            for (int i = 0; i < n; ++i) if (ls(a[x][i], 0) &&
                (y == -1 || a[x][i] < a[x][y])) y = i;
            if (y == -1) return 1;
            pivot(x, y);
        }
        while (1) {
            int x = -1, y = -1;
            for (int i = 0; i < n; ++i) if (ls(0, c[i]) && (y
                == -1 || c[i] > c[y])) y = i;
            if (y == -1) break;
            for (int i = 0; i < m; ++i) if (ls(0, a[i][y]) &&
                (x == -1 || b[i] / a[i][y] < b[x] / a[x][y]))
                x = i;
            if (x == -1) return 2;
            pivot(x, y);
        }
        for (int i = 0; i < m; ++i) if (Left[i] < n) sol[
            Left[i]] = b[i];
    }
};
```



```

    return 0;
}
};

```

6.9 Berlekamp Massey

```

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

```

6.10 Linear Programming Construction

Standard form: maximize $\mathbf{c}^T \mathbf{x}$ subject to $A\mathbf{x} \leq \mathbf{b}$ and $\mathbf{x} \geq 0$.

Dual LP: minimize $\mathbf{b}^T \mathbf{y}$ subject to $A^T \mathbf{y} \geq \mathbf{c}$ and $\mathbf{y} \geq 0$.

$\bar{\mathbf{x}}$ and $\bar{\mathbf{y}}$ are optimal if and only if for all $i \in [1, n]$, either $\bar{x}_i = 0$ or $\sum_{j=1}^m A_{ji} \bar{y}_j = c_i$ holds and for all $i \in [1, m]$ either $\bar{y}_i = 0$ or $\sum_{j=1}^n A_{ij} \bar{x}_j = b_j$ holds.

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

6.11 Euclidean

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

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

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

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

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

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

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

6.12 Theorem

- Kirchhoff's Theorem

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

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

- Tutte's Matrix

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

- Cayley's Formula

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

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

spanning trees.

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

- Erdős-Gallai Theorem

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

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

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

- Burnside's Lemma

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

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

Then

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

- Gale-Ryser theorem

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

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

- Fulkerson-Chen-Anstee theorem

A sequence $(a_1, b_1), \dots, (a_n, b_n)$ of nonnegative integer pairs with $a_1 \geq \dots \geq a_n$ is digraphic if and only if $\sum_{i=1}^n a_i = \sum_{i=1}^n b_i$ and

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

- Möbius inversion formula

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

- Spherical cap

- A portion of a sphere cut off by a plane.
- r : sphere radius, a : radius of the base of the cap, h : height of the cap, θ : $\arcsin(a/r)$.

- Volume = $\pi h^2(3r - h)/3 = \pi h(3a^2 + h^2)/6 = \pi r^3(2 + \cos \theta)(1 - \cos \theta)^2/3$.
- Area = $2\pi rh = \pi(a^2 + h^2) = 2\pi r^2(1 - \cos \theta)$.

Chinese Remainder Theorem

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

6.13 Estimation

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

6.14 General Purpose Numbers

Bernoulli numbers

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

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

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

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

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

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

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

Pentagonal number theorem

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

Catalan numbers

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

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

Eulerian numbers

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

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

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

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

6.15 Tips for Generating Funtion

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

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

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

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

Special Generating Function

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

7 Polynomial

7.1 Number Theoretic Transform

```
// mul, add, sub, mpow
// LL -> int if too slow
struct NTT {
    ll w[N];
    NTT() {
        ll dw = mpow(G, (mod - 1) / N);
        w[0] = 1;
        for (int i = 1; i < N; ++i) w[i] = mul(w[i - 1], dw);
    }
    void operator()(vector<ll>& a, bool inv = false) { //
        0 <= a[i] < P
        int x = 0, n = a.size();
        for (int j = 1; j < n - 1; ++j) {
            for (int k = n >> 1; (x ^= k) < k; k >>= 1);
            if (j < x) swap(a[j], a[x]);
        }
        for (int L = 2; L <= n; L <= 1) {
            int dx = N / L, dl = L >> 1;
            for (int i = 0; i < n; i += L) {
                for (int j = i, x = 0; j < i + dl; ++j, x += dx) {
                    ll tmp = mul(a[j + dl], w[x]);
                    a[j + dl] = sub(a[j], tmp);
                    a[j] = add(a[j], tmp);
                }
            }
        }
        if (inv) {
            reverse(a.begin() + 1, a.end());
            ll invn = mpow(n, mod - 2);
            for (int i = 0; i < n; ++i) a[i] = mul(a[i], invn);
        }
    }
} ntt;
```

7.2 Fast Fourier Transform

```
using T = complex<double>;
const double PI = acos(-1);
struct NTT {
    T w[N];
    FFT() {
        T dw = {cos(2 * PI / N), sin(2 * PI / N)};
        w[0] = 1;
        for (int i = 1; i < N; ++i) w[i] = w[i - 1] * dw;
    }
    void operator()(vector<T>& a, bool inv = false) {
        // see NTT, replace LL with T
        if (inv) {
            reverse(a.begin() + 1, a.end());
            T invn = 1.0 / n;
            for (int i = 0; i < n; ++i) a[i] = a[i] * invn;
        }
    }
} ntt;
```

// after mul, round i.real()

7.3 Primes

Prime	Root	Prime	Root
7681	17	167772161	3
12289	11	104857601	3
40961	3	985661441	3
65537	3	998244353	3
786433	10	1107296257	10
5767169	3	2013265921	31
7340033	3	2810183681	11
23068673	3	2885681153	3
469762049	3	605028353	3
2061584302081	7	1945555039024054273	5
2748779069441	3	9223372036737335297	3

7.4 Polynomial Operations

```
vector<ll> Mul(vector<ll> a, vector<ll> b, int bound
    = N) {
    int m = a.size() + b.size() - 1, n = 1;
    while (n < m) n <= 1;
```

