

UPLB Eliens ICPC Notebook (C++)

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1 Data Structures

1.1 Disjoint Set Union

```

struct DSU {
    vector<int> parent, size;
    DSU(int n) {
        parent.resize(n);
        size.resize(n);
        for (int i = 0; i < n; i++) make_set(i);
    }
    void make_set(int v) {
        parent[v] = v;
        size[v] = 1;
    }
    bool is_same(int a, int b) { return find_set(a) ==
        find_set(b); }
    int find_set(int v) { return v == parent[v] ? v :
        parent[v] = find_set(parent[v]); }
    void union_sets(int a, int b) {
        a = find_set(a);
        b = find_set(b);
        if (a != b) {
            if (size[a] < size[b]) swap(a, b);
            parent[b] = a;
            size[a] += size[b];
        }
    }
};

```

1.2 Minimum Queue

```

ll get_minimum(stack<pair<ll, ll>> &s1, stack<pair<ll,
ll>> &s2) {
    if (s1.empty() || s2.empty()) {
        return s1.empty() ? s2.top().second : s1.top().
            second;
    } else {
        return min(s1.top().second, s2.top().second);
    }
}
void add_element(ll new_element, stack<pair<ll, ll>> &s1
) {
    ll minimum = s1.empty() ? new_element : min(
        new_element, s1.top().second);
    s1.push({new_element, minimum});
}
ll remove_element(stack<pair<ll, ll>> &s1, stack<pair<ll
, ll>> &s2) {

```

```

if (s2.empty()) {
    while (!s1.empty()) {
        ll element = s1.top().first;
        s1.pop();
        ll minimum = s2.empty() ? element : min(element,
            s2.top().second);
        s2.push({element, minimum});
    }
}
ll removed_element = s2.top().first;
s2.pop();
return removed_element;
}

```

1.3 Range Add Point Query

```

template<class T>
class SegTreeNode {
public:
    const T IDENTITY = 0;
    int i, j;
    T value;
    SegTreeNode<T>* lc, * rc;
    SegTreeNode(int i, int j) : i(i), j(j) {
        value = IDENTITY;
        if (j - i == 1) {
            lc = rc = nullptr;
            return;
        }
        int k = (i + j) / 2;
        lc = new SegTreeNode(i, k);
        rc = new SegTreeNode(k, j);
    }
    SegTreeNode(const vector<T>& a, int i, int j) : i(i),
        j(j) {
        value = j - i == 1 ? a[i] : IDENTITY;
        if (j - i == 1) {
            lc = rc = nullptr;
            return;
        }
        int k = (i + j) / 2;
        lc = new SegTreeNode(a, i, k);
        rc = new SegTreeNode(a, k, j);
    }
    void range_update(int l, int r, T x) {
        if (r <= i || j <= l) return;
        if (l <= i && j <= r) {
            value = op(value, x);
            return;
        }
    }
}

```

```

lc->range_update(l, r, x);
rc->range_update(l, r, x);
}
T point_query(int k) {
    if (k < i || j <= k) return IDENTITY;
    if (j - i == 1) {
        return value;
    }
    return op(value, op(lc->point_query(k), rc->
        point_query(k)));
}
T op(T x, T y) { return x + y; }
};
template<class T>
class SegTree {
public:
    SegTreeNode<T> root;
    SegTree(int n) : root(0, n) {}
    SegTree(const vector<T>& a) : root(a, 0, a.size()) {}
    void range_update(int l, int r, T x) { root.
        range_update(l, r, x); }
    T point_query(int k) { return root.point_query(k); }
};

```

1.4 Segment Tree

```

template<class T>
class SegTreeNode {
public:
    const T IDENTITY = 0, DEFAULT = 0;
    int i, j;
    T val;
    SegTreeNode<T>* lc, * rc;
    SegTreeNode(int i, int j) : i(i), j(j) {
        if (j - i == 1) {
            lc = rc = nullptr;
            val = DEFAULT;
            return;
        }
        int k = (i + j) / 2;
        lc = new SegTreeNode(i, k);
        rc = new SegTreeNode(k, j);
        val = op(lc->val, rc->val);
    }
    SegTreeNode(const vector<T>& a, int i, int j) : i(i),
        j(j) {
        if (j - i == 1) {
            lc = rc = nullptr;
            val = a[i];
            return;
        }
    }
}

