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		<b>Wconversion -fsanitize=address,undefined &amp;&amp; echo</b>	
		<b>success&lt;CR&gt;</b>	
		<b>map &lt;F9&gt; &lt;ESC&gt;:w&lt;CR&gt;:!g++ "%" -o "%&lt;" -O2 -g -std=gnu</b>	
		<b>++20 &amp;&amp; echo success&lt;CR&gt;</b>	
		<b>map &lt;F10&gt; &lt;ESC&gt;:!. / "%&lt;"&lt;CR&gt;</b>	
		<b>ca Hash w !cpp -dD -P -fpreprocessed \   tr -d '[:space</b>	
		<b>:]' \   md5sum \   cut -c-6</b>	
		<b>let c_no_curly_error=1</b>	
		<b>" setxkbmap -option caps:ctrl_modifier</b>	
		<b>1.2 Debug Macro [645ef3]</b>	
		<b>#define all(x) begin(x), end(x)</b>	
		<b>#ifndef CKISEKI</b>	
		<b>#define safe cerr&lt;&lt;__PRETTY_FUNCTION__&lt;&lt;" line "&lt;&lt;</b>	
		<b>__LINE__&lt;&lt;" safe\n"</b>	
		<b>#define debug(a...) debug_(#a, a)</b>	
		<b>#define orange(a...) orange_(#a, a)</b>	
		<b>template &lt;typename ...T&gt;</b>	
		<b>void debug_(const char *s, T ...a) {</b>	
		<b>cerr &lt;&lt; "\e[1;32m(" &lt;&lt; s &lt;&lt; ") = (";</b>	
		<b>int cnt = sizeof...(T);</b>	
		<b>(..., (cerr &lt;&lt; a &lt;&lt; (--cnt ? ", " : ") \e[0m\n"));</b>	
		<b>}</b>	
		<b>template &lt;typename I&gt;</b>	
		<b>void orange_(const char *s, I L, I R) {</b>	
		<b>cerr &lt;&lt; "\e[1;32m[ " &lt;&lt; s &lt;&lt; " ] = [ ";</b>	
		<b>for (int f = 0; L != R; ++L)</b>	
		<b>cerr &lt;&lt; (f++ ? ", " : "") &lt;&lt; *L;</b>	
		<b>cerr &lt;&lt; " ] \e[0m\n";</b>	
		<b>}</b>	
		<b>#else</b>	
		<b>#define safe ((void)0)</b>	
		<b>#define debug(...) safe</b>	
		<b>#define orange(...) safe</b>	
		<b>#endif</b>	
		<b>1.3 Increase Stack</b>	
		<b>const int size = 256 &lt;&lt; 20;</b>	
		<b>register long rsp asm("rsp");</b>	
		<b>char *p = (char*)malloc(size)+size, *bak = (char*)rsp;</b>	
		<b>__asm__ ("movq %0, %%rsp\n"::"r"(p));</b>	
		<b>// main</b>	
		<b>__asm__ ("movq %0, %%rsp\n"::"r"(bak));</b>	
		<b>1.4 Pragma Optimization [f63b0a]</b>	
		<b>#pragma GCC optimize("Ofast,no-stack-protector")</b>	
		<b>#pragma GCC optimize("no-math-errno,unroll-loops")</b>	
		<b>#pragma GCC target("sse,sse2,sse3,ssse3,sse4")</b>	
		<b>#pragma GCC target("popcnt,abm,mmx,avx,tune=native")</b>	
		<b>__builtin_ia32_ldmxcsr(__builtin_ia32_stmxcsr()   0x8000)</b>	
		<b>1.5 IO Optimization [c9494b]</b>	
		<b>static inline int gc() {</b>	
		<b>constexpr int B = 1&lt;&lt;20; static char buf[B], *p, *q;</b>	
		<b>if (p == q) q = (p = buf) + fread(buf, 1, B, stdin);</b>	
		<b>return q == buf ? EOF : *p++;</b>	
		<b>}</b>	
		<b>2 Data Structure</b>	
		<b>2.1 Dark Magic [095f25]</b>	
		<b>#include &lt;ext/pb_ds/assoc_container.hpp&gt;</b>	
		<b>#include &lt;ext/pb_ds/priority_queue.hpp&gt;</b>	
		<b>using namespace __gnu_pbds;</b>	
		<b>// heap tags: pairing/binary/binomial/rc_binomial/thin</b>	
		<b>template&lt;typename T&gt;</b>	
		<b>using pbds_heap=__gnu_pbds::prioity_queue&lt;T,less&lt;T&gt;, \</b>	
		<b>pairing_heap_tag&gt;;</b>	
		<b>// pbds_heap::point_iterator</b>	
		<b>// x = pq.push(10); pq.modify(x, 87); a.join(b);</b>	
		<b>// tree tags: rb_tree_tag/ov_tree_tag/splay_tree_tag</b>	
		<b>template&lt;typename T&gt;</b>	
		<b>using ordered_set = tree&lt;T, null_type, less&lt;T&gt;,</b>	
		<b>rb_tree_tag, tree_order_statistics_node_update&gt;;</b>	
		<b>// find_by_order, order_of_key</b>	
		<b>// hash tables: cc_hash_table/gp_hash_table</b>	
<b>1 Basic</b>			
<b>1.1 vimrc</b>			

