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## 1 Basic

### 1.1 .vimrc

```
sy on
set ru nu cin cul sc so=3 ts=4 sw=4 bs=2 ls=2 mouse=a
inoremap {<CR> {<CR>}<C-o>0
map <F7> :w<CR>:!g++
      "% " -std=c++17 -Wall -Wextra -Wshadow -Wconversion
      -fsanitize=address,undefined -g && ./a.out<CR>
```

### 1.2 PBDS

```
// Tree and fast PQ
#include <bits/extc++.h>
using namespace __gnu_pbds;

#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/tree_policy.hpp>
tree<int, null_type, less<int>, rb_tree_tag,
    tree_order_statistics_node_update> bst;
// order_of_key(n): # of elements <= n
// find_by_order(n): 0-indexed

#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/priority_queue.hpp>
__gnu_pbds::priority_queue
    <int, greater<int>, thin_heap_tag> pq;
```

### 1.3 pragma

```
#pragma GCC optimize("Ofast,unroll-loops")
#pragma GCC target("avx,avx2,sse,sse2
    ,sse3,ssse3,sse4,popcnt,abm,mmx,fma,tune=native")
// chrono
::steady_clock::now().time_since_epoch().count())
```

### 1.4 LambdaCompare

```
auto cmp = [](int x, int y) { /* return x < y; */ };
std::set<int, decltype(cmp)> st(cmp);
```

## 2 Graph

### 2.1 2SAT/SCC

```
struct SAT { // 0-base
    int low[N], dfn[N], bln[N], n, Time, nScc;
    bool instack[N], istrue[N];
    stack<int> st;
    vector<int> G[N], SCC[N];
    void init(int _n) {
        n = _n; // assert(n * 2 <= N);
        for (int i = 0; i < n + n; ++i) G[i].clear();
    }
    void add_edge(int a, int b) { G[a].emplace_back(b); }
    int rv(int a) {
        if (a >= n) return a - n;
        return a + n;
    }
    void add_clause(int a, int b) {
        add_edge(rv(a), b), add_edge(rv(b), a);
    }
    void dfs(int u) {
        dfn[u] = low[u] = ++Time;
        instack[u] = 1, st.push(u);
        for (int i : G[u])
            if (!dfn[i])
                dfs(i), low[u] = min(low[i], low[u]);
            else if (instack[i] && dfn[i] < dfn[u])
                low[u] = min(low[u], dfn[i]);
        if (low[u] == dfn[u]) {
            int tmp;
            do {
                tmp = st.top(), st.pop();
                instack[tmp] = 0, bln[tmp] = nScc;
            } while (tmp != u);
            ++nScc;
        }
    }
    bool solve() {
        Time = nScc = 0;
        for (int i = 0; i < n + n; ++i)
            SCC[i].clear(), low[i] = dfn[i] = bln[i] = 0;
        for (int i = 0; i < n + n; ++i)
            if (!dfn[i]) dfs(i);
        for (int i = 0; i < n + n; ++i) SCC[bln[i]].emplace_back(i);
        for (int i = 0; i < n; ++i) {
            if (bln[i] == bln[i + n]) return false;
            istrue[i] = bln[i] < bln[i + n];
            istrue[i + n] = !istrue[i];
        }
        return true;
    }
};
```

### 2.2 BCC Vertex

```
int n, m, dfn[N], low[N], is_cut[N], nbcc = 0, t = 0;
vector<int> g[N], bcc[N], G[2 * N];
stack<int> st;
void tarjan(int p, int lp) {
    dfn[p] = low[p] = ++t;
    st.push(p);
    for (auto i : g[p]) {
        if (!dfn[i]) {
            tarjan(i, p);
```

```

    low[p] = min(low[p], low[i]);
    if (dfn[p] <= low[i]) {
        nbcc++;
        is_cut[p] = 1;
        for (int x = 0; x != i; st.pop()) {
            x = st.top();
            bcc[nbcc].push_back(x);
        }
        bcc[nbcc].push_back(p);
    }
    else low[p] = min(low[p], dfn[i]);
}
}
void build() { // [n+1,n+nbcc] cycle, [1,n] vertex
    for (int i = 1; i <= nbcc; i++) {
        for (auto j : bcc[i]) {
            G[i + n].push_back(j);
            G[j].push_back(i + n);
        }
    }
}
}

```

## 2.3 MinimumMeanCycle

```

/* O(V^3)
let dp[i][j] = min length from 1 to j exactly i edges
ans = min (dp[n + 1][u] - dp[i][u]) / (n + 1 - i) */

```

## 2.4 MaximumCliqueDyn

```

struct MaxClique { // fast when N <= 100
    bitset<N> G[N], cs[N];
    int ans, sol[N], q, cur[N], d[N], n;
    void init(int _n) {
        n = _n;
        for (int i = 0; i < n; ++i) G[i].reset();
    }
    void add_edge(int u, int v) {
        G[u][v] = G[v][u] = 1;
    }
    void pre_dfs(vector<int> &r, int l, bitset<N> mask) {
        if (l < 4) {
            for (int i : r) d[i] = (G[i] & mask).count();
            sort(all(r), [&](int x, int y) { return d[x] > d[y]; });
        }
        vector<int> c(r.size());
        int lft = max(ans - q + 1, 1), rgt = 1, tp = 0;
        cs[1].reset(), cs[2].reset();
        for (int p : r) {
            int k = 1;
            while ((cs[k] & G[p]).any()) ++k;
            if (k > rgt) cs[++rgt].reset();
            cs[k][p] = 1;
            if (k < lft) r[tp++] = p;
        }
        for (int k = lft; k <= rgt; ++k)
            for (int p = cs[k]._Find_first(); p < N; p = cs[k]._Find_next(p))
                r[tp] = p, c[tp] = k, ++tp;
        dfs(r, c, l + 1, mask);
    }
    void dfs(vector<int> &r, vector<int> &c, int l, bitset<N> 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;
            for (int i : r) if (G[p][i]) nr.emplace_back(i);
            if (!nr.empty()) pre_dfs(nr, l, mask & G[p]);
            else if (q > ans) ans = q, copy_n(cur, q, sol);
            c.pop_back(), --q;
        }
    }
}

```

```

int solve() {
    vector<int> r(n);
    ans = q = 0, iota(all(r), 0);
    pre_dfs(r, 0, bitset<N>(string(n, '1')));
    return ans;
}
};

```

## 2.5 DMST(slow)

```

struct DMST { // O(VE)
    struct edge {
        int u, v;
        ll w;
    };
    vector<edge> E; // 0-base
    int pe[N], id[N], vis[N];
    ll in[N];
    void init() { E.clear(); }
    void add_edge(int u, int v, ll w) {
        if (u != v) E.emplace_back(edge{u, v, w});
    }
    ll build(int root, int n) {
        ll ans = 0;
        for (;;) {
            fill_n(in, n, INF);
            for (int i = 0; i < E.size(); ++i)
                if (E[i].u != E[i].v && E[i].w < in[E[i].v])
                    pe[E[i].v] = i, in[E[i].v] = E[i].w;
            for (int u = 0; u < n; ++u) // no solution
                if (u != root && in[u] == INF) return -INF;
            int cntnode = 0;
            fill_n(id, n, -1), fill_n(vis, n, -1);
            for (int u = 0; u < n; ++u) {
                if (u != root) ans += in[u];
                int v = u;
                while (vis[v] != u && !~id[v] && v != root)
                    vis[v] = u, v = E[pe[v]].u;
                if (v != root && !~id[v]) {
                    for (int x = E[pe[v]].u; x != v;
                        x = E[pe[x]].u)
                        id[x] = cntnode;
                    id[v] = cntnode++;
                }
            }
            if (!cntnode) break; // no cycle
            for (int u = 0; u < n; ++u)
                if (!~id[u]) id[u] = cntnode++;
            for (int i = 0; i < E.size(); ++i) {
                int v = E[i].v;
                E[i].u = id[E[i].u], E[i].v = id[E[i].v];
                if (E[i].u != E[i].v) E[i].w -= in[v];
            }
            n = cntnode, root = id[root];
        }
        return ans;
    }
};

```

## 2.6 DMST

```

#define rep(i, a, b) for (int i = a; i < (b); ++i)
#define all(x) begin(x), end(x)
#define sz(x) (int)(x).size()
typedef vector<int> vi;
struct RollbackUF {
    vi e;
    vector<pii> st;
    RollbackUF(int n) : e(n, -1) {}
    int size(int x) { return -e[find(x)]; }
    int find(int x) { return e[x] < 0 ? x : find(e[x]); }
    int time() { return sz(st); }
    void rollback(int t) {
        for (int i = time(); i-- > t;)
            e[st[i].first] = st[i].second;
        st.resize(t);
    }
};

```

```

bool join(int a, int b) {
    a = find(a), b = find(b);
    if (a == b) return false;
    if (e[a] > e[b]) swap(a, b);
    st.push_back({a, e[a]});
    st.push_back({b, e[b]});
    e[a] += e[b];
    e[b] = a;
    return true;
}
};

struct Edge {
    int a, b;
    ll w;
};

struct Node { /// lazy skew heap node
    Edge key;
    Node *l, *r;
    ll delta;
    void prop() {
        key.w += delta;
        if (l) l->delta += delta;
        if (r) r->delta += delta;
        delta = 0;
    }
    Edge top() {
        prop();
        return key;
    }
};

Node *merge(Node *a, Node *b) {
    if (!a || !b) return a ? b;
    a->prop(), b->prop();
    if (a->key.w > b->key.w) swap(a, b);
    swap(a->l, (a->r = merge(b, a->r)));
    return a;
}

void pop(Node *&a) {
    a->prop();
    a = merge(a->l, a->r);
}

pair<ll, vi> dmst(int n, int r, vector<Edge> &g) {
    RollbackUF uf(n);
    vector<Node*> heap(n);
    for (Edge e : g)
        heap[e.b] = merge(heap[e.b], new Node{e});
    ll res = 0;
    vi seen(n, -1), path(n), par(n);
    seen[r] = r;
    vector<Edge> Q(n), in(n, {-1, -1}), comp;
    deque<tuple<int, int, vector<Edge>>> cys;
    rep(s, 0, n) {
        int u = s, qi = 0, w;
        while (seen[u] < 0) {
            if (!heap[u]) return {-1, {}};
            Edge e = heap[u]->top();
            heap[u]->delta -= e.w, pop(heap[u]);
            Q[qi] = e, path[qi++] = u, seen[u] = s;
            res += e.w, u = uf.find(e.a);
            if (seen[u] == s) { /// found cycle, contract
                Node *cyc = 0;
                int end = qi, time = uf.time();
                do cyc = merge(cyc, heap[w = path[--qi]]);
                while (uf.join(u, w));
                u = uf.find(u), heap[u] = cyc, seen[u] = -1;
                cys.push_front({u, time, {&Q[qi], &Q[end]}});
            }
        }
        rep(i, 0, qi) in[uf.find(Q[i].b)] = Q[i];
    }

    for (auto &[u, t, comp] :
        cys) { /// restore sol (optional)
        uf.rollback(t);
        Edge inEdge = in[u];
        for (auto &e : comp) in[uf.find(e.b)] = e;
    }
}

```

```

    in[uf.find(inEdge.b)] = inEdge;
}
rep(i, 0, n) par[i] = in[i].a;
return {res, par};
}

```

## 2.7 VizingTheorem

```

namespace Vizing { /// Edge coloring
                  /// G: coloring adjM
int C[N][N], G[N][N];
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<pii> &E, int n, int m) {
    int X[n] = {}, 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++) {
        int u = E[t].first, v0 = E[t].second, v = v0,
            c0 = X[u], c = c0, d;
        vector<pii> L;
        int vst[n] = {};
        while (!G[u][v0]) {
            L.emplace_back(v, d = X[v]);
            if (!C[v][c])
                for (a = (int)L.size() - 1; a >= 0; a--)
                    c = color(u, L[a].first, c);
            else if (!C[u][d])
                for (a = (int)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]) {
                for (a = (int)L.size() - 2;
                    a >= 0 && L[a].second != c; a--)
                    ;
                for (; a >= 0; a--)
                    color(u, L[a].first, L[a].second);
            } else t--;
        }
    }
}
} // namespace Vizing

```

## 2.8 MinimumCliqueCover

```

struct CliqueCover { /// 0-base, O(n2^n)
    int co[1 << N], n, E[N];
    int dp[1 << N];
    void init(int _n) {
        n = _n, fill_n(dp, 1 << n, 0);
    }
};

```

```

    fill_n(E, n, 0), fill_n(co, 1 << n, 0);
}
void add_edge(int u, int v) {
    E[u] |= 1 << v, E[v] |= 1 << u;
}
int solve() {
    for (int i = 0; i < n; ++i)
        co[1 << i] = E[i] | (1 << i);
    co[0] = (1 << n) - 1;
    dp[0] = (n & 1) * 2 - 1;
    for (int i = 1; i < (1 << n); ++i) {
        int t = i & -i;
        dp[i] = -dp[i ^ t];
        co[i] = co[i ^ t] & co[t];
    }
    for (int i = 0; i < (1 << n); ++i)
        co[i] = (co[i] & i) == i;
    fwt(co, 1 << n, 1);
    for (int ans = 1; ans < n; ++ans) {
        int sum = 0; // probabilistic
        for (int i = 0; i < (1 << n); ++i)
            sum += (dp[i] * co[i]);
        if (sum) return ans;
    }
    return n;
}
};

```

## 2.9 CountMaximalClique

```

struct BronKerbosch { // 1-base
    int n, a[N], g[N][N];
    int S, all[N][N], some[N][N], none[N][N];
    void init(int _n) {
        n = _n;
        for (int i = 1; i <= n; ++i)
            for (int j = 1; j <= n; ++j) g[i][j] = 0;
    }
    void add_edge(int u, int v) {
        g[u][v] = g[v][u] = 1;
    }
    void dfs(int d, int an, int sn, int nn) {
        if (S > 1000) return; // pruning
        if (sn == 0 && nn == 0) ++S;
        int u = some[d][0];
        for (int i = 0; i < sn; ++i) {
            int v = some[d][i];
            if (g[u][v]) continue;
            int tsn = 0, tnn = 0;
            copy_n(all[d], an, all[d + 1]);
            all[d + 1][an] = v;
            for (int j = 0; j < sn; ++j)
                if (g[v][some[d][j]])
                    some[d + 1][tsn++] = some[d][j];
            for (int j = 0; j < nn; ++j)
                if (g[v][none[d][j]])
                    none[d + 1][tnn++] = none[d][j];
            dfs(d + 1, an + 1, tsn, tnn);
            some[d][i] = 0, none[d][nn++] = v;
        }
    }
    int solve() {
        iota(some[0], some[0] + n, 1);
        S = 0, dfs(0, 0, n, 0);
        return S;
    }
};

```

### 2.10 Theorems

$|\text{max independent edge set}| = |V| - |\text{min edge cover}|$   
 $|\text{max independent set}| = |V| - |\text{min vertex cover}|$