```

```

    }
    int k = (i + j) / 2;
    lc = new SegTreeNode(a, i, k);
    rc = new SegTreeNode(a, k, j);
    val = op(lc->val, rc->val);
}
void set(int k, T x) { // update a[k] := x
    if (k < i || j <= k) return;
    if (j - i == 1) {
        val = x;
        return;
    }
    lc->set(k, x);
    rc->set(k, x);
    val = op(lc->val, rc->val);
}
T range_query(int l, int r) { // [l, r)
    if (l <= i && j <= r) return val;
    if (j <= l || r <= i) return IDENTITY;
    return op(lc->range_query(l, r), rc->range_query(l,
        r));
}
T op(T x, T y) {}
};
template<class T>
class SegTree {
public:
    SegTreeNode<T> root;
    SegTree(int n) : root(0, n) {}
    SegTree(const vector<T>& a) : root(a, 0, a.size()) {}
    void set(int k, T x) { root.set(k, x); }
    T range_query(int l, int r) { return root.range_query(
        l, r); }
};

```

1.5 Sparse Table

```

ll log2_floor(ll i) {
    return i ? __builtin_clzll(1) - __builtin_clzll(i) :
        -1;
}
vector<vector<ll>> build_sum(ll N, ll K, vector<ll> &
    array) {
    vector<vector<ll>> st(K + 1, vector<ll>(N + 1));
    for (ll i = 0; i < N; i++) st[0][i] = array[i];
    for (ll i = 1; i <= K; i++)
        for (ll j = 0; j + (1 << i) <= N; j++)
            st[i][j] = st[i - 1][j] + st[i - 1][j + (1 << (i -
                1))];
    return st;
}

```

```

}
ll sum_query(ll L, ll R, ll K, vector<vector<ll>> &st) {
    ll sum = 0;
    for (ll i = K; i >= 0; i--) {
        if ((1 << i) <= R - L + 1) {
            sum += st[i][L];
            L += 1 << i;
        }
    }
    return sum;
}
vector<vector<ll>> build_min(ll N, ll K, vector<ll> &
    array) {
    vector<vector<ll>> st(K + 1, vector<ll>(N + 1));
    for (ll i = 0; i < N; i++) st[0][i] = array[i];
    for (ll i = 1; i <= K; i++)
        for (ll j = 0; j + (1 << i) <= N; j++)
            st[i][j] = min(st[i - 1][j], st[i - 1][j + (1 << (i -
                1))]);
    return st;
}
ll min_query(ll L, ll R, vector<vector<ll>> &st) {
    ll i = log2_floor(R - L + 1);
    return min(st[i][L], st[i][R - (1 << i) + 1]);
}

```

2 Dynamic Programming

2.1 Divide And Conquer

```

ll m, n;
vector<ll> dp_before(n), dp_cur(n);
ll C(ll i, ll j);
void compute(ll l, ll r, ll optl, ll opttr) {
    if (l > r) {
        return;
    }
    ll mid = (l + r) >> 1;
    pair<ll, ll> best = {LLONG_MAX, -1};
    for (ll k = optl; k <= min(mid, opttr); k++) {
        best = min(best, {(k ? dp_before[k - 1] : 0) + C(k,
            mid), k});
    }
    dp_cur[mid] = best.first;
    ll opt = best.second;
    compute(l, mid - 1, optl, opt);
    compute(mid + 1, r, opt, opttr);
}
ll solve() {

```

```

for (ll i = 0; i < n; i++) {
    dp_before[i] = C(0, i);
}
for (ll i = 1; i < m; i++) {
    compute(0, n - 1, 0, n - 1);
    dp_before = dp_cur;
}
return dp_before[n - 1];
}

```

2.2 Edit Distance

```

ll edit_distance(string x, string y, ll n, ll m) {
    vector<vector<int>> dp(n + 1, vector<int>(m + 1, INF))
    ;
    dp[0][0] = 0;
    for (int i = 1; i <= n; i++) {
        dp[i][0] = i;
    }
    for (int j = 1; j <= m; j++) {
        dp[0][j] = j;
    }
    for (int i = 1; i <= n; i++) {
        for (int j = 1; j <= m; j++) {
            dp[i][j] = min({dp[i - 1][j] + 1, dp[i][j - 1] +
                1, dp[i - 1][j - 1] + (x[i - 1] != y[j - 1])});
        }
    }
    return dp[n][m];
}

```

2.3 Knapsack

```

ll knapsack(ll W, vector<ll> &wt, vector<ll> &val, ll n)
{
    vector<ll> dp(W + 1, 0);
    for (ll i = 1; i <= n; i++) {
        for (ll w = W; w >= 0; w--) {
            if (wt[i - 1] <= w) {
                dp[w] = max(dp[w], dp[w - wt[i - 1]] + val[i -
                    1]);
            }
        }
    }
    return dp[W];
}

