

# Contents

## 1 Basic

1.1	vimrc	1
1.2	Debug Macro	1
1.3	Increase Stack	1
1.4	Pragma Optimization	1
1.5	IO Optimization	1

## 2 Data Structure

2.1	Dark Magic	1
2.2	Link-Cut Tree	2
2.3	LiChao Segment Tree	2
2.4	Treap	2
2.5	Linear Basis	3
2.6	Binary Search On Segtree	3

## 3 Graph

3.1	2-SAT (SCC)	3
3.2	BCC	3
3.3	Round Square Tree	4
3.4	Edge TCC	4
3.5	Centroid Decomposition	4
3.6	DMST	4
3.7	Dominator Tree	5
3.8	Edge Coloring	5
3.9	Lowbit Decomposition	5
3.10	Manhattan MST	6
3.11	MaximalClique	6
3.12	MaximumClique	6
3.13	Minimum Mean Cycle	7
3.14	Mo's Algorithm on Tree	7
3.15	Tree Hashing	7
3.16	Virtual Tree	7

## 4 Matching & Flow

4.1	HopcroftKarp	7
4.2	Dijkstra Cost Flow	7
4.3	Dinic	8
4.4	Flow Models	8
4.5	General Graph Matching	8
4.6	Global Min-Cut	9
4.7	GomoryHu Tree	9
4.8	Kuhn Munkres	9
4.9	Minimum Cost Circulation	9
4.10	Minimum Cost Max Flow	10
4.11	Weighted Matching	10

## 5 Math

5.1	Common Bounds	12
5.2	Strling Number	12
5.3	ax+by=gcd	12
5.4	Chinese Remainder	12
5.5	De-Bruijn	12
5.6	DiscreteLog	12
5.7	Quadratic residue	12
5.8	Extended Euler	12
5.9	Extended FloorSum	12
5.10	FloorSum	13
5.11	ModMin	13
5.12	Fast Fourier Transform	13
5.13	FWT	13
5.14	CRT for arbitrary mod	14
5.15	NTT	14
5.16	Partition Number	14
5.17	Pi Count (+Linear Sieve)	14
5.18	Miller Rabin	14

5.19	Pollard Rho	14
5.20	Berlekamp Massey	15
5.21	Charateristic Polynomial	15
5.22	Polynomial Operations	15
5.23	Simplex	16
5.24	Simplex Construction	16
5.25	Adaptive Simpson	16

## 6 Geometry

6.1	Basic Geometry	16
6.2	2D Convex Hull	17
6.3	2D Farthest Pair	17
6.4	MinMax Enclosing Rect	17
6.5	Minkowski Sum	17
6.6	Segment Intersection	17
6.7	Half Plane Intersection	17
6.8	SegmentDist (Sausage)	17
6.9	Rotating Sweep Line	18
6.10	Point In Simple Polygon	18
6.11	Point In Hull (Fast)	18
6.12	Tangent of Points To Hull	18
6.13	Circle Class & Intersection	18
6.14	Circle Common Tangent	18
6.15	Line-Circle Intersection	18
6.16	Poly-Circle Intersection	18
6.17	Minimum Covering Circle	19
6.18	Circle Union	19
6.19	Polygon Union	19
6.20	3D Convex Hull	19
6.21	Delaunay	20
6.22	kd Tree (Nearest Point)	20
6.23	kd Closest Pair (3D ver.)	20
6.24	Simulated Annealing	21
6.25	Triangle Centers	21

## 7 Stringology

7.1	Hash	21
7.2	Suffix Array	21
7.3	Ex SAM	21
7.4	Z value	22
7.5	Manacher	22
7.6	Lexico Smallest Rotation	22
7.7	Main Lorentz	22
7.8	BWT	22
7.9	Palindromic Tree	22

## 8 Misc

8.1	Theorems	23
8.2	Weight Matroid Intersection	23
8.3	Bitset LCS	23
8.4	Prefix Substring LCS	23
8.5	Convex ID/ID DP	23
8.6	ConvexHull Optimization	24
8.7	Josephus Problem	24
8.8	Tree Knapsack	24
8.9	N Queens Problem	24
8.10	Stable Marriage	24
8.11	Binary Search On Fraction	24

```
se is nu ru et tgc sc hls cin cino+=j1 sw=2 sts=2 bs=2
mouse=a "encoding=utf-8 ls=2
syn on | colo desert | filetype indent on
inoremap {<CR> {<CR>}<ESC>O
map <F8> <ESC>:w<CR>:!g++ "%" -o "%<" -g -std=gnu++20 -
    DCKISEKI -Wall -Wextra -Wshadow -Wfatal-errors -
    Wconversion -fsanitize=address,undefined && echo
    success<CR>
map <F9> <ESC>:w<CR>:!g++ "%" -o "%<" -O2 -g -std=gnu
    ++20 && echo success<CR>
map <F10> <ESC>:!. / "%<"<CR>
ca Hash w !cpp -dD -P -fpreprocessed \ | tr -d '[:space
    :]' \ | md5sum \ | cut -c-6
let c_no_curly_error=1
" setxkbmap -option caps:ctrl_modifier
```

## 1.2 Debug Macro [645ef3]

```
#define all(x) begin(x), end(x)
#ifdef CKISEKI
#define safe cerr<<__PRETTY_FUNCTION__<<" line "<<
    __LINE__<<" safe\n"
#define debug(a...) debug_(&a, a)
#define orange(a...) orange_(&a, a)
template<typename ...T>
void debug_(const char *s, T ...a) {
    cerr << "\e[1;32m(" << s << ") = (" ;
    int cnt = sizeof...(T);
    (... , (cerr << a << (--cnt ? ", " : ") \e[0m\n")));
}
template<typename I>
void orange_(const char *s, I L, I R) {
    cerr << "\e[1;32m[ " << s << " ] = [ " ;
    for (int f = 0; L != R; ++L)
        cerr << (f++ ? ", " : "") << *L;
    cerr << " ] \e[0m\n";
}
#else
#define safe ((void)0)
#define debug(...) safe
#define orange(...) safe
#endif
```

## 1.3 Increase Stack

```
const int size = 256 << 20;
register long rsp asm("rsp");
char *p = (char*)malloc(size)+size, *bak = (char*)rsp;
__asm__ ("movq %0, %%rsp\n"::"r"(p));
// main
__asm__ ("movq %0, %%rsp\n"::"r"(bak));
```

## 1.4 Pragma Optimization [f63b0a]

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

## 1.5 IO Optimization [c9494b]

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

# 2 Data Structure

## 2.1 Dark Magic [095f25]

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

## 1 Basic

### 1.1 vimrc

## 2.2 Link-Cut Tree [7ce2b4]

```

template <typename Val, typename SVal> class LCT {
    struct node {
        int pa, ch[2];
        bool rev;
        Val v, prod, rprod;
        SVal sv, sub, vir;
        node() : pa{0}, ch{0, 0}, rev{false}, v{}, prod{},
            rprod{}, sv{}, sub{}, vir{} {};
    };
    #define cur o[u]
    #define lc cur.ch[0]
    #define rc cur.ch[1]
    vector<node> o;
    bool is_root(int u) const {
        return o[cur.pa].ch[0]!=u && o[cur.pa].ch[1]!=u;
    }
    bool is_rch(int u) const {
        return o[cur.pa].ch[1] == u && !is_root(u);
    }
    void down(int u) {
        if (not cur.rev) return;
        if (lc) set_rev(lc);
        if (rc) set_rev(rc);
        cur.rev = false;
    }
    void up(int u) {
        cur.prod = o[lc].prod * cur.v * o[rc].prod;
        cur.rprod = o[rc].rprod * cur.v * o[lc].rprod;
        cur.sub = cur.vir + o[lc].sub + o[rc].sub + cur.sv;
    }
    void set_rev(int u) {
        swap(lc, rc);
        swap(cur.prod, cur.rprod);
        cur.rev ^= 1;
    }
    void rotate(int u) {
        int f=cur.pa, g=o[f].pa, l=is_rch(u);
        if (cur.ch[l ^ 1]) o[cur.ch[l ^ 1]].pa = f;
        if (not is_root(f)) o[g].ch[is_rch(f)] = u;
        o[f].ch[l] = cur.ch[l ^ 1];
        cur.ch[l ^ 1] = f;
        cur.pa = g, o[f].pa = u;
        up(f);
    }
    void splay(int u) {
        vector<int> stk = {u};
        while (not is_root(stk.back()))
            stk.push_back(o[stk.back()].pa);
        while (not stk.empty()) {
            down(stk.back());
            stk.pop_back();
        }
        for (int f = cur.pa; not is_root(u); f = cur.pa) {
            if (!is_root(f)) rotate(is_rch(u)==is_rch(f)?f:u);
            rotate(u);
        }
        up(u);
    }
    void access(int x) {
        for (int u = x, last = 0; u; u = cur.pa) {
            splay(u);
            cur.vir = cur.vir + o[rc].sub - o[last].sub;
            rc = last; up(last = u);
        }
        splay(x);
    }
    int find_root(int u) {
        int la = 0;
        for (access(u); u; u = lc) down(la = u);
        return la;
    }
    void split(int x, int y) {change_root(x);access(y);}
    void change_root(int u) {access(u);set_rev(u);}
public:
    LCT(int n = 0) : o(n + 1) {}
    int add(const Val &v = {}) {
        o.push_back(v);
        return int(o.size()) - 2;
    }
    int add(Val &&v) {

```

```

        o.emplace_back(move(v));
        return int(o.size()) - 2;
    }
    void set_val(int u, const Val &v) {
        splay(++u); cur.v = v; up(u);
    }
    void set_sval(int u, const SVal &v) {
        splay(++u); cur.sv = v; up(u);
    }
    Val query(int x, int y) {
        split(++x, ++y); return o[y].prod;
    }
    SVal subtree(int p, int u) {
        change_root(++p); access(++u);
        return cur.vir + cur.sv;
    }
    bool connected(int u, int v) {
        return find_root(++u) == find_root(++v);
    }
    void link(int x, int y) {
        change_root(++x); access(++y);
        o[y].vir = o[y].vir + o[x].sub;
        up(o[x].pa = y);
    }
    void cut(int x, int y) {
        split(++x, ++y);
        o[y].ch[0] = o[x].pa = 0; up(y);
    }
    #undef cur
    #undef lc
    #undef rc
};

```

## 2.3 LiChao Segment Tree [b9c827]

```

struct L {
    int m, k, id;
    L() : id(-1) {}
    L(int a, int b, int c) : m(a), k(b), id(c) {}
    int at(int x) { return m * x + k; }
};
class LiChao {
private:
    int n; vector<L> nodes;
    static int lc(int x) { return 2 * x + 1; }
    static int rc(int x) { return 2 * x + 2; }
    void insert(int l, int r, int id, L ln) {
        int m = (l + r) >> 1;
        if (nodes[id].id == -1)
            return nodes[id] = ln, void();
        bool atLeft = nodes[id].at(l) < ln.at(l);
        if (nodes[id].at(m) < ln.at(m))
            atLeft ^= 1, swap(nodes[id], ln);
        if (r - l == 1) return;
        if (atLeft) insert(l, m, lc(id), ln);
        else insert(m, r, rc(id), ln);
    }
    int query(int l, int r, int id, int x) {
        int m = (l + r) >> 1, ret = 0;
        if (nodes[id].id != -1) ret = nodes[id].at(x);
        if (r - l == 1) return ret;
        if (x < m) return max(ret, query(l, m, lc(id), x));
        return max(ret, query(m, r, rc(id), x));
    }
public:
    LiChao(int n_) : n(n_), nodes(n * 4) {}
    void insert(L ln) { insert(0, n, 0, ln); }
    int query(int x) { return query(0, n, 0, x); }
};

```

## 2.4 Treap [ae576c]

```

__gnu_cxx::sfmt19937 rnd(7122);
namespace Treap {
    struct node {
        int size, pri; node *lc, *rc, *pa;
        node() : size(1), pri(rnd()), lc(0), rc(0), pa(0) {}
        void pull() {
            size = 1; pa = 0;
            if (lc) { size += lc->size; lc->pa = this; }
            if (rc) { size += rc->size; rc->pa = this; }
        }
    };
    int SZ(node *x) { return x ? x->size : 0; }
    node *merge(node *L, node *R) {

```

```

if (not L or not R) return L ? L : R;
if (L->pri > R->pri)
    return L->rc = merge(L->rc, R), L->pull(), L;
else
    return R->lc = merge(L, R->lc), R->pull(), R;
}
void splitBySize(node *o, int k, node *&L, node *&R) {
    if (not o) L = R = 0;
    else if (int s = SZ(o->lc) + 1; s <= k)
        L=o, splitBySize(o->rc, k-s, L->rc, R), L->pull();
    else
        R=o, splitBySize(o->lc, k, L, R->lc), R->pull();
    // SZ(L) == k
}
int getRank(node *o) { // 1-base
    int r = SZ(o->lc) + 1;
    for (; o->pa; o = o->pa)
        if (o->pa->rc == o) r += SZ(o->pa->lc) + 1;
    return r;
}
} // namespace Treap

```

## 2.5 Linear Basis [138d5d]

```

template <int BITS, typename S = int> struct Basis {
    static constexpr S MIN = numeric_limits<S>::min();
    array<pair<llu, S>, BITS> b;
    Basis() { b.fill({0, MIN}); }
    void add(llu x, S p) {
        for (int i = BITS-1; i>=0; i--) if (x >> i & 1) {
            if (b[i].first == 0) return b[i]={x, p}, void();
            if (b[i].second < p)
                swap(b[i].first, x), swap(b[i].second, p);
            x ^= b[i].first;
        }
    }
    optional<llu> query_kth(llu v, llu k) {
        vector<pair<llu, int>> o;
        for (int i = 0; i < BITS; i++)
            if (b[i].first) o.emplace_back(b[i].first, i);
        if (k >= (1ULL << o.size())) return {};
        for (int i = int(o.size()) - 1; i >= 0; i--)
            if ((k >> i & 1) ^ (v >> o[i].second & 1))
                v ^= o[i].first;
        return v;
    }
    Basis filter(S l) {
        Basis res = *this;
        for (int i = 0; i < BITS; i++)
            if (res.b[i].second < l) res.b[i] = {0, MIN};
        return res;
    }
};