## 3 Flow-Matching

### 3.1 HopcroftKarp

```

struct HopcroftKarp
{
    // 0-based, return btoa to get matching
    bool dfs(int a, int L, vector<vector<int>> &g,
        vector<int> &btoa, vector<int> &A,
        vector<int> &B) {
        if (A[a] != L) return 0;
        A[a] = -1;
        for (int b : g[a])
            if (B[b] == L + 1) {
                B[b] = 0;
                if (btoa[b] == -1 ||
                    dfs(btoa[b], L + 1, g, btoa, A, B))
                    return btoa[b] = a, 1;
            }
        return 0;
    }
    int solve(vector<vector<int>> &g, int m) {
        int res = 0;
        vector<int> btoa(m, -1), A(g.size()),
            B(btoa.size(), cur, next);
        for (;;) {
            fill(all(A), 0), fill(all(B), 0);
            cur.clear();
            for (int a : btoa)
                if (a != -1) A[a] = -1;
            for (int a = 0; a < g.size(); a++)
                if (A[a] == 0) cur.push_back(a);
            for (int lay = 1;; lay++) {
                bool islast = 0;
                next.clear();
                for (int a : cur)
                    for (int b : g[a]) {
                        if (btoa[b] == -1) {
                            B[b] = lay;
                            islast = 1;
                        } else if (btoa[b] != a && !B[b]) {
                            B[b] = lay;
                            next.push_back(btoa[b]);
                        }
                    }
                if (islast) break;
                if (next.empty()) return res;
                for (int a : next) A[a] = lay;
                cur.swap(next);
            }
            for (int a = 0; a < g.size(); a++)
                res += dfs(a, 0, g, btoa, A, B);
        }
    }
};

```

### 3.2 KM

```

struct KM { // 0-base
    ll w[N][N], hl[N], hr[N], slk[N];
    int fl[N], fr[N], pre[N], qu[N], ql, qr, n;
    bool vl[N], vr[N];
    void init(int _n) {
        n = _n;
        for (int i = 0; i < n; ++i)
            fill_n(w[i], n, -INF);
    }
    void add_edge(int a, int b, ll wei) {
        w[a][b] = wei;
    }
    bool Check(int x) {
        if (vl[x] = 1, ~fl[x])
            return vr[qu[qr++] = fl[x]] = 1;
        while (~x) swap(x, fr[fl[x] = pre[x]]);
        return 0;
    }
    void bfs(int s) {
        fill_n(slk, n, INF), fill_n(vl, n, 0), fill_n(vr, n, 0);
        ql = qr = 0, qu[qr++] = s, vr[s] = 1;
        for (ll d;;) {

```

```

while (ql < qr)
    for (int x = 0, y = qu[ql++]; x < n; ++x)
        if (!vl[x] && slk
            [x] >= (d = hl[x] + hr[y] - w[x][y])) {
            if (pre[x] = y, d) slk[x] = d;
            else if (!Check(x)) return;
        }
d = INF;
for (int x = 0; x < n; ++x)
    if (!vl[x] && d > slk[x]) d = slk[x];
for (int x = 0; x < n; ++x) {
    if (vl[x]) hl[x] += d;
    else slk[x] -= d;
    if (vr[x]) hr[x] -= d;
}
for (int x = 0; x < n; ++x)
    if (!vl[x] && !slk[x] && !Check(x)) return;
}
ll solve() {
    fill_n(fl
        , n, -1), fill_n(fr, n, -1), fill_n(hr, n, 0);
    for (int i = 0; i < n; ++i)
        hl[i] = *max_element(w[i], w[i] + n);
    for (int i = 0; i < n; ++i) bfs(i);
    ll res = 0;
    for (int i = 0; i < n; ++i) res += w[i][fl[i]];
    return res;
}
};

```

### 3.3 MCMF

```

struct MinCostMaxFlow { // 0-base
    struct Edge {
        ll from, to, cap, flow, cost, rev;
    } *past[N];
    vector<Edge> G[N];
    int inq[N], n, s, t;
    ll dis[N], up[N], pot[N];
    bool BellmanFord() {
        fill_n(dis, n, INF), fill_n(inq, n, 0);
        queue<int> q;
        auto relax = [&](int u, ll d, ll cap, Edge *e) {
            if (cap > 0 && dis[u] > d) {
                dis[u] = d, up[u] = cap, past[u] = e;
                if (!inq[u]) inq[u] = 1, q.push(u);
            }
        };
        relax(s, 0, INF, 0);
        while (!q.empty()) {
            int u = q.front();
            q.pop(), inq[u] = 0;
            for (auto &e : G[u]) {
                ll d2 = dis[u] + e.cost + pot[u] - pot[e.to];
                relax(
                    e.to, d2, min(up[u], e.cap - e.flow), &e);
            }
        }
        return dis[t] != INF;
    }
    bool Dijkstra() {
        fill_n(dis, n, INF);
        priority_queue<pll, vector<pll>, greater<pll>> pq;
        auto relax = [&](int u, ll d, ll cap, Edge *e) {
            if (cap > 0 && dis[u] > d) {
                dis[u] = d, up[u] = cap, past[u] = e;
                pq.push(pll(d, u));
            }
        };
        relax(s, 0, INF, 0);
        while (!pq.empty()) {
            auto [d, u] = pq.top();
            pq.pop();
            if (dis[u] != d) continue;
            for (auto &e : G[u]) {

```

```

                ll d2 = dis[u] + e.cost + pot[u] - pot[e.to];
                relax(
                    e.to, d2, min(up[u], e.cap - e.flow), &e);
            }
        }
        return dis[t] != INF;
    }
    void solve(int _s, int _t, ll &flow, ll &cost,
        bool neg = true) {
        s = _s, t = _t, flow = 0, cost = 0;
        if (neg) BellmanFord(), copy_n(dis, n, pot);
        // do BellmanFord() if time isn't tight
        for (; Dijkstra(); copy_n(dis, n, pot)) {
            for (int i = 0; i < n; ++i)
                dis[i] += pot[i] - pot[s];
            flow += up[t], cost += up[t] * dis[t];
            for (int i = t; past[i]; i = past[i]->from) {
                auto &e = *past[i];
                e.flow += up[t], G[e.to][e.rev].flow -= up[t];
            }
        }
    }
    void init(int _n) {
        n = _n, fill_n(pot, n, 0);
        for (int i = 0; i < n; ++i) G[i].clear();
    }
    void add_edge(ll a, ll b, ll cap, ll cost) {
        G[a].emplace_back(
            Edge{a, b, cap, 0, cost, (int)G[b].size()});
        G[b].emplace_back(
            Edge{b, a, 0, 0, -cost, (int)G[a].size() - 1});
    }
};

```

### 3.4 GeneralGraphMatching

```

struct Matching { // 0-base
    queue<int> q; int n;
    vector<int> fa, s, vis, pre, match;
    vector<vector<int>> G;
    int Find(int u)
    { return u == fa[u] ? u : fa[u] = Find(fa[u]); }
    int LCA(int x, int y) {
        static int tk = 0; tk++; x = Find(x); y = Find(y);
        for (; swap(x, y)) if (x != n) {
            if (vis[x] == tk) return x;
            vis[x] = tk;
            x = Find(pre[match[x]]);
        }
    }
    void Blossom(int x, int y, int l) {
        for (; Find(x) != l; x = pre[y]) {
            pre[x] = y, y = match[x];
            if (s[y] == 1) q.push(y), s[y] = 0;
            for (int z: {x, y}) if (fa[z] == z) fa[z] = l;
        }
    }
    bool Bfs(int r) {
        iota(all(fa), 0); fill(all(s), -1);
        q = queue<int>(); q.push(r); s[r] = 0;
        for (; !q.empty(); q.pop()) {
            for (int x = q.front(); int u : G[x])
                if (s[u] == -1) {
                    if (pre[u] = x, s[u] = 1, match[u] == n) {
                        for (int a = u, b = x, last;
                            b != n; a = last, b = pre[a])
                            last =
                                match[b], match[b] = a, match[a] = b;
                        return true;
                    }
                    q.push(match[u]); s[match[u]] = 0;
                }
            else if (!s[u] && Find(u) != Find(x)) {
                int l = LCA(u, x);
                Blossom(x, u, l); Blossom(u, x, l);
            }
        }
    }
};

```

```

    return false;
}
Matching(int _n) : n(_n), fa(n + 1), s(n + 1), vis
    (n + 1), pre(n + 1, n), match(n + 1, n), G(n) {}
void add_edge(int u, int v)
{ G[u].emplace_back(v), G[v].emplace_back(u); }
int solve() {
    int ans = 0;
    for (int x = 0; x < n; ++x)
        if (match[x] == n) ans += Bfs(x);
    return ans;
} // match[x] == n means not matched
};

```

### 3.5 MaxWeightMaching

```

#define rep(i, l, r) for (int i = (l); i <= (r); ++i)
struct WeightGraph { // 1-based
    struct edge {
        int u, v, w;
    };
    int n, nx;
    vector<int> lab;
    vector<vector<edge>> g;
    vector<int> slack, match, st, pa, S, vis;
    vector<vector<int>> flo, flo_from;
    queue<int> q;
    WeightGraph(int n_)
        : n(n_), nx(n * 2), lab(nx + 1),
          g(nx + 1, vector<edge>(nx + 1)), slack(nx + 1),
          flo(nx + 1), flo_from(nx + 1, vector(n + 1, 0)) {
        match = st = pa = S = vis = slack;
        rep(u, 1, n) rep(v, 1, n) g[u][v] = {u, v, 0};
    }
    int ED(edge e) {
        return lab[e.u] + lab[e.v] - g[e.u][e.v].w * 2;
    }
    void update_slack(int u, int x, int &s) {
        if (!s || ED(g[u][x]) < ED(g[s][x])) s = 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, slack[x]);
    }
    void q_push(int x) {
        if (x <= n) q.push(x);
        else
            for (int y : flo[x]) q.push(y);
    }
    void set_st(int x, int b) {
        st[x] = b;
        if (x > n)
            for (int y : flo[x]) set_st(y, b);
    }
    vector<int> split_flo(auto &f, int xr) {
        auto it = find(ALL(f), xr);
        if (auto pr = it - f.begin(); pr % 2 == 1)
            reverse(1 + ALL(f), it = f.end() - pr);
        auto res = vector(f.begin(), it);
        return f.erase(f.begin(), it), res;
    }
    void set_match(int u, int v) {
        match[u] = g[u][v].v;
        if (u <= n) return;
        int xr = flo_from[u][g[u][v].u];
        auto &f = flo[u], z = split_flo(f, xr);
        rep(i, 0, (int)z.size() - 1)
            set_match(z[i], z[i ^ 1]);
        set_match(xr, v);
        f.insert(f.end(), all(z));
    }
    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 lca(int u, int v) {
        static int t = 0;
        ++t;
        for (++t; u || v; swap(u, v))
            if (u) {
                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 o, int v) {
        int b = find(n + 1 + all(st), 0) - begin(st);
        lab[b] = 0, S[b] = 0;
        match[b] = match[o];
        vector<int> f = {o};
        for (int x = u, y; x != o; x = st[pa[y]])
            f.emplace_back(x),
            f.emplace_back(y = st[match[x]]), q_push(y);
        reverse(1 + all(f));
        for (int x = v, y; x != o; x = st[pa[y]])
            f.emplace_back(x),
            f.emplace_back(y = st[match[x]]), q_push(y);
        flo[b] = f;
        set_st(b, b);
        for (int x = 1; x <= nx; ++x)
            g[b][x].w = g[x][b].w = 0;
        fill(all(flo_from[b]), 0);
        for (int xs : flo[b]) {
            for (int x = 1; x <= nx; ++x)
                if (g[b][x].w == 0 ||
                    ED(g[xs][x]) < ED(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 (int x : flo[b]) set_st(x, x);
        int xr = flo_from[b][g[b][pa[b]].u], xs = -1;
        for (int x : split_flo(flo[b], xr)) {
            if (xs == -1) {
                xs = x;
                continue;
            }
            pa[xs] = g[x][xs].u;
            S[xs] = 1, S[x] = 0;
            slack[xs] = 0;
            set_slack(x);
            q_push(x);
            xs = -1;
        }
        for (int x : flo[b])
            if (x == xr) S[x] = 1, pa[x] = pa[b];
            else S[x] = -1, set_slack(x);
        st[b] = 0;
    }
    bool on_found_edge(const edge &e) {
        if (int u = st[e.u], v = st[e.v]; S[v] == -1) {
            int nu = st[match[v]];
            pa[v] = e.u;
            S[v] = 1;
            slack[v] = slack[nu] = 0;
            S[nu] = 0;
            q_push(nu);
        } else if (S[v] == 0) {
            if (int o = lca(u, v)) add_blossom(u, o, v);
            else return augment(u, v), augment(v, u), true;

```



```

    }
    return false;
}
bool matching() {
    fill(all(S), -1), fill(all(slack), 0);
    q = queue<int>();
    for (int x = 1; x <= nx; ++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 (ED(g[u][v]) != 0)
                        update_slack(u, st[v], slack[st[v]]);
                    else if (on_found_edge(g[u][v]))
                        return true;
                }
        }
        int d = INF;
        for (int b = n + 1; b <= nx; ++b)
            if (st[b] == b && S[b] == 1)
                d = min(d, lab[b] / 2);
        for (int x = 1; x <= nx; ++x)
            if (int s = slack[x];
                st[x] == x && s && S[x] <= 0)
                d = min(d, ED(g[s][x]) / (S[x] + 2));
        for (int u = 1; u <= n; ++u)
            if (S[st[u]] == 1) lab[u] += d;
            else if (S[st[u]] == 0) {
                if (lab[u] <= d) return false;
                lab[u] -= d;
            }
        rep(b, n + 1, nx) if (st[b] == b && S[b] >= 0)
            lab[b] += d * (2 - 4 * S[b]);
        for (int x = 1; x <= nx; ++x)
            if (int s = slack[x]; st[x] == x && s &&
                st[s] != x && ED(g[s][x]) == 0)
                if (on_found_edge(g[s][x])) return true;
        for (int b = n + 1; b <= nx; ++b)
            if (st[b] == b && S[b] == 1 && lab[b] == 0)
                expand_blossom(b);
    }
    return false;
}
pair<ll, int> solve() {
    fill(all(match), 0);
    rep(u, 0, n) st[u] = u, flo[u].clear();
    int w_max = 0;
    rep(u, 1, n) rep(v, 1, n) {
        flo_from[u][v] = (u == v ? u : 0);
        w_max = max(w_max, g[u][v].w);
    }
    fill(all(lab), w_max);
    int n_matches = 0;
    ll tot_weight = 0;
    while (matching()) ++n_matches;
    rep(u, 1, n) if (match[u] && match[u] < u)
        tot_weight += g[u][match[u]].w;
    return make_pair(tot_weight, n_matches);
}
void add_edge(int u, int v, int w) {
    g[u][v].w = g[v][u].w = w;
}
};