```

2.4 Knuth Optimization

```

ll solve() {
    ll N;
    // read N and input
    vector<vector<ll>> dp(N, vector<ll>(N)), opt(N, vector
        <ll>(N));
    auto C = [&](ll i, ll j) {
        // Implement cost function C.
    };
    for (ll i = 0; i < N; i++) {
        opt[i][i] = i;
        ... // Initialize dp[i][i] according to the problem
    }
    for (ll i = N - 2; i >= 0; i--) {
        for (ll j = i + 1; j < N; j++) {
            ll mn = ll_MAX, cost = C(i, j);
            for (ll k = opt[i][j - 1]; k <= min(j - 1, opt[i +
                1][j]); k++) {
                if (mn >= dp[i][k] + dp[k + 1][j] + cost) {
                    opt[i][j] = k;
                    mn = dp[i][k] + dp[k + 1][j] + cost;
                }
            }
            dp[i][j] = mn;
        }
    }
    cout << dp[0][N - 1] << '\n';
}

```

2.5 Longest Common Subsequence

```

ll LCS(string x, string y, ll n, ll m) {
    vector<vector<ll>> dp(n + 1, vector<ll>(m + 1));
    for (ll i = 0; i <= n; i++) {
        for (ll j = 0; j <= m; j++) {
            if (i == 0 || j == 0) {
                dp[i][j] = 0;
            } else if (x[i - 1] == y[j - 1]) {
                dp[i][j] = dp[i - 1][j - 1] + 1;
            } else {
                dp[i][j] = max(dp[i - 1][j], dp[i][j - 1]);
            }
        }
    }
    ll index = dp[n][m];
    vector<char> lcs(index + 1);
    lcs[index] = '\0';
}

```

```

11 i = n, j = m;
while (i > 0 && j > 0) {
    if (x[i - 1] == y[j - 1]) {
        lcs[index - 1] = x[i - 1];
        i--;
        j--;
        index--;
    } else if (dp[i - 1][j] > dp[i][j - 1]) {
        i--;
    } else {
        j--;
    }
}
return dp[n][m];
}

```

2.6 Longest Increasing Subsequence

```

11 get_ceil_idx(vector<ll> &a, vector<ll> &T, ll l, ll r
, ll x) {
    while (r - l > 1) {
        ll m = l + (r - l) / 2;
        if (a[T[m]] >= x) {
            r = m;
        } else {
            l = m;
        }
    }
    return r;
}
11 LIS(ll n, vector<ll> &a) {
    ll len = 1;
    vector<ll> T(n, 0), R(n, -1);
    T[0] = 0;
    for (ll i = 1; i < n; i++) {
        if (a[i] < a[T[0]]) {
            T[0] = i;
        } else if (a[i] > a[T[len - 1]]) {
            R[i] = T[len - 1];
            T[len++] = i;
        } else {
            ll pos = get_ceil_idx(a, T, -1, len - 1, a[i]);
            R[i] = T[pos - 1];
            T[pos] = i;
        }
    }
    return len;
}

```

2.7 Subset Sum

```

bool subset_sum(ll n, vector<ll> &arr, ll sum) {
    vector<vector<ll>> dp(n + 1, vector<ll>(sum + 1, false
));
    dp[0][0] = true;
    for (ll i = 1; i <= n; i++) {
        for (ll j = 0; j <= sum; j++) {
            dp[i][j] = dp[i - 1][j];
            if (j >= arr[i]) {
                dp[i][j] |= dp[i - 1][j - arr[i]];
            }
        }
    }
    return dp[n][sum];
}

```

3 Geometry

3.1 Circle Line Intersection

```

double r, a, b, c; // given as input
double x0 = -a * c / (a * a + b * b);
double y0 = -b * c / (a * a + b * b);
if (c * c > r * r * (a * a + b * b) + EPS) {
    puts ("no points");
} else if (abs (c * c - r * r * (a * a + b * b)) < EPS)
{
    puts ("1 point");
    cout << x0 << ' ' << y0 << '\n';
} else {
    double d = r * r - c * c / (a * a + b * b);
    double mult = sqrt (d / (a * a + b * b));
    double ax, ay, bx, by;
    ax = x0 + b * mult;
    bx = x0 - b * mult;
    ay = y0 - a * mult;
    by = y0 + a * mult;
    puts ("2 points");
    cout << ax << ' ' << ay << '\n' << bx << ' ' << by <<
'\n';
}