```

a.resize(n), b.resize(n);
ntt(a), ntt(b);
vector<ll> out(n);
for (int i = 0; i < n; ++i) out[i] = mul(a[i], b[i]);
ntt(out, true), out.resize(min(m, bound));
return out;
}

vector<ll> Inverse(vector<ll> a) {
    // O(NlogN), a[0] != 0
    int n = a.size();
    vector<ll> res(1, mpow(a[0], mod - 2));
    for (int m = 1; m < n; m <= 1) {
        if (n < m * 2) a.resize(m * 2);
        vector<ll> v1(a.begin(), a.begin() + m * 2), v2 = res;
        v1.resize(m * 4), v2.resize(m * 4);
        ntt(v1), ntt(v2);
        for (int i = 0; i < m * 4; ++i) v1[i] = mul(mul(v1[i], v2[i]), v2[i]);
        ntt(v1, true);
        res.resize(m * 2);
        for (int i = 0; i < m; ++i) res[i] = add(res[i], res[i]);
        for (int i = 0; i < m * 2; ++i) res[i] = sub(res[i], v1[i]);
    }
    res.resize(n);
    return res;
}

pair<vector<ll>, vector<ll>> Divide(vector<ll> a, vector<ll> b) {
    // a = bQ + R, O(NlogN), b.back() != 0
    int n = a.size(), m = b.size(), k = n - m + 1;
    if (n < m) return {{0}, a};
    vector<ll> ra = a, rb = b;
    reverse(all(ra)), ra.resize(k);
    reverse(all(rb)), rb.resize(k);
    vector<ll> Q = Mul(ra, Inverse(rb), k);
    reverse(all(Q));
    vector<ll> res = Mul(b, Q), R(m - 1);
    for (int i = 0; i < m - 1; ++i) R[i] = sub(a[i], res[i]);
    return {Q, R};
}

vector<ll> SqrtImpl(vector<ll> a) {
    if (a.empty()) return {0};
    int z = QuadraticResidue(a[0], mod), n = a.size();
    if (z == -1) return {-1};
    vector<ll> q(1, z);
    const int inv2 = (mod + 1) / 2;
    for (int m = 1; m < n; m <= 1) {
        if (n < m * 2) a.resize(m * 2);
        q.resize(m * 2);
        vector<ll> f2 = Mul(q, q, m * 2);
        for (int i = 0; i < m * 2; ++i) f2[i] = sub(f2[i], a[i]);
        f2 = Mul(f2, Inverse(q), m * 2);
        for (int i = 0; i < m * 2; ++i) q[i] = sub(q[i], mul(f2[i], inv2));
    }
    q.resize(n);
    return q;
}

vector<ll> Sqrt(vector<ll> a) {
    // O(NlogN), return {-1} if not exists
    int n = a.size(), m = 0;
    while (m < n && a[m] == 0) m++;
    if (m == n) return vector<ll>(n);
    if (m & 1) return {-1};
    vector<ll> s = SqrtImpl(vector<ll>(a.begin() + m, a.end()));
    if (s[0] == -1) return {-1};
    vector<ll> res(n);
    for (int i = 0; i < s.size(); ++i) res[i + m / 2] = s[i];
    return res;
}

vector<ll> Derivative(vector<ll> a) {
    int n = a.size();
    vector<ll> res(n - 1);
    for (int i = 0; i < n - 1; ++i) res[i] = mul(a[i + 1], i + 1);
}

```

```

return res;
}

vector<ll> Integral(vector<ll> a) {
    int n = a.size();
    vector<ll> res(n + 1);
    for (int i = 0; i < n; ++i) {
        res[i + 1] = mul(a[i], mpow(i + 1, mod - 2));
    }
    return res;
}

vector<ll> Ln(vector<ll> a) {
    // O(NlogN), a[0] = 1
    int n = a.size();
    if (n == 1) return {0};
    vector<ll> d = Derivative(a);
    a.pop_back();
    return Integral(Mul(d, Inverse(a), n - 1));
}

vector<ll> Exp(vector<ll> a) {
    // O(NlogN), a[0] = 0
    int n = a.size();
    vector<ll> q(1, 1);
    a[0] = add(a[0], 1);
    for (int m = 1; m < n; m <= 1) {
        if (n < m * 2) a.resize(m * 2);
        vector<ll> g(a.begin(), a.begin() + m * 2), h(all(q));
        h.resize(m * 2), h = Ln(h);
        for (int i = 0; i < m * 2; ++i) {
            g[i] = sub(g[i], h[i]);
        }
        q = Mul(g, q, m * 2);
    }
    q.resize(n);
    return q;
}

vector<ll> Pow(vector<ll> a, ll k) {
    int n = a.size(), m = 0;
    vector<ll> ans(n, 0);
    while (m < n && a[m] == 0) m++;
    if (k && m && (k >= n || k * m >= n)) return ans;
    if (m == n) return ans[0] = 1, ans;
    ll lead = m * k;
    vector<ll> b(a.begin() + m, a.end());
    ll base = mpow(b[0], k), inv = mpow(b[0], mod - 2);
    for (int i = 0; i < n - m; ++i) b[i] = mul(b[i], inv);
    b = Ln(b);
    for (int i = 0; i < n - m; ++i) b[i] = mul(b[i], k % mod);
    b = Exp(b);
    for (int i = lead; i < n; ++i) ans[i] = mul(b[i - lead], base);
    return ans;
}

vector<ll> Evaluate(vector<ll> a, vector<ll> x) {
    if (x.empty()) return {};
    int n = x.size();
    vector<vector<ll>> up(n * 2);
    for (int i = 0; i < n; ++i) up[i + n] = {sub(0, x[i]), 1};
    for (int i = n - 1; i > 0; --i) up[i] = Mul(up[i * 2], up[i * 2 + 1]);
    vector<vector<ll>> down(n * 2);
    down[1] = Divide(a, up[1]).second;
    for (int i = 2; i < n * 2; ++i) down[i] = Divide(down[i > 1], up[i]).second;
    vector<ll> y(n);
    for (int i = 0; i < n; ++i) y[i] = down[i + n][0];
    return y;
}

vector<ll> Interpolate(vector<ll> x, vector<ll> y) {
    int n = x.size();
    vector<vector<ll>> up(n * 2);
    for (int i = 0; i < n; ++i) up[i + n] = {sub(0, x[i]), 1};
    for (int i = n - 1; i > 0; --i) up[i] = Mul(up[i * 2], up[i * 2 + 1]);
    vector<ll> a = Evaluate(Derivative(up[1]), x);
    for (int i = 0; i < n; ++i) {
        a[i] = mul(y[i], mpow(a[i], mod - 2));
    }
}

```