```

## 2.6 Binary Search On Segtree [29b3cb]

```

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

```

```

r--;
while (r > 1 and (r & 1)) r >>= 1;
if (check(f(data[r], sum))) {
    while (r < sz) {
        propagate(r); r = (r << 1) + 1;
        if (auto nxt = f(data[r], sum); not check(nxt))
            sum = nxt, r--;
    }
    return r - sz;
}
sum = f(data[r], sum);
} while ((r & -r) != r);
return -1;
}

```

## 3 Graph

### 3.1 2-SAT (SCC) [76434f]

```

class TwoSat { // test @ CSES Giant Pizza
private:
    int n; vector<vector<int>> G, rG, sccs;
    vector<int> ord, idx, vis, res;
    void dfs(int u) {
        vis[u] = true;
        for (int v : G[u]) if (!vis[v]) dfs(v);
        ord.push_back(u);
    }
    void rdfs(int u) {
        vis[u] = false; idx[u] = sccs.size() - 1;
        sccs.back().push_back(u);
        for (int v : rG[u]) if (vis[v]) rdfs(v);
    }
public:
    TwoSat(int n_) : n(n_), G(n), rG(n), idx(n), vis(n),
        res(n) {}
    void add_edge(int u, int v) {
        G[u].push_back(v); rG[v].push_back(u);
    }
    void orr(int x, int y) {
        if ((x ^ y) == 1) return;
        add_edge(x ^ 1, y); add_edge(y ^ 1, x);
    }
    bool solve() {
        for (int i = 0; i < n; ++i) if (not vis[i]) dfs(i);
        reverse(ord.begin(), ord.end());
        for (int u : ord)
            if (vis[u]) sccs.emplace_back(), rdfs(u);
        for (int i = 0; i < n; i += 2)
            if (idx[i] == idx[i + 1]) return false;
        vector<bool> c(sccs.size());
        for (size_t i = 0; i < sccs.size(); ++i)
            for (int z : sccs[i])
                res[z] = c[i], c[idx[z ^ 1]] = !c[i];
        return true;
    }
    bool get(int x) { return res[x]; }
    int get_id(int x) { return idx[x]; }
    int count() { return sccs.size(); }
};

```

### 3.2 BCC [6ac6db]

```

class BCC {
    int n, ecnt, bcnt;
    vector<vector<pair<int, int>>> g;
    vector<int> dfn, low, bcc, stk;
    vector<bool> ap, bridge;
    void dfs(int u, int f) {
        dfn[u] = low[u] = dfn[f] + 1;
        int ch = 0;
        for (auto [v, t] : g[u]) if (bcc[t] == -1) {
            bcc[t] = 0; stk.push_back(t);
            if (dfn[v]) {
                low[u] = min(low[u], dfn[v]);
                continue;
            }
            ++ch, dfs(v, u);
            low[u] = min(low[u], low[v]);
            if (low[v] > dfn[u]) bridge[t] = true;
            if (low[v] < dfn[u]) continue;
            ap[u] = true;
            while (not stk.empty()) {

```

```

    int o = stk.back(); stk.pop_back();
    bcc[o] = bcnt;
    if (o == t) break;
}
bcnt += 1;
}
ap[u] = ap[u] and (ch != 1 or u != f);
}
public:
BCC(int n_) : n(n_), ecnt(0), bcnt(0), g(n), dfn(n),
    low(n), stk(), ap(n) {}
void add_edge(int u, int v) {
    g[u].emplace_back(v, ecnt);
    g[v].emplace_back(u, ecnt++);
}
void solve() {
    bridge.assign(ecnt, false); bcc.assign(ecnt, -1);
    for (int i = 0; i < n; ++i) if (!dfn[i]) dfs(i, i);
}
int bcc_id(int x) const { return bcc[x]; }
bool is_ap(int x) const { return ap[x]; }
bool is_bridge(int x) const { return bridge[x]; }
};

```

### 3.3 Round Square Tree [528440]

```

struct RST {
    int n; vector<vector<int>> T;
    RST(auto &G) : n(G.size()), T(n) {
        vector<int> stk, vis(n), low(n);
        auto dfs = [&](auto self, int u, int d) -> void {
            low[u] = vis[u] = d; stk.push_back(u);
            for (int v : G[u]) if (!vis[v]) {
                self(self, v, d + 1);
                if (low[v] == vis[u]) {
                    int cnt = T.size(); T.emplace_back();
                    for (int x = -1; x != v; stk.pop_back())
                        T[cnt].push_back(x = stk.back());
                    T[u].push_back(cnt); // T is rooted
                } else low[u] = min(low[u], low[v]);
            } else low[u] = min(low[u], vis[v]);
        };
        for (int u = 0; u < N; u++)
            if (!vis[u]) dfs(dfs, u, 1);
    } // T may be forest; after dfs, stk are the roots
}; // test @ 2020 Shanghai K

```

### 3.4 Edge TCC [5a2668]

```

vector<vector<int>> ETCC(auto &adj) {
    const int n = static_cast<int>(adj.size());
    vector<int> up(n), low(n), in, out, nx, id;
    in = out = nx = id = vector<int>(n, -1);
    int dfc = 0, cnt = 0; Dsu dsu(n);
    auto merge = [&](int u, int v) {
        dsu.join(u, v); up[u] += up[v]; };
    auto dfs = [&](auto self, int u, int p) -> void {
        in[u] = low[u] = dfc++;
        for (int v : adj[u]) if (v != u) {
            if (v == p) { p = -1; continue; }
            if (in[v] == -1) {
                self(self, v, u);
                if (nx[v] == -1 && up[v] <= 1) {
                    up[u] += up[v]; low[u] = min(low[u], low[v]);
                    continue;
                }
            }
            if (up[v] == 0) v = nx[v];
            if (low[u] > low[v])
                low[u] = low[v], swap(nx[u], v);
            for (; v != -1; v = nx[v]) merge(u, v);
        } else if (in[v] < in[u]) {
            low[u] = min(low[u], in[v]); up[u]++;
        } else {
            for (int &x = nx[u]; x != -1 &&
                in[x] <= in[v] && in[v] < out[x]; x = nx[x])
                merge(u, x);
            up[u]--;
        }
    };
    out[u] = dfc;
};
for (int i = 0; i < n; i++)
    if (in[i] == -1) dfs(dfs, i, -1);
for (int i = 0; i < n; i++)

```

```

    if (dsu.anc(i) == i) id[i] = cnt++;
    vector<vector<int>> comps(cnt);
    for (int i = 0; i < n; i++)
        comps[id[dsu.anc(i)]].push_back(i);
    return comps;
} // test @ yosupo judge

```

### 3.5 Centroid Decomposition [63b2fb]

```

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

```

### 3.6 DMST [0ae901]

```

using D = int64_t;
struct E { int s, t; D w; }; // 0-base
vector<int> dmst(const vector<E> &e, int n, int root) {
    using PQ = pair<min_heap<pair<D, int>>, D>;
    auto push = [](PQ &pq, pair<D, int> v) {
        pq.first.emplace(v.first - pq.second, v.second);
    };
    auto top = [](const PQ &pq) -> pair<D, int> {
        auto r = pq.first.top();
        return {r.first + pq.second, r.second};
    };
    auto join = [&push, &top](PQ &a, PQ &b) {
        if (a.first.size() < b.first.size()) swap(a, b);
        while (!b.first.empty()) {

```

```

    push(a, top(b));
    b.first.pop();
}
};
vector<PQ> h(n * 2);
for (size_t i = 0; i < e.size(); ++i)
    push(h[e[i].t], {e[i].w, i});
vector<int> a(n*2), v(n*2, -1), pa(n*2, -1), r(n*2);
iota(a.begin(), a.end(), 0);
auto o = [&](int x) { int y;
    for (y = x; a[y] != y; y = a[y]);
    for (int ox = x; x != y; ox = x)
        x = a[x], a[ox] = y;
    return y;
};
v[root] = n + 1;
int pc = n;
for (int i = 0; i < n; ++i) if (v[i] == -1) {
    for (int p = i; v[p] == -1 || v[p] == i; p = o(e[r[p]
        ]].s)) {
        if (v[p] == i) {
            int q = p; p = pc++;
            do {
                h[q].second = -h[q].first.top().first;
                join(h[pa[q] = a[q] = p], h[q]);
            } while ((q = o(e[r[q]].s)) != p);
        }
        v[p] = i;
        while (!h[p].first.empty() && o(e[top(h[p]).second].
            s) == p)
            h[p].first.pop();
        r[p] = top(h[p]).second;
    }
}
vector<int> ans;
for (int i = pc - 1; i >= 0; i--) if (i != root && v[i]
    ] != n) {
    for (int f = e[r[i]].t; f != -1 && v[f] != n; f = pa[
        f])
        v[f] = n;
    ans.push_back(r[i]);
}
return ans; // default minimize, returns edgeid array
}

```

### 3.7 Dominator Tree [ea5b7c]

```

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

```

```

    if (i) merge(i, rp[i]);
}
vector<int> p(n, -2); p[s] = -1;
for (int i = 1; i < tk; ++i)
    if (sdom[i] != dom[i]) dom[i] = dom[dom[i]];
for (int i = 1; i < tk; ++i)
    p[rev[i]] = rev[dom[i]];
return p;
} // test @ yosupo judge
}

```

### 3.8 Edge Coloring [029763]

```

// max(d_u) + 1 edge coloring, time: O(NM)
int C[kN][kN], G[kN][kN]; // 1-based, G: ans
void clear(int N) {
    for (int i = 0; i <= N; i++)
        for (int j = 0; j <= N; j++)
            C[i][j] = G[i][j] = 0;
}
void solve(vector<pair<int, int>> &E, int N) {
    int X[kN] = {}, a;
    auto update = [&](int u) {
        for (X[u] = 1; C[u][X[u]]; X[u]++);
    };
    auto color = [&](int u, int v, int c) {
        int p = G[u][v];
        G[u][v] = G[v][u] = c;
        C[u][c] = v, C[v][c] = u;
        C[u][p] = C[v][p] = 0;
        if (p) X[u] = X[v] = p;
        else update(u), update(v);
        return p;
    };
    auto flip = [&](int u, int c1, int c2) {
        int p = C[u][c1];
        swap(C[u][c1], C[u][c2]);
        if (p) G[u][p] = G[p][u] = c2;
        if (!C[u][c1]) X[u] = c1;
        if (!C[u][c2]) X[u] = c2;
        return p;
    };
    for (int i = 1; i <= N; i++) X[i] = 1;
    for (int t = 0; t < E.size(); t++) {
        auto [u, v] = E[t];
        int v0 = v, c = X[u], c0 = c, d;
        vector<pair<int, int>> L; int vst[kN] = {};
        while (!G[u][v0]) {
            L.emplace_back(v, d = X[v]);
            if (!C[v][c]) for (a=L.size()-1; a>=0; a--)
                c = color(u, L[a].first, c);
            else if (!C[u][d]) for (a=L.size()-1; a>=0; a--)
                color(u, L[a].first, L[a].second);
            else if (vst[d]) break;
            else vst[d] = 1, v = C[u][d];
        }
        if (!G[u][v0]) {
            for (; v; v = flip(v, c, d), swap(c, d));
            if (C[u][c0]) { a = int(L.size()) - 1;
                while (--a >= 0 && L[a].second != c);
                for (; a>=0; a--) color(u, L[a].first, L[a].second);
            } else t--;
        }
    }
}

```

### 3.9 Lowbit Decomposition [aa3f57]

```

class LBD {
    int timer, chains;
    vector<vector<int>> G;
    vector<int> tl, tr, chain, head, dep, pa;
    // chains : number of chain
    // tl, tr[u] : subtree interval in the seq. of u
    // head[i] : head of the chain i
    // chain[u] : chain id of the chain u is on
    void predfs(int u, int f) {
        dep[u] = dep[pa[u] = f] + 1;
        for (int v : G[u]) if (v != f) {
            predfs(v, u);
            if (lowbit(chain[u]) < lowbit(chain[v]))
                chain[u] = chain[v];
        }
        if (chain[u] == 0) chain[u] = ++chains;
    }
}

```



```

}
void dfschain(int u, int f) {
    tl[u] = timer++;
    if (head[chain[u]] == -1)
        head[chain[u]] = u;
    for (int v : G[u])
        if (v != f and chain[v] == chain[u])
            dfschain(v, u);
    for (int v : G[u])
        if (v != f and chain[v] != chain[u])
            dfschain(v, u);
    tr[u] = timer;
}
public:
LBD(int n) : timer(0), chains(0), G(n), tl(n), tr(n),
    chain(n), head(n, -1), dep(n), pa(n) {}
void add_edge(int u, int v) {
    G[u].push_back(v); G[v].push_back(u);
}
void decompose() { predfs(0, 0); dfschain(0, 0); }
PII get_subtree(int u) { return {tl[u], tr[u]}; }
vector<PII> get_path(int u, int v) {
    vector<PII> res;
    while (chain[u] != chain[v]) {
        if (dep[head[chain[u]]] < dep[head[chain[v]]])
            swap(u, v);
        int s = head[chain[u]];
        res.emplace_back(tl[s], tl[u] + 1);
        u = pa[s];
    }
    if (dep[u] < dep[v]) swap(u, v);
    res.emplace_back(tl[v], tl[u] + 1);
    return res;
}
};