## 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
};
```

```
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 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
    // chian[u] : chain id of the chain u is on
    void predfs(int u, int f) {
        dep[u] = dep[pa[u] = f] + 1;
        for (int v : G[u]) if (v != f) {
            predfs(v, u);
            if (lowbit(chain[u]) < lowbit(chain[v]))
                chain[u] = chain[v];
        }
    }
}

```

```

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

```

### 3.7 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
}

```

### 3.8 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

```

### 3.9 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)]

```

### 3.10 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
}

```

### 3.11 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
};

```

### 3.12 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--;
        }
    }
}

```

### 3.13 Count Cycles [c7e8f2]

```

// ord = sort by deg decreasing, rk[ord[i]] = i

```

```

// D[i] = edge point from rk small to rk big
for (int x : ord) { // c3
    for (int y : D[x]) vis[y] = 1;
    for (int y : D[x]) for (int z : D[y]) c3 += vis[z];
    for (int y : D[x]) vis[y] = 0;
}
for (int x : ord) { // c4
    for (int y : D[x]) for (int z : adj[y])
        if (rk[z] > rk[x]) c4 += vis[z]++;
    for (int y : D[x]) for (int z : adj[y])
        if (rk[z] > rk[x]) --vis[z];
} // both are O(M*sqrt(M)), test @ 2022 CCPC guangzhou

```

### 3.14 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());
    }
};

```

### 3.15 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;
```

### 3.16 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;
    }
}
```

## 4 Flow & Matching

### 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  $G'$ .
- Submodular functions minimization
  - For a function  $f: 2^V \rightarrow \mathbb{R}$ ,  $f$  is a submodular function iff
    - $\forall S, T \subseteq V, f(S) + f(T) \geq f(S \cup T) + f(S \cap T)$ , or
    - $\forall X \subseteq Y \subseteq V, x \notin Y, f(X \cup \{x\}) - f(X) \geq f(Y \cup \{x\}) - f(Y)$ .
  - To minimize  $\sum_i \theta_i(x_i) + \sum_{i < j} \phi_{ij}(x_i, x_j)$
  - If  $\theta_i(1) \geq \theta_i(0)$ , add edge  $(S, i, \theta_i(1) - \theta_i(0))$  and  $\theta_i(0)$  to answer; otherwise,  $(i, T, \theta_i(0) - \theta_i(1))$  and  $\theta_i(1)$ .
  - Add edges  $(i, j, \phi_{ij}(0, 1) + \phi_{ij}(1, 0) - \phi_{ij}(0, 0) - \phi_{ij}(1, 1))$ .
  - Denote  $x_{ijk}$  as helper nodes. Let  $P = \psi_{ijk}(0, 0, 0) + \psi_{ijk}(0, 1, 1) + \psi_{ijk}(1, 0, 1) + \psi_{ijk}(1, 1, 0) - \psi_{ijk}(0, 0, 1) - \psi_{ijk}(0, 1, 0) - \psi_{ijk}(1, 0, 0) - \psi_{ijk}(1, 1, 1)$ . Add  $-P$  to answer. If  $P \geq 0$ , add edges  $(i, x_{ijk}, P), (j, x_{ijk}, P), (k, x_{ijk}, P), (x_{ijk}, T, P)$ ; otherwise  $(x_{ijk}, i, -P), (x_{ijk}, j, -P), (x_{ijk}, k, -P), (S, x_{ijk}, -P)$ .
  - The minimum cut of this graph will be the the minimum value of the function above.