```

vector<vector<ll>> down(n * 2);
for (int i = 0; i < n; ++i) down[i + n] = {a[i]};
for (int i = n - 1; i > 0; --i) {
    vector<ll> lhs = Mul(down[i * 2], up[i * 2 + 1]);
    vector<ll> rhs = Mul(down[i * 2 + 1], up[i * 2]);
    down[i].resize(lhs.size());
    for (int j = 0; j < lhs.size(); ++j) {
        down[i][j] = add(lhs[j], rhs[j]);
    }
}
return down[1];
}

```

7.5 Fast Linear Recursion

```

ll FastLinearRecursion(vector<ll> a, vector<ll> c, ll
    k) {
    // a_n = sigma c_j * a_{n-j-1}, 0-based
    // O(NLogNLogK), |a| = |c|
    int n = a.size();
    if (k < n) return a[k];
    vector<ll> base(n + 1, 1);
    for (int i = 0; i < n; ++i) base[i] = sub(0, c[n - i
        - 1]);
    vector<ll> poly(n);
    (n == 1 ? poly[0] = c[n - 1] : poly[1] = 1);
    auto calc = [&](vector<ll> p1, vector<ll> p2) {
        // O(n^2) brute force or O(n log n) NTT
        return Divide(Mul(p1, p2), base).second;
    };
    vector<ll> res(n, 0); res[0] = 1;
    for (; k; k >= 1, poly = calc(poly, poly)) {
        if (k & 1) res = calc(res, poly);
    }
    ll ans = 0;
    for (int i = 0; i < n; ++i) {
        (ans += res[i] * a[i]) %= mod;
    }
    return ans;
}

```

7.6 Fast Walsh Transform

```

void fwt(vector<int> &a) {
    // and : x += y * (1, -1)
    // or : y += x * (1, -1)
    // xor : x = (x + y) * (1, 1/2)
    //       y = (x - y) * (1, 1/2)
    int n = __lg(a.size());
    for (int i = 0; i < n; ++i) {
        for (int j = 0; j < 1 << n; ++j) if (j >> i & 1) {
            int x = a[j ^ (1 << i)], y = a[j];
            // do something
        }
    }
}

vector<int> subs_conv(vector<int> a, vector<int> b) {
    // c_i = sum_{j+k=i} a_j * b_k
    int n = __lg(a.size());
    vector<vector<int>> ha(n + 1, vector<int>(1 << n));
    vector<vector<int>> hb(n + 1, vector<int>(1 << n));
    vector<vector<int>> c(n + 1, vector<int>(1 << n));
    for (int i = 0; i < 1 << n; ++i) {
        ha[__builtin_popcount(i)][i] = a[i];
        hb[__builtin_popcount(i)][i] = b[i];
    }
    for (int i = 0; i <= n; ++i) or_fwt(ha[i]), or_fwt(hb[i]);
    for (int i = 0; i <= n; ++i)
        for (int j = 0; i + j <= n; ++j)
            for (int k = 0; k < 1 << n; ++k)
                // mind overflow
                c[i + j][k] += ha[i][k] * hb[j][k];
    for (int i = 0; i <= n; ++i) or_fwt(c[i], true);
    vector<int> ans(1 << n);
    for (int i = 0; i < 1 << n; ++i)
        ans[i] = c[__builtin_popcount(i)][i];
    return ans;
}

```

8 Geometry

8.1 Basic

```

const double eps = 1e-8, PI = acos(-1);
int sign(double x) {return abs(x) <= eps ? 0 : (x > 0 ?
    1 : -1);}
double norm(double x) {
    while (x < -eps) x += PI * 2;
    while (x > PI * 2 + eps) x -= PI * 2;
    return x;
}
struct Pt {
    double x, y;
    Pt (double _x, double _y) : x(_x), y(_y) {}
    Pt operator + (Pt o) {return Pt(x + o.x, y + o.y);}
    Pt operator - (Pt o) {return Pt(x - o.x, y - o.y);}
    Pt operator * (double k) {return Pt(x * k, y * k);}
    Pt operator / (double k) {return Pt(x / k, y / k);}
    double operator * (Pt o) {return x * o.x + y * o.y;}
    double operator ^ (Pt o) {return x * o.y - y * o.x;}
};
struct Line {
    Pt a, b;
};
struct Cir {
    Pt o; double r;
};
double abs2(Pt o) {return o.x * o.x + o.y * o.y;}
double abs(Pt o) {return sqrt(abs2(o));}
int ori(Pt o, Pt a, Pt b) {return sign((o - a) ^ (o - b
    ));}
bool btw(Pt a, Pt b, Pt c) { // c on segment ab?
    return ori(a, b, c) == 0 && sign((c - a) * (c - b))
        <= 0;
}
int pos(Pt a) {return sign(a.y) == 0 ? sign(a.x) < 0 :
    a.y < 0;}
double area(Pt a, Pt b, Pt c) {return abs((a - b) ^ (a
    - c)) / 2;}
double angle(Pt a, Pt b) {return norm(atan2(b.y - a.y,
    b.x - a.x));}
Pt unit(Pt o) {return o / abs(o);}
Pt rot(Pt a, double o) { // CCW
    double c = cos(o), s = sin(o);
    return Pt(c * a.x - s * a.y, s * a.x + c * a.y);
}
Pt perp(Pt a) {return Pt(-a.y, a.x);}
Pt proj_vector(Pt a, Pt b, Pt c) { // vector ac proj to
    ab
    return (b - a) * ((c - a) * (b - a)) / (abs2(b - a));
}
Pt proj_pt(Pt a, Pt b, Pt c) { // point c proj to ab
    return proj_vector(a, b, c) + a;
}

```

8.2 Heart