```

### 3.10 Manhattan MST [df6f59]

```

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

```

### 3.11 MaximalClique [293730]

```

// contain a self loop u to u, than u won't in clique
template <size_t maxn> class MaxClique {
private:
    using bits = bitset<maxn>;
    bits popped, G[maxn], ans;
    size_t deg[maxn], deo[maxn], n;
    void sort_by_degree() {
        popped.reset();
        for (size_t i = 0; i < n; ++i)
            deg[i] = G[i].count();
        for (size_t i = 0; i < n; ++i) {
            size_t mi = maxn, id = 0;
            for (size_t j = 0; j < n; ++j)
                if (not popped[j] and deg[j] < mi)
                    mi = deg[id = j];
            popped[deo[i] = id] = 1;
            for (size_t u = G[i]._Find_first(); u < n;

```

```

        u = G[i]._Find_next(u))
            --deg[u];
    }
}
void BK(bits R, bits P, bits X) {
    if (R.count() + P.count() <= ans.count()) return;
    if (not P.count() and not X.count()) {
        if (R.count() > ans.count()) ans = R;
        return;
    }
    /* greedily choose max degree as pivot
    bits cur = P | X; size_t pivot = 0, sz = 0;
    for (size_t u = cur._Find_first();
        u < n; u = cur._Find_next(u))
        if (deg[u] > sz) sz = deg[pivot = u];
    cur = P & (~G[pivot]);
    */ // or simply choose first
    bits cur = P & (~G[P | X]._Find_first());
    for (size_t u = cur._Find_first(); u < n;
        u = cur._Find_next(u)) {
        if (R[u]) continue;
        R[u] = 1;
        BK(R, P & G[u], X & G[u]);
        R[u] = P[u] = 0, X[u] = 1;
    }
}
public:
void init(size_t n_) {
    n = n_;
    for (size_t i = 0; i < n; ++i) G[i].reset();
    ans.reset();
}
void add_edges(int u, bits S) { G[u] = S; }
void add_edge(int u, int v) { G[u][v] = G[v][u] = 1; }
int solve() {
    sort_by_degree(); // or simply iota(deo... )
    for (size_t i = 0; i < n; ++i)
        deg[i] = G[i].count();
    bits pob, nob = 0; pob.set();
    for (size_t i = n; i < maxn; ++i) pob[i] = 0;
    for (size_t i = 0; i < n; ++i) {
        size_t v = deo[i];
        bits tmp;
        tmp[v] = 1;
        BK(tmp, pob & G[v], nob & G[v]);
        pob[v] = 0, nob[v] = 1;
    }
    return static_cast<int>(ans.count());
}
};

```

### 3.12 MaximumClique [938b69]

```

constexpr int kN = 150;
struct MaxClique { // Maximum Clique
    bitset<kN> a[kN], cs[kN];
    int ans, sol[kN], q, cur[kN], d[kN], n;
    void init(int _n) {
        n = _n, ans = q = 0;
        for (int i = 0; i < n; i++) a[i].reset();
    }
    void addEdge(int u, int v) { a[u][v] = a[v][u] = 1; }
    void csort(vector<int> &r, vector<int> &c) {
        int mx = 1, km = max(ans - q + 1, 1), t = 0,
            m = int(r.size());
        cs[1].reset(); cs[2].reset();
        for (int i = 0; i < m; i++) {
            int p = r[i], k = 1;
            while ((cs[k] & a[p]).count()) k++;
            if (k > mx) cs[++mx + 1].reset();
            cs[k][p] = 1;
            if (k < km) r[t++] = p;
        }
        c.resize(m);
        if (t) c[t - 1] = 0;
        for (int k = km; k <= mx; k++) {
            for (int p = int(cs[k]._Find_first());
                p < kN; p = int(cs[k]._Find_next(p))) {
                r[t] = p; c[t++] = k;
            }
        }
    }
    void dfs(vector<int> &r, vector<int> &c, int l,

```

```

bitset<kN> mask) {
while (!r.empty()) {
    int p = r.back(); r.pop_back();
    mask[p] = 0;
    if (q + c.back() <= ans) return;
    cur[q++] = p;
    vector<int> nr, nc;
    bitset<kN> nmask = mask & a[p];
    for (int i : r)
        if (a[p][i]) nr.push_back(i);
    if (!nr.empty()) {
        if (l < 4) {
            for (int i : nr)
                d[i] = int((a[i] & nmask).count());
            sort(nr.begin(), nr.end(),
                [&](int x, int y) {
                    return d[x] > d[y];
                });
            csort(nr, nc); dfs(nr, nc, l + 1, nmask);
        } else if (q > ans) {
            ans = q; copy(cur, cur + q, sol);
        }
        c.pop_back(); q--;
    }
}

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

} graph;

```

### 3.13 Minimum Mean Cycle [e23bc0]

```

// WARNING: TYPE matters
struct Edge { int s, t; llf c; };
llf solve(vector<Edge> &e, int n) {
    // O(VE), returns inf if no cycle, mmc otherwise
    vector<VI> prv(n + 1, VI(n)), prve = prv;
    vector<vector<llf>> d(n + 1, vector<llf>(n, inf));
    d[0] = vector<llf>(n, 0);
    for (int i = 0; i < n; i++) {
        for (int j = 0; j < (int)e.size(); j++) {
            auto [s, t, c] = e[j];
            if (d[i][s] < inf && d[i + 1][t] > d[i][s] + c) {
                d[i + 1][t] = d[i][s] + c;
                prv[i + 1][t] = s; prve[i + 1][t] = j;
            }
        }
    }
    llf mmc = inf; int st = -1;
    for (int i = 0; i < n; i++) {
        llf avg = -inf;
        for (int k = 0; k < n; k++) {
            if (d[n][i] < inf - eps)
                avg = max(avg, (d[n][i] - d[k][i]) / (n - k));
            else avg = inf;
        }
        if (avg < mmc) tie(mmc, st) = tie(avg, i);
    }
    if (st == -1) return inf;
    vector<int> vst(n), eid, cycle, rho;
    for (int i = n; !vst[st]; st = prv[i--][st]) {
        vst[st]++; eid.emplace_back(prve[i][st]);
        rho.emplace_back(st);
    }
    while (vst[st] != 2) {
        int v = rho.back(); rho.pop_back();
        cycle.emplace_back(v); vst[v]++;
    }
    reverse(all(eid)); eid.resize(cycle.size());
    return mmc;
}

```

### 3.14 Mo's Algorithm on Tree

```

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

```

### 3.15 Tree Hashing [707efa]

```

llu F(llu z) { // xorshift64star from iwiwi
    z ^= z >> 12; z ^= z << 25; z ^= z >> 27;
    return z * 2685821657736338717LL;
}

llu hsah(int u, int f) {
    llu r = 127; // bigger?
    for (int v : G[u]) if (v != f) r += F(hsah(v, u));
    return F(r);
} // test @ UOJ 763

```

### 3.16 Virtual Tree [ad5cf5]

```

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

```

## 4 Matching & Flow

### 4.1 HopcroftKarp [4e7e69]

```

struct HK {
    vector<int> l, r, a, p; int ans;
    HK(int n, int m, auto &g) : l(n, -1), r(m, -1), ans(0) {
        for (bool match = true; match; ) {
            match = false; a.assign(n, -1); p = a;
            queue<int> q; int z;
            for (int i = 0; i < n; i++)
                if (l[i] == -1) q.push(a[i] = p[i] = i);
            // bitset<maxn> nvis, t; nvis.set();
            while (!q.empty()) {
                int x = q.front(); q.pop();
                if (l[a[x]] != -1) continue;
                // or use _Find_first and _Find_next here
                for (int y : g[x]) {
                    // nvis.reset(y);
                    if (r[y] == -1) {
                        while (y != -1)
                            r[y] = x, swap(l[x], y), x = p[x];
                        match = true; ans++; break;
                    } else if (p[r[y]] == -1)
                        q.push(z = r[y]), p[z] = x, a[z] = a[x];
                }
            }
        }
    }
};

```

### 4.2 Dijkstra Cost Flow [06a723]

```

template <typename F, typename C> class MCMF {
    static constexpr F INF_F = numeric_limits<F>::max();
    static constexpr C INF_C = numeric_limits<C>::max();

    struct E {
        int to, r;

```

```

F f; C c;
E() {}
E(int a, int b, F x, C y)
: to(a), r(b), f(x), c(y) {}
};
vector<vector<E>> g;
vector<pair<int, int>> f;
vector<F> up;
vector<C> d, h;
optional<pair<F, C>> step(int S, int T) {
    priority_queue<pair<C, int>> q;
    q.emplace(d[S] = 0, S), up[S] = INF_F;
    while (not q.empty()) {
        auto [l, u] = q.top(); q.pop();
        if (up[u] == 0 or l != -d[u]) continue;
        for (int i = 0; i < int(g[u].size()); ++i) {
            auto e = g[u][i]; int v = e.to;
            auto nd = d[u] + e.c + h[u] - h[v];
            if (e.f <= 0 or d[v] <= nd)
                continue;
            f[v] = {u, i};
            up[v] = min(up[u], e.f);
            q.emplace(-(d[v] = nd), v);
        }
        if (d[T] == INF_C) return nullopt;
        for (size_t i = 0; i < d.size(); i++) h[i] += d[i];
        for (int i = T; i != S; i = f[i].first) {
            auto &eg = g[f[i].first][f[i].second];
            eg.f -= up[T];
            g[eg.to][eg.r].f += up[T];
        }
        return pair{up[T], h[T]};
    }
}

public:
MCMF(int n) : g(n), f(n), up(n), d(n, INF_C), h(n) {}
void add_edge(int s, int t, F c, C w) {
    g[s].emplace_back(t, int(g[t].size()), c, w);
    g[t].emplace_back(s, int(g[s].size()) - 1, 0, -w);
}
pair<F, C> solve(int a, int b) {
    F c = 0; C w = 0;
    while (auto r = step(a, b)) {
        c += r->first, w += r->first * r->second;
        fill(d.begin(), d.end(), INF_C);
    }
    return {c, w};
}
};

```

### 4.3 Dinic [659ddd]

```

template <typename Cap = int64_t> class Dinic {
private:
    struct E { int to, rev; Cap cap; }; int n, st, ed;
    vector<vector<E>> G; vector<size_t> lv, idx;
    bool BFS() {
        lv.assign(n, 0); idx.assign(n, 0);
        queue<int> bfs; bfs.push(st); lv[st] = 1;
        while (not bfs.empty()) {
            int u = bfs.front(); bfs.pop();
            for (auto e: G[u]) if (e.cap > 0 and !lv[e.to])
                bfs.push(e.to), lv[e.to] = lv[u] + 1;
        }
        return lv[ed];
    }
    Cap DFS(int u, Cap f = numeric_limits<Cap>::max()) {
        if (u == ed) return f;
        Cap ret = 0;
        for (auto &i = idx[u]; i < G[u].size(); ++i) {
            auto &[to, rev, cap] = G[u][i];
            if (cap <= 0 or lv[to] != lv[u] + 1) continue;
            Cap nf = DFS(to, min(f, cap));
            ret += nf; cap -= nf; f -= nf;
            G[to][rev].cap += nf;
            if (f == 0) return ret;
        }
        if (ret == 0) lv[u] = 0;
        return ret;
    }
public:
    void init(int n_) { G.assign(n = n_, vector<E>()); }

```

```

void add_edge(int u, int v, Cap c) {
    G[u].push_back({v, int(G[v].size()), c});
    G[v].push_back({u, int(G[u].size())-1, 0});
}
Cap max_flow(int st_, int ed_) {
    st = st_, ed = ed_; Cap ret = 0;
    while (BFS()) ret += DFS(st);
    return ret;
}
}; // test @ luogu P3376

```

## 4.4 Flow Models

- Maximum/Minimum flow with lower bound / Circulation problem
  - Construct super source  $S$  and sink  $T$ .
  - For each edge  $(x, y, l, u)$ , connect  $x \rightarrow y$  with capacity  $u - l$ .
  - For each vertex  $v$ , denote by  $in(v)$  the difference between the sum of incoming lower bounds and the sum of outgoing lower bounds.
  - If  $in(v) > 0$ , connect  $S \rightarrow v$  with capacity  $in(v)$ , otherwise, connect  $v \rightarrow T$  with capacity  $-in(v)$ .
    - To maximize, connect  $t \rightarrow s$  with capacity  $\infty$  (skip this in circulation problem), and let  $f$  be the maximum flow from  $S$  to  $T$ . If  $f \neq \sum_{v \in V, in(v) > 0} in(v)$ , there's no solution. Otherwise, the maximum flow from  $s$  to  $t$  is the answer.
    - To minimize, let  $f$  be the maximum flow from  $S$  to  $T$ . Connect  $t \rightarrow s$  with capacity  $\infty$  and let the flow from  $S$  to  $T$  be  $f'$ . If  $f + f' \neq \sum_{v \in V, in(v) > 0} in(v)$ , there's no solution. Otherwise,  $f'$  is the answer.
  - The solution of each edge  $e$  is  $l_e + f_e$ , where  $f_e$  corresponds to the flow of edge  $e$  on the graph.
- Construct minimum vertex cover from maximum matching  $M$  on bipartite graph  $(X, Y)$ 
  - Redirect every edge:  $y \rightarrow x$  if  $(x, y) \in M, x \rightarrow y$  otherwise.
  - DFS from unmatched vertices in  $X$ .
  - $x \in X$  is chosen iff  $x$  is unvisited.
  - $y \in Y$  is chosen iff  $y$  is visited.
- Minimum cost cyclic flow
  - Construct super source  $S$  and sink  $T$
  - For each edge  $(x, y, c)$ , connect  $x \rightarrow y$  with  $(cost, cap) = (c, 1)$  if  $c > 0$ , otherwise connect  $y \rightarrow x$  with  $(cost, cap) = (-c, 1)$
  - For each edge with  $c < 0$ , sum these cost as  $K$ , then increase  $d(y)$  by 1, decrease  $d(x)$  by 1
  - For each vertex  $v$  with  $d(v) > 0$ , connect  $S \rightarrow v$  with  $(cost, cap) = (0, d(v))$
  - For each vertex  $v$  with  $d(v) < 0$ , connect  $v \rightarrow T$  with  $(cost, cap) = (0, -d(v))$
  - Flow from  $S$  to  $T$ , the answer is the cost of the flow  $C + K$
- Maximum density induced subgraph
  - Binary search on answer, suppose we're checking answer  $T$
  - Construct a max flow model, let  $K$  be the sum of all weights
  - Connect source  $s \rightarrow v, v \in G$  with capacity  $K$
  - For each edge  $(u, v, w)$  in  $G$ , connect  $u \rightarrow v$  and  $v \rightarrow u$  with capacity  $w$
  - For  $v \in G$ , connect it with sink  $v \rightarrow t$  with capacity  $K + 2T - (\sum_{e \in E(v)} w(e)) - 2w(v)$
  - $T$  is a valid answer if the maximum flow  $f < K|V|$
- Minimum weight edge cover
  - For each  $v \in V$  create a copy  $v'$ , and connect  $u' \rightarrow v'$  with weight  $w(u, v)$ .
  - Connect  $v \rightarrow v'$  with weight  $2\mu(v)$ , where  $\mu(v)$  is the cost of the cheapest edge incident to  $v$ .
  - Find the minimum weight perfect matching on  $G'$ .
- Project selection problem
  - If  $p_v > 0$ , create edge  $(s, v)$  with capacity  $p_v$ ; otherwise, create edge  $(v, t)$  with capacity  $-p_v$ .
  - Create edge  $(u, v)$  with capacity  $w$  with  $w$  being the cost of choosing  $u$  without choosing  $v$ .
  - The mincut is equivalent to the maximum profit of a subset of projects.