### 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] and 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() { // 1-based
    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->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[slack[x]][x]) < e_delta(g[slack[x]][x])) slack[x] = u; }
    void set_slack(int x) {
        slack[x] = 0;
        for (int u = 1; u <= n; ++u)
            if (g[u][x].w > 0 && st[u] != x && S[st[u]] == 0)
                update_slack(u, x);
    }
    void q_push(int x) {
        if (x <= n) q.push(x);
        else for (size_t i = 0; i < flo[x].size(); ++i)
            q_push(flo[x][i]);
    }
    void set_st(int x, int b) {
        st[x] = b;
        if (x > n) for (size_t i = 0; i < flo[x].size(); ++i)
            set_st(flo[x][i], b);
    }
    int get_pr(int b, int xr) {
        int pr = find(flo[b].begin(), flo[b].end(), xr) - flo[b].begin();
        if (pr % 2 == 1) {
            reverse(flo[b].begin() + 1, flo[b].end());
            return (int)flo[b].size() - pr;
        }
        return pr;
    }
    void set_match(int u, int v) {
        match[u] = g[u][v].v;
        if (u <= n) return;
        edge e = g[u][v];
        int xr = flo_from[u][e.u], pr = get_pr(u, xr);
        for (int i = 0; i < pr; ++i) set_match(flo[u][i], flo[u][i ^ 1]);
        set_match(xr, v);
        rotate(flo[u].begin(), flo[u].begin() + pr, flo[u].end());
    }
    void augment(int u, int v) {
        for (; ; ) {

```

```

    int xnv = st[match[u]];
    set_match(u, v);
    if (!xnv) return;
    set_match(xnv, st[pa[xnv]]);
    u = st[pa[xnv]], v = xnv;
}
}

int get_lca(int u, int v) {
    static int t = 0;
    for (++t; u || v; swap(u, v)) {
        if (u == 0) continue;
        if (vis[u] == t) return u;
        vis[u] = t;
        u = st[match[u]];
        if (u) u = st[pa[u]];
    }
    return 0;
}

void add_blossom(int u, int lca, int v) {
    int b = n + 1;
    while (b <= n_x && st[b]) ++b;
    if (b > n_x) ++n_x;
    lab[b] = 0, S[b] = 0;
    match[b] = match[lca];
    flo[b].clear();
    flo[b].push_back(lca);
    for (int x = u, y; x != lca; x = st[pa[y]])
        flo[b].push_back(x), flo[b].push_back(y = st[match[x]]), q_push(y);
    reverse(flo[b].begin() + 1, flo[b].end());
    for (int x = v, y; x != lca; x = st[pa[y]])
        flo[b].push_back(x), flo[b].push_back(y = st[match[x]]), q_push(y);
    set_st(b, b);
    for (int x = 1; x <= n_x; ++x) g[b][x].w = g[x][b].w = 0;
    for (int x = 1; x <= n; ++x) flo_from[b][x] = 0;
    for (size_t i = 0; i < flo[b].size(); ++i) {
        int xs = flo[b][i];
        for (int x = 1; x <= n_x; ++x)
            if (g[b][x].w == 0 || e_delta(g[xs][x]) < e_delta(g[b][x]))
                g[b][x] = g[xs][x], g[x][b] = g[x][xs];
        for (int x = 1; x <= n; ++x)
            if (flo_from[xs][x]) flo_from[b][x] = xs;
    }
    set_slack(b);
}

void expand_blossom(int b) {
    for (size_t i = 0; i < flo[b].size(); ++i)
        set_st(flo[b][i], flo[b][i]);
    int xr = flo_from[b][g[b][pa[b]].u], pr = get_pr(b, xr);
    for (int i = 0; i < pr; i += 2) {
        int xs = flo[b][i], xns = flo[b][i + 1];
        pa[xs] = g[xns][xs].u;
        S[xs] = 1, S[xns] = 0;
        slack[xs] = 0, set_slack(xns);
        q_push(xns);
    }
    S[xr] = 1, pa[xr] = pa[b];
    for (size_t i = pr + 1; i < flo[b].size(); ++i) {
        int xs = flo[b][i];
        S[xs] = -1, set_slack(xs);
    }
    st[b] = 0;
}

bool on_found_edge(const edge &e) {
    int u = st[e.u], v = st[e.v];
    if (S[v] == -1) {
        pa[v] = e.u, S[v] = 1;
        int nu = st[match[v]];
        slack[v] = slack[nu] = 0;
        S[nu] = 0, q_push(nu);
    } else if (S[v] == 0) {
        int lca = get_lca(u, v);
        if (!lca) return augment(u, v), augment(v, u), true;
        else add_blossom(u, lca, v);
    }
    return false;
}

bool matching() {

```

```

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

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

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

```

## 5 Math

### 5.1 Common Bounds

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

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

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

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

### 5.2 Stirling 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 [d0cbdd]