```

Pt circenter(Pt p0, Pt p1, Pt p2) { // radius = abs(
    center)
    p1 = p1 - p0, p2 = p2 - p0;
    double x1 = p1.x, y1 = p1.y, x2 = p2.x, y2 = p2.y;
    double m = 2. * (x1 * y2 - y1 * x2);
    Pt center(0, 0);
    center.x = (x1 * x1 * y2 - x2 * x2 * y1 + y1 * y2 * (
        y1 - y2)) / m;
    center.y = (x1 * x2 * (x2 - x1) - y1 * y1 * x2 + x1 *
        y2 * y2) / m;
    return center + p0;
}
Pt incenter(Pt p1, Pt p2, Pt p3) { // radius = area / s
    * 2
    double a = abs(p2 - p3), b = abs(p1 - p3), c = abs(p1
        - p2);
    double s = a + b + c;
    return (p1 * a + p2 * b + p3 * c) / s;
}
Pt masscenter(Pt p1, Pt p2, Pt p3)
{ return (p1 + p2 + p3) / 3; }
Pt orthocenter(Pt p1, Pt p2, Pt p3)
{ return masscenter(p1, p2, p3) * 3 - circenter(p1, p2,
    p3) * 2; }

```

8.3 External Bisector

```
Pt external_bisector(Pt p1, Pt p2, Pt p3) { //213
    Pt L1 = p2 - p1, L2 = p3 - p1;
    L2 = L2 * abs(L1) / abs(L2);
    return L1 + L2;
}
```

8.4 Intersection of Segments

```
Pt LinesInter(Line a, Line b) {
    double abc = (a.b - a.a) ^ (b.a - a.a);
    double abd = (a.b - a.a) ^ (b.b - a.a);
    if (sign(abc - abd) == 0) return b.b; // no inter
    return (b.b * abc - b.a * abd) / (abc - abd);
}
vector<Pt> SegsInter(Line a, Line b) {
    if (btw(a.a, a.b, b.a)) return {b.a};
    if (btw(a.a, a.b, b.b)) return {b.b};
    if (btw(b.a, b.b, a.a)) return {a.a};
    if (btw(b.a, b.b, a.b)) return {a.b};
    if (ori(a.a, a.b, b.a) * ori(a.a, a.b, b.b) == -1 &&
        ori(b.a, b.b, a.a) * ori(b.a, b.b, a.b) == -1)
        return {LinesInter(a, b)};
    return {};
}
```

8.5 Intersection of Circle and Line

```
vector<Pt> CircleLineInter(Cir c, Line l) {
    Pt p = l.a + (l.b - l.a) * ((c.o - l.a) * (l.b - l.a)
        ) / abs2(l.b - l.a);
    double s = (l.b - l.a) ^ (c.o - l.a), h2 = c.r * c.r
        - s * s / abs2(l.b - l.a);
    if (sign(h2) == -1) return {};
    if (sign(h2) == 0) return {p};
    Pt h = (l.b - l.a) / abs(l.b - l.a) * sqrt(h2);
    return {p - h, p + h};
}
```

8.6 Intersection of Circles

```
vector<Pt> CirclesInter(Cir c1, Cir c2) {
    double d2 = abs2(c1.o - c2.o), d = sqrt(d2);
    if (d < max(c1.r, c2.r) - min(c1.r, c2.r) || d > c1.r
        + c2.r) return {};
    Pt u = (c1.o + c2.o) / 2 + (c1.o - c2.o) * ((c2.r *
        c2.r - c1.r * c1.r) / (2 * d2));
    double A = sqrt((c1.r + c2.r + d) * (c1.r - c2.r + d)
        * (c1.r + c2.r - d) * (-c1.r + c2.r + d));
    Pt v = Pt(c1.o.y - c2.o.y, -c1.o.x + c2.o.x) * A / (2
        * d2);
    if (sign(v.x) == 0 && sign(v.y) == 0) return {u};
    return {u + v, u - v};
}
```

8.7 Intersection of Polygon and Circle

```
double _area(Pt pa, Pt pb, double r) {
    if (abs(pa) < abs(pb)) swap(pa, pb);
    if (abs(pb) < eps) return 0;
    double S, h, theta;
    double a = abs(pb), b = abs(pa), c = abs(pb - pa);
    double cosB = pb * (pb - pa) / a / c, B = acos(cosB);
    double cosC = (pa * pb) / a / b, C = acos(cosC);
    if (a > r) {
        S = (C / 2) * r * r;
        h = a * b * sin(C) / c;
        if (h < r && B < pi / 2) S -= (acos(h / r) * r * r
            - h * sqrt(r * r - h * h));
    } else if (b > r) {
        theta = pi - B - asin(sin(B) / r * a);
        S = .5 * a * r * sin(theta) + (C - theta) / 2 * r *
            r;
    } else S = .5 * sin(C) * a * b;
    return S;
}
double area_poly_circle(vector<Pt> poly, Pt O, double r)
{
    double S = 0; int n = poly.size();
    for (int i = 0; i < n; ++i)
        S += _area(poly[i] - O, poly[(i + 1) % n] - O, r) *
            ori(O, poly[i], poly[(i + 1) % n]);
}
```

```
return fabs(S);
}
```

8.8 Tangent Lines of Circle and Point

```
vector<Line> tangent(Cir c, Pt p) {
    vector<Line> z;
    double d = abs(p - c.o);
    if (sign(d - c.r) == 0) {
        Pt i = rot(p - c.o, pi / 2);
        z.push_back({p, p + i});
    } else if (d > c.r) {
        double o = acos(c.r / d);
        Pt i = unit(p - c.o), j = rot(i, o) * c.r, k = rot(
            i, -o) * c.r;
        z.push_back({c.o + j, p});
        z.push_back({c.o + k, p});
    }
    return z;
}
```

8.9 Tangent Lines of Circles