## 4.5 General Graph Matching [00732c]

```

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

```



```

int LCA(int x, int y, int n) {
    static int tk = 0; tk++;
    x = Find(x), y = Find(y);
    for (; ; swap(x, y)) {
        if (x != n) {
            if (v[x] == tk) return x;
            v[x] = tk;
            x = Find(pre[match[x]]);
        }
    }
}

void Blossom(int x, int y, int l) {
    while (Find(x) != l) {
        pre[x] = y, y = match[x];
        if (s[y] == 1) q.push(y), s[y] = 0;
        if (fa[x] == x) fa[x] = l;
        if (fa[y] == y) fa[y] = l;
        x = pre[y];
    }
}

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

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

```

## 4.6 Global Min-Cut [1f0306]

```

const int maxn = 500 + 5;
int w[maxn][maxn], g[maxn];
bool v[maxn], del[maxn];
void add_edge(int x, int y, int c) {
    w[x][y] += c; w[y][x] += c;
}

pair<int, int> phase(int n) {
    memset(v, false, sizeof(v));
    memset(g, 0, sizeof(g));
    int s = -1, t = -1;
    while (true) {
        int c = -1;
        for (int i = 0; i < n; ++i) {
            if (del[i] || v[i]) continue;
            if (c == -1 || g[i] > g[c]) c = i;
        }
        if (c == -1) break;
        v[s = t, t = c] = true;
        for (int i = 0; i < n; ++i) {
            if (del[i] || v[i]) continue;
            g[i] += w[c][i];
        }
    }
    return make_pair(s, t);
}

int mincut(int n) {

```

```

    int cut = 1e9;
    memset(del, false, sizeof(del));
    for (int i = 0; i < n - 1; ++i) {
        int s, t; tie(s, t) = phase(n);
        del[t] = true; cut = min(cut, g[t]);
        for (int j = 0; j < n; ++j) {
            w[s][j] += w[t][j]; w[j][s] += w[j][t];
        }
    }
    return cut;
}

```

## 4.7 GomoryHu Tree [f8938f]

```

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

```

## 4.8 Kuhn Munkres [2c09ed]

```

struct KM { // maximize, test @ UOJ 80
    int n, l, r; lld ans; // fl and fr are the match
    vector<lld> hl, hr; vector<int> fl, fr, pre, q;
    void bfs(const auto &w, int s) {
        vector<int> vl(n), vr(n); vector<lld> slk(n, INF);
        l = r = 0; vr[q[r++] = s] = true;
        const auto check = [&](int x) -> bool {
            if (vl[x] || slk[x] > 0) return true;
            vl[x] = true; slk[x] = INF;
            if (fl[x] != -1) return vr[q[r++] = fl[x]] = true;
            while (x != -1) swap(x, fr[fl[x] = pre[x]]);
            return false;
        };
        while (true) {
            while (l < r)
                for (int x = 0, y = q[l++]; x < n; ++x) if (!vl[x])
                    if (chmin(slk[x], hl[x] + hr[y] - w[x][y]))
                        if (pre[x] = y, !check(x)) return;
            lld d = ranges::min(slk);
            for (int x = 0; x < n; ++x)
                vl[x] ? hl[x] += d : slk[x] -= d;
            for (int x = 0; x < n; ++x) if (vr[x]) hr[x] -= d;
            for (int x = 0; x < n; ++x) if (!check(x)) return;
        }
    }
    KM(int n_, const auto &w) : n(n_), ans(0),
        hl(n), hr(n), fl(n, -1), fr(fl), pre(n), q(n) {
        for (int i = 0; i < n; ++i) hl[i] = ranges::max(w[i]);
        for (int i = 0; i < n; ++i) bfs(w, i);
        for (int i = 0; i < n; ++i) ans += w[i][fl[i]];
    }
};

```

## 4.9 Minimum Cost Circulation [0f0e85]

```

int vis[N], visc, fa[N], fae[N], head[N], mlc = 1;
struct ep {
    int to, next;
    ll flow, cost;
} e[M << 1];
void adde(int u, int v, ll fl, int cs) {
    e[++mlc] = {v, head[u], fl, cs};
    head[u] = mlc;
    e[++mlc] = {u, head[v], 0, -cs};
    head[v] = mlc;
}

void dfs(int u) {
    vis[u] = 1;
    for (int i = head[u], v; i; i = e[i].next)
        if (!vis[v = e[i].to] && e[i].flow)

```

```

    fa[v] = u, fae[v] = i, dfs(v);
}
ll phi(int x) {
    static ll pi[N];
    if (x == -1) return 0;
    if (vis[x] == visc) return pi[x];
    return vis[x] = visc, pi[x] = phi(fa[x]) - e[fae[x]].cost;
}
void pushflow(int x, ll &cost) {
    int v = e[x ^ 1].to, u = e[x].to;
    ++visc;
    while (v != -1) vis[v] = visc, v = fa[v];
    while (u != -1 && vis[u] != visc)
        vis[u] = visc, u = fa[u];
    vector<int> cyc;
    int e2 = 0, pa = 2;
    ll f = e[x].flow;
    for (int i = e[x ^ 1].to; i != u; i = fa[i]) {
        cyc.push_back(fae[i]);
        if (e[fae[i]].flow < f)
            f = e[fae[i2 = i] ^ (pa = 0)].flow;
    }
    for (int i = e[x].to; i != u; i = fa[i]) {
        cyc.push_back(fae[i] ^ 1);
        if (e[fae[i] ^ 1].flow < f)
            f = e[fae[i2 = i] ^ (pa = 1)].flow;
    }
    cyc.push_back(x);
    for (int cyc_i : cyc) {
        e[cyc_i].flow -= f, e[cyc_i ^ 1].flow += f;
        cost += 1ll * f * e[cyc_i].cost;
    }
    if (pa == 2) return;
    int le = x ^ pa, l = e[le].to, o = e[le ^ 1].to;
    while (l != e2) {
        vis[o] = 0;
        swap(le ^ 1, fae[o]), swap(l, fa[o]), swap(l, o);
    }
}
ll simplex() {
    ll cost = 0;
    memset(fa, -1, sizeof(fa)), dfs(1);
    vis[1] = visc = 2, fa[1] = -1;
    for (int i = 2, pre = -1; i != pre; i = (i == mlc ? 2 : i + 1))
        if (e[i].flow and e[i].cost < phi(e[i ^ 1].to) - phi(e[i].to))
            pushflow(pre = i, cost);
    return cost;
}

```

#### 4.10 Minimum Cost Max Flow [6d1b01]

```

template <typename F, typename C> class MCMF {
    static constexpr F INF_F = numeric_limits<F>::max();
    static constexpr C INF_C = numeric_limits<C>::max();
    struct E {
        int to, r;
        F f; C c;
        E() {}
        E(int a, int b, F x, C y) : to(a), r(b), f(x), c(y) {}
    };
    vector<vector<E>> g;
    vector<pair<int, int>> f;
    vector<bool> inq;
    vector<F> up; vector<C> d;
    optional<pair<F, C>> step(int S, int T) {
        queue<int> q;
        for (q.push(S), d[S] = 0, up[S] = INF_F;
            not q.empty(); q.pop()) {
            int u = q.front(); inq[u] = false;
            if (up[u] == 0) continue;
            for (int i = 0; i < int(g[u].size()); ++i) {
                auto e = g[u][i]; int v = e.to;
                if (e.f <= 0 or d[v] <= d[u] + e.c) continue;
                d[v] = d[u] + e.c; f[v] = {u, i};
                up[v] = min(up[u], e.f);
                if (not inq[v]) q.push(v);
                inq[v] = true;
            }
        }
    }
}

```

```

    }
    if (d[T] == INF_C) return nullopt;
    for (int i = T; i != S; i = f[i].first) {
        auto &eg = g[f[i].first][f[i].second];
        eg.f -= up[T];
        g[eg.to][eg.r].f += up[T];
    }
    return pair{up[T], d[T]};
}
public:
MCMF(int n) : g(n), f(n), inq(n), up(n), d(n, INF_C) {}
void add_edge(int s, int t, F c, C w) {
    g[s].emplace_back(t, int(g[t].size()), c, w);
    g[t].emplace_back(s, int(g[s].size()) - 1, 0, -w);
}
pair<F, C> solve(int a, int b) {
    F c = 0; C w = 0;
    while (auto r = step(a, b)) {
        c += r->first, w += r->first * r->second;
        fill(inq.begin(), inq.end(), false);
        fill(d.begin(), d.end(), INF_C);
    }
    return {c, w};
}
};

```

#### 4.11 Weighted Matching [60ca53]

```

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

```

```

    rotate(flo[u].begin(), flo[u].begin() + pr, flo[u].end());
}
void augment(int u, int v) {
    for (; ; ) {
        int xnv = st[match[u]];
        set_match(u, v);
        if (!xnv) return;
        set_match(xnv, st[pa[xnv]]);
        u = st[pa[xnv]], v = xnv;
    }
}
int get_lca(int u, int v) {
    static int t = 0;
    for (++t; u || v; swap(u, v)) {
        if (u == 0) continue;
        if (vis[u] == t) return u;
        vis[u] = t;
        u = st[match[u]];
        if (u) u = st[pa[u]];
    }
    return 0;
}
void add_blossom(int u, int lca, int v) {
    int b = n + 1;
    while (b <= n_x && st[b]) ++b;
    if (b > n_x) ++n_x;
    lab[b] = 0, S[b] = 0;
    match[b] = match[lca];
    flo[b].clear();
    flo[b].push_back(lca);
    for (int x = u, y; x != lca; x = st[pa[y]])
        flo[b].push_back(x), flo[b].push_back(y = st[match[x]]), q_push(y);
    reverse(flo[b].begin() + 1, flo[b].end());
    for (int x = v, y; x != lca; x = st[pa[y]])
        flo[b].push_back(x), flo[b].push_back(y = st[match[x]]), q_push(y);
    set_st(b, b);
    for (int x = 1; x <= n_x; ++x) g[b][x].w = g[x][b].w = 0;
    for (int x = 1; x <= n; ++x) flo_from[b][x] = 0;
    for (size_t i = 0; i < flo[b].size(); ++i) {
        int xs = flo[b][i];
        for (int x = 1; x <= n_x; ++x)
            if (g[b][x].w == 0 || e_delta(g[xs][x]) < e_delta(g[b][x]))
                g[b][x] = g[xs][x], g[x][b] = g[x][xs];
        for (int x = 1; x <= n; ++x)
            if (flo_from[xs][x]) flo_from[b][x] = xs;
    }
    set_slack(b);
}
void expand_blossom(int b) {
    for (size_t i = 0; i < flo[b].size(); ++i)
        set_st(flo[b][i], flo[b][i]);
    int xr = flo_from[b][g[b][pa[b]].u], pr = get_pr(b, xr);
    for (int i = 0; i < pr; i += 2) {
        int xs = flo[b][i], xns = flo[b][i + 1];
        pa[xs] = g[xns][xs].u;
        S[xs] = 1, S[xns] = 0;
        slack[xs] = 0, set_slack(xns);
        q_push(xns);
    }
    S[xr] = 1, pa[xr] = pa[b];
    for (size_t i = pr + 1; i < flo[b].size(); ++i) {
        int xs = flo[b][i];
        S[xs] = -1, set_slack(xs);
    }
    st[b] = 0;
}
bool on_found_edge(const edge &e) {
    int u = st[e.u], v = st[e.v];
    if (S[v] == -1) {
        pa[v] = e.u, S[v] = 1;
        int nu = st[match[v]];
        slack[v] = slack[nu] = 0;
        S[nu] = 0, q_push(nu);
    } else if (S[v] == 0) {
        int lca = get_lca(u, v);
        if (!lca) return augment(u, v), augment(v, u), true;
        else add_blossom(u, lca, v);
    }
    return false;
}
bool matching() {
    memset(S + 1, -1, sizeof(int) * n_x);
    memset(slack + 1, 0, sizeof(int) * n_x);
    q = queue<int>();
    for (int x = 1; x <= n_x; ++x)
        if (st[x] == x && !match[x]) pa[x] = 0, S[x] = 0, q_push(x);
    if (q.empty()) return false;
    for (; ; ) {
        while (q.size()) {
            int u = q.front(); q.pop();
            if (S[st[u]] == 1) continue;
            for (int v = 1; v <= n; ++v)
                if (g[u][v].w > 0 && st[u] != st[v]) {
                    if (e_delta(g[u][v]) == 0) {
                        if (on_found_edge(g[u][v])) return true;
                    } else update_slack(u, st[v]);
                }
        }
        int d = inf;
        for (int b = n + 1; b <= n_x; ++b)
            if (st[b] == b && S[b] == 1) d = min(d, lab[b] / 2);
        for (int x = 1; x <= n_x; ++x)
            if (st[x] == x && slack[x]) {
                if (S[x] == -1) d = min(d, e_delta(g[slack[x]][x]));
                else if (S[x] == 0) d = min(d, e_delta(g[slack[x]][x]) / 2);
            }
        for (int u = 1; u <= n; ++u) {
            if (S[st[u]] == 0) {
                if (lab[u] <= d) return 0;
                lab[u] -= d;
            } else if (S[st[u]] == 1) lab[u] += d;
        }
        for (int b = n + 1; b <= n_x; ++b)
            if (st[b] == b) {
                if (S[st[b]] == 0) lab[b] += d * 2;
                else if (S[st[b]] == 1) lab[b] -= d * 2;
            }
        q = queue<int>();
        for (int x = 1; x <= n_x; ++x)
            if (st[x] == x && slack[x] && st[slack[x]] != x && e_delta(g[slack[x]][x]) == 0)
                if (on_found_edge(g[slack[x]][x])) return true;
        for (int b = n + 1; b <= n_x; ++b)
            if (st[b] == b && S[b] == 1 && lab[b] == 0)
                expand_blossom(b);
    }
    return false;
}
pair<long long, int> solve() {
    memset(match + 1, 0, sizeof(int) * n);
    n_x = n;
    int n_matches = 0;
    long long tot_weight = 0;
    for (int u = 0; u <= n; ++u) st[u] = u, flo[u].clear();
    int w_max = 0;
    for (int u = 1; u <= n; ++u)
        for (int v = 1; v <= n; ++v) {
            flo_from[u][v] = (u == v ? u : 0);
            w_max = max(w_max, g[u][v].w);
        }
    for (int u = 1; u <= n; ++u) lab[u] = w_max;
    while (matching()) ++n_matches;
    for (int u = 1; u <= n; ++u)
        if (match[u] && match[u] < u)
            tot_weight += g[u][match[u]].w;
    return make_pair(tot_weight, n_matches);
}
void add_edge(int ui, int vi, int wi) { g[ui][vi].w = g[vi][ui].w = wi; }
void init(int _n) {
    n = _n;
    for (int u = 1; u <= n; ++u)
        for (int v = 1; v <= n; ++v)