```

### 3.6 GlobalMinCut

```

struct StoerWagner { //  $O(V^3)$ , is it  $O(VE + V \log V)$ ?
    int vst[N], edge[N][N], wei[N];
    void init(int n) {
        for (int i = 0; i < n; ++i) fill_n(edge[i], n, 0);
    }
};

```

```

}
void addEdge(int u, int v, int w) {
    edge[u][v] += w;
    edge[v][u] += w;
}
int search(int &s, int &t, int n) {
    fill_n(vst, n, 0), fill_n(wei, n, 0);
    s = t = -1;
    int mx, cur;
    for (int j = 0; j < n; ++j) {
        mx = -1, cur = 0;
        for (int i = 0; i < n; ++i)
            if (wei[i] > mx) cur = i, mx = wei[i];
        vst[cur] = 1, wei[cur] = -1;
        s = t;
        t = cur;
        for (int i = 0; i < n; ++i)
            if (!vst[i]) wei[i] += edge[cur][i];
    }
    return mx;
}
int solve(int n) {
    int res = INF;
    for (int x, y; n > 1; n--) {
        res = min(res, search(x, y, n));
        for (int i = 0; i < n; ++i)
            edge[i][x] = (edge[x][i] += edge[y][i]);
        for (int i = 0; i < n; ++i) {
            edge[y][i] = edge[n - 1][i];
            edge[i][y] = edge[i][n - 1];
        } // edge[y][y] = 0;
    }
    return res;
}
} sw;

```

### 3.7 BoundedFlow(Dinic)

```

struct BoundedFlow { //  $\theta$ -base
    struct edge {
        int to, cap, flow, rev;
    };
    vector<edge> G[N];
    int n, s, t, dis[N], cur[N], cnt[N];
    void init(int _n) {
        n = _n;
        for (int i = 0; i < n + 2; ++i)
            G[i].clear(), cnt[i] = 0;
    }
    void add_edge(int u, int v, int lcap, int rcap) {
        cnt[u] -= lcap, cnt[v] += lcap;
        G[u].emplace_back
            (edge{v, rcap, lcap, (int)G[v].size()});
        G[v].emplace_back
            (edge{u, 0, 0, (int)G[u].size() - 1});
    }
    void add_edge(int u, int v, int cap) {
        G[u].emplace_back
            (edge{v, cap, 0, (int)G[v].size()});
        G[v].emplace_back
            (edge{u, 0, 0, (int)G[u].size() - 1});
    }
    int dfs(int u, int cap) {
        if (u == t || !cap) return cap;
        for (int &i = cur[u]; i < G[u].size(); ++i) {
            edge &e = G[u][i];
            if (dis[e.to] == dis[u] + 1 && e.cap != e.flow) {
                int df = dfs(e.to, min(e.cap - e.flow, cap));
                if (df) {
                    e.flow += df, G[e.to][e.rev].flow -= df;
                    return df;
                }
            }
        }
    }
    dis[u] = -1;
    return 0;
}

```

```

bool bfs() {
    fill_n(dis, n + 3, -1);
    queue<int> q;
    q.push(s), dis[s] = 0;
    while (!q.empty()) {
        int u = q.front();
        q.pop();
        for (edge &e : G[u])
            if (!dis[e.to] && e.flow != e.cap)
                q.push(e.to), dis[e.to] = dis[u] + 1;
    }
    return dis[t] != -1;
}

int maxflow(int _s, int _t) {
    s = _s, t = _t;
    int flow = 0, df;
    while (bfs()) {
        fill_n(cur, n + 3, 0);
        while ((df = dfs(s, INF))) flow += df;
    }
    return flow;
}

bool solve() {
    int sum = 0;
    for (int i = 0; i < n; ++i)
        if (cnt[i] > 0)
            add_edge(n + 1, i, cnt[i]), sum += cnt[i];
        else if (cnt[i] < 0) add_edge(i, n + 2, -cnt[i]);
    if (sum != maxflow(n + 1, n + 2)) sum = -1;
    for (int i = 0; i < n; ++i)
        if (cnt[i] > 0)
            G[n + 1].pop_back(), G[i].pop_back();
        else if (cnt[i] < 0)
            G[i].pop_back(), G[n + 2].pop_back();
    return sum != -1;
}

int solve(int _s, int _t) {
    add_edge(_t, _s, INF);
    if (!solve()) return -1; // invalid flow
    int x = G[_t].back().flow;
    return G[_t].pop_back(), G[_s].pop_back(), x;
}
};

```

### 3.8 GomoryHuTree

```

MaxFlow Dinic;
int g[N];
void GomoryHu(int n) { // 0-base
    fill_n(g, n, 0);
    for (int i = 1; i < n; ++i) {
        Dinic.reset();
        add_edge(i, g[i], Dinic.maxflow(i, g[i]));
        for (int j = i + 1; j <= n; ++j)
            if (g[j] == g[i] && ~Dinic.dis[j])
                g[j] = i;
    }
}

```

### 3.9 MinCostCirculation

```

struct MinCostCirculation { // 0-base
    struct Edge {
        ll from, to, cap, fcap, flow, cost, rev;
    } *past[N];
    vector<Edge> G[N];
    ll dis[N], inq[N], n;
    void BellmanFord(int s) {
        fill_n(dis, n, INF), fill_n(inq, n, 0);
        queue<int> q;
        auto relax = [&](int u, ll d, Edge *e) {
            if (dis[u] > d) {
                dis[u] = d, past[u] = e;
                if (!inq[u]) inq[u] = 1, q.push(u);
            }
        };
        relax(s, 0, 0);
    }
};

```

```

while (!q.empty()) {
    int u = q.front();
    q.pop(), inq[u] = 0;
    for (auto &e : G[u])
        if (e.cap > e.flow)
            relax(e.to, dis[u] + e.cost, &e);
}

void try_edge(Edge &cur) {
    if (cur.cap > cur.flow) return ++cur.cap, void();
    BellmanFord(cur.to);
    if (dis[cur.from] + cur.cost < 0) {
        ++cur.flow, --G[cur.to][cur.rev].flow;
        for (int i = cur.from; past[i]; i = past[i]->from) {
            auto &e = *past[i];
            ++e.flow, --G[e.to][e.rev].flow;
        }
        ++cur.cap;
    }
}

void solve(int mxlg) {
    for (int b = mxlg; b >= 0; --b) {
        for (int i = 0; i < n; ++i)
            for (auto &e : G[i])
                e.cap *= 2, e.flow *= 2;
        for (int i = 0; i < n; ++i)
            for (auto &e : G[i])
                if (e.fcap >> b & 1)
                    try_edge(e);
    }
}

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

void add_edge(ll a, ll b, ll cap, ll cost) {
    G[a].emplace_back(Edge{a, b,
        0, cap, 0, cost, (ll)G[b].size() + (a == b)});
    G[b].emplace_back(Edge
        {b, a, 0, 0, 0, -cost, (ll)G[a].size() - 1});
}

} mcmf; // O(VE * ElogC)

```

### 3.10 FlowModelsBuilding

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



5. For each vertex  $v$  with  $d(v) < 0$ , connect  $v \rightarrow T$  with  $(cost, cap) = (0, -d(v))$
6. Flow from  $S$  to  $T$ , the answer is the cost of the flow  $C + K$
- Maximum density induced subgraph
  1. Binary search on answer, suppose we're checking answer  $T$
  2. Construct a max flow model, let  $K$  be the sum of all weights
  3. Connect source  $s \rightarrow v$ ,  $v \in G$  with capacity  $K$
  4. For each edge  $(u, v, w)$  in  $G$ , connect  $u \rightarrow v$  and  $v \rightarrow u$  with capacity  $w$
  5. For  $v \in G$ , connect it with sink  $v \rightarrow t$  with capacity  $K + 2T - (\sum_{e \in E(v)} w(e)) - 2w(v)$
  6.  $T$  is a valid answer if the maximum flow  $f < K|V|$
- Minimum weight edge cover
  1. For each  $v \in V$  create a copy  $v'$ , and connect  $u' \rightarrow v'$  with weight  $w(u, v)$ .
  2. Connect  $v \rightarrow v'$  with weight  $2\mu(v)$ , where  $\mu(v)$  is the cost of the cheapest edge incident to  $v$ .
  3. Find the minimum weight perfect matching on  $G'$ .
- Project selection problem
  1. If  $p_v > 0$ , create edge  $(s, v)$  with capacity  $p_v$ ; otherwise, create edge  $(v, t)$  with capacity  $-p_v$ .
  2. Create edge  $(u, v)$  with capacity  $w$  with  $w$  being the cost of choosing  $u$  without choosing  $v$ .
  3. The mincut is equivalent to the maximum profit of a subset of projects.
- Dual of minimum cost maximum flow
  1. Capacity  $c_{uv}$ , Flow  $f_{uv}$ , Cost  $w_{uv}$ , Required Flow difference for vertex  $b_u$ .
  2. If all  $w_{uv}$  are integers, then optimal solution can happen when all  $p_u$  are integers.

$$\min \sum_{uv} w_{uv} f_{uv} \quad \min \sum_u b_u p_u + \sum_{uv} c_{uv} \max(0, p_v - p_u - w_{uv})$$

$$-f_{uv} \geq -c_{uv} \Leftrightarrow \sum_v f_{vu} - \sum_v f_{uv} = -b_u \quad p_u \geq 0$$

## 4 Data Structure

### 4.1 LinkCutTree

```
#define ls(x) Tree[x].son[0]
#define rs(x) Tree[x].son[1]
#define fa(x) Tree[x].fa
struct node {
    int son[2], Min, id, fa, lazy;
} Tree[N];
int n, m, q, w[N], Min;
struct Node {
    int u, v, w;
} a[N];
inline bool IsRoot(int x) {
    return (ls(fa(x)) == x || rs(fa(x)) == x) ? false : true;
}
inline void PushUp(int x) {
    Tree[x].Min = w[x], Tree[x].id = x;
    if (ls(x) && Tree[ls(x)].Min < Tree[x].Min) {
        Tree[x].Min = Tree[ls(x)].Min;
        Tree[x].id = Tree[ls(x)].id;
    }
    if (rs(x) && Tree[rs(x)].Min < Tree[x].Min) {
        Tree[x].Min = Tree[rs(x)].Min;
        Tree[x].id = Tree[rs(x)].id;
    }
}
inline void Update(int x) {
    Tree[x].lazy ^= 1;
    swap(ls(x), rs(x));
}
inline void PushDown(int x) {
    if (!Tree[x].lazy) return;
    if (ls(x)) Update(ls(x));
    if (rs(x)) Update(rs(x));
    Tree[x].lazy = 0;
}
inline void Rotate(int x) {
    int y = fa(x), z = fa(y), k = rs(y) == x;
```

```
w = Tree[x].son[!k];
if (!IsRoot(y)) Tree[z].son[rs(z) == y] = x;
fa(x) = z, fa(y) = x;
if (w) fa(w) = y;
Tree[x].son[!k] = y, Tree[y].son[k] = w;
PushUp(y);
}
inline void Splay(int x) {
    stack<int> Stack;
    int y = x, z;
    Stack.push(y);
    while (!IsRoot(y)) Stack.push(y = fa(y));
    while (!Stack.empty())
        PushDown(Stack.top()), Stack.pop();
    while (!IsRoot(x)) {
        y = fa(x), z = fa(y);
        if (!IsRoot(y))
            Rotate((ls(y) == x) ^ (ls(z) == y) ? x : y);
        Rotate(x);
    }
    PushUp(x);
}
inline void Access(int root) {
    for (int x = 0; root; x = root, root = fa(root))
        Splay(root), rs(root) = x, PushUp(root);
}
inline void MakeRoot(int x) {
    Access(x), Splay(x), Update(x);
}
inline int FindRoot(int x) {
    Access(x), Splay(x);
    while (ls(x)) x = ls(x);
    return Splay(x), x;
}
inline void Link(int u, int v) {
    MakeRoot(u);
    if (FindRoot(v) != u) fa(u) = v;
}
inline void Cut(int u, int v) {
    MakeRoot(u);
    if (FindRoot(v) != u || fa(v) != u || ls(v)) return;
    fa(v) = rs(u) = 0;
}
inline void Split(int u, int v) {
    MakeRoot(u), Access(v), Splay(v);
}
inline bool Check(int u, int v) {
    return MakeRoot(u), FindRoot(v) == u;
}
inline int LCA(int root, int u, int v) {
    MakeRoot(root), Access(u), Access(v), Splay(u);
    if (!fa(u)) {
        Access(u), Splay(v);
        return fa(v);
    }
    return fa(u);
}
/* ETT
每次進入節點和走邊都放入一次共 3n - 2
node(u) 表示進入節點 u 放入 treap 的位置
edge(u, v) 表示 u -> v 的邊放入 treap 的位置 (push v)
Makeroot u :
    L1 = [begin, node(u) - 1], L2 = [node(u), end]
    -> L2 + L1
Insert u, v :
    Tu -> L1 = [begin, node(u) - 1], L2 = [node(u), end]
    Tv -> L3 = [begin, node(v) - 1], L4 = [node(v), end]
    -> L2 + L1 + edge(u, v) + L4 + L3 + edge(v, u)
Delete u, v :
    maybe need swap u, v
    T -> L1 + edge(u, v) + L2 + edge(v, u) + L3
    -> L1 + L3, L2
*/
```

## 5 String

### 5.1 KMP

```
int KMP(string s, string t) {
    t = " " + t; // consistency with ACa
    int n = t.size(), ans = 0;
    vector<int> f(t.size(), 0);
    f[0] = -1;
    for (int i = 1, j = -1; i < t.size(); i++) {
        while (j >= 0 && t[j + 1] != t[i])
            j = f[j];
        f[i] = ++j;
    }
    for (int i = 0, j = 0; i < s.size(); i++) {
        while (j >= 0 && t[j + 1] != s[i])
            j = f[j];
        if (++j + 1 == t.size()) ans++, j = f[j];
    }
    return ans;
}
```

### 5.2 Z

```
int Z[N];
void z(string s) {
    for (int i = 1, mx = 0; i < s.size(); i++) {
        if (i < Z[mx] + mx)
            Z[i] = min(Z[mx] - i + mx, Z[i - mx]);
        while (
            Z[i] + i < s.size() && s[i + Z[i]] == s[Z[i]])
            Z[i]++;
        if (Z[i] + i > Z[mx] + mx) mx = i;
    }
}
```

### 5.3 Manacher

```
int man[N]; // len: man[i] - 1
void manacher(string s) { // uses 2/s+1
    string t;
    for (int i = 0; i < (int)s.size(); i++) {
        t.push_back('$');
        t.push_back(s[i]);
    }
    t.push_back('$');
    int mx = 1;
    for (int i = 0; i < (int)t.size(); i++) {
        man[i] = 1;
        man[i] = min(man[mx] + mx - i, man[2 * mx - i]);
        while (man[i] + i < (int)t.size() && i >= man[i] &&
            t[i + man[i]] == t[i - man[i]])
            man[i]++;
        if (i + man[i] > mx + man[mx]) mx = i;
    }
}
```