```
vector<Line> tangent(Cir c1, Cir c2, int sign1) {
    // sign1 = 1 for outer tang, -1 for inter tang
    vector<Line> ret;
    double d_sq = abs2(c1.o - c2.o);
    if (sign(d_sq) == 0) return ret;
    double d = sqrt(d_sq);
    Pt v = (c2.o - c1.o) / d;
    double c = (c1.r - sign1 * c2.r) / d;
    if (c * c > 1) return ret;
    double h = sqrt(max(0.0, 1.0 - c * c));
    for (int sign2 = 1; sign2 >= -1; sign2 -= 2) {
        Pt n = Pt(v.x * c - sign2 * h * v.y, v.y * c +
            sign2 * h * v.x);
        Pt p1 = c1.o + n * c1.r;
        Pt p2 = c2.o + n * (c2.r * sign1);
        if (sign(p1.x - p2.x) == 0 && sign(p1.y - p2.y) ==
            0)
            p2 = p1 + perp(c2.o - c1.o);
        ret.pb({p1, p2});
    }
    return ret;
}
```

8.10 Point In Convex

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

8.11 Point Segment Distance

```
double PointSegDist(Pt q0, Pt q1, Pt p) {
    if (sign(abs(q0 - q1)) == 0) return abs(q0 - p);
    if (sign((q1 - q0) * (p - q0)) >= 0 && sign((q0 - q1)
        * (p - q1)) >= 0)
        return fabs(((q1 - q0) ^ (p - q0)) / abs(q0 - q1));
    return min(abs(p - q0), abs(p - q1));
}
```

8.12 Convex Hull

```
vector<Pt> ConvexHull(vector<Pt> pt) {
    int n = pt.size();
    sort(all(pt), [&](Pt a, Pt b) {return a.x == b.x ? a.
        y < b.y : a.x < b.x;});
    vector<Pt> ans = {pt[0]};
    for (int t : {0, 1}) {
```

```

    int m = ans.size();
    for (int i = 1; i < n; ++i) {
        while (ans.size() > m && ori(ans[ans.size() - 2],
            ans.back(), pt[i]) <= 0)
            ans.pop_back();
        ans.push_back(pt[i]);
    }
    reverse(all(pt));
}
ans.pop_back();
return ans;
}

```

8.13 Convex Hull Distance

```

double ConvexHullDist(vector<Pt> A, vector<Pt> B) {
    for (auto &p : B) p = Pt(0, 0) - p;
    auto C = Minkowski(A, B); // assert SZ(C) > 0
    if (PointInConvex(C, Pt(0, 0))) return 0;
    double ans = PointSegDist(C.back(), C[0], Pt(0, 0));
    for (int i = 0; i + 1 < C.size(); ++i) {
        ans = min(ans, PointSegDist(C[i], C[i + 1], Pt(0,
            0)));
    }
    return ans;
}

```

8.14 Minimum Enclosing Circle

```

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

```

8.15 Union of Circles

```

vector<pair<double, double>> CoverSegment(Cir a, Cir b)
{
    double d = abs(a.o - b.o);
    vector<pair<double, double>> res;
    if (sign(a.r + b.r - d) == 0);
    else if (d <= abs(a.r - b.r) + eps) {
        if (a.r < b.r) res.emplace_back(0, 2 * pi);
    } else if (d < abs(a.r + b.r) - eps) {
        double o = acos((a.r * a.r + d * d - b.r * b.r) /
            (2 * a.r * d)), z = atan2((b.o - a.o).y, (b.o -
            a.o).x);
        if (z < 0) z += 2 * pi;
        double l = z - o, r = z + o;
        if (l < 0) l += 2 * pi;
        if (r > 2 * pi) r -= 2 * pi;
        if (l > r) res.emplace_back(l, 2 * pi), res.
            emplace_back(0, r);
        else res.emplace_back(l, r);
    }
    return res;
}
double CircleUnionArea(vector<Cir> c) { // circle
    should be identical
    int n = c.size();
    double a = 0, w;
    for (int i = 0; w = 0, i < n; ++i) {
        vector<pair<double, double>> s = {{2 * pi, 9}}, z;
        for (int j = 0; j < n; ++j) if (i != j) {
            z = CoverSegment(c[i], c[j]);

```

```

            for (auto &e : z) s.push_back(e);
        }
        sort(s.begin(), s.end());
        auto F = [&](double t) { return c[i].r * (c[i].r *
            t + c[i].o.x * sin(t) - c[i].o.y * cos(t)); };
        for (auto &e : s) {
            if (e.first > w) a += F(e.first) - F(w);
            w = max(w, e.second);
        }
    }
    return a * 0.5;
}

```

8.16 Union of Polygons

```

double polyUnion(vector<vector<Pt>> poly) {
    int n = poly.size();
    double ans = 0;
    auto solve = [&](Pt a, Pt b, int cid) {
        vector<pair<Pt, int>> event;
        for (int i = 0; i < n; ++i) {
            int st = 0, sz = poly[i].size();
            while (st < sz && ori(poly[i][st], a, b) != 1) st
                ++;
            if (st == sz) continue;
            for (int j = 0; j < sz; ++j) {
                Pt c = poly[i][(j + st) % sz], d = poly[i][(j +
                    st + 1) % sz];
                if (sign((a - b) ^ (c - d)) != 0) {
                    int ok1 = ori(c, a, b) == 1, ok2 = ori(d, a,
                        b) == 1;
                    if (ok1 ^ ok2) event.emplace_back(LinesInter
                        ({a, b}, {c, d}), ok1 ? 1 : -1);
                } else if (ori(c, a, b) == 0 && sign((a - b) *
                    (c - d)) > 0 && i <= cid) {
                    event.emplace_back(c, -1);
                    event.emplace_back(d, 1);
                }
            }
        }
        sort(all(event), [&](pair<Pt, int> i, pair<Pt,
            int> j) {
            return ((a - i.first) * (a - b)) < ((a - j.first)
                * (a - b));
        });
        int now = 0;
        Pt lst = a;
        for (auto [x, y] : event) {
            if (btw(a, b, lst) && btw(a, b, x) && !now) ans
                += lst ^ x;
            now += y, lst = x;
        }
    };
    for (int i = 0; i < n; ++i) for (int j = 0; j < poly[
        i].size(); ++j) {
        solve(poly[i][j], poly[i][(j + 1) % int(poly[i].
            size())], i);
    }
    return ans / 2;
}

```

8.17 Polar Angle Sort