```

```

    g[u][v] = edge(u, v, 0);
}
};

```

## 5 Math

### 5.1 Common Bounds

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

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

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

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

### 5.2 Strling Number

#### First Kind

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

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

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

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

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

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

#### Second Kind

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

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

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

### 5.3 ax+by=gcd [d0cbbd]

```

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

```

### 5.4 Chinese Remainder [d69e74]

```

// please ensure r_i \in [0, m_i)
bool crt(lld &m1, lld &r1, lld m2, lld r2) {
    if (m2 > m1) swap(m1, m2), swap(r1, r2);
    lld g, a, b; exgcd(m1, m2, g, a, b);
    if ((r2 - r1) % g != 0) return false;
    m2 /= g; lld D = (r2 - r1) / g % m2 * a % m2;
    r1 += (D < 0 ? D + m2 : D) * m1; m1 *= m2;
    assert (r1 >= 0 && r1 < m1);
    return true;
}

```

### 5.5 De-Bruijn [7f536e]

```

int res[maxn], aux[maxn], sz;
void db(int t, int p, int n, int k) {
    if (t > n) {
        if (n % p == 0)
            for (int i = 1; i <= p; ++i)
                res[sz++] = aux[i];
    } else {
        aux[t] = aux[t - p];
        db(t + 1, p, n, k);
        for (int i = aux[t - p] + 1; i < k; ++i) {
            aux[t] = i;
            db(t + 1, t, n, k);
        }
    }
}

```

```

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

```

### 5.6 DiscreteLog [86e463]

```

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

```

### 5.7 Quadratic residue [1eabad]

```

int get_root(int n, int P) { // ensure 0 <= n < p
    if (P == 2 || n == 0) return n;
    auto check = [&](int x) {
        return modpow(x, (P - 1) / 2, P);
    };
    if (check(n) != 1) return -1;
    mt19937 rnd(7122); lld z = 1, w;
    while (check(w = (z * z - n + P) % P) != P - 1)
        z = rnd() % P;
    const auto M = [P, w](auto &u, auto &v) {
        auto [a, b] = u; auto [c, d] = v;
        return make_pair((a * c + b * d % P * w) % P,
            (a * d + b * c) % P);
    };
    pair<lld, lld> r(1, 0), e(z, 1);
    for (int w = (P + 1) / 2; w; w >>= 1, e = M(e, e))
        if (w & 1) r = M(r, e);
    return r.first; // sqrt(n) mod P where P is prime
}

```

### 5.8 Extended Euler

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

### 5.9 Extended FloorSum

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

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

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

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

## 5.10 FloorSum [bda6b2]

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

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

## 5.11 ModMin [07d5e1]

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

## 5.12 Fast Fourier Transform [993ee3]

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

```
for (int i = 0; i < n; i += s) {
    for (int k = 0; k < z; ++k) {
        cplx x = v[i + z + k] * omega[maxn / s * k];
        v[i + z + k] = v[i + k] - x;
        v[i + k] = v[i + k] + x;
    }
}
}

void ifft(vector<cplx> &v, int n) {
    fft(v, n); reverse(v.begin() + 1, v.end());
    for (int i = 0; i < n; ++i) v[i] = v[i] * cplx(1. / n, 0);
}

VL convolution(const VI &a, const VI &b) {
    // Should be able to handle N <= 10^5, C <= 10^4
    int sz = 1;
    while (sz < a.size() + b.size() - 1) sz <= 1;
    vector<cplx> v(sz);
    for (int i = 0; i < sz; ++i) {
        double re = i < a.size() ? a[i] : 0;
        double im = i < b.size() ? b[i] : 0;
        v[i] = cplx(re, im);
    }
    fft(v, sz);
    for (int i = 0; i <= sz / 2; ++i) {
        int j = (sz - i) & (sz - 1);
        cplx x = (v[i] + v[j].conj()) * (v[i] - v[j].conj())
            * cplx(0, -0.25);
        if (j != i) v[j] = (v[j] + v[i].conj()) * (v[j] - v[i]
            ].conj()) * cplx(0, -0.25);
        v[i] = x;
    }
    ifft(v, sz);
    VL c(sz);
    for (int i = 0; i < sz; ++i) c[i] = round(v[i].re);
    return c;
}

VI convolution_mod(const VI &a, const VI &b, int p) {
    int sz = 1;
    while (sz + 1 < a.size() + b.size()) sz <= 1;
    vector<cplx> fa(sz), fb(sz);
    for (int i = 0; i < (int)a.size(); ++i)
        fa[i] = cplx(a[i] & ((1 << 15) - 1), a[i] >> 15);
    for (int i = 0; i < (int)b.size(); ++i)
        fb[i] = cplx(b[i] & ((1 << 15) - 1), b[i] >> 15);
    fft(fa, sz), fft(fb, sz);
    double r = 0.25 / sz;
    cplx r2(0, -1), r3(r, 0), r4(0, -r), r5(0, 1);
    for (int i = 0; i <= (sz >> 1); ++i) {
        int j = (sz - i) & (sz - 1);
        cplx a1 = (fa[i] + fa[j].conj());
        cplx a2 = (fa[i] - fa[j].conj()) * r2;
        cplx b1 = (fb[i] + fb[j].conj()) * r3;
        cplx b2 = (fb[i] - fb[j].conj()) * r4;
        if (i != j) {
            cplx c1 = (fa[j] + fa[i].conj());
            cplx c2 = (fa[j] - fa[i].conj()) * r2;
            cplx d1 = (fb[j] + fb[i].conj()) * r3;
            cplx d2 = (fb[j] - fb[i].conj()) * r4;
            fa[i] = c1 * d1 + c2 * d2 * r5;
            fb[i] = c1 * d2 + c2 * d1;
        }
        fa[j] = a1 * b1 + a2 * b2 * r5;
        fb[j] = a1 * b2 + a2 * b1;
    }
    fft(fa, sz), fft(fb, sz);
    vector<int> res(sz);
    for (int i = 0; i < sz; ++i) {
        long long a = round(fa[i].re), b = round(fb[i].re),
            c = round(fa[i].im);
        res[i] = (a + ((b % p) << 15) + ((c % p) << 30)) % p;
    }
    return res;
}
}
```

## 5.13 FWT [c5167a]

```
/* or convolution:
* x = (x0, x0+x1), inv = (x0, x1-x0) w/o final div
* and convolution:
* x = (x0+x1, x1), inv = (x0-x1, x1) w/o final div */
void fwt(int x[], int N, bool inv = false) {
    for (int d = 1; d < N; d <= 1)
```



```

for (int s = 0; s < N; s += d * 2)
    for (int i = s; i < s + d; i++) {
        int j = i + d, ta = x[i], tb = x[j];
        x[i] = modadd(ta, tb);
        x[j] = modsub(ta, tb);
    }
if (inv) {
    const int invn = modinv(N);
    for (int i = 0; i < N; i++)
        x[i] = modmul(x[i], invn);
}
}

```

## 5.14 CRT for arbitrary mod [7272c4]

```

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

```

## 5.15 NTT [946e8e]

```

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

```

## 5.16 Partition Number [9bb845]

```

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

```

## 5.17 Pi Count (+Linear Sieve) [47e0de]

```

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

```

## 5.18 Miller Rabin [0edab2]

```

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

```

## 5.19 Pollard Rho [2aclad]

```

// does not work when n is prime
// return any non-trivial factor
llu pollard_rho(llu n) {
    static auto f = [](llu x, llu k, llu m) {
        return add(k, mul(x, x, m), m);
    };
    if (!(n & 1)) return 2;
    mt19937 rnd(120821011);
}

```

```

while (true) {
    llu y = 2, yy = y, x = rnd() % n, t = 1;
    for (llu sz = 2; t == 1; sz <= 1, y = yy) {
        for (llu i = 0; t == 1 && i < sz; ++i) {
            yy = f(yy, x, n);
            t = gcd(yy > y ? yy - y : y - yy, n);
        }
    }
    if (t != 1 && t != n) return t;
}
}

```

## 5.20 Berlekamp Massey [a94d00]

```

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

```

## 5.21 Characteristic Polynomial [e006eb]

```

#define rep(x, y, z) for (int x=y; x<z; x++)
using VI = vector<int>; using VVI = vector<VI>;
void Hessenberg(VVI &H, int N) {
    for (int i = 0; i < N - 2; ++i) {
        for (int j = i + 1; j < N; ++j) if (H[j][i]) {
            rep(k, i, N) swap(H[i+1][k], H[j][k]);
            rep(k, 0, N) swap(H[k][i+1], H[k][j]);
            break;
        }
        if (!H[i + 1][i]) continue;
        for (int j = i + 2; j < N; ++j) {
            int co = mul(modinv(H[i + 1][i]), H[j][i]);
            rep(k, i, N) subeq(H[j][k], mul(H[i+1][k], co));
            rep(k, 0, N) addeq(H[k][i+1], mul(H[k][j], co));
        }
    }
}
VI CharacteristicPoly(VVI &A) {
    int N = A.size(); Hessenberg(A, N);
    VVI P(N + 1, VI(N + 1)); P[0][0] = 1;
    for (int i = 1; i <= N; ++i) {
        rep(j, 0, i+1) P[i][j] = j ? P[i-1][j-1] : 0;
        for (int j = i - 1, val = 1; j >= 0; --j) {
            int co = mul(val, A[j][i - 1]);
            rep(k, 0, j+1) subeq(P[i][k], mul(P[j][k], co));
            if (j) val = mul(val, A[j][j - 1]);
        }
    }
    if (N & 1) for (int &pi : P[N]) pi = sub(0, pi);
    return P[N]; // test: 2021 PTZ Korea K
}

```

## 5.22 Polynomial Operations [d40491]

```

using V = vector<int>;
#define fi(l, r) for (int i = int(l); i < int(r); ++i)
template <int mod, int G, int maxn> struct Poly : V {
    static uint32_t n2k(uint32_t n) {
        if (n <= 1) return 1;
        return 1u << (32 - __builtin_clz(n - 1));
    }
    static NTT<mod, G, maxn> ntt; // coefficients in [0, P)
    explicit Poly(int n = 1) : V(n) {}
    Poly(const V &v) : V(v) {}
    Poly(const Poly &p, size_t n) : V(n) {
        copy_n(p.data(), min(p.size(), n), data());
    }
}