### 5.4 SuffixArray

```
struct SuffixArray {
#define add(x, k) (x + k + n) % n
    vector<int> sa, cnt, rk, tmp, lcp;
    // sa: order, rk[i]: pos of s[i..],
    // lcp[i]: LCP of sa[i], sa[i-1]
    void SA(string s) { // remember to append '\1'
        int n = s.size();
        sa.resize(n), cnt.resize(n);
        rk.resize(n), tmp.resize(n);
        iota(all(sa), 0);
        sort(all(sa),
            [&](int i, int j) { return s[i] < s[j]; });
        rk[0] = 0;
        for (int i = 1; i < n; i++)
            rk[sa[i]] =
                rk[sa[i - 1]] + (s[sa[i - 1]] != s[sa[i]]);
        for (int k = 1; k <= n; k <= 1) {
            fill(all(cnt), 0);

```

```
            for (int i = 0; i < n; i++)
                cnt[rk[add(sa[i], -k)]]++;
            for (int i = 1; i < n; i++) cnt[i] += cnt[i - 1];
            for (int i = n - 1; i >= 0; i--)
                tmp[--cnt[rk[add(sa[i], -k)]]] =
                    add(sa[i], -k);
            sa.swap(tmp);
            tmp[sa[0]] = 0;
            for (int i = 1; i < n; i++)
                tmp[sa[i]] = tmp[sa[i - 1]] +
                    (rk[sa[i - 1]] != rk[sa[i]] ||
                     rk[add(sa[i - 1], k)] !=
                     rk[add(sa[i], k)]);
            rk.swap(tmp);
        }
    }
    void LCP(string s) {
        int n = s.size(), k = 0;
        lcp.resize(n);
        for (int i = 0; i < n; i++)
            if (rk[i] == 0) lcp[rk[i]] = 0;
            else {
                if (k) k--;
                int j = sa[rk[i] - 1];
                while (
                    max(i, j) + k < n && s[i + k] == s[j + k])
                    k++;
                lcp[rk[i]] = k;
            }
    }
};
```

### 5.5 SAIS

```
auto sais(const auto &s) {
    const int n = SZ(s), z = ranges::max(s) + 1;
    if (n == 1) return vector{0};
    vector<int> c(z); for (int x : s) ++c[x];
    partial_sum(ALL(c), begin(c));
    vector<int> sa(n); auto I = views::iota(0, n);
    vector<bool> t(n, true);
    for (int i = n - 2; i >= 0; --i)
        t[i] = (
            s[i] == s[i + 1] ? t[i + 1] : s[i] < s[i + 1]);
    auto is_lms = views::filter([&t](int x) {
        return x && t[x] && !t[x - 1];
    });
    auto induce = [&] {
        for (auto x = c; int y : sa)
            if (y-- && !t[y]) sa[x[s[y] - 1]++] = y;
        for (auto x = c; int y : sa | views::reverse)
            if (y-- && t[y]) sa[--x[s[y]]] = y;
    };
    vector<int> lms, q(n); lms.reserve(n);
    for (auto x = c; int i : I | is_lms)
        q[i] = SZ(lms), lms.pb(sa[-x[s[i]]] = i);
    induce(); vector<int> ns(SZ(lms));
    for (int j = -1, nz = 0; int i : sa | is_lms) {
        if (j >= 0) {
            int len = min({n - i, n - j, lms[q[i] + 1] - i});
            ns[q[i]] = nz += lexicographical_compare(
                begin(s) + j, begin(s) + j + len,
                begin(s) + i, begin(s) + i + len);
        }
        j = i;
    }
    fill(ALL(sa), 0); auto nsa = sais(ns);
    for (auto x = c; int y : nsa | views::reverse)
        y = lms[y], sa[-x[s[y]]] = y;
    return induce(), sa;
}
// sa[i]: sa[i]-th suffix
// is the i-th lexicographically smallest suffix.
// hi[i]: LCP of suffix sa[i] and suffix sa[i - 1].
struct Suffix {
    int n; vector<int> sa, hi, ra;

```

```

Suffix
    (const auto &s, int _n) : n(_n), hi(n), ra(n) {
        vector<int> s(n + 1); // s[n] = 0;
        copy_n(s, n, begin(s)); // _s shouldn't contain 0
        sa = sais(s); sa.erase(sa.begin());
        for (int i = 0; i < n; ++i) ra[sa[i]] = i;
        for (int i = 0, h = 0; i < n; ++i) {
            if (!ra[i]) { h = 0; continue; }
            for (int j = sa[ra[i] - 1]; max
                (i, j) + h < n && s[i + h] == s[j + h];) ++h;
            hi[ra[i]] = h ? h-- : 0;
        }
    }
};

```

## 5.6 ACAutomaton

```

#define sigma 26
#define base 'a'
struct AhoCorasick { // N: sum of length
    int ch[N][sigma] = {{}}, f[N] = {-1}, tag[N],
        mv[N][sigma], jump[N], cnt[N];
    int idx = 0, t = -1;
    vector<int> E[N], q;
    pii o[N];
    int insert(string &s, int t) {
        int j = 0;
        for (int i = 0; i < (int)s.size(); i++) {
            if (!ch[j][s[i] - base])
                ch[j][s[i] - base] = ++idx;
            j = ch[j][s[i] - base];
        }
        tag[j] = 1;
        return j;
    }
    int next(int u, int c) {
        return u < 0 ? 0 : mv[u][c];
    }
    void dfs(int u) {
        o[u].F = ++t;
        for (auto v : E[u]) dfs(v);
        o[u].S = t;
    }
    void build() {
        int k = -1;
        q.emplace_back(0);
        while (++k < q.size()) {
            int u = q[k];
            for (int v = 0; v < sigma; v++) {
                if (ch[u][v]) {
                    f[ch[u][v]] = next(f[u], v);
                    q.emplace_back(ch[u][v]);
                }
                mv[u][v] =
                    (ch[u][v] ? ch[u][v] : next(f[u], v));
            }
            if (u) jump[u] = (tag[f[u]] ? f[u] : jump[f[u]]);
        }
        reverse(q.begin(), q.end());
        for (int i = 1; i <= idx; i++)
            E[f[i]].emplace_back(i);
        dfs(0);
    }
    void match(string &s) {
        fill(cnt, cnt + idx + 1, 0);
        for (int i = 0, j = 0; i < (int)s.size(); i++)
            cnt[j = next(j, s[i] - base)]++;
        for (int i : q)
            if (f[i] > 0) cnt[f[i]] += cnt[i];
    }
} ac;

```

## 5.7 MinRotation

```

int mincyc(string s) {
    int n = s.size();
    s = s + s;

```

```

    int i = 0, ans = 0;
    while (i < n) {
        ans = i;
        int j = i + 1, k = i;
        while (j < s.size() && s[j] >= s[k]) {
            k = (s[j] > s[k] ? i : k + 1);
            ++j;
        }
        while (i <= k) i += j - k;
    }
    return ans;
}

```

## 5.8 ExtSAM

```

#define CNUM 26
struct exSAM {
    int len[N * 2], link[N * 2]; // maxlength, suflink
    int next[N * 2][CNUM], tot; // [0, tot), root = 0
    int lenSorted[N * 2]; // topo. order
    int cnt[N * 2]; // occurence
    int newnode() {
        fill_n(next[tot], CNUM, 0);
        len[tot] = cnt[tot] = link[tot] = 0;
        return 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 < CNUM; ++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 (auto 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 < CNUM; ++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) lenSorted[--lc[len[i]]] = i;
    }
    void solve() {
        for (int i = tot - 2; i >= 0; --i)
            cnt[link[lenSorted[i]]] += cnt[lenSorted[i]];
    }
};

```

## 5.9 PalindromeTree

```
struct PalindromicTree {
    struct node {
        int next[26], fail, len;
        int cnt, num; // cnt: appear times, num: number of
                       // pal. suf.
        node(int l = 0) : fail(0), len(l), cnt(0), num(0) {
            for (int i = 0; i < 26; ++i) next[i] = 0;
        }
    };
    vector<node> St;
    vector<char> s;
    int last, n;
    PalindromicTree() : St(2), last(1), n(0) {
        St[0].fail = 1, St[1].len = -1, s.emplace_back(-1);
    }
    inline void clear() {
        St.clear(), s.clear(), last = 1, n = 0;
        St.emplace_back(0), St.emplace_back(-1);
        St[0].fail = 1, s.emplace_back(-1);
    }
    inline int get_fail(int x) {
        while (s[n - St[x].len - 1] != s[n])
            x = St[x].fail;
        return x;
    }
    inline void add(int c) {
        s.push_back(c == 'a'), ++n;
        int cur = get_fail(last);
        if (!St[cur].next[c]) {
            int now = St.size();
            St.emplace_back(St[cur].len + 2);
            St[now].fail =
                St[get_fail(St[cur].fail)].next[c];
            St[cur].next[c] = now;
            St[now].num = St[St[now].fail].num + 1;
        }
        last = St[cur].next[c], ++St[last].cnt;
    }
    inline void count() { // counting cnt
        auto i = St.rbegin();
        for (; i != St.rend(); ++i) {
            St[i->fail].cnt += i->cnt;
        }
    }
    inline int size() { // The number of diff. pal.
        return (int)St.size() - 2;
    }
};
```

## 6 Number Theory

### 6.1 Primes

```
12721 13331 14341 75577 123457 222557 556679 999983
1097774749 1076767633 100102021 999997771 1001010013
1000512343 987654361 999991231 999888733 98789101
987777733 999991921 1010101333 1010102101 1000000000039
100000000000037 2305843009213693951 4611686018427387847
9223372036854775783 18446744073709551557
```

### 6.2 ExtGCD

```
// beware of negative numbers!
void extgcd(ll a, ll b, ll c, ll &x, ll &y) {
    if (b == 0) x = c / a, y = 0;
    else {
        extgcd(b, a % b, c, y, x);
        y -= x * (a / b);
    }
} // |x| <= b/2, |y| <= a/2
```

### 6.3 FloorCeil

```
int floor(int a, int b)
{ return a / b - (a % b && (a < 0) ^ (b < 0)); }
int ceil(int a, int b)
{ return a / b + (a % b && (a < 0) ^ (b > 0)); }
```

## 6.4 FloorSum

Computes

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

Furthermore, Let  $m = \left\lfloor \frac{an+b}{c} \right\rfloor$ :

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

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

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

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

```
ll floorsum(ll A, ll B, ll C, ll N) {
    if (A == 0) return (N + 1) * (B / C);
    if (A > C || B > C)
        return (N + 1) * (B / C) +
            N * (N + 1) / 2 * (A / C) +
            floorsum(A % C, B % C, C, N);
    ll M = (A * N + B) / C;
    return N * M - floorsum(C, C - B - 1, A, M - 1);
}
```

## 6.5 MillerRabin

```
// n < 4,759,123,141      3 : 2, 7, 61
// n < 1,122,004,669,633  4 : 2, 13, 23, 1662803
// n < 3,474,749,660,383  6 : primes <= 13
// n < 2^64                7 :
// 2, 325, 9375, 28178, 450775, 9780504, 1795265022
```

```
bool Miller_Rabin(ll a, ll n) {
    if ((a = a % n) == 0) return 1;
    if (n % 2 == 0) return n == 2;
    ll tmp = (n - 1) / ((n - 1) & (1 - n));
    ll t = __lg(((n - 1) & (1 - n))), x = 1;
    for (; tmp; tmp >>= 1, a = mul(a, a, n))
        if (tmp & 1) x = mul(x, a, n);
    if (x == 1 || x == n - 1) return 1;
    while (--t)
        if ((x = mul(x, x, n)) == n - 1) return 1;
    return 0;
}
```

## 6.6 PollardRho

```
map<ll, int> cnt;
void PollardRho(ll n) {
    if (n == 1) return;
    if (prime(n)) return ++cnt[n], void();
    if (n % 2
        == 0) return PollardRho(n / 2), ++cnt[2], void();
    ll x = 2, y = 2, d = 1, p = 1;
    #define f(x, n, p) ((mul(x, x, n) + p) % n)
    while (true) {
        if (d != n && d != 1) {
            PollardRho(n / d);
            PollardRho(d);
            return;
        }
        if (d == n) ++p;
        x = f(x, n, p), y = f(f(y, n, p), n, p);
```

```

    d = gcd(abs(x - y), n);
}
}

```

## 6.7 Fraction

```

struct fraction {
    ll n, d;
    fraction
        (const ll &n=0, const ll &d=1): n(_n), d(_d) {
        ll t = gcd(n, d);
        n /= t, d /= t;
        if (d < 0) n = -n, d = -d;
    }
    fraction operator-() const
    { return fraction(-n, d); }
    fraction operator+(const fraction &b) const
    { return fraction(n * b.d + b.n * d, d * b.d); }
    fraction operator-(const fraction &b) const
    { return fraction(n * b.d - b.n * d, d * b.d); }
    fraction operator*(const fraction &b) const
    { return fraction(n * b.n, d * b.d); }
    fraction operator/(const fraction &b) const
    { return fraction(n * b.d, d * b.n); }
    void print() {
        cout << n;
        if (d != 1) cout << "/" << d;
    }
};

```

## 6.8 ChineseRemainder

```

ll solve(ll x1, ll m1, ll x2, ll m2) {
    ll g = gcd(m1, m2);
    if ((x2 - x1) % g) return -1; // no sol
    m1 /= g; m2 /= g;
    ll x, y;
    extgcd(m1, m2, __gcd(m1, m2), x, y);
    ll lcm = m1 * m2 * g;
    ll res = x * (x2 - x1) * m1 + x1;
    // be careful with overflow
    return (res % lcm + lcm) % lcm;
}

```

## 6.9 FactorialMod $p^k$

```

//  $O(p^k + \log^2 n)$ ,  $pk = p^k$ 
ll prod[MAXP];
ll fac_no_p(ll n, ll p, ll pk) {
    prod[0] = 1;
    for (int i = 1; i <= pk; ++i)
        if (i % p) prod[i] = prod[i - 1] * i % pk;
        else prod[i] = prod[i - 1];
    ll rt = 1;
    for (; n; n /= p) {
        rt = rt * mpow(prod[pk], n / pk, pk) % pk;
        rt = rt * prod[n % pk] % pk;
    }
    return rt;
} // (n! without factor p) %  $p^k$ 

```

## 6.10 QuadraticResidue

```

// Berlekamp-Rabin,  $\log^2(p)$ 
ll trial(ll y, ll z, ll m) {
    ll a0 = 1, a1 = 0, b0 = z, b1 = 1, p = (m - 1) / 2;
    while (p) {
        if (p & 1)
            tie(a0, a1) =
                make_pair((a1 * b1 % m * y + a0 * b0) % m,
                    (a0 * b1 + a1 * b0) % m);
            tie(b0, b1) =
                make_pair((b1 * b1 % m * y + b0 * b0) % m,
                    (2 * b0 * b1) % m);
        p >>= 1;
    }
    if (a1) return inv(a1, m);
    return -1;
}