```
// 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 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[s] = ++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;
}
```

### 5.6 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
}
```

### 5.7 Extended Euler

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

### 5.8 Extended FloorSum

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

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

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

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

### 5.9 FloorSum [fb5917]

```
// @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;
        if (llu y_max = a * n + b; y_max >= m) {
            n = (llu)(y_max / m), b = (llu)(y_max % m);
            swap(m, a);
        } else break;
    }
    return ans;
}

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

### 5.10 ModMin [253e4d]

```
// min{k | l <= ((ak) mod m) <= r}
optional<llu> mod_min(u32 a, u32 m, u32 l, u32 r) {
    if (a == 0) return l ? nullopt : 0;
    if (auto k = llu(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;
}

```

## 5.11 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;
}
}

```

## 5.12 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);
    }
}

```

## 5.13 CRT for arbitrary mod [e4dde7]

```

const int mod = 1000000007;
const int M1 = 985661441; // G = 3 for M1, M2, M3
const int M2 = 998244353;
const int M3 = 1004535809;
int superBigCRT(lld A, lld B, lld C) {
    static_assert (M1 < M2 && M2 < M3);
    constexpr lld r12 = modpow(M1, M2-2, M2);
    constexpr lld r13 = modpow(M1, M3-2, M3);
    constexpr lld r23 = modpow(M2, M3-2, M3);
    constexpr lld 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;
}

```

## 5.14 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);
}
}
};

```

### 5.15 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]);
}

```

### 5.16 Pi Count (+Linear Sieve) [8a4382]

```

static constexpr int N = 1000000 + 5;
lld pi[N]; vector<int> primes; bool sieved[N];
lld cube_root(lld x) {
    lld s = cbrt(x - 0.1L);
    while (s * s * s <= x) ++s;
    return s - 1;
}
lld square_root(lld x) {
    lld s = sqrt(x - 0.1L);
    while (s * s <= x) ++s;
    return s - 1;
}
void init() {
    primes.reserve(N);
    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 (i * p >= N) break;
            sieved[p * i] = true;
            if (i % p == 0) break;
        }
    }
    primes.insert(primes.begin(), 1);
}
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);
}

```

### 5.17 Miller Rabin [ef5775]

```

bool isprime(llu x) {
    auto witn = [&](llu a, int t) {
        for (llu a2; t--; a = a2) {
            a2 = mmul(a, a, x);
            if (a2 == 1 && a != 1 && a != x - 1) return true;
        }
        return a != 1;
    };
    if (x <= 2) 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 (m % x != 0 && witn(mpow(m % x, odd, x), t))
        return false;
    return true;
} // test @ luogu 143

```

### 5.18 Pollard Rho [638efe]

```

// 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_64 rnd(120821011);
    while (true) {
        llu y = 2, yy = y, x = rnd() % n, t = 1;
        for (llu sz = 2; t == 1; sz <= 1, y = yy) {
            for (llu i = 0; t == 1 && i < sz; ++i) {
                yy = f(yy, x, n);
                t = gcd(yy > y ? yy - y : y - yy, n);
            }
        }
        if (t != 1 && t != n) return t;
    }
}

```

### 5.19 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;
}