```

```

}
Poly &irev() { return reverse(data(), data() + size())
    , *this; }
Poly &isz(int sz) { return resize(sz), *this; }
Poly &iadd(const Poly &rhs) { // n() == rhs.n()
    fi(0, size())(*this)[i] = modadd((*this)[i], rhs[i]);
    return *this;
}
Poly &imul(int k) {
    fi(0, size())(*this)[i] = modmul((*this)[i], k);
    return *this;
}
Poly Mul(const Poly &rhs) const {
    const int sz = n2k(size() + rhs.size() - 1);
    Poly X(*this, sz), Y(rhs, sz);
    ntt(X.data(), sz), ntt(Y.data(), sz);
    fi(0, sz) X[i] = modmul(X[i], Y[i]);
    ntt(X.data(), sz, true);
    return X.isz(size() + rhs.size() - 1);
}
Poly Inv() const { // coef[0] != 0
    if (size() == 1) return V{modinv(*begin())};
    const int sz = n2k(size() * 2);
    Poly X = Poly(*this, (size() + 1) / 2).Inv().isz(sz),
        Y(*this, sz);
    ntt(X.data(), sz), ntt(Y.data(), sz);
    fi(0, sz) X[i] = modmul(X[i], modsub(2, modmul(X[i],
        Y[i])));
    ntt(X.data(), sz, true);
    return X.isz(size());
}
Poly Sqrt() const { // coef[0] \in [1, mod)^2
    if (size() == 1) return V{QuadraticResidue(*this)
        [0], mod});
    Poly X = Poly(*this, (size() + 1) / 2).Sqrt().isz(
        size());
    return X.iadd(Mul(X.Inv()).isz(size())).imul(mod / 2
        + 1);
}
pair<Poly, Poly> DivMod(const Poly &rhs) const {
    if (size() < rhs.size()) return {V{0}, *this};
    const int sz = size() - rhs.size() + 1;
    Poly X(rhs); X.irev().isz(sz);
    Poly Y(*this); Y.irev().isz(sz);
    Poly Q = Y.Mul(X.Inv()).isz(sz).irev();
    X = rhs.Mul(Q), Y = *this;
    fi(0, size()) Y[i] = modsub(Y[i], X[i]);
    return {Q, Y.isz(max<int>(1, rhs.size() - 1))};
}
Poly Dx() const {
    Poly ret(size() - 1);
    fi(0, ret.size()) ret[i] = modmul(i + 1, (*this)[i +
        1]);
    return ret.isz(max<int>(1, ret.size()));
}
Poly Sx() const {
    Poly ret(size() + 1);
    fi(0, size()) ret[i + 1] = modmul(modinv(i + 1), (*
        this)[i]);
    return ret;
}
Poly Ln() const { // coef[0] == 1; res[0] == 0
    return Dx().Mul(Inv()).Sx().isz(size());
}
Poly Exp() const { // coef[0] == 0; res[0] == 1
    if (size() == 1) return V{1};
    Poly X = Poly(*this, (size() + 1) / 2).Exp().isz(size
        ());
    Poly Y = X.Ln(); Y[0] = mod - 1;
    fi(0, size()) Y[i] = modsub((*this)[i], Y[i]);
    return X.Mul(Y).isz(size());
}
Poly Pow(const string &K) const {
    int nz = 0;
    while (nz < size() && !(*this)[nz]) ++nz;
    int nk = 0, nk2 = 0;
    for (char c : K) {
        nk = (nk * 10 + c - '0') % mod;
        nk2 = nk2 * 10 + c - '0';
        if (nk2 * nz >= size())
            return Poly(size());
        nk2 %= mod - 1;
    }
}

```

```

}
if (!nk && !nk2) return Poly(V{1}, size());
Poly X = V(data() + nz, data() + size() - nz * (nk2 - 1));
int x0 = X[0];
return X.imul(modinv(x0)).Ln().imul(nk).Exp().imul(modpow(x0, nk2)).irev().isz(size()).irev();
}
V Eval(V x) const {
if (x.empty()) return {};
const size_t n = max(x.size(), size());
vector<Poly> t(n * 2, V{1, 0}), f(n * 2);
for (size_t i = 0; i < x.size(); ++i)
t[n + i] = V{1, mod-x[i]};
for (size_t i = n - 1; i > 0; --i)
t[i] = t[i * 2].Mul(t[i * 2 + 1]);
f[1] = Poly(*this, n).irev().Mul(t[1].Inv()).isz(n).irev();
for (size_t i = 1; i < n; ++i) {
auto o = f[i]; auto sz = o.size();
f[i*2] = o.irev().Mul(t[i*2+1]).isz(sz).irev().isz(t[i*2].size());
f[i*2+1] = o.Mul(t[i*2]).isz(sz).irev().isz(t[i*2+1].size());
}
for (size_t i=0; i<x.size(); ++i) x[i] = f[n+i][0];
return x;
}

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

```

## 5.23 Simplex [e975d5]

```

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

```

```

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

```

## 5.24 Simplex Construction

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

1. In case of minimization, let  $c'_i = -c_i$
2.  $\sum_{1 \leq i \leq n} A_{ji} x_i \geq b_j \rightarrow \sum_{1 \leq i \leq n} -A_{ji} x_i \leq -b_j$
3.  $\sum_{1 \leq i \leq n} A_{ji} x_i = b_j$ 
  - $\sum_{1 \leq i \leq n} A_{ji} x_i \leq b_j$
  - $\sum_{1 \leq i \leq n} A_{ji} x_i \geq b_j$

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

## 5.25 Adaptive Simpson [09669e]

```

llf simp(llf l, llf r) {
llf m = (l + r) / 2;
return (f(l) + f(r) + 4.0 * f(m)) * (r - l) / 6.0;
}
llf F(llf L, llf R, llf v, llf eps) {
llf M = (L + R) / 2, vl = simp(L, M), vr = simp(M, R);
if (abs(vl + vr - v) <= 15 * eps)
return vl + vr + (vl + vr - v) / 15.0;
return F(L, M, vl, eps / 2.0) +
F(M, R, vr, eps / 2.0);
} // call F(l, r, simp(l, r), 1e-6)

```

# 6 Geometry

## 6.1 Basic Geometry [17fa9b]

```

#define IM imag
#define RE real
using lld = int64_t;
using llf = long double;
using PT = std::complex<lld>;
using PTF = std::complex<llf>;
using P = PT;
llf abs(P p) { return sqrtl(norm(p)); }
PTF toPTF(PT p) { return PTF{RE(p), IM(p)}; }
int sgn(lld x) { return (x > 0) - (x < 0); }
lld dot(P a, P b) { return RE(conj(a) * b); }
lld cross(P a, P b) { return IM(conj(a) * b); }
int ori(P a, P b, P c) {
return sgn(cross(b - a, c - a));
}
int quad(P p) {
return (IM(p) == 0) // use sgn for PTF

```

```

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

```

## 6.2 2D Convex Hull [ecba37]

```

// from NaCl, counterclockwise, be careful of n<=2
vector<P> convex_hull(vector<P> v) {
    sort(all(v)); // by X then Y
    if (v[0] == v.back()) return {v[0]};
    int t = 0, s = 1; vector<P> h(v.size() + 1);
    for (int _ = 2; _--; s = t--, reverse(all(v)))
        for (P p : v) {
            while (t > s && ori(p, h[t-1], h[t-2]) >= 0) t--;
            h[t++] = p;
        }
    return h.resize(t), h;
}

```

## 6.3 2D Farthest Pair [8b5844]

```

// p is CCW convex hull w/o colinear points
int n = (int)p.size(), pos = 1; llf ans = 0;
for (int i = 0; i < n; i++) {
    P e = p[(i + 1) % n] - p[i];
    while (cross(e, p[(pos + 1) % n] - p[i]) >
            cross(e, p[pos] - p[i]))
        pos = (pos + 1) % n;
    for (int j: {i, (i + 1) % n})
        ans = max(ans, norm(p[pos] - p[j]));
} // tested @ A0J CGL_4_B

```

## 6.4 MinMax Enclosing Rect [e4470c]

```

// from 8BQube, plz ensure p is strict convex hull
const llf INF = 1e18, qi = acos(-1) / 2 * 3;
pair<llf, llf> solve(const vector<P> &p) {
    llf mx = 0, mn = INF; int n = (int)p.size();
    for (int i = 0, u = 1, r = 1, l = 1; i < n; ++i) {
#define Z(v) (p[(v) % n] - p[i])
        P e = Z(i + 1);
        while (cross(e, Z(u + 1)) > cross(e, Z(u))) ++u;
        while (dot(e, Z(r + 1)) > dot(e, Z(r))) ++r;
        if (!i) l = r + 1;
        while (dot(e, Z(l + 1)) < dot(e, Z(l))) ++l;
        P D = p[r % n] - p[l % n];
        llf H = cross(e, Z(u)) / llf(norm(e));
        mn = min(mn, dot(e, D) * H);
        llf B = sqrt(norm(D)) * sqrt(norm(Z(u)));
        llf deg = (qi - acos(dot(D, Z(u)) / B)) / 2;
        mx = max(mx, B * sin(deg) * sin(deg));
    }
    return {mn, mx};
} // test @ UVA 819

```

## 6.5 Minkowski Sum [602806]

```

// A, B are strict convex hull rotate to min by (X, Y)
vector<P> Minkowski(vector<P> A, vector<P> B) {
    const int N = (int)A.size(), M = (int)B.size();
    vector<P> sa(N), sb(M), C(N + M + 1);
    for (int i = 0; i < N; i++) sa[i] = A[(i+1)%N] - A[i];
    for (int i = 0; i < M; i++) sb[i] = B[(i+1)%M] - B[i];
    C[0] = A[0] + B[0];
    for (int i = 0, j = 0; i < N || j < M; ) {
        P e = (j>=M || (i<N && cross(sa[i], sb[j])>=0))
            ? sa[i++] : sb[j++];
        C[i + j] = e;
    }
    partial_sum(all(C), C.begin()); C.pop_back();
}

```

```

return convex_hull(C); // just to remove colinear
}

```

## 6.6 Segment Intersection [60d016]

```

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

```

## 6.7 Half Plane Intersection [e98068]

```

struct Line {
    P st, ed, dir;
    Line(P s, P e) : st(s), ed(e), dir(e - s) {}
}; using L = const Line &;
PTF intersect(L A, L B) {
    llf t = cross(B.st - A.st, B.dir) /
        llf(cross(A.dir, B.dir));
    return toPTF(A.st) + toPTF(A.dir) * t; // C^3 / C^2
}
bool cov(L l, L A, L B) {
    i128 u = cross(B.st - A.st, B.dir);
    i128 v = cross(A.dir, B.dir);
    // ori(l.st, l.ed, A.st + A.dir*(u/v)) <= 0?
    i128 x = RE(A.dir) * u + RE(A.st - l.st) * v;
    i128 y = IM(A.dir) * u + IM(A.st - l.st) * v;
    return sgn(x*IM(l.dir) - y*RE(l.dir)) * sgn(v) >= 0;
} // x, y are C^3, also sgn<i128> is needed
bool operator<(L a, L b) {
    if (int c = argCmp(a.dir, b.dir)) return c == -1;
    return ori(a.st, a.ed, b.st) < 0;
}
// cross(pt-line.st, line.dir)<=0 <-> pt in half plane
// the half plane is the LHS when going from st to ed
llf HPI(vector<Line> &q) {
    sort(q.begin(), q.end());
    int n = (int)q.size(), l = 0, r = -1;
    for (int i = 0; i < n; i++) {
        if (i && !argCmp(q[i].dir, q[i-1].dir)) continue;
        while (l < r && cov(q[i], q[r-1], q[r])) --r;
        while (l < r && cov(q[i], q[l], q[l+1])) ++l;
        q[++r] = q[i];
    }
    while (l < r && cov(q[l], q[r-1], q[r])) --r;
    while (l < r && cov(q[r], q[l], q[l+1])) ++l;
    n = r - l + 1; // q[l .. r] are the lines
    if (n <= 1 || !argCmp(q[l].dir, q[r].dir)) return 0;
    vector<PTF> pt(n);
    for (int i = 0; i < n; i++)
        pt[i] = intersect(q[i+l], q[(i+1)%n+l]);
    return area(pt);
} // test @ 2020 Nordic NCP C : BigBrother

```

## 6.8 SegmentDist (Sausage) [9d8603]

```

// be careful of abs<complex<int>> (replace _abs below)
llf PointSegDist(P A, Seg B) {
    if (B.dir == P(0)) return _abs(A - B.st);
    if (sgn(dot(A - B.st, B.dir)) *
        sgn(dot(A - B.ed, B.dir)) <= 0)

```

```

    return abs(cross(A - B.st, B.dir)) / _abs(B.dir);
    return min(_abs(A - B.st), _abs(A - B.ed));
}
llf SegSegDist(const Seg &s1, const Seg &s2) {
    if (isInter(s1, s2)) return 0;
    return min({
        PointSegDist(s1.st, s2),
        PointSegDist(s1.ed, s2),
        PointSegDist(s2.st, s1),
        PointSegDist(s2.ed, s1) });
} // test @ QOJ2444 / PTZ19 Summer.D3

```

## 6.9 Rotating Sweep Line [1d9b4d]

```

void rotatingSweepLine(P a[], int n) {
    vector<pair<int, int>> ls; ls.reserve(n*(n-1)/2);
    for (int i = 0; i < n; ++i)
        for (int j = i + 1; j < n; ++j)
            ls.emplace_back(i, j);
    sort(all(ls), [&a](auto &u, auto &v){
        P zu = a[u.first] - a[u.second];
        P zv = a[v.first] - a[v.second];
        int s = sgn(RE(zu)) * sgn(RE(zv));
        if (s == 0) return RE(zu) != 0;
        return sgn(cross(zu, zv)) * s > 0;
    });
    vector<int> idx(n), p(n);
    iota(all(idx), 0);
    sort(all(idx), [&a](int i, int j) {
        return cmpxy(a[i], a[j]); });
    for (int i = 0; i < n; ++i) p[idx[i]] = i;
    for (auto [i, j]: ls) {
        // do here
        assert (abs(p[i] - p[j]) == 1);
        swap(p[i], p[j]); idx[p[i]] = i; idx[p[j]] = j;
    } // consider swap same slope together?
}

```

## 6.10 Point In Simple Polygon [037c52]

```

bool PIP(const vector<P> &p, P z, bool strict = true) {
    int cnt = 0, n = (int)p.size();
    for (int i = 0; i < n; i++) {
        P A = p[i], B = p[(i + 1) % n];
        if (isInter(Seg(A, B), z)) return !strict;
        auto zy = IM(z), Ay = IM(A), By = IM(B);
        cnt ^= ((zy < Ay) - (zy < By)) * ori(z, A, B) > 0;
    }
    return cnt;
}