```

```

}
mt19937 rd(49);
ll psqrt(ll y, ll p) {
    if (fpow(y, (p - 1) / 2, p) != 1) return -1;
    for (int i = 0; i < 30; i++) {
        ll z = rd() % p;
        if (z * z % p == y) return z;
        ll x = trial(y, z, p);
        if (x == -1) continue;
        return x;
    }
    return -1;
}

```

## 6.11 MeisselLehmer

```

ll PrimeCount(ll n) { //  $n \sim 10^{13} \Rightarrow < 2s$ 
    if (n <= 1) return 0;
    int v = sqrt(n), s = (v + 1) / 2, pc = 0;
    vector<int> smalls(v + 1), skip(v + 1), roughs(s);
    vector<ll> larges(s);
    for (int i = 2; i <= v; ++i) smalls[i] = (i + 1) / 2;
    for (int i = 0; i < s; ++i) {
        roughs[i] = 2 * i + 1;
        larges[i] = (n / (2 * i + 1) + 1) / 2;
    }
    for (int p = 3; p <= v; ++p) {
        if (smalls[p] > smalls[p - 1]) {
            int q = p * p;
            ++pc;
            if (1LL * q * q > n) break;
            skip[p] = 1;
            for (int i = q; i <= v; i += 2 * p) skip[i] = 1;
            int ns = 0;
            for (int k = 0; k < s; ++k) {
                int i = roughs[k];
                if (skip[i]) continue;
                ll d = 1LL * i * p;
                larges[ns] = larges[k] - (d <= v ? larges
                    [smalls[d] - pc] : smalls[n / d]) + pc;
                roughs[ns++] = i;
            }
            s = ns;
            for (int j = v / p; j >= p; --j) {
                int c =
                    smalls[j] - pc, e = min(j * p + p, v + 1);
                for (int i = j * p; i < e; ++i) smalls[i] -= c;
            }
        }
    }
    for (int k = 1; k < s; ++k) {
        const ll m = n / roughs[k];
        ll t = larges[k] - (pc + k - 1);
        for (int l = 1; l < k; ++l) {
            int p = roughs[l];
            if (1LL * p * p > m) break;
            t -= smalls[m / p] - (pc + l - 1);
        }
        larges[0] -= t;
    }
    return larges[0];
}

```

## 6.12 DiscreteLog

```

int DiscreteLog(int s, int x, int y, int m) {
    constexpr int kStep = 32000;
    unordered_map<int, int> p;
    int b = 1;
    for (int i = 0; i < kStep; ++i) {
        p[y] = i;
        y = 1LL * y * x % m;
        b = 1LL * b * x % m;
    }
    for (int i = 0; i < m + 10; i += kStep) {
        s = 1LL * s * b % m;
        if (p.find(s) != p.end()) return i + kStep - p[s];
    }
}

```

```

return -1;
}
int DiscreteLog(int x, int y, int m) {
    if (m == 1) return 0;
    int s = 1;
    for (int i = 0; i < 100; ++i) {
        if (s == y) return i;
        s = 1LL * s * x % m;
    }
    if (s == y) return 100;
    int p = 100 + DiscreteLog(s, x, y, m);
    if (fpow(x, p, m) != y) return -1;
    return p;
}

```

## 6.13 Theorems

### • Cramer's Rule

$$\begin{aligned} ax+by=e & \quad x=\frac{ed-bf}{ad-bc} \\ cx+dy=f & \Rightarrow y=\frac{af-ec}{ad-bc} \end{aligned}$$

### • Vandermonde's Identity

$$C(n+m, k) = \sum_{i=0}^k C(n, i) C(m, k-i)$$

### • Kirchhoff's Theorem

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

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

### • Tutte's Matrix

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

### • Cayley's Formula

- Given a degree sequence  $d_1, d_2, \dots, d_n$  for each labeled vertices, there are  $\frac{(n-2)!}{(d_1-1)!(d_2-1)!\dots(d_n-1)!}$  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 nonnegative integers  $d_1 \geq \dots \geq d_n$  can be represented as the degree sequence of a finite simple graph on  $n$  vertices if and only if  $d_1 + \dots + d_n$  is even and

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

### • Gale-Ryser Theorem

A pair of sequences of nonnegative integers  $a_1 \geq \dots \geq a_n$  and  $b_1, \dots, b_n$  is bigraphic (degree sequence of bipartite graph) if and only if

$$\sum_{i=1}^n a_i = \sum_{i=1}^n b_i \text{ and } \sum_{i=1}^k a_i \leq \sum_{i=1}^n \min(b_i, k)$$

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

### • Fulkerson-Chen-Anstee Theorem

A sequence  $(a_1, b_1), \dots, (a_n, b_n)$  of nonnegative integer pairs with  $a_1 \geq \dots \geq a_n$  is digraphic (in, out degree of a directed graph) if and only if  $\sum_{i=1}^n a_i = \sum_{i=1}^n b_i$  and  $\sum_{i=1}^k a_i \leq \sum_{i=1}^n \min(b_i, k)$

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

### • Möbius Inversion Formula

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

### • Lagrange Multiplier

- Optimize  $f(x_1, \dots, x_n)$  when  $k$  constraints  $g_i(x_1, \dots, x_n) = 0$ .
- Lagrangian function  $\mathcal{L}(x_1, \dots, x_n, \lambda_1, \dots, \lambda_k) = f(x_1, \dots, x_n) - \sum_{i=1}^k \lambda_i g_i(x_1, \dots, x_n)$ .
- The solution corresponding to the original constrained optimization is always a saddle point of the Lagrangian function.

## 6.14 Estimation

### • Estimation

- Number of divisors

$n \leq$	100	10 <sup>3</sup>	10 <sup>6</sup>	10 <sup>9</sup>	10 <sup>12</sup>	10 <sup>15</sup>	10 <sup>18</sup>
$\max d(n)$	12	32	240	1344	6720	26880	103680

- Unordered integer partition

$n$	2	3	4	5	6	7	8	9	20	30	40	50	100
$p(n)$	2	3	5	7	11	15	22	30	627	5604	4.10 <sup>4</sup>	2.10 <sup>5</sup>	2.10 <sup>8</sup>

- Ways of partitions of  $n$  distinct elements

$n$	2	3	4	5	6	7	8	9	10	11	12	13
$B_n$	2	5	15	52	203	877	4140	21147	115975	7.10 <sup>5</sup>	4.10 <sup>6</sup>	3.10 <sup>7</sup>

## 6.15 Numbers

### • Bernoulli numbers

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

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

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

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

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

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

- Pentagonal number theorem

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

- Catalan numbers

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

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

- Eulerian numbers

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

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

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

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

## 6.16 Generating Functions

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

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

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

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

- Special Generating Function

- $(1+x)^n = \sum_{i \geq 0} \binom{n}{i} x^i$
- $\frac{1}{(1-x)^n} = \sum_{i \geq 0} \binom{n+i-1}{n-1} x^i$
- $S_k = \sum_{x=1}^n x^k: S = \sum_{p=0}^{\infty} x^p = \frac{e^x - e^{x(n+1)}}{1 - e^x}$

## 7 Linear Algebra

### 7.1 Gaussian Elimination

```

struct matrix { // m variables, n equations
    int n, m;
    fraction A[N][N+1], sol[N];
    int solve() { // -1: inconsistent, >= 0: rank
        for (int i = 0; i < n; ++i) {
            int piv = 0;
            while (piv < m && !A[i][piv].n) ++piv;
            if (piv == m) continue;
            for (int j = 0; j < n; ++j) {
                if (i == j) continue;
                fraction tmp = -A[j][piv] / A[i][piv];
                for (int k = 0; k <= m; ++k)
                    A[j][k] = tmp * A[i][k] + A[j][k];
            }
        }
        int rank = 0;
    }
}

```



```

    for (int i = 0; i < n; ++i) {
        int piv = 0;
        while (piv < m && !A[i][piv].n) ++piv;
        if (piv == m && A[i][m].n) return -1;
        else if (piv < m)
            ++rank, sol[piv] = A[i][m] / A[i][piv];
    }
    return rank;
};

```

## 7.2 BerlekampMassey

```

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

```

## 7.3 Simplex

Standard form: maximize  $c^T x$  subject to  $Ax \leq b$  and  $x \geq 0$ .  
 Dual LP: minimize  $b^T y$  subject to  $A^T y \geq c$  and  $y \geq 0$ .  
 $\bar{x}$  and  $\bar{y}$  are optimal if and only if for all  $i \in [1, n]$ , either  $\bar{x}_i = 0$  or  $\sum_{j=1}^m A_{ji} \bar{y}_j = c_i$  holds and for all  $i \in [1, m]$  either  $\bar{y}_i = 0$  or  $\sum_{j=1}^n A_{ij} \bar{x}_j = b_j$  holds.

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

```

// n variable, m constraints, M >= n + 2m
struct simplex {
    const double inf = 1 / .0, eps = 1e-9;
    int n, m, k, var[N], inv[N], art[N];
    double A[M][N], B[M], x[N];
    void init(int _n) { n = _n, m = 0; }
    void equation(vector<double> a, double b) {
        for (int i = 0; i < n; i++) A[m][i] = a[i];
        B[m] = b, var[m] = n + m, ++m;
    }
    void pivot(int r, int c, double bx) {
        for (int i = 0; i <= m + 1; i++)
            if (i != r && abs(A[i][c]) > eps) {
                x[var[i]] -= bx * A[i][c] / A[r][c];
                double f = A[i][c] / A[r][c];
                for (int j = 0; j <= n + m + k; j++)
                    A[i][j] -= A[r][j] * f;
                B[i] -= B[r] * f;
            }
    }
    double phase(int p) {
        while (true) {
            int in = min_element(
                A[m + p], A[m + p] + n + m + k + 1) -
                A[m + p];
            if (A[m + p][in] >= -eps) break;
            double bx = inf;

```

```

        int piv = -1;
        for (int i = 0; i < m; i++)
            if (A[i][in] > eps && B[i] / A[i][in] <= bx)
                piv = i, bx = B[i] / A[i][in];
        if (piv == -1) return inf;
        int out = var[piv];
        pivot(piv, in, bx);
        x[out] = 0, x[in] = bx, var[piv] = in;
    }
    return x[n + m];
}

double solve(vector<double> c) {
    auto invert = [&](int r) {
        for (int j = 0; j <= n + m; j++) A[r][j] *= -1;
        B[r] *= -1;
    };
    k = 1;
    for (int i = 0; i < n; i++) A[m][i] = -c[i];
    fill(A[m + 1], A[m + 1] + N, 0.0);
    for (int i = 0; i <= m + 1; i++)
        fill(A[i] + n, A[i] + n + m + 2, 0.0),
        var[i] = n + i, A[i][n + i] = 1;

    for (int i = 0; i < m; i++) {
        if (B[i] < 0) {
            ++k;
            for (int j = 0; j <= n + m; j++)
                A[m + 1][j] += A[i][j];
            invert(i);
            var[i] = n + m + k, A[i][var[i]] = 1,
            art[var[i]] = n + i;
        }
        x[var[i]] = B[i];
    }

    phase(1);
    if (*max_element(
        x + (n + m + 2), x + (n + m + k + 1)) > eps)
        return .0 / .0;
    for (int i = 0; i <= m; i++)
        if (var[i] > n + m)
            var[i] = art[var[i]], invert(i);
    k = 0;
    return phase(0);
}
} lp;

```

## 8 Polynomials

### 8.1 NTT (FFT)

	Mod	g	Form
	65 537	3	$2^{16} + 1$
	998 244 353	3	$119 \cdot 2^{23} + 1$
	1 315 962 881	3	$1255 \cdot 2^{20} + 1$
	1 711 276 033	29	$51 \cdot 2^{25} + 1$
	9 223 372 036 737 335 297	29	$549755813881 \cdot 2^{24} + 1$

```

#define base ll // complex<double>
// const double PI = acos(-1);
const ll mod = 998244353, g = 3;
base omega[4 * N], omega_[4 * N];
int rev[4 * N];

ll fpow(ll b, ll p);

ll inverse(ll a) { return fpow(a, mod - 2); }

void calcw(int n) {
    ll r = fpow(g, (mod - 1) / n), invr = inverse(r);
    omega[0] = omega_[0] = 1;
    for (int i = 1; i < n; i++) {
        omega[i] = omega[i - 1] * r % mod;
        omega_[i] = omega_[i - 1] * invr % mod;
    }
    // double arg = 2.0 * PI / n;
    // for (int i = 0; i < n; i++)
    // {

```

```

// omega[i] = base(cos(i * arg), sin(i * arg));
// omega_[i] = base(cos(-i * arg), sin(-i * arg));
// }
}

void calcrev(int n) {
    int k = __lg(n);
    for (int i = 0; i < n; i++) rev[i] = 0;
    for (int i = 0; i < n; i++)
        for (int j = 0; j < k; j++)
            if (i & (1 << j)) rev[i] ^= 1 << (k - j - 1);
}

vector<base> NTT(vector<base> poly, bool inv) {
    base *w = (inv ? omega_ : omega);
    int n = poly.size();
    for (int i = 0; i < n; i++)
        if (rev[i] > i) swap(poly[i], poly[rev[i]]);

    for (int len = 1; len < n; len <= 1) {
        int arg = n / len / 2;
        for (int i = 0; i < n; i += 2 * len)
            for (int j = 0; j < len; j++) {
                base odd =
                    w[j * arg] * poly[i + j + len] % mod;
                poly[i + j + len] =
                    (poly[i + j] - odd + mod) % mod;
                poly[i + j] = (poly[i + j] + odd) % mod;
            }
    }
    if (inv)
        for (auto &a : poly) a = a * inverse(n) % mod;
    return poly;
}

vector<base> mul(vector<base> f, vector<base> g) {
    int sz = 1 << (__lg(f.size() + g.size() - 1) + 1);
    f.resize(sz), g.resize(sz);
    calcrev(sz);
    calcW(sz);
    f = NTT(f, 0), g = NTT(g, 0);
    for (int i = 0; i < sz; i++)
        f[i] = f[i] * g[i] % mod;
    return NTT(f, 1);
}

```

## 8.2 FHT

```

/* x: a[j], y: a[j + (L >> 1)]
or: (y += x * op), and: (x += y * op)
xor: (x, y = (x + y) * op, (x - y) * op)
invop: or, and, xor = -1, -1, 1/2 */
void fwt(int *a, int n, int op) { //or
    for (int L = 2; L <= n; L <= 1)
        for (int i = 0; i < n; i += L)
            for (int j = i; j < i + (L >> 1); ++j)
                a[j + (L >> 1)] += a[j] * op;
}

const int N = 21;
int f[
    N][1 << N], g[N][1 << N], h[N][1 << N], ct[1 << N];
void
    subset_convolution(int *a, int *b, int *c, int L) {
    // c_k = \sum_{i+j=k, i&j=0} a_i * b_j
    int n = 1 << L;
    for (int i = 1; i < n; ++i)
        ct[i] = ct[i & (i - 1)] + 1;
    for (int i = 0; i < n; ++i)
        f[ct[i]][i] = a[i], g[ct[i]][i] = b[i];
    for (int i = 0; i <= L; ++i)
        fwt(f[i], n, 1), fwt(g[i], n, 1);
    for (int i = 0; i <= L; ++i)
        for (int j = 0; j <= i; ++j)
            for (int x = 0; x < n; ++x)
                h[i][x] += f[j][x] * g[i - j][x];
    for (int i = 0; i <= L; ++i)
        fwt(h[i], n, -1);
}