```

void PolarAngleSort(vector<Pt> &pts) {
    sort(all(pts), [&](Pt a, Pt b) {return pos(a) == pos(
        b) ? sign(a ^ b) > 0 : pos(a) < pos(b)};});
}

```

8.18 Rotating Caliper

```

void RotatingCaliper(vector<Pt> &pts) {
    int n = pts.size();
    for (int i = 0, j = 2; i < n; ++i) {
        int ni = (i + 1) % n;
        while (true) {
            int nj = (j + 1) % n;
            if (area(pts[j], pts[i], pts[ni]) < area(pts[nj],
                pts[i], pts[ni])) {
                j = nj;
            } else {
                break;
            }
        }
    }
}

```



```

    }
    // do something
}
}

```

8.19 Rotating SweepLine

```

void RotatingSweepLine(vector<Pt> &pt) {
    int n = pt.size();
    vector<int> ord(n), cur(n);
    vector<pii> line;
    for (int i = 0; i < n; ++i) for (int j = 0; j < n; ++j) if (i ^ j)
        line.emplace_back(i, j);
    sort(all(line), [&](pii i, pii j) {
        Pt a = pt[i.second] - pt[i.first], b = pt[j.second] - pt[j.first];
        return (pos(a) == pos(b) ? sign(a ^ b) > 0 : pos(a) < pos(b));
    });
    iota(all(ord), 0);
    sort(all(ord), [&](int i, int j) {
        return (sign(pt[i].y - pt[j].y) == 0 ? pt[i].x < pt[j].x : pt[i].y < pt[j].y);
    });
    for (int i = 0; i < n; ++i) cur[ord[i]] = i;
    for (auto [i, j] : line) {
        // point sort by the distance to Line(i, j)
        tie(cur[i], cur[j], ord[cur[i]], ord[cur[j]]) =
            make_tuple(cur[j], cur[i], j, i);
    }
}

```

8.20 Half Plane Intersection

```

vector<Pt> HalfPlaneInter(vector<Line> vec) {
    // x
    // Line.a -----> Line.b
    int n = vec.size();
    sort(all(vec), [&](Line a, Line b) {
        Pt A = a.b - a.a, B = b.b - b.a;
        if (pos(A) == pos(B)) {
            if (sign(A ^ B) == 0) return sign((b.a - a.a) ^ (b.b - a.a)) > 0;
            return sign(A ^ B) > 0;
        }
        return pos(A) < pos(B);
    });
    auto same = [&](Line a, Line b) {
        return sign((a.b - a.a) ^ (b.b - b.a)) == 0 && sign((a.b - a.a) * (b.b - b.a)) > 0;
    };
    deque<Pt> inter;
    deque<Line> seg;
    for (int i = 0; i < n; ++i) if (!i || !same(vec[i - 1], vec[i])) {
        while (seg.size() >= 2 && sign((vec[i].b - inter.back()) ^ (vec[i].a - inter.back())) == 1) seg.pop_back(), inter.pop_back();
        while (seg.size() >= 2 && sign((vec[i].b - inter.front()) ^ (vec[i].a - inter.front())) == 1) seg.pop_front(), inter.pop_front();
        seg.pb(vec[i]);
        if (seg.size() >= 2) inter.pb(LinesInter(seg[seg.size() - 2], seg.back()));
    }
    while (seg.size() >= 2 && sign((seg.front().b - inter.back()) ^ (seg.front().a - inter.back())) == 1) seg.pop_back(), inter.pop_back();
    inter.pb(LinesInter(seg.front(), seg.back()));
    return vector<Pt>(all(inter));
}

```

8.21 Minkowski Sum

```

void reorder(vector<Pt> &P) {
    rotate(P.begin(), min_element(all(P), [&](Pt a, Pt b) {
        return make_pair(a.y, a.x) < make_pair(b.y, b.x);
    })), P.end());
}
vector<Pt> Minkowski(vector<Pt> P, vector<Pt> Q) {
    // P, Q: convex polygon

```

```

    reorder(P), reorder(Q);
    int n = P.size(), m = Q.size();
    P.pb(P[0]), P.pb(P[1]), Q.pb(Q[0]), Q.pb(Q[1]);
    vector<Pt> ans;
    for (int i = 0, j = 0; i < n || j < m; ) {
        ans.pb(P[i] + Q[j]);
        auto val = (P[i + 1] - P[i]) ^ (Q[j + 1] - Q[j]);
        if (val >= 0) i++;
        if (val <= 0) j++;
    }
    return ans;
}

```

8.22 Delaunay Triangulation

```

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

```

```

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

```

8.23 Triangulation Voronoi

```

vector<Line> ls[N];
pll arr[N];
Line make_line(pdd p, Line l) {
    pdd d = l.Y - l.X; d = perp(d);
    pdd m = (l.X + l.Y) / 2;
    l = Line(m, m + d);
    if (ori(l.X, l.Y, p) < 0)
        l = Line(m + d, m);
    return l;
}
double calc_area(int id) {
    // use to calculate the area of point "strictly in the convex hull"
    vector<Line> hpi = halfPlaneInter(ls[id]);
    vector<pdd> ps;
    for (int i = 0; i < SZ(hpi); ++i)
        ps.pb(intersect(hpi[i].X, hpi[i].Y, hpi[(i + 1) % SZ(hpi)].X, hpi[(i + 1) % SZ(hpi)].Y));
    double rt = 0;
    for (int i = 0; i < SZ(ps); ++i)

```