```

## 6.11 Point In Hull (Fast) [060ba1]

```

bool PIH(const vector<P> &h, P z, bool strict = true) {
    int n = (int)h.size(), a = 1, b = n - 1, r = !strict;
    if (n < 3) return r && isInter(Seg(h[0], h[n-1]), z);
    if (ori(h[0], h[a], h[b]) > 0) swap(a, b);
    if (ori(h[0], h[a], z) >= r || ori(h[0], h[b], z) <= -r)
        return false;
    while (abs(a - b) > 1) {
        int c = (a + b) / 2;
        (ori(h[0], h[c], z) > 0 ? b : a) = c;
    }
    return ori(h[a], h[b], z) < r;
}

```

## 6.12 Tangent of Points To Hull [6d7cd7]

```

pair<int, int> get_tangent(const vector<P> &v, P p) {
    const auto gao = [&, N = (int)(v.size())](int s) {
        const auto lt = [&](int x, int y) {
            return ori(p, v[x % N], v[y % N]) == s; };
        int l = 0, r = N; bool up = lt(0, 1);
        while (r - l > 1) {
            int m = (l + r) / 2;
            if (lt(m, 0) ? up : !lt(m, m+1)) r = m;
            else l = m;
        }
        return (lt(l, r) ? r : l) % N;
    }; // test @ codeforces.com/gym/101201/problem/E
    return {gao(-1), gao(1)}; // (a,b):ori(p,v[a],v[b])<0
} // plz ensure that point strictly out of hull

```

## 6.13 Circle Class & Intersection [5111af]

```

llf FMOD(llf x) {
    if (x < -PI) x += PI * 2;
    if (x > PI) x -= PI * 2;
    return x;
}
struct Cir { PTF o; llf r; };
// be careful when tangent
vector<llf> intersectAngle(Cir a, Cir b) {
    llf dis = b.o - a.o; llf d2 = norm(dis);
    if (norm(a.r - b.r) >= d2) { // norm(x) := |x|^2
        if (a.r < b.r) return {-PI, PI}; // a in b
        else return {}; // b in a
    } else if (norm(a.r + b.r) <= d2) return {};
    llf dis = abs(dis), theta = arg(dis);
    llf phi = acos((a.r * a.r + d2 - b.r * b.r) /
        (2 * a.r * dis)); // is acos_safe needed?
    llf L = FMOD(theta - phi), R = FMOD(theta + phi);
    return {L, R};
}
vector<PTF> intersectPoint(Cir a, Cir b) {
    llf d = abs(a.o - b.o);
    if (d > b.r + a.r || d < abs(b.r - a.r)) return {};
    llf dt = (b.r * b.r - a.r * a.r) / d, d1 = (d + dt) / 2;
    PTF dir = (a.o - b.o) / d;
    PTF u = dir * d1 + b.o;
    PTF v = rot90(dir) * sqrt(max(0.0L, b.r * b.r - d1 * d1));
    return {u + v, u - v};
} // test @ AOJ CGL probs

```

## 6.14 Circle Common Tangent [5ff02c]

```

// be careful of tangent / exact same circle
// sign1 = 1 for outer tang, -1 for inner tang
vector<Line> common_tan(const Cir &a, const Cir &b, int
    sign1) {
    if (norm(a.o - b.o) < eps) return {};
    llf d = abs(a.o - b.o), c = (a.r - sign1 * b.r) / d;
    PTF v = (b.o - a.o) / d;
    if (c * c > 1) return {};
    if (abs(c * c - 1) < eps) {
        PTF p = a.o + c * v * a.r;
        return {Line(p, p + rot90(b.o - a.o))};
    }
    vector<Line> ret; llf h = sqrt(max(0.0L, 1 - c * c));
    for (int sign2 : {1, -1}) {
        PTF n = c * v + sign2 * h * rot90(v);
        PTF p1 = a.o + n * a.r;
        PTF p2 = b.o + n * (b.r * sign1);
        ret.emplace_back(p1, p2);
    }
    return ret;
}

```

## 6.15 Line-Circle Intersection [12b42a]

```

vector<PTF> LineCircleInter(PTF p1, PTF p2, PTF o, llf
    r) {
    PTF ft = p1 + project(o - p1, p2 - p1), vec = p2 - p1;
    llf dis = abs(o - ft);
    if (abs(dis - r) < eps) return {ft};
    if (dis > r) return {};
    vec = vec * sqrt(r * r - dis * dis) / abs(vec);
    return {ft + vec, ft - vec}; // sqrt_safe?
}

```

## 6.16 Poly-Circle Intersection [7f140a]

```

// Divides into multiple triangle, and sum up
// from 8BQube, test by HDU2892 & AOJ CGL_7_H
llf _area(PTF pa, PTF pb, llf r) {
    if (abs(pa) < abs(pb)) swap(pa, pb);
    if (abs(pb) < eps) return 0;
    llf S, h, theta;
    llf a = abs(pb), b = abs(pa), c = abs(pb - pa);
    llf cB = dot(pb, pb - pa) / a / c, B = acos_safe(cB);
    llf cC = dot(pa, pb) / a / b, C = acos_safe(cC);
    if (a > r) {
        S = (C / 2) * r * r; h = a * b * sin(C) / c;
        if (h < r && B < PI / 2)
            S -= (acos_safe(h/r) * r * r - h * sqrt_safe(r * r - h * h));
    } else if (b > r) {
        theta = PI - B - asin_safe(sin(B) / r * a);
        S = 0.5 * a * r * sin(theta) + (C - theta) / 2 * r * r;
    }
}

```



```

} else
    S = 0.5 * sin(C) * a * b;
return S;
}
llf area_poly_circle(const vector<PTF> &v, PTF O, llf r
    ) {
    llf S = 0;
    for (size_t i = 0, N = v.size(); i < N; ++i)
        S += _area(v[i] - O, v[(i + 1) % N] - O, r) *
            ori(O, v[i], v[(i + 1) % N]);
    return abs(S);
}

```

### 6.17 Minimum Covering Circle [f549d4]

```

Cir getCircum(P a, P b, P c) { // P = complex<llf>
    P z1 = a - b, z2 = a - c; llf D = cross(z1, z2) * 2;
    llf c1 = dot(a + b, z1), c2 = dot(a + c, z2);
    P o = rot90(c2 * z1 - c1 * z2) / D;
    return { o, abs(o - a) };
}
Cir minCircleCover(vector<P> &pts) {
    assert (!pts.empty());
    ranges::shuffle(pts, mt19937(114514));
    Cir c = { 0, 0 };
    for (size_t i = 0; i < pts.size(); i++) {
        if (dist(pts[i], c.o) <= c.r) continue;
        c = { pts[i], 0 };
        for (size_t j = 0; j < i; j++) {
            if (dist(pts[j], c.o) <= c.r) continue;
            c.o = (pts[i] + pts[j]) / llf(2);
            c.r = dist(pts[i], c.o);
            for (size_t k = 0; k < j; k++) {
                if (dist(pts[k], c.o) <= c.r) continue;
                c = getCircum(pts[i], pts[j], pts[k]);
            }
        }
    }
    return c;
} // test @ TIOJ 1093 & luogu P1742

```

### 6.18 Circle Union [1a5265]

```

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

```

```

            sort(eve.begin(), eve.end());
            eve.eb(eve[0]); eve.back().a += PI * 2;
            for (size_t j = 0; j + 1 < eve.size(); j++) {
                cnt += eve[j].add;
                area[cnt] += cross(eve[j].p, eve[j+1].p) * .5;
                llf t = eve[j + 1].a - eve[j].a;
                area[cnt] += (t - sin(t)) * c[i].r * c[i].r * .5;
            }
        }
    }
    return area;
}

```

### 6.19 Polygon Union [2bff43]

```

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

```

### 6.20 3D Convex Hull [93b153]

```

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

```

```

}
now = next;
}
return now;
}
// delaunay: facets with negative z normal of
// convexhull of (x, y, x^2 + y^2)

```

## 6.21 Delaunay [7f0d57f]

```

/* A triangulation such that no points will strictly
inside circumcircle of any triangle.
find(root, p) : return a triangle contain given point
add_point : add a point into triangulation
Region of triangle u: iterate each u.e[i].tri,
each points are u.p[(i+1)%3], u.p[(i+2)%3]
Voronoi diagram: for each triangle in `res`,
the bisector of all its edges will split the region. */
#define L(i) ((i)==0 ? 2 : (i)-1)
#define R(i) ((i)==2 ? 0 : (i)+1)
#define F3 for (int i = 0; i < 3; i++)
bool in_cc(const array<P,3> &p, P q) {
    i128 det = 0;
    F3 det += i128(norm(p[i]) - norm(q)) *
        cross(p[R(i)] - q, p[L(i)] - q);
    return det > 0;
}
struct Tri;
struct E {
    Tri *t; int side; E() : t(0), side(0) {}
    E(Tri *t_, int side_) : t(t_), side(side_) {}
};
struct Tri {
    array<P,3> p; array<Tri*,3> ch; array<E,3> e;
    Tri(P a = 0, P b = 0, P c = 0) : p{a, b, c}, ch{} {}
    bool has_chd() const { return ch[0] != nullptr; }
    bool contains(P q) const {
        F3 if (ori(p[i], p[R(i)], q) < 0) return false;
        return true;
    }
}
pool[maxn * 10], *it;
void link(E a, E b) {
    if (a.t) a.t->e[a.side] = b;
    if (b.t) b.t->e[b.side] = a;
}
struct Trigs {
    Tri *root;
    Trigs() { // should at least contain all points
        root = // C = 100*MAXC^2 or just MAXC?
            new(it++) Tri(P(-C, -C), P(C*2, -C), P(-C, C*2));
    }
    void add_point(P p) { add_point(find(p, root), p); }
    static Tri* find(P p, Tri *r) {
        while (r->has_chd()) for (Tri *c: r->ch)
            if (c && c->contains(p)) { r = c; break; }
        return r;
    }
    void add_point(Tri *r, P p) {
        array<Tri*, 3> t; /* split into 3 triangles */
        F3 t[i] = new(it++) Tri(r->p[i], r->p[R(i)], p);
        F3 link(E(t[i], 0), E(t[R(i)], 1));
        F3 link(E(t[i], 2), r->e[L(i)]);
        r->ch = t;
        F3 flip(t[i], 2);
    }
    void flip(Tri* A, int a) {
        auto [B, b] = A->e[a]; /* flip edge between A,B */
        if (!B || !in_cc(A->p, B->p[b])) return;
        Tri *X = new(it++)Tri(A->p[R(a)],B->p[b],A->p[a]);
        Tri *Y = new(it++)Tri(B->p[R(b)],A->p[a],B->p[b]);
        link(E(X,0), E(Y,0));
        link(E(X,1), A->e[L(a)]); link(E(X,2), B->e[R(b)]);
        link(E(Y,1), B->e[L(b)]); link(E(Y,2), A->e[R(a)]);
        A->ch = B->ch = {X, Y, nullptr};
        flip(X, 1); flip(X, 2); flip(Y, 1); flip(Y, 2);
    }
};
vector<Tri*> res; set<Tri*> vis;
void go(Tri *now) { // store all tri into res
    if (!vis.insert(now).second) return;
    if (!now->has_chd()) return res.push_back(now);
    for (Tri *c: now->ch) if (c) go(c);
}

```

```

void build(vector<P> ps) {
    it = pool; res.clear(); vis.clear();
    shuffle(ps.begin(), ps.end(), mt19937(114514));
    Trigs tr; for (P p: ps) tr.add_point(p);
    go(tr.root); // use `res` afterwards
}

```

## 6.22 kd Tree (Nearest Point) [dbade8f]

```

struct KDTree {
    struct Node {
        int x, y, x1, y1, x2, y2, id, f; Node *L, *R;
    } tree[maxn], *root;
    lld dis2(int x1, int y1, int x2, int y2) {
        lld dx = x1 - x2, dy = y1 - y2;
        return dx * dx + dy * dy;
    }
    static bool cmpx(Node& a, Node& b){return a.x<b.x;}
    static bool cmpy(Node& a, Node& b){return a.y<b.y;}
    void init(vector<pair<int,int>> &ip) {
        const int n = ip.size();
        for (int i = 0; i < n; i++) {
            tree[i].id = i;
            tree[i].x = ip[i].first;
            tree[i].y = ip[i].second;
        }
        root = build(0, n-1, 0);
    }
    Node* build(int L, int R, int d) {
        if (L>R) return nullptr; int M = (L+R)/2;
        nth_element(tree+L, tree+M, tree+R+1, d%2?cmpy:cmpx);
        Node &o = tree[M]; o.f = d % 2;
        o.x1 = o.x2 = o.x; o.y1 = o.y1 = o.y;
        o.L = build(L, M-1, d+1); o.R = build(M+1, R, d+1);
        for (Node *s: {o.L, o.R}) if (s) {
            o.x1 = min(o.x1, s->x1); o.x2 = max(o.x2, s->x2);
            o.y1 = min(o.y1, s->y1); o.y2 = max(o.y2, s->y2);
        }
        return tree+M;
    }
    bool touch(int x, int y, lld d2, Node *r){
        lld d = sqrt(d2)+1;
        return x >= r->x1 - d && x <= r->x2 + d &&
            y >= r->y1 - d && y <= r->y2 + d;
    }
    using P = pair<lld, int>;
    void dfs(int x, int y, P &mn, Node *r) {
        if (!r || !touch(x, y, mn.first, r)) return;
        mn = min(mn, P(dis2(r->x, r->y, x, y), r->id));
        if (r->f == 1 ? y < r->y : x < r->x)
            dfs(x, y, mn, r->L), dfs(x, y, mn, r->R);
        else
            dfs(x, y, mn, r->R), dfs(x, y, mn, r->L);
    }
    int query(int x, int y) {
        P mn(INF, -1); dfs(x, y, mn, root);
        return mn.second;
    }
} tree;