```

```

for (int i = 0; i < n; ++i)
    c[i] = h[ct[i]][i];
}

```

## 8.3 Polynomial Operations

```

#define poly vector<ll>
poly inv(poly A) {
    A.resize(1 << (__lg(A.size() - 1) + 1));
    poly B = {inverse(A[0])};
    for (int n = 1; n < (int)A.size(); n <= 1) {
        poly pA(A.begin(), A.begin() + 2 * n);
        calcrev(4 * n), calcW(4 * n);
        pA.resize(4 * n), B.resize(4 * n);
        pA = NTT(pA, 0);
        B = NTT(B, 0);
        for (int i = 0; i < 4 * n; i++)
            B[i] =
                ((B[i] * 2 - pA[i] * B[i] % mod * B[i]) % mod +
                 mod) %
                mod;
        B = NTT(B, 1);
        B.resize(2 * n);
    }
    return B;
}

pair<poly, poly> div(poly A, poly B) {
    if (A.size() < B.size()) return make_pair(poly(), A);
    int n = A.size(), m = B.size();
    poly revA = A, invrevB = B;
    reverse(all(revA)), reverse(all(invrevB));
    revA.resize(n - m + 1);
    invrevB.resize(n - m + 1);
    invrevB = inv(invrevB);
    poly Q = mul(revA, invrevB);
    Q.resize(n - m + 1);
    reverse(all(Q));
    poly R = mul(Q, B);
    R.resize(m - 1);
    for (int i = 0; i < m - 1; i++)
        R[i] = (A[i] - R[i] + mod) % mod;
    return make_pair(Q, R);
}

poly modulo(poly A, poly B) { return div(A, B).S; }
ll fast_kitamasala(ll k, poly A, poly C) {
    int n = A.size();
    C.emplace_back(mod - 1);
    poly Q, R = {0, 1}, F = {1};
    R = modulo(R, C);
    for (; k; k >= 1) {
        if (k & 1) F = modulo(mul(F, R), C);
        R = modulo(mul(R, R), C);
        k >= 1;
    }
    ll ans = 0;
    for (int i = 0; i < F.size(); i++)
        ans = (ans + A[i] * F[i]) % mod;
    return ans;
}

vector<ll> fpow(vector<ll> f, ll p, ll m) {
    int b = 0;
    while (b < f.size() && f[b] == 0) b++;
    f = vector<ll>(f.begin() + b, f.end());
    int n = f.size();
    f.emplace_back(0);
    vector<ll> q(min(m, b * p), 0);
    q.emplace_back(fpow(f[0], p));
    for (int k = 0; q.size() < m; k++) {
        ll res = 0;
        for (int i = 0; i < min(n, k + 1); i++)
            res = (res +
                    p * (i + 1) % mod * f[i + 1] % mod *
                    q[k - i + b * p]) %
                    mod;
        for (int i = 1; i < min(n, k + 1); i++)
            res = (res -
                    f[i] * (k - i + 1) % mod *

```

```

        q[k - i + 1 + b * p]) %
        mod;
    res = (res < 0 ? res + mod : res) *
    inv(f[0] * (k + 1) % mod) % mod;
    q.emplace_back(res);
}
return q;
}

```

## 8.4 NewtonMethod+MiscGF

Given  $F(x)$  where

$$F(x) = \sum_{i=0}^{\infty} \alpha_i (x - \beta)^i$$

for  $\beta$  being some constant. Polynomial  $P$  such that  $F(P) = 0$  can be found iteratively. Denote by  $Q_k$  the polynomial such that  $F(Q_k) = 0 \pmod{x^{2^k}}$ , then

$$Q_{k+1} = Q_k - \frac{F(Q_k)}{F'(Q_k)} \pmod{x^{2^{k+1}}}$$

- $A^{-1}$ :  $B_{k+1} = B_k(2 - AB_k) \pmod{x^{2^{k+1}}}$
- $\ln A$ :  $(\ln A)' = \frac{A'}{A}$
- $\exp A$ :  $B_{k+1} = B_k(1 + A - \ln B_k) \pmod{x^{2^{k+1}}}$
- $\sqrt{A}$ :  $B_{k+1} = \frac{1}{2}(B_k + AB_k^{-1}) \pmod{x^{2^{k+1}}}$

## 9 Geometry

### 9.1 Basic

```

typedef pair<pdd, pdd> Line;
struct Cir{ pdd 0; double R; };
const double eps = 1e-8;
pll operator+(pll a, pll b)
{ return pll(a.F + b.F, a.S + b.S); }
pll operator-(pll a, pll b)
{ return pll(a.F - b.F, a.S - b.S); }
pll operator-(pll a)
{ return pll(-a.F, -a.S); }
pll operator*(pll a, ll b)
{ return pll(a.F * b, a.S * b); }
pdd operator/(pll a, double b)
{ return pdd(a.F / b, a.S / b); }
ll dot(pll a, pll b)
{ return a.F * b.F + a.S * b.S; }
ll cross(pll a, pll b)
{ return a.F * b.S - a.S * b.F; }
ll abs2(pll a)
{ return dot(a, a); }
double abs(pll a)
{ return sqrt(dot(a, a)); }
int sign(ll a)
{ return fabs(a) < eps ? 0 : a > 0 ? 1 : -1; }
int ori(pll a, pll b, pll c)
{ return sign(cross(b - a, c - a)); }
bool collinearity(pll p1, pll p2, pll p3)
{ return sign(cross(p1 - p3, p2 - p3)) == 0; }
bool btw(pll a, pll b, pll c) {
    return collinearity
        (a, b, c) && sign(dot(a - c, b - c)) <= 0;
}
bool seg_intersect(pdd p1, pdd p2, pdd p3, pdd p4) {
    int a123 = ori(p1, p2, p3);
    int a124 = ori(p1, p2, p4);
    int a341 = ori(p3, p4, p1);
    int a342 = ori(p3, p4, p2);
    if (a123 == 0 && a124 == 0)
        return btw(p1, p2, p3) || btw(p1, p2, p4) ||
            btw(p3, p4, p1) || btw(p3, p4, p2);
    return a123 * a124 <= 0 && a341 * a342 <= 0;
}
pdd intersect(pdd p1, pdd p2, pdd p3, pdd p4) {
    double a123 = cross(p2 - p1, p3 - p1);
    double a124 = cross(p2 - p1, p4 - p1);
    return (p4
        * a123 - p3 * a124) / (a123 - a124); // C^3 / C^2
}

```

```

pdd perp(pdd p1)
{ return pdd(-p1.S, p1.F); }
pdd projection(pdd p1, pdd p2, pdd p3)
{ return p1 + (
    p2 - p1) * dot(p3 - p1, p2 - p1) / abs2(p2 - p1); }
pdd reflection(pdd p1, pdd p2, pdd p3)
{ return p3 + perp(p2 - p1
    ) * cross(p3 - p1, p2 - p1) / abs2(p2 - p1) * 2; }
pdd linearTransformation
    (pdd p0, pdd p1, pdd q0, pdd q1, pdd r) {
    pdd dp = p1 - p0
        , dq = q1 - q0, num(cross(dp, dq), dot(dp, dq));
    return q0 + pdd(
        cross(r - p0, num), dot(r - p0, num)) / abs2(dp);
} // from line p0--p1 to q0--q1, apply to r

```

### 9.2 ConvexHull

```

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

```

### 9.3 SortByAngle

```

int cmp(pll a, pll b, bool same = true) {
#define is_neg(k) (
    sign(k.S) < 0 || (sign(k.S) == 0 && sign(k.F) < 0))
    int A = is_neg(a), B = is_neg(b);
    if (A != B)
        return A < B;
    if (sign(cross(a, b)) == 0)
        return same ? abs2(a) < abs2(b) : -1;
    return sign(cross(a, b)) > 0;
}

```

### 9.4 Formulas

#### • Rotation

$$M(\theta) = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

90 degree:  $(x, y) = (Y - y, x)$

#### • Pick's theorem

For simple integer-coordinate polygon,

$$A = B + \frac{I}{2} - 1$$

Where  $A$  is the area;  $B, I$  is #lattice points in the interior, on the boundary.

#### • Spherical Cap

- A portion of a sphere cut off by a plane.
- $r$ : sphere radius,  $a$ : radius of the base of the cap,  $h$ : height of the cap,  $\theta$ :  $\arcsin(a/r)$ .
- Volume =  $\pi h^2(3r - h)/3 = \pi h(3a^2 + h^2)/6 = \pi r^3(2 + \cos\theta)(1 - \cos\theta)^2/3$ .
- Area =  $2\pi r h = \pi(a^2 + h^2) = 2\pi r^2(1 - \cos\theta)$ .

#### • Nearest points of two skew lines

- Line 1:  $v_1 = p_1 + t_1 d_1$
- Line 2:  $v_2 = p_2 + t_2 d_2$
- $n = d_1 \times d_2$
- $n_1 = d_1 \times n$
- $n_2 = d_2 \times n$
- $c_1 = p_1 + \frac{(p_2 - p_1) \cdot n_2}{d_1 \cdot n_2} d_1$
- $c_2 = p_2 + \frac{(p_1 - p_2) \cdot n_1}{d_2 \cdot n_1} d_2$

## 9.5 TriangleHearts

```
pdd excenter(
    pdd p0, pdd p1, pdd p2) { // radius = abs(center)
    p1 = p1 - p0, p2 = p2 - p0;
    auto [x1, y1] = p1;
    auto [x2, y2] = p2;
    double m = 2. * cross(p1, p2);
    pdd center = pdd((x1 * x1 * y2 - x2 * x2 * y1 +
        y1 * y2 * (y1 - y2)),
        (x1 * x2 * (x2 - x1) - y1 * y1 * x2 +
        x1 * y2 * y2)) / m;
    return center + p0;
}

pdd incenter(
    pdd p1, pdd p2, pdd p3) { // radius = area / s * 2
    double a = abs(p2 - p3), b = abs(p1 - p3),
        c = abs(p1 - p2);
    double s = a + b + c;
    return (a * p1 + b * p2 + c * p3) / s;
}

pdd masscenter(pdd p1, pdd p2, pdd p3) {
    return (p1 + p2 + p3) / 3;
}

pdd orthcenter(pdd p1, pdd p2, pdd p3) {
    return masscenter(p1, p2, p3) * 3 -
        excenter(p1, p2, p3) * 2;
}
```

## 9.6 PointSegmentDist

```
double PointSegDist(pdd q0, pdd q1, pdd p) {
    if (abs(q0 - q1) <= eps) return abs(q0 - p);
    if (dot(q1 - q0,
        p - q0) >= -eps && dot(q0 - q1, p - q1) >= -eps)
        return fabs(cross(q1 - q0, p - q0) / abs(q0 - q1));
    return min(abs(p - q0), abs(p - q1));
}
```

## 9.7 PointInCircle

```
// return q'
// s relation with circumcircle of tri(p[0],p[1],p[2])
bool in_cc(const array<pll, 3> &p, pll q) {
    __int128 det = 0;
    for (int i = 0; i < 3; ++i)
        det += __int128(abs2(p[i]) - abs2(q)) *
            cross(p[(i + 1) % 3] - q, p[(i + 2) % 3] - q);
    return det > 0; // in: >0, on: =0, out: <0
}
```

## 9.8 PointInConvex

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

## 9.9 PointTangentConvex

```
/* The point should be strictly out of hull
    return arbitrary point on the tangent line */
/* bool pred(int a, int b);
f(0) ~ f(n - 1) is a cyclic-shift U-function
return idx s.t. pred(x, idx) is false forall x*/
int cyc_tsearch(int n, auto pred) {
```

```
    if (n == 1) return 0;
    int l = 0, r = n; bool rv = pred(1, 0);
    while (r - l > 1) {
        int m = (l + r) / 2;
        if (pred(0, m) ? rv : pred(m, (m + 1) % n)) r = m;
        else l = m;
    }
    return pred(l, r % n) ? l : r % n;
}

pii get_tangent(vector<pll> &C, pll p) {
    auto gao = [&](int s) {
        return cyc_tsearch((int)C.size(), [&](int x, int y)
            { return ori(p, C[x], C[y]) == s; });
    };
    return pii(gao(1), gao(-1));
} // return (a, b), ori(p, C[a], C[b]) >= 0
```

## 9.10 CircTangentCirc

```
vector<Line>
    > go(const Cir& c1, const Cir& c2, int sign1) {
    // sign1 = 1 for outer tang, -1 for inner tang
    vector<Line> ret;
    double d_sq = abs2(c1.0 - c2.0);
    if (sign(d_sq) == 0) return ret;
    double d = sqrt(d_sq);
    pdd v = (c2.0 - c1.0) / d;
    double c = (c1.R - sign1 * c2.R) / d;
    if (c * c > 1) return ret;
    double h = sqrt(max(0.0, 1.0 - c * c));
    for (int sign2 = 1; sign2 >= -1; sign2 -= 2) {
        pdd n = pdd(v.F * c - sign2 * h * v.S,
            v.S * c + sign2 * h * v.F);
        pdd p1 = c1.0 + n * c1.R;
        pdd p2 = c2.0 + n * (c2.R * sign1);
        if (sign(p1.F - p2.F) == 0 and
            sign(p1.S - p2.S) == 0)
            p2 = p1 + perp(c2.0 - c1.0);
        ret.emplace_back(Line(p1, p2));
    }
    return ret;
}
```

## 9.11 LineCircleIntersect

```
vector<pdd> circleLine(pdd c, double r, pdd a, pdd b) {
    pdd p
        = a + (b - a) * dot(c - a, b - a) / abs2(b - a);
    double s = cross
        (b - a, c - a), h2 = r * r - s * s / abs2(b - a);
    if (h2 < 0) return {};
    if (h2 == 0) return {p};
    pdd h = (b - a) / abs(b - a) * sqrt(h2);
    return {p - h, p + h};
}
```