```

3.2 Convex Hull

```

struct pt {
    double x, y;
}

```

```

};
ll orientation(pt a, pt b, pt c) {
    double v = a.x * (b.y - c.y) + b.x * (c.y - a.y) + c.x
               * (a.y - b.y);
    if (v < 0) {
        return -1;
    } else if (v > 0) {
        return +1;
    }
    return 0;
}
bool cw(pt a, pt b, pt c, bool include_collinear) {
    ll o = orientation(a, b, c);
    return o < 0 || (include_collinear && o == 0);
}
bool collinear(pt a, pt b, pt c) {
    return orientation(a, b, c) == 0;
}
void convex_hull(vector<pt>& a, bool include_collinear =
    false) {
    pt p0 = *min_element(a.begin(), a.end(), [](pt a, pt b)
        ) {
        return make_pair(a.y, a.x) < make_pair(b.y, b.x);
    });
    sort(a.begin(), a.end(), [&p0](const pt& a, const pt&
        b) {
        ll o = orientation(p0, a, b);
        if (o == 0) {
            return (p0.x - a.x) * (p0.x - a.x) + (p0.y - a.y)
                * (p0.y - a.y)
                < (p0.x - b.x) * (p0.x - b.x) + (p0.y - b.y)
                    * (p0.y - b.y);
        }
        return o < 0;
    });
    if (include_collinear) {
        ll i = (ll) a.size() - 1;
        while (i >= 0 && collinear(p0, a[i], a.back())) i--;
        reverse(a.begin() + i + 1, a.end());
    }
    vector<pt> st;
    for (ll i = 0; i < (ll) a.size(); i++) {
        while (st.size() > 1 && !cw(st[st.size() - 2], st.
            back(), a[i], include_collinear)) {
            st.pop_back();
        }
        st.push_back(a[i]);
    }
    a = st;
}

```

3.3 Line Sweep

```

const double EPS = 1E-9;
struct pt {
    double x, y;
};
struct seg {
    pt p, q;
    ll id;
    double get_y(double x) const {
        if (abs(p.x - q.x) < EPS) {
            return p.y;
        }
        return p.y + (q.y - p.y) * (x - p.x) / (q.x - p.x);
    }
};
bool intersectld(double l1, double r1, double l2, double
    r2) {
    if (l1 > r1) {
        swap(l1, r1);
    }
    if (l2 > r2) {
        swap(l2, r2);
    }
    return max(l1, l2) <= min(r1, r2) + EPS;
}
ll vec(const pt& a, const pt& b, const pt& c) {
    double s = (b.x - a.x) * (c.y - a.y) - (b.y - a.y) * (
        c.x - a.x);
    return abs(s) < EPS ? 0 : s > 0 ? +1 : -1;
}
bool intersect(const seg& a, const seg& b) {
    return intersectld(a.p.x, a.q.x, b.p.x, b.q.x) &&
        intersectld(a.p.y, a.q.y, b.p.y, b.q.y) &&
        vec(a.p, a.q, b.p) * vec(a.p, a.q, b.q) <= 0 &&
        vec(b.p, b.q, a.p) * vec(b.p, b.q, a.q) <= 0;
}
bool operator<(const seg& a, const seg& b) {
    double x = max(min(a.p.x, a.q.x), min(b.p.x, b.q.x))
        ;
    return a.get_y(x) < b.get_y(x) - EPS;
}
struct event {
    double x;
    ll tp, id;
    event() {}
    event(double x, ll tp, ll id) : x(x), tp(tp), id(id)
        {}
    bool operator<(const event& e) const {

```

```

    if (abs(x - e.x) > EPS) {
        return x < e.x;
    }
    return tp > e.tp;
}
};
set<seg> s;
vector<set<seg>::iterator> where;
set<seg>::iterator prev(set<seg>::iterator it) {
    return it == s.begin() ? s.end() : --it;
}
set<seg>::iterator next(set<seg>::iterator it) {
    return ++it;
}
pair<ll, ll> solve(const vector<seg>& a) {
    ll n = (ll) a.size();
    vector<event> e;
    for (ll i = 0; i < n; ++i) {
        e.push_back(event(min(a[i].p.x, a[i].q.x), +1, i));
        e.push_back(event(max(a[i].p.x, a[i].q.x), -1, i));
    }
    sort(e.begin(), e.end());
    s.clear();
    where.resize(a.size());
    for (size_t i = 0; i < e.size(); ++i) {
        ll id = e[i].id;
        if (e[i].tp == +1) {
            set