```

        rt += cross(ps[i], ps[(i + 1) % SZ(ps)]);
    return fabs(rt) / 2;
}
void solve(int n, pii *oarr) {
    map<pll, int> mp;
    for (int i = 0; i < n; ++i)
        arr[i] = pll(oarr[i].X, oarr[i].Y), mp[arr[i]] = i;
    build(n, arr); // Triangulation
    for (auto t : triang) {
        vector<int> p;
        for (int i = 0; i < 3; ++i)
            if (mp.find(t->p[i]) != mp.end())
                p.pb(mp[t->p[i]]);
        for (int i = 0; i < SZ(p); ++i)
            for (int j = i + 1; j < SZ(p); ++j) {
                Line l(oarr[p[i]], oarr[p[j]]);
                ls[p[i]].pb(make_line(oarr[p[i]], l));
                ls[p[j]].pb(make_line(oarr[p[j]], l));
            }
    }
}

```

9 Else

9.1 Bit Hack

```

long long next_perm(long long v) {
    long long t = v | (v - 1);
    return (t + 1) | (((~t & -~t) - 1) >> (__builtin_ctz(v) + 1));
}
void subset(long long s) {
    long long sub = s;
    while (sub) sub = (sub - 1) & s;
}

```

9.2 Dynamic Programming Condition

9.2.1 Totally Monotone (Concave/Convex)

$$\forall i < i', j < j', B[i][j] \leq B[i'][j] \implies B[i][j'] \leq B[i'][j']$$

$$\forall i < i', j < j', B[i][j] \geq B[i'][j] \implies B[i][j'] \geq B[i'][j']$$

9.2.2 Monge Condition (Concave/Convex)

$$\forall i < i', j < j', B[i][j] + B[i'][j'] \geq B[i][j'] + B[i'][j]$$

$$\forall i < i', j < j', B[i][j] + B[i'][j'] \leq B[i][j'] + B[i'][j]$$

9.2.3 Optimal Split Point

If

$$B[i][j] + B[i+1][j+1] \geq B[i][j+1] + B[i+1][j]$$

then

$$H_{i,j-1} \leq H_{i,j} \leq H_{i+1,j}$$

9.3 Slope Trick

```

template<typename T>
struct slope_trick_convex {
    T minn = 0, ground_l = 0, ground_r = 0;
    priority_queue<T, vector<T>, less<T>> left;
    priority_queue<T, vector<T>, greater<T>> right;
    slope_trick_convex() {left.push(numeric_limits<T>::min() / 2), right.push(numeric_limits<T>::max() / 2);}
    void push_left(T x) {left.push(x - ground_l);}
    void push_right(T x) {right.push(x - ground_r);}
    //add a line with slope 1 to the right starting from x
    void add_right(T x) {
        T l = left.top() + ground_l;
        if (l <= x) push_right(x);
        else push_left(x), push_right(l), left.pop(), minn += 1 - x;
    }
    //add a line with slope -1 to the left starting from x
    void add_left(T x) {
        T r = right.top() + ground_r;
        if (r >= x) push_left(x);
        else push_right(x), push_left(r), right.pop(), minn += x - r;
    }
}

```

```

//val[i]=min(val[j]) for all i-l<=j<=i+r
void expand(T l, T r) {ground_l -= l, ground_r += r;}
void shift_up(T x) {minn += x;}
T get_val(T x) {
    T l = left.top() + ground_l, r = right.top() +
        ground_r;
    if (x >= l && x <= r) return minn;
    if (x < l) {
        vector<T> trash;
        T cur_val = minn, slope = 1, res;
        while (1) {
            trash.push_back(left.top());
            left.pop();
            if (left.top() + ground_l <= x) {
                res = cur_val + slope * (l - x);
                break;
            }
            cur_val += slope * (l - (left.top() + ground_l));
            l = left.top() + ground_l;
            slope += 1;
        }
        for (auto i : trash) left.push(i);
        return res;
    }
    if (x > r) {
        vector<T> trash;
        T cur_val = minn, slope = 1, res;
        while (1) {
            trash.push_back(right.top());
            right.pop();
            if (right.top() + ground_r >= x) {
                res = cur_val + slope * (x - r);
                break;
            }
            cur_val += slope * ((right.top() + ground_r) -
                r);
            r = right.top() + ground_r;
            slope += 1;
        }
        for (auto i : trash) right.push(i);
        return res;
    }
    assert(0);
}
};

```

9.4 Manhattan MST

```

void solve(int n) {
    init();
    vector<int> v(n), ds;
    for (int i = 0; i < n; ++i) {
        v[i] = i;
        ds.push_back(x[i] - y[i]);
    }
    sort(ds.begin(), ds.end());
    ds.resize(unique(ds.begin(), ds.end()) - ds.begin());
    sort(v.begin(), v.end(), [&](int i, int j) { return x
        [i] == x[j] ? y[i] > y[j] : x[i] > x[j]; });
    int j = 0;
    for (int i = 0; i < n; ++i) {
        int p = lower_bound(ds.begin(), ds.end(), x[v[i]] -
            y[v[i]]) - ds.begin() + 1;
        pair<int, int> q = query(p);
        // query return prefix minimum
        if (~q.second) add_edge(v[i], q.second);
        add(p, make_pair(x[v[i]] + y[v[i]], v[i]));
    }
}
void make_graph() {
    solve(n);
    for (int i = 0; i < n; ++i) swap(x[i], y[i]);
    solve(n);
    for (int i = 0; i < n; ++i) x[i] = -x[i];
    solve(n);
    for (int i = 0; i < n; ++i) swap(x[i], y[i]);
    solve(n);
}

```

9.5 Dynamic MST