## 9.12 LineConvexIntersect

```
int TangentDir(vector<pll> &C, pll dir) {
    return cyc_tsearch((int)C.size(), [&](int a, int b) {
        return cross(dir, C[a]) > cross(dir, C[b]);
    });
}

#define cml(i) sign(cross(C[i] - a, b - a))
pii lineHull(pll a, pll b, vector<pll> &C) {
    int A = TangentDir(C, a - b);
    int B = TangentDir(C, b - a);
    int n = (int)C.size();
    if (cml(A) < 0 || cml(B) > 0)
        return pii(-1, -1); // no collision
    auto gao = [&](int l, int r) {
        for (int t = l; (l + 1) % n != r; ) {
            int m = ((l + r + (l < r ? 0 : n)) / 2) % n;
            (cml(m) == cml(t) ? l : r) = m;
        }
        return (l + !cml(r)) % n;
    };
}
```

```

pii res = pii(gao(B, A), gao(A, B)); // (i, j)
if (res.F == res.S) // touching the corner i
    return pii(res.F, -1);
if (!
    cmpL(res.F) && !cmpL(res.S)) // along side i, i+1
    switch ((res.F - res.S + n + 1) % n) {
        case 0: return pii(res.F, res.F);
        case 2: return pii(res.S, res.S);
    }
/* crossing sides (i, i+1) and (j, j+1)
crossing corner i is treated as side (i, i+1)
returned
    in the same order as the line hits the convex */
return res;
} // convex cut: (r, l]

```

### 9.13 CircIntersectCirc

```

bool CCinter(Cir &a, Cir &b, pdd &p1, pdd &p2) {
    pdd o1 = a.O, o2 = b.O;
    double r1 =
        a.R, r2 = b.R, d2 = abs2(o1 - o2), d = sqrt(d2);
    if (d < max
        (r1, r2) - min(r1, r2) || d > r1 + r2) return 0;
    pdd u = (o1 + o2) * 0.5
        + (o1 - o2) * ((r2 * r2 - r1 * r1) / (2 * d2));
    double A = sqrt((r1 + r2 + d) *
        (r1 - r2 + d) * (r1 + r2 - d) * (-r1 + r2 + d));
    pdd v
        = pdd(o1.S - o2.S, -o1.F + o2.F) * A / (2 * d2);
    p1 = u + v, p2 = u - v;
    return 1;
}

```

### 9.14 PolyIntersectCirc

```

// Divides into multiple triangle, and sum up
const double PI = acos(-1);
double _area(pdd pa, pdd pb, double r) {
    if (abs(pa) < abs(pb)) swap(pa, pb);
    if (abs(pb) < eps) return 0;
    double S, h, theta;
    double a = abs(pb), b = abs(pa), c = abs(pb - pa);
    double cosB = dot(pb, pb - pa) / a / c,
        B = acos(cosB);
    double cosC = dot(pa, pb) / a / b, C = acos(cosC);
    if (a > r) {
        S = (C / 2) * r * r;
        h = a * b * sin(C) / c;
        if (h < r && B < PI / 2)
            S -= (acos(h / r) * r * r -
                h * sqrt(r * r - h * h));
    } else if (b > r) {
        theta = PI - B - asin(sin(B) / r * a);
        S = .5 * a * r * sin(theta) +
            (C - theta) / 2 * r * r;
    } else S = .5 * sin(C) * a * b;
    return S;
}
double area_poly_circle(const vector<pdd> poly,
    const pdd &o, const double r) {
    double S = 0;
    for (int i = 0; i < (int)poly.size(); ++i)
        S += _area(poly[i] - o,
            poly[(i + 1) % (int)poly.size()] - o, r) *
            ori(
                0, poly[i], poly[(i + 1) % (int)poly.size()]);
    return fabs(S);
}

```

### 9.15 MinkowskiSum

```

vector<pll> Minkowski
    (vector<pll> A, vector<pll> B) { // |A|, |B| >= 3
    hull(A), hull(B);
    vector<pll> C(1, A[0] + B[0]), s1, s2;
    for (int i = 0; i < A.size(); ++i)
        s1.emplace_back(A[(i + 1) % A.size()] - A[i]);

```

```

    for (int i = 0; i < B.size(); i++)
        s2.emplace_back(B[(i + 1) % B.size()] - B[i]);
    for (int i = 0, j = 0; i < A.size() || j < B.size(); )
        if (j >= B.size()
            || (i < A.size() && cross(s1[i], s2[j]) >= 0))
            C.emplace_back(B[j % B.size()] + A[i++]);
        else
            C.emplace_back(A[i % A.size()] + B[j++]);
    return hull(C), C;
}

```

### 9.16 MinMaxEnclosingRect

```

const double INF = 1e18, qi = acos(-1) / 2 * 3;
pdd solve(vector<pll> &dots) {
    #define diff(u, v) (dots[u] - dots[v])
    #define vec(v) (dots[v] - dots[i])
    hull(dots);
    double Max = 0, Min = INF, deg;
    int n = (int)dots.size();
    dots.emplace_back(dots[0]);
    for (int i = 0, u = 1, r = 1, l = 1; i < n; ++i) {
        pll nw = vec(i + 1);
        while (cross(nw, vec(u + 1)) > cross(nw, vec(u)))
            u = (u + 1) % n;
        while (dot(nw, vec(r + 1)) > dot(nw, vec(r)))
            r = (r + 1) % n;
        if (!l) l = (r + 1) % n;
        while (dot(nw, vec(l + 1)) < dot(nw, vec(l)))
            l = (l + 1) % n;
        Min = min(Min, (double)(dot(nw, vec(r)) - dot
            (nw, vec(l))) * cross(nw, vec(u)) / abs2(nw));
        deg = acos(dot(diff(r, l), vec(u)) / abs(diff(r, l)) / abs(vec(u)));
        deg = (qi - deg) / 2;
        Max = max(Max, abs(diff
            (r, l)) * abs(vec(u)) * sin(deg) * sin(deg));
    }
    return pdd(Min, Max);
}

```

### 9.17 MinEnclosingCircle

```

pdd Minimum_Enclosing_Circle
    (vector<pdd> dots, double &r) {
    pdd cent;
    random_shuffle(all(dots));
    cent = dots[0], r = 0;
    for (int i = 1; i < (int)dots.size(); ++i)
        if (abs(dots[i] - cent) > r) {
            cent = dots[i], r = 0;
            for (int j = 0; j < i; ++j)
                if (abs(dots[j] - cent) > r) {
                    cent = (dots[i] + dots[j]) / 2;
                    r = abs(dots[i] - cent);
                    for (int k = 0; k < j; ++k)
                        if (abs(dots[k] - cent) > r)
                            cent = excenter
                                (dots[i], dots[j], dots[k], r);
                }
            return cent;
        }
    }

```

### 9.18 CircleCover

```

const int N = 1021;
struct CircleCover {
    int C;
    Cir c[N];
    bool g[N][N], overlap[N][N];
    // Area[i] : area covered by at least i circles
    double Area[ N ];
    void init(int _C) { C = _C; }
    struct Teve {
        pdd p; double ang; int add;
        Teve() {}

```



```

    Teve(pdd _a
        , double _b, int _c):p(_a), ang(_b), add(_c){}
    bool operator<(const Teve &a) const
    {return ang < a.ang;}
}eve[N * 2];
// strict: x = 0, otherwise x = -1
bool disjunct(Cir &a, Cir &b, int x)
{return sign(abs(a.O - b.O) - a.R - b.R) > x;}
bool contain(Cir &a, Cir &b, int x)
{return sign(a.R - b.R - abs(a.O - b.O)) > x;}
bool contain(int i, int j) {
    /* c[j] is non-strictly in c[i]. */
    return (sign
        (c[i].R - c[j].R) > 0 || (sign(c[i].R - c[j].
            R) == 0 && i < j)) && contain(c[i], c[j], -1);
}
void solve(){
    fill_n(Area, C + 2, 0);
    for(int i = 0; i < C; ++i)
        for(int j = 0; j < C; ++j)
            overlap[i][j] = contain(i, j);
    for(int i = 0; i < C; ++i)
        for(int j = 0; j < C; ++j)
            g[i][j] = !(overlap[i][j] || overlap[j][i] ||
                disjunct(c[i], c[j], -1));
    for(int i = 0; i < C; ++i){
        int E = 0, cnt = 1;
        for(int j = 0; j < C; ++j)
            if(j != i && overlap[j][i])
                ++cnt;
        for(int j = 0; j < C; ++j)
            if(i != j && g[i][j]) {
                pdd aa, bb;
                CCinter(c[i], c[j], aa, bb);
                double A =
                    atan2(aa.Y - c[i].O.Y, aa.X - c[i].O.X);
                double B =
                    atan2(bb.Y - c[i].O.Y, bb.X - c[i].O.X);
                eve[E++] = Teve
                    (bb, B, 1), eve[E++] = Teve(aa, A, -1);
                if(B > A) ++cnt;
            }
        if(E == 0) Area[cnt] += pi * c[i].R * c[i].R;
        else{
            sort(eve, eve + E);
            eve[E] = eve[0];
            for(int j = 0; j < E; ++j){
                cnt += eve[j].add;
                Area[cnt]
                    += cross(eve[j].p, eve[j + 1].p) * .5;
                double theta = eve[j + 1].ang - eve[j].ang;
                if (theta < 0) theta += 2. * pi;
                Area[cnt] += (theta
                    - sin(theta)) * c[i].R * c[i].R * .5;
            }
        }
    }
}
};

```

## 9.19 LineCmp

```

using Line = pair<pll, pll>;
struct LineCmp { // coordinates should be even!
    bool operator()(Line l1, Line l2) const {
        int X =
            (max(l1.F.F, l2.F.F) + min(l1.S.F, l2.S.F)) / 2;
        ll p1 =
            (X - l1.F.F) * l1.S.S + (l1.S.F - X) * l1.F.S,
            p2 =
            (X - l2.F.F) * l2.S.S + (l2.S.F - X) * l2.F.S,
            q1 = (l1.S.F - l1.F.F), q2 = (l2.S.F - l2.F.F);
        if (q1 == 0) p1 = l1.F.S + l1.S.S, q1 = 2;
        if (q2 == 0) p2 = l2.F.S + l2.S.S, q2 = 2;
        if (l1.F == l2.F || l2.F == l2.S) l1 = l2;
        return make_tuple((__int128)(p1 * q2), l1) <
            make_tuple((__int128)(p2 * q1), l2);
    }
};

```

```

}
};

```

## 9.20 Trapezoidalization

```

template<class T>
struct SweepLine {
    struct cmp {
        cmp(const SweepLine &swp): swp(_swp) {}
        bool operator()(int a, int b) const {
            if (abs(swp.get_y(a) - swp.get_y(b)) <= swp.eps)
                return swp.slope_cmp(a, b);
            return swp.get_y(a) + swp.eps < swp.get_y(b);
        }
        const SweepLine &swp;
    } _cmp;
    T curTime, eps, curQ;
    vector<Line> base;
    multiset<int, cmp> sweep;
    multiset<pair<T, int>> event;
    vector<typename multiset<int, cmp>::iterator> its;
    vector
        <typename multiset<pair<T, int>>::iterator> eits;
    bool slope_cmp(int a, int b) const {
        assert(a != -1);
        if (b == -1) return 0;
        return sign(cross(base
            [a].Y - base[a].X, base[b].Y - base[b].X)) < 0;
    }
    T get_y(int idx) const {
        if (idx == -1) return curQ;
        Line l = base[idx];
        if (l.X.X == l.Y.X) return l.Y.Y;
        return ((curTime - l.X.X) * l.Y.Y
            + (l.Y.X - curTime) * l.X.Y) / (l.Y.X - l.X.X);
    }
    void insert(int idx) {
        its[idx] = sweep.insert(idx);
        if (its[idx] != sweep.begin())
            update_event(*prev(its[idx]));
        update_event(idx);
        event.emplace
            (base[idx].Y.X, idx + 2 * (int)base.size());
    }
    void erase(int idx) {
        assert(eits[idx] == event.end());
        auto p = sweep.erase(its[idx]);
        its[idx] = sweep.end();
        if (p != sweep.begin())
            update_event(*prev(p));
    }
    void update_event(int idx) {
        if (eits[idx] != event.end())
            event.erase(eits[idx]);
        eits[idx] = event.end();
        auto nxt = next(its[idx]);
        if (nxt ==
            sweep.end() || !slope_cmp(idx, *nxt)) return;
        auto t = intersect(base[idx].
            X, base[idx].Y, base[*nxt].X, base[*nxt].Y).X;
        if (t + eps < curTime || t
            >= min(base[idx].Y.X, base[*nxt].Y.X)) return;
        eits[idx]
            = event.emplace(t, idx + (int)base.size());
    }
    void swp(int idx) {
        assert(eits[idx] != event.end());
        eits[idx] = event.end();
        int nxt = *next(its[idx]);
        swap((int*)&its[idx], (int*)&its[nxt]);
        swap(its[idx], its[nxt]);
        if (its[nxt] != sweep.begin())
            update_event(*prev(its[nxt]));
        update_event(idx);
    }
    // only expected to call the functions below

```



```

SweepLine(T t, T e, vector<Line> vec): _cmp
(*this), curTime(t), eps(e), curQ(), base(vec),
sweep(_cmp), event(), its((int)vec.size(), sweep
.end()), eits((int)vec.size(), event.end()) {
for (int i = 0; i < (int)base.size(); ++i) {
    auto &p, q = base[i];
    if (p > q) swap(p, q);
    if (p.X <= curTime && curTime <= q.X)
        insert(i);
    else if (curTime < p.X)
        event.emplace(p.X, i);
}
}
void setTime(T t, bool ers = false) {
    assert(t >= curTime);
    while (!event.empty() && event.begin()->X <= t) {
        auto [et, idx] = *event.begin();
        int s = idx / (int)base.size();
        idx %= (int)base.size();
        if (abs(et - t) <= eps && s == 2 && !ers) break;
        curTime = et;
        event.erase(event.begin());
        if (s == 2) erase(idx);
        else if (s == 1) swp(idx);
        else insert(idx);
    }
    curTime = t;
}
T nextEvent() {
    if (event.empty()) return INF;
    return event.begin()->X;
}
int lower_bound(T y) {
    curQ = y;
    auto p = sweep.lower_bound(-1);
    if (p == sweep.end()) return -1;
    return *p;
}
};

```

## 9.21 HalfPlaneIntersect

```

pll area_pair(Line a, Line b)
{ return pll(cross(a.S
- a.F, b.F - a.F), cross(a.S - a.F, b.S - a.F)); }
bool isin(Line l0, Line l1, Line l2) {
    // Check inter(l1, l2) strictly in l0
    auto [a02X, a02Y] = area_pair(l0, l2);
    auto [a12X, a12Y] = area_pair(l1, l2);
    if (a12X - a12Y < 0) a12X *= -1, a12Y *= -1;
    return (__int128)
        a02Y * a12X - (__int128) a02X * a12Y > 0; // C^4
}
/* Having solution, check size > 2 */
/* --^-- Line.X --^-- Line.Y --^-- */
vector<Line> halfPlaneInter(vector<Line> arr) {
    sort(all(arr), [&](Line a, Line b) -> int {
        if (cmp(a.S - a.F, b.S - b.F, 0) != -1)
            return cmp(a.S - a.F, b.S - b.F, 0);
        return ori(a.F, a.S, b.S) < 0;
    });
    deque<Line> dq(1, arr[0]);
    for (auto p : arr) {
        if (cmp(
            dq.back().S - dq.back().F, p.S - p.F, 0) == -1)
            continue;
        while ((int)dq.size() >= 2
            && !isin(p, dq[(int)dq.size() - 2], dq.back()))
            dq.pop_back();
        while
            ((int)dq.size() >= 2 && !isin(p, dq[0], dq[1]))
            dq.pop_front();
        dq.emplace_back(p);
    }
    while ((int)dq.size() >= 3 &&
        !isin(dq[0], dq[(int)dq.size() - 2], dq.back()))