```

## 6.23 kd Closest Pair (3D ver.) [84d9eb]

```

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

```

```

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

```

## 6.24 Simulated Annealing [4e0fe5]

```

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

```

## 6.25 Triangle Centers [adb146]

```

O = ... // see min circle cover
G = (A + B + C) / 3;
H = G * 3 - O * 2; // orthogonal center
llf a = abs(B - C), b = abs(A - C), c = abs(A - B);
I = (a * A + b * B + c * C) / (a + b + c);
// FermatPoint: minimizes sum of distance
// if max. angle >= 120 deg then vertex
// otherwise, make eq. triangle AB'C, CA'B, BC'A
// line AA', BB', CC' intersects at P

```

# 7 Stringology

## 7.1 Hash [7afe3e]

```

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

```

## 7.2 Suffix Array [2846f0]

```

namespace sfx {
    bool _t[maxn * 2];
    int hi[maxn], rev[maxn];
    int _s[maxn * 2], sa[maxn * 2], _c[maxn * 2];
    int x[maxn], _p[maxn], _q[maxn * 2];
    // sa[i]: sa[i]-th suffix is the
    // i-th lexicographically smallest suffix.
    // hi[i]: longest common prefix
    // of suffix sa[i] and suffix sa[i - 1].
    void pre(int *a, int *c, int n, int z) {
        memset(a, 0, sizeof(int) * n);
    }
}

```

```

memcpy(x, c, sizeof(int) * z);
}
void induce(int *a, int *c, int *s, bool *t, int n, int z) {
    memcpy(x + 1, c, sizeof(int) * (z - 1));
    for (int i = 0; i < n; ++i)
        if (a[i] && !t[a[i] - 1])
            a[x[s[a[i] - 1]]++] = a[i] - 1;
    memcpy(x, c, sizeof(int) * z);
    for (int i = n - 1; i >= 0; --i)
        if (a[i] && t[a[i] - 1])
            a[--x[s[a[i] - 1]]] = a[i] - 1;
}
void sais(int *s, int *a, int *p, int *q,
    bool *t, int *c, int n, int z) {
    bool uniq = t[n - 1] = true;
    int nn=0, nmzx=-1, *nsa = a+n, *ns=s+n, last=-1;
    memset(c, 0, sizeof(int) * z);
    for (int i = 0; i < n; ++i) uniq &= ++c[s[i]] < 2;
    for (int i = 0; i < z - 1; ++i) c[i + 1] += c[i];
    if (uniq) {
        for (int i = 0; i < n; ++i) a[--c[s[i]]] = i;
        return;
    }
    for (int i = n - 2; i >= 0; --i)
        t[i] = (s[i]==s[i + 1] ? t[i + 1] : s[i]<s[i + 1]);
    pre(a, c, n, z);
    for (int i = 1; i <= n - 1; ++i)
        if (t[i] && !t[i - 1])
            a[--x[s[i]]] = p[q[i] = nn++] = i;
    induce(a, c, s, t, n, z);
    for (int i = 0; i < n; ++i) {
        if (a[i] && t[a[i]] && !t[a[i] - 1]) {
            bool neq = last < 0 ||
                memcmp(s + a[i], s + last,
                    (p[q[a[i]] + 1] - a[i]) * sizeof(int));
            ns[q[last = a[i]]] = nmzx += neq;
        }
    }
    sais(ns, nsa, p+nn, q+n, t+n, c+z, nn, nmzx+1);
    pre(a, c, n, z);
    for (int i = nn - 1; i >= 0; --i)
        a[--x[s[p[nsa[i]]]]] = p[nsa[i]];
    induce(a, c, s, t, n, z);
}
void build(const string &s) {
    const int n = int(s.size());
    for (int i = 0; i < n; ++i) _s[i] = s[i];
    _s[n] = 0; // s shouldn't contain 0
    sais(_s, sa, _p, _q, _t, _c, n + 1, 256);
    for (int i = 0; i < n; ++i) rev[sa[i]] = sa[i+1] = i;
    int ind = hi[0] = 0;
    for (int i = 0; i < n; ++i) {
        if (!rev[i]) {
            ind = 0;
            continue;
        }
        while (i + ind < n &&
            s[i + ind] == s[sa[rev[i] - 1] + ind]) ++ind;
        hi[rev[i]] = ind ? ind - 1 : 0;
    }
}

```

## 7.3 Ex SAM [58374b]

```

struct exSAM {
    int len[maxn * 2], link[maxn * 2]; // maxlen, suflink
    int next[maxn * 2][maxc], tot; // [0, tot), root = 0
    int ord[maxn * 2]; // topo. order (sort by length)
    int cnt[maxn * 2]; // occurrence
    int newnode() {
        fill_n(next[tot], maxc, 0);
        return len[tot] = cnt[tot] = link[tot] = 0, tot++;
    }
    void init() { tot = 0, newnode(), link[0] = -1; }
    int insertSAM(int last, int c) {
        int cur = next[last][c];
        len[cur] = len[last] + 1;
        int p = link[last];
        while (p != -1 && !next[p][c])
            next[p][c] = cur, p = link[p];
        if (p == -1) return link[cur] = 0, cur;
        int q = next[p][c];
        if (len[p] + 1 == len[q]) return link[cur] = q, cur;
        int clone = newnode();
    }
}

```

```

for (int i = 0; i < maxc; ++i)
    next[clone][i] = len[next[q][i]] ? next[q][i] : 0;
len[clone] = len[p] + 1;
while (p != -1 && next[p][c] == q)
    next[p][c] = clone, p = link[p];
link[link[cur] = clone] = link[q];
link[q] = clone;
return cur;
}
void insert(const string &s) {
    int cur = 0;
    for (char ch : s) {
        int &nxt = next[cur][int(ch - 'a')];
        if (!nxt) nxt = newnode();
        cnt[cur = nxt] += 1;
    }
}
void build() {
    queue<int> q; q.push(0);
    while (!q.empty()) {
        int cur = q.front(); q.pop();
        for (int i = 0; i < maxc; ++i)
            if (next[cur][i]) q.push(insertSAM(cur, i));
    }
    vector<int> lc(tot);
    for (int i = 1; i < tot; ++i) ++lc[len[i]];
    partial_sum(all(lc), lc.begin());
    for (int i = 1; i < tot; ++i) ord[--lc[len[i]]] = i;
}
void solve() {
    for (int i = tot - 2; i >= 0; --i)
        cnt[link[ord[i]]] += cnt[ord[i]];
}
};

```

## 7.4 Z value [6a7fd0]

```

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

```

## 7.5 Manacher [365720]

```

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

```

## 7.6 Lexico Smallest Rotation [0e9fb8]

```

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

```

## 7.7 Main Lorentz [615b8f]

```

vector<pair<int, int>> rep[kN]; // 0-base [l, r]
void main_lorentz(const string &s, int sft = 0) {
    const int n = s.size();

```

```

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

```

## 7.8 BWT [5a9b3a]

```

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

```

## 7.9 Palindromic Tree [0673ee]

```

struct PalindromicTree {
    struct node {
        int nxt[26], f, len; // num = depth of fail link
        int cnt, num; // = #pal_suffix of this node
        node(int l = 0) : nxt{}, f(0), len(l), cnt(0), num(0) {}
    };
    vector<node> st; vector<char> s; int last, n;
    void init() {
        st.clear(); s.clear();
        last = 1; n = 0;
        st.push_back(0); st.push_back(-1);
        st[0].f = 1; s.push_back(-1);
    }
    int getFail(int x) {
        while (s[n - st[x].len - 1] != s[n]) x = st[x].f;
        return x;
    }
    void add(int c) {
        s.push_back(c - 'a'); ++n;
        int cur = getFail(last);
        if (!st[cur].nxt[c]) {
            int now = st.size();

```

```

    st.push_back(st[cur].len + 2);
    st[now].f = st[getFail(st[cur].f)].nxt[c];
    st[cur].nxt[c] = now;
    st[now].num = st[st[now].f].num + 1;
}
last = st[cur].nxt[c]; ++st[last].cnt;
}
void dpcnt() { // cnt = #occurrence in whole str
    for (int i = st.size() - 1; i >= 0; i--)
        st[st[i].f].cnt += st[i].cnt;
}
int size() { return st.size() - 2; }
} pt;
/* usage
string s; cin >> s; pt.init();
for (int i = 0; i < SZ(s); i++) {
    int prvsz = pt.size(); pt.add(s[i]);
    if (prvsz != pt.size()) {
        int r = i, l = r - pt.st[pt.last].len + 1;
        // pal @ [l,r]: s.substr(l, r-l+1)
    }
}
*/

```

## 8 Misc

### 8.1 Theorems

#### Sherman-Morrison formula

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

#### 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 uniform randomly) if  $i < j$  and  $(i, j) \in E$ , otherwise  $d_{ij} = -d_{ji}$ .  $\frac{\text{rank}(D)}{2}$  is the maximum matching on  $G$ .

#### Cayley's Formula

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

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

#### Havel-Hakimi algorithm

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

#### Euler's planar graph formula

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

#### Pick's theorem

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

#### Matroid Intersection

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

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

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

## 8.2 Weight Matroid Intersection [c376a9]

```

struct Matroid {
    Matroid(bitset<N>); // init from an independent set
    bool can_add(int); // check if break independence
    Matroid remove(int); // removing from the set
};
auto matroid_intersection(const vector<int> &w) {
    const int n = w.size(); bitset<N> S;
    for (int sz = 1; sz <= n; sz++) {
        Matroid M1(S), M2(S); vector<vector<pii>> e(n + 2);
        for (int j = 0; j < n; j++) if (!S[j]) {
            if (M1.can_add(j)) e[n].eb(j, -w[j]);
            if (M2.can_add(j)) e[j].eb(n + 1, 0);
        }
        for (int i = 0; i < n; i++) if (S[i]) {
            Matroid T1 = M1.remove(i), T2 = M2.remove(i);
            for (int j = 0; j < n; j++) if (!S[j]) {
                if (T1.can_add(j)) e[i].eb(j, -w[j]);
                if (T2.can_add(j)) e[j].eb(i, w[i]);
            }
        }
        // maybe implicit build graph for more speed
        vector<pii> d(n + 2, {INF, 0}); d[n] = {0, 0};
        vector<int> prv(n + 2, -1);
        // change to SPFA for more speed, if necessary
        bool upd = 1;
        while (upd) {
            upd = 0;
            for (int u = 0; u < n + 2; u++)
                for (auto [v, c] : e[u]) {
                    pii x(d[u].first + c, d[u].second + 1);
                    if (x < d[v]) d[v] = x, prv[v] = u, upd = 1;
                }
            if (d[n + 1].first >= INF) break;
            for (int x = prv[n + 1]; x != n; x = prv[x]) S.flip(x);
            // S is the max-weighted independent set w/ size sz
        }
        return S;
    } // from Nacl
}

```

## 8.3 Bitset LCS [5e6c56]

```

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

```

## 8.4 Prefix Substring LCS [7d8fa7]

```

void all_lcs(string S, string T) { // 0-base
    vector<size_t> h(T.size()); iota(all(h), 1);
    for (size_t a = 0; a < S.size(); ++a) {
        for (size_t c = 0, v = 0; c < T.size(); ++c)
            if (S[a] == T[c] || h[c] < v) swap(h[c], v);
        // here, LCS(s[0, a], t[b, c]) =
        // c - b + 1 - sum{h[i] > b} | i <= c
    }
} // test @ yosupo judge

```

## 8.5 Convex 1D/1D DP [6e0124]

```

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

```



```

    int d = 1 << 20, c = dq.back().l;
    while (d >= 1) if (c + d <= dq.back().r)
        if (f(i, c+d) > f(dq.back().i, c+d)) c += d;
        dq.back().r = c; seg.l = c + 1;
    }
    if (seg.l <= n) dq.push_back(seg);
}
}

```

## 8.6 ConvexHull Optimization [25eb56]

```

struct L {
    mutable lld a, b, p;
    bool operator<(const L &r) const {
        return a < r.a; /* here */
    }
    bool operator<(lld x) const { return p < x; }
};

lld Div(lld a, lld b) {
    return a / b - ((a ^ b) < 0 && a % b);
};

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

```

## 8.7 Josephus Problem [f4494f]

```

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

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

```

## 8.8 Tree Knapsack [f42766]

```

vector<int> G[N]; int dp[N][K]; pair<int,int> obj[N];
void dfs(int u, int mx) {
    for (int s : G[u]) {
        auto [w, v] = obj[s];
        if (mx < w) continue;
        for (int i = 0; i <= mx - w; i++)
            dp[s][i] = dp[u][i];
        dfs(s, mx - w);
        for (int i = w; i <= mx; i++)
            dp[u][i] = max(dp[u][i], dp[s][i - w] + v);
    }
}

```

## 8.9 N Queens Problem [31f83e]

```

void solve(VI &ret, int n) { // no sol when n=2,3
    if (n % 6 == 2) {
        for (int i = 2; i <= n; i += 2) ret.push_back(i);
        ret.push_back(3); ret.push_back(1);
        for (int i = 7; i <= n; i += 2) ret.push_back(i);
        ret.push_back(5);
    } else if (n % 6 == 3) {
        for (int i = 4; i <= n; i += 2) ret.push_back(i);
        ret.push_back(2);
        for (int i = 5; i <= n; i += 2) ret.push_back(i);
        ret.push_back(1); ret.push_back(3);
    } else {
        for (int i = 2; i <= n; i += 2) ret.push_back(i);
        for (int i = 1; i <= n; i += 2) ret.push_back(i);
    }
}

```

```

}
}

```

## 8.10 Stable Marriage

```

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

```

## 8.11 Binary Search On Fraction [765c5a]

```

struct Q {
    ll p, q;
    Q go(Q b, ll d) { return {p + b.p*d, q + b.q*d}; }
};

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

```