```

int cnt[maxn], cost[maxn], st[maxn], ed[maxn];
pair<int, int> qr[maxn];
// qr[i].first = id of edge to be changed, qr[i].second
// = weight after operation
// cnt[i] = number of operation on edge i
// call solve(0, q - 1, v, 0), where v contains edges i
// such that cnt[i] == 0
void contract(int l, int r, vector<int> v, vector<int>
    &x, vector<int> &y) {
    sort(v.begin(), v.end(), [&](int i, int j) {
        if (cost[i] == cost[j]) return i < j;
        return cost[i] < cost[j];
    });
    djs.save();
    for (int i = l; i <= r; ++i) djs.merge(st[qr[i].first],
        ed[qr[i].first]);
    for (int i = 0; i < (int)v.size(); ++i) {
        if (djs.find(st[v[i]]) != djs.find(ed[v[i]])) {
            x.push_back(v[i]);
            djs.merge(st[v[i]], ed[v[i]]);
        }
    }
    djs.undo();
    djs.save();
    for (int i = 0; i < (int)x.size(); ++i) djs.merge(st[x[i]],
        ed[x[i]]);
    for (int i = 0; i < (int)v.size(); ++i) {
        if (djs.find(st[v[i]]) != djs.find(ed[v[i]])) {
            y.push_back(v[i]);
            djs.merge(st[v[i]], ed[v[i]]);
        }
    }
    djs.undo();
}
void solve(int l, int r, vector<int> v, long long c) {
    if (l == r) {
        cost[qr[l].first] = qr[l].second;
        if (st[qr[l].first] == ed[qr[l].first]) {
            printf("%Lld\n", c);
            return;
        }
        int minv = qr[l].second;
        for (int i = 0; i < (int)v.size(); ++i) minv = min(
            minv, cost[v[i]]);
        printf("%Lld\n", c + minv);
        return;
    }
    int m = (l + r) >> 1;
    vector<int> lv = v, rv = v;
    vector<int> x, y;
    for (int i = m + 1; i <= r; ++i) {
        cnt[qr[i].first]--;
        if (cnt[qr[i].first] == 0) lv.push_back(qr[i].first);
    }
    contract(l, m, lv, x, y);
    long long lc = c, rc = c;
    djs.save();
    for (int i = 0; i < (int)x.size(); ++i) {
        lc += cost[x[i]];
        djs.merge(st[x[i]], ed[x[i]]);
    }
    solve(l, m, y, lc);
    djs.undo();
    x.clear(), y.clear();
    for (int i = m + 1; i <= r; ++i) cnt[qr[i].first]++;
    for (int i = l; i <= m; ++i) {
        cnt[qr[i].first]--;
        if (cnt[qr[i].first] == 0) rv.push_back(qr[i].first);
    }
    contract(m + 1, r, rv, x, y);
    djs.save();
    for (int i = 0; i < (int)x.size(); ++i) {
        rc += cost[x[i]];
        djs.merge(st[x[i]], ed[x[i]]);
    }
    solve(m + 1, r, y, rc);
    djs.undo();
    for (int i = l; i <= m; ++i) cnt[qr[i].first]++;
}

```

9.6 ALL LCS

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

9.7 Hilbert Curve

```
long long hilbertOrder(int x, int y, int pow, int
    rotate) {
    if (pow == 0) return 0;
    int hpow = 1 << (pow-1);
    int seg = (x < hpow) ? ((y < hpow) ? 0 : 3) : ((y <
        hpow) ? 1 : 2);
    seg = (seg + rotate) & 3;
    const int rotateDelta[4] = {3, 0, 0, 1};
    int nx = x & (x ^ hpow), ny = y & (y ^ hpow);
    int nrot = (rotate + rotateDelta[seg]) & 3;
    long long subSquareSize = 1ll << (pow * 2 - 2);
    long long ans = seg * subSquareSize;
    long long add = hilbertOrder(nx, ny, pow - 1, nrot);
    ans += (seg == 1 || seg == 2) ? add : (subSquareSize
        - add - 1);
    return ans;
}
```

9.8 Pbds

```
#include <ext/pb_ds/priority_queue.hpp>
#include <ext/pb_ds/assoc_container.hpp>
using namespace __gnu_pbds;
#include <ext/rope>
using namespace __gnu_cxx;
__gnu_pbds::priority_queue<int> pq1, pq2;
pq1.join(pq2); // pq1 += pq2, pq2 = {}
cc_hash_table<int, int> m1;
tree<int, null_type, less<int>, rb_tree_tag,
    tree_order_statistics_node_update> oset;
oset.insert(2), oset.insert(4);
*oset.find_by_order(1), oset.order_of_key(1); // 4 0
bitset<100> BS;
BS.flip(3), BS.flip(5);
BS._Find_first(), BS._Find_next(3); // 3 5
rope<int> rp1, rp2;
rp1.push_back(1), rp1.push_back(3);
rp1.insert(0, 2); // pos, num
rp1.erase(0, 2); // pos, len
rp1.substr(0, 2); // pos, len
rp2.push_back(4);
rp1 += rp2, rp2 = rp1;
rp2[0], rp2[1]; // 3 4
```

9.9 Random

```
struct custom_hash {
    static uint64_t splitmix64(uint64_t x) {
        x += 0x9e3779b97f4a7c15;
        x = (x ^ (x >> 30)) * 0xbf58476d1ce4e5b9;
        x = (x ^ (x >> 27)) * 0x94d049bb133111eb;
        return x ^ (x >> 31);
    }
    size_t operator()(uint64_t a) const {
        static const uint64_t FIXED_RANDOM = chrono::
            steady_clock::now().time_since_epoch().count();
        return splitmix64(i + FIXED_RANDOM);
    }
};
unordered_map<int, int, custom_hash> m1;
random_device rd; mt19937 rng(rd());
```

9.10 Smawk Algorithm

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

9.11 Matroid Intersection

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

- $Y_1 = \{x \notin S \mid S \cup \{x\} \in I_1\}$
- $Y_2 = \{x \notin S \mid S \cup \{x\} \in I_2\}$

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

- $x \rightarrow y$ if $S - \{x\} \cup \{y\} \in I_1$.
- $y \rightarrow x$ if $S - \{x\} \cup \{y\} \in I_2$.

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

9.12 Python Misc

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