```

```

        dq.pop_back();
    while ((int)
        dq.size() >= 3 && !isin(dq.back(), dq[0], dq[1]))
        dq.pop_front();
    return vector<Line>(all(dq));
}

```

## 9.22 RotatingSweepLine

```

void rotatingSweepLine(vector<pii> &ps) {
    int n = (int)ps.size(), m = 0;
    vector<int> id(n), pos(n);
    vector<pii> line(n * (n - 1));
    for (int i = 0; i < n; ++i)
        for (int j = 0; j < n; ++j)
            if (i != j) line[m++] = pii(i, j);
    sort(all(line), [&](pii a, pii b) {
        return cmp(ps[a.S] - ps[a.F], ps[b.S] - ps[b.F]);
    }); // cmp(): polar angle compare
    iota(all(id), 0);
    sort(all(id), [&](int a, int b) {
        if (ps[a].S != ps[b].S) return ps[a].S < ps[b].S;
        return ps[a] < ps[b];
    }); // initial order, since (1, 0) is the smallest
    for (int i = 0; i < n; ++i) pos[id[i]] = i;
    for (int i = 0; i < m; ++i) {
        auto l = line[i];
        // do something
        tie(pos[l.F], pos[l.S], id[pos[l.F]], id[pos[l.S]
        ]) = make_tuple(pos[l.S], pos[l.F], l.S, l.F);
    }
}

```

## 9.23 DelaunayTriangulation

```

/* Delaunay Triangulation:
Given a sets of points in 2D plane, find a
triangulation such that no points will strictly
inside circumcircle of any triangle.
find : return a triangle contain given point
add_point : add a point into triangulation
A Triangle is in triangulation iff. its has_chd is 0.
Region of triangle u: iterate each u.edge[i].tri,
each points are u.p[(i+1)%3], u.p[(i+2)%3]
Voronoi diagram: for each triangle in triangulation,
the bisector of all its edges will split the region.
nearest point will belong to the triangle containing it
*/
const
    ll inf = MAXC * MAXC * 100; // lower_bound unknown
struct Tri;
struct Edge {
    Tri* tri; int side;
    Edge(): tri(0), side(0){}
    Edge(Tri* _tri, int _side): tri(_tri), side(_side){}
};
struct Tri {
    pll p[3];
    Edge edge[3];
    Tri* chd[3];
    Tri() {}
    Tri(const pll& p0, const pll& p1, const pll& p2) {
        p[0] = p0; p[1] = p1; p[2] = p2;
        chd[0] = chd[1] = chd[2] = 0;
    }
    bool has_chd() const { return chd[0] != 0; }
    int num_chd() const {
        return !!chd[0] + !!chd[1] + !!chd[2];
    }
    bool contains(pll const& q) const {
        for (int i = 0; i < 3; ++i)
            if (ori(p[i], p[(i + 1) % 3], q) < 0)
                return 0;
        return 1;
    }
} pool[N * 10], *tris;
void edge(Edge a, Edge b) {
    if(a.tri) a.tri->edge[a.side] = b;
}

```

```

    if(b.tri) b.tri->edge[b.side] = a;
}
struct Trig { // Triangulation
    Trig() {
        the_root
            = // Tri should at least contain all points
              new(tris++) Tri(pll(-inf, -inf),
                             pll(inf + inf, -inf), pll(-inf, inf + inf));
    }
    Tri* find(pll p) { return find(the_root, p); }
    void add_point(const
        pll &p) { add_point(find(the_root, p), p); }
    Tri* the_root;
    static Tri* find(Tri* root, const pll &p) {
        while (1) {
            if (!root->has_chd())
                return root;
            for (int i = 0; i < 3 && root->chd[i]; ++i)
                if (root->chd[i]->contains(p)) {
                    root = root->chd[i];
                    break;
                }
        }
        assert(0); // "point not found"
    }
    void add_point(Tri* root, pll const& p) {
        Tri* t[3];
        /* split it into three triangles */
        for (int i = 0; i < 3; ++i)
            t[i] = new(tris
                ++i) Tri(root->p[i], root->p[(i + 1) % 3], p);
        for (int i = 0; i < 3; ++i)
            edge(Edge(t[i], 0), Edge(t[(i + 1) % 3], 1));
        for (int i = 0; i < 3; ++i)
            edge(Edge(t[i], 2), root->edge[(i + 2) % 3]);
        for (int i = 0; i < 3; ++i)
            root->chd[i] = t[i];
        for (int i = 0; i < 3; ++i)
            flip(t[i], 2);
    }
    void flip(Tri* tri, int pi) {
        Tri* trj = tri->edge[pi].tri;
        int pj = tri->edge[pi].side;
        if (!trj) return;
        if (!in_cc(tri->p
            [0], tri->p[1], tri->p[2], trj->p[pj])) return;
        /* flip edge between tri, trj */
        Tri* trk = new(tris++) Tri
            (tri->p[(pi + 1) % 3], trj->p[pj], tri->p[pi]);
        Tri* trl = new(tris++) Tri
            (trj->p[(pj + 1) % 3], tri->p[pi], trj->p[pj]);
        edge(Edge(trk, 0), Edge(trl, 0));
        edge(Edge(trk, 1), tri->edge[(pi + 2) % 3]);
        edge(Edge(trk, 2), trj->edge[(pj + 2) % 3]);
        edge(Edge(trl, 1), trj->edge[(pj + 2) % 3]);
        edge(Edge(trl, 2), tri->edge[(pi + 1) % 3]);
        tri->chd
            [0] = trk; tri->chd[1] = trl; tri->chd[2] = 0;
        trj->chd
            [0] = trk; trj->chd[1] = trl; trj->chd[2] = 0;
        flip(trk, 1); flip(trk, 2);
        flip(trl, 1); flip(trl, 2);
    }
};
vector<Tri*> triang; // vector of all triangle
set<Tri*> vst;
void go(Tri* now) { // store all tri into triang
    if (vst.find(now) != vst.end())
        return;
    vst.insert(now);
    if (!now->has_chd())
        return triang.emplace_back(now);
    for (int i = 0; i < now->num_chd(); ++i)
        go(now->chd[i]);
}
void build(int n, pll* ps) { // build triangulation

```

```

    tris = pool; triang.clear(); vst.clear();
    random_shuffle(ps, ps + n);
    Trig tri; // the triangulation structure
    for (int i = 0; i < n; ++i)
        tri.add_point(ps[i]);
    go(tri.the_root);
}

```

## 9.24 VoronoiDiagram

```

// all coord. is even
// , you may want to call halfPlaneInter after then
vector<vector<Line>> vec;
void build_voronoi_line(int n, pll *arr) {
    tool.init(n, arr); // Delaunay
    vec.clear(), vec.resize(n);
    for (int i = 0; i < n; ++i)
        for (auto e : tool.head[i]) {
            int u = tool.oidx[i], v = tool.oidx[e.id];
            pll m = (arr[v
                ] + arr[u]) / 2LL, d = perp(arr[v] - arr[u]);
            vec[u].emplace_back(Line(m, m + d));
        }
}

```

## 10 Misc

### 10.1 MoAlgoWithModify

```

// Mo's Algorithm With modification
// Block:  $N^{2/3}$ , Complexity:  $N^{5/3}$ 
struct Query {
    const int blk = 2000;
    int L, R, LBid, RBid, T;
    Query(int l, int r, int t):
        L(l), R(r), LBid(l / blk), RBid(r / blk), T(t) {}
    bool operator<(const Query &q) const {
        if (LBid != q.LBid) return LBid < q.LBid;
        if (RBid != q.RBid) return RBid < q.RBid;
        return T < q.T;
    }
};
void solve(vector<Query> query) {
    sort(all(query));
    int L=0, R=0, T=-1;
    for (auto q : query) {
        while (T < q.T) addTime(L, R, ++T); // TODO
        while (T > q.T) subTime(L, R, T--); // TODO
        while (R < q.R) add(arr[++R]); // TODO
        while (L > q.L) add(arr[--L]); // TODO
        while (R > q.R) sub(arr[R--]); // TODO
        while (L < q.L) sub(arr[L--]); // TODO
        // answer query
    }
}

```

### 10.2 MoAlgoOnTree

```

/*
Mo's Algorithm On Tree
Preprocess:
1) LCA
2) dfs with in[u] = dft++, out[u] = dft++
3) ord[in[u]] = ord[out[u]] = u
4) bitset<MAXN> inset
*/
struct Query {
    int L, R, LBid, lca;
    Query(int u, int v) {
        int c = LCA(u, v);
        if (c == u || c == v)
            q.lca = -1, q.L = out[c ^ u ^ v], q.R = out[c];
        else if (out[u] < in[v])
            q.lca = c, q.L = out[u], q.R = in[v];
        else
            q.lca = c, q.L = out[v], q.R = in[u];
        q.Lid = q.L / blk;
    }
}

```

```

bool operator<(const Query &q) const {
    if (LBid != q.LBid) return LBid < q.LBid;
    return R < q.R;
}
};

void flip(int x) {
    if (inset[x]) sub(arr[x]); // TODO
    else add(arr[x]); // TODO
    inset[x] = ~inset[x];
}

void solve(vector<Query> query) {
    sort(ALL(query));
    int L = 0, R = 0;
    for (auto q : query) {
        while (R < q.R) flip(ord[++R]);
        while (L > q.L) flip(ord[--L]);
        while (R > q.R) flip(ord[R--]);
        while (L < q.L) flip(ord[L++]);
        if (~q.lca) add(arr[q.lca]);
        // answer query
        if (~q.lca) sub(arr[q.lca]);
    }
}

```

### 10.3 MoAlgoAdvanced

- Mo's Algorithm With Addition Only
  - Sort queries same as the normal Mo's algorithm.
  - For each query  $[l, r]$ :
  - If  $l/blk = r/blk$ , brute-force.
  - If  $l/blk \neq curL/blk$ , initialize  $curL := (l/blk + 1) \cdot blk, curR := curL - 1$
  - If  $r > curR$ , increase  $curR$
  - decrease  $curL$  to fit  $l$ , and then undo after answering
- Mo's Algorithm With Offline Second Time
  - Require: Changing answer  $\equiv$  adding  $f([l, r], r+1)$ .
  - Require:  $f([l, r], r+1) = f([l, r], r+1) - f([l, l], r+1)$ .
  - Part1: Answer all  $f([l, r], r+1)$  first.
  - Part2: Store  $curR \rightarrow R$  for  $curL$  (reduce the space to  $O(N)$ ), and then answer them by the second offline algorithm.
  - Note: You must do the above symmetrically for the left boundaries.

### 10.4 HilbertCurve

```

ll hilbert(int n, int x, int y) {
    ll res = 0;
    for (int s = n / 2; s; s >>= 1) {
        int rx = (x & s) > 0;
        int ry = (y & s) > 0;
        res += s * 1ll * s * ((3 * rx) ^ ry);
        if (ry == 0) {
            if (rx == 1) x = s - 1 - x, y = s - 1 - y;
            swap(x, y);
        }
    }
    return res;
} // n = 2^k

```

### 10.5 SternBrocotTree

- Construction: Root  $\frac{1}{1}$ , left/right neighbor  $\frac{0}{1}, \frac{1}{0}$ , each node is sum of last left/right neighbor:  $\frac{a}{b}, \frac{c}{d} \rightarrow \frac{a+c}{b+d}$
- Property: Adjacent (mid-order DFS)  $\frac{a}{b}, \frac{c}{d} \Rightarrow bc - ad = 1$ .
- Search known  $\frac{p}{q}$ : keep L-R alternative. Each step can be calculated in  $O(1) \Rightarrow$  total  $O(\log C)$ .
- Search unknown  $\frac{p}{q}$ : keep L-R alternative. Each step can be calculated in  $O(\log C)$  checks  $\Rightarrow$  total  $O(\log^2 C)$  checks.

### 10.6 ALLCS

```

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

```

```

// c - b + 1 - sum([h[i] >= b] | i <= c)
// h[i] might become -1 !!
    }
}

```

### 10.7 SimulatedAnnealing

```

double factor = 1000000;
const int base = 1e9; // remember to run ~ 10 times
for (int it = 1; it <= 1000000; ++it) {
    // ans:
    answer, nw: current value, rnd(): mt19937 rnd()
    if (exp(-(nw - ans) / factor) >= (double)(rnd() % base) / base)
        ans = nw;
    factor *= 0.99995;
}

```

### 10.8 SMAWK

```

int opt[N];
ll A(int x, int y); // target func
void smawk(vector<int> &r, vector<int> &c);
void interpolate(vector<int> &r, vector<int> &c) {
    int n = (int)r.size();
    vector<int> er;
    for (int i = 1; i < n; i += 2) er.emplace_back(r[i]);
    smawk(er, c);
    for (int i = 0, j = 0; j < c.size(); j++) {
        if (A(r[i], c[j]) < A(r[i], opt[r[i]]))
            opt[r[i]] = c[j];
        if (i + 2 < n && c[j] == opt[r[i + 1]])
            j--, i += 2;
    }
}

void reduce(vector<int> &r, vector<int> &c) {
    int n = (int)r.size();
    vector<int> nc;
    for (int i : c) {
        int j = (int)nc.size();
        while (
            j && A(r[j - 1], nc[j - 1]) > A(r[j - 1], i))
            nc.pop_back(), j--;
        if (nc.size() < n) nc.emplace_back(i);
    }
    smawk(r, nc);
}

void smawk(vector<int> &r, vector<int> &c) {
    if (r.size() == 1 && c.size() == 1) opt[r[0]] = c[0];
    else if (r.size() >= c.size()) interpolate(r, c);
    else reduce(r, c);
}

```

### 10.9 Python

```

import math
math.isqrt(2) # integer sqrt

```

### 10.10 LineContainer

```

struct Line {
    mutable ll k, m, p;
    bool operator<(const Line &o) const {
        return k < o.k;
    }
    bool operator<(ll x) const { return p < x; }
};

struct LineContainer : multiset<Line, less<>> {
    // (for doubles, use inf = 1/.0, div(a,b) = a/b)
    static const ll inf = LLONG_MAX;
    ll div(ll a, ll b) { // floored division
        return a / b - ((a ^ b) < 0 && a % b);
    }
    bool isect(iterator x, iterator y) {
        if (y == end()) return x->p = inf, 0;
        if (x->k == y->k) x->p = x->m > y->m ? inf : -inf;

```

```
    else x->p = div(y->m - x->m, x->k - y->k);
    return x->p >= y->p;
}
void add(ll k, ll m) {
    auto z = insert({k, m, 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));
}
ll query(ll x) {
    assert(!empty());
    auto l = *lower_bound(x);
    return l.k * x + l.m;
}
};
```