```

### 5.20 Characteristic Polynomial [ff2159]

```

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

```

## 5.21 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 = {};
```

## 5.22 Simplex [0ba963]

```
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<llf>;
    using VVD = vector<vector<llf>>;
    const llf eps = 1e-9, inf = 1e+9;
    int n, m; VVD d; vector<int> p, q;
    void pivot(int r, int s) {
        llf 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 = (int)b.size(), n = (int)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;
}

```

## 5.23 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.  $\sum_{1 \leq i \leq n} A_{ji} x_i = b_j$

$$\cdot \sum_{1 \leq i \leq n} A_{ji} x_i \leq b_j$$

$$\cdot \sum_{1 \leq i \leq n} A_{ji} x_i \geq b_j$$

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

## 5.24 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) {
    lld ret = 0;
    for (int i = 1; i + 1 < (int)pt.size(); i++)
        ret += cross(pt[i] - pt[0], pt[i+1] - pt[0]);
    return ret / 2.0;
}

P rot90(P p) { return P{-IM(p), RE(p)}; }
PTF project(PTF p, PTF q) { // p onto q
    return dot(p, q) * q / dot(q, q); // 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; lld 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 @ AOJ 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(lld p, lld q) {
        // is there t s.t. 0 <= t <= 1 && qt == p ?
        if (q < 0) q = -q, p = -p;
        return 0 <= p && p <= q;
    }
    vector<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; lld 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 [45e909]

```

struct Line {
    P st, ed, dir;
    Line(P s, P e) : st(s), ed(e), dir(e - s) {}
}; using LN = const Line &;
PTF intersect(LN A, LN B) {
    lld t = cross(B.st - A.st, B.dir) /
        lld(cross(A.dir, B.dir));
    return toPTF(A.st) + toPTF(A.dir) * t; // C^3 / C^2
}

bool cov(LN l, LN A, LN 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<(LN a, LN 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
lld 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 : BigBrother

## 6.8 SegmentDist (Sausage) [9d8603]

```

// be careful of abs<complex<int>> (replace _abs below)
lld 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));
}

lld 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 @ Q0J2444 / 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) {
    PTF dir = b.o - a.o; llf d2 = norm(dir);
    if (norm(a.r - b.r) >= d2) { // norm(x) := |x|^2
        if (a.r < b.r) return {-PI, PI}; // a in b
        else return {}; // b in a
    } else if (norm(a.r + b.r) <= d2) return {};
    llf dis = abs(dir), theta = arg(dir);
    llf phi = acos((a.r * a.r + d2 - b.r * b.r) /
        (2 * a.r * dis)); // 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 [3c6db5]

```

// 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); }
// all points coplanar case will WA
vector<Face> convex_hull_3D(vector<P3> pt) {
    int n = int(pt.size()); vector<Face> now;
    if (n <= 3) return {}; // be careful about edge case
    // ensure first 4 points are not coplanar
    #define S(I, E...) swap(pt[I], *find_if(all(pt), \
        [&](auto z) { return E; })))
    S(1, pt[0] != z);
    S(2, ver(z, pt[0], pt[1]) != (P3){0, 0, 0});
    S(3, (z - pt[0]).dot(ver(pt[0], pt[1], pt[2])) != 0);
    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;
}
const auto F = [&](int x, int y) {
    if (flag[x][y] > 0 && flag[y][x] <= 0)
        next.emplace_back(x, y, i);
};
for (const auto &f : now)
    F(f.a, f.b), F(f.b, f.c), F(f.c, f.a);
now = next;
return now;
}
// n^2 delaunay: facets with negative z normal of
// convexhull of (x, y, x^2 + y^2), use a pseudo-point
// (0, 0, inf) to avoid degenerate case

```

## 6.21 Delaunay [59b02e]

```

/* please ensure input points are unique */
/* 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 {
    bool vis;
    array<P,3> p; array<Tri*,3> ch; array<E,3> e;
    Tri(P a=0, P b=0, P c=0) : vis(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;
void go(Tri *now) { // store all tri into res
    if (now->vis) return;
    now->vis = true;
    if (!now->has_chd()) res.push_back(now);
    for (Tri *c: now->ch) if (c) go(c);
}
void build(vector<P> ps) {
    it = pool; res.clear();
    shuffle(ps.begin(), ps.end(), mt19937(114514));
    Trigs tr; for (P p: ps) tr.add_point(p);
    go(tr.root); // use `res` afterwards
    // build_voronoi_cells(ps, res);
}

```

## 6.22 Build Voronoi [fb7e8b]

```

void build_voronoi_cells(auto &p, auto &res) {
    vector<vector<int>> adj(p.size());
    map<pair<lld, lld>, int> mp;
    for (size_t i = 0; i < p.size(); ++i)
        mp[{RE(p[i]), IM(p[i])}] = i;
    const auto Get = [&](P z) {
        auto it = mp.find({RE(z), IM(z)});
        return it==mp.end() ? -1 : it->second;
    };
    for (Tri *t: res) F3 {
        P A = t->p[i], B = t->p[R(i)];
        int a = Get(A), b = Get(B);
        if (a == -1 || b == -1) continue;
        adj[a].emplace_back(b);
    }
    // use `adj` and `p` and HPI to build cells
    for (size_t i = 0; i < p.size(); i++) {
        vector<Line> ls = frame; // the frame
        for (int j : adj[i]) {
            P m = p[i] + p[j], d = rot90(p[j] - p[i]);
            assert(norm(d) != 0);
            ls.emplace_back(m, m + d); // doubled coordinate
        } // HPI(ls)
    }
}

```

## 6.23 kd Tree (Nearest Point) [dbade8]

```

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?cmpx:cmpy);
        Node &o = tree[M]; o.f = d % 2;
        o.x1 = o.x2 = o.x; o.y1 = o.y2 = 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;

```

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

```

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

```

## 6.25 Simulated Annealing [4e0fe5]

```

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

```

## 6.26 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-- : 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]; // occurence
    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] && s[i + j] == s[j]; ++j);
        if (i + (z[i] = j) > r) r = i + z[i] = 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 Lyndon Factorization [41c4f5]

```
// partition s = w[0] + w[1] + ... + w[k-1],
// w[0] >= w[1] >= ... >= w[k-1]
// each w[i] strictly smaller than all its suffix
void duval(const auto &s, auto &&report) {
    int n = (int)s.size(), i = 0, j, k;
    while (i < n) {
        for (j = i + 1, k = i; j < n && s[k] <= s[j]; j++)
            k = (s[k] < s[j] ? i : k + 1);
        // if (i < n / 2 && j >= n / 2) {
        // for min cyclic shift, call duval(s + s)
        // then here s.substr(i, n / 2) is min cyclic shift
        // }
        for (; i <= k; i += j - k)
            report(i, j - k); // s.substr(l, len)
    }
} // tested @ luogu 6114, 1368 & UVA 719
```

## 7.8 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);
    }
}
```

## 7.9 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;
}
```

## 7.10 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

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

#### 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  $S \sqcup \{x\}$ )
- $x \rightarrow y: S \setminus \{x\} \sqcup \{y\} \in I_2$  ( $y$  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 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
```

### 8.4 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());
```

### 8.5 Prefix Substring LCS [7d8fa]

```
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
```

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

```
struct segment {
    int i, l, r;
    segment() {}
    segment(int a, int b, int c): i(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().i, i);
        while(dq.size() && dq.front().r < i+1) dq.pop_front();
        dq.front().l = i + 1;
        segment seg = segment(i, i + 1, n);
        while (dq.size() && f(i, dq.back().l) < f(dq.back().i, dq.back().l))
            dq.pop_back();
        if (dq.size()) {
            int d = 1 << 20, c = dq.back().l;
            while (d >= 1) if (c + d <= dq.back().r)
                if (f(i, c+d) > f(dq.back().i, c+d)) c += d;
            dq.back().r = c; seg.l = c + 1;
        }
        if (seg.l <= n) dq.push_back(seg);
    }
}
```

### 8.7 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 "<>"
    }
};

```

## 8.8 De-Bruijn [c0a223]

```

vector<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.
    vector<int> aux(n + 1), res;
    auto db = [&](auto self, int t, int p) -> void {
        if (t <= n)
            for (int i = aux[t - p]; i < k; ++i, p = t)
                aux[t] = i, self(self, t + 1, p);
        else if (n % p == 0) for (int i = 1; i <= p; ++i)
            res.push_back(aux[i]);
    }; db(db, 1, 1);
    return res;
}

```

## 8.9 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;
}

```

## 8.10 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);
    }
}

```

## 8.11 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);
    }
}

```

## 8.12 Manhattan MST [1008bc]

```

vector<array<int, 3>> manhattanMST(vector<P> ps) {
    vector<int> id(ps.size()); iota(all(id), 0);
    vector<array<int, 3>> edges;
    for (int k = 0; k < 4; k++) {
        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++)) {
                if (P d = ps[i] - ps[it->second]; d.y > d.x) break;
                else edges.push_back({d.y + d.x, i, it->second});
            }
            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}, ...]
} // test @ yosupo judge

```

## 8.13 Binary Search On Fraction [765c5a]

```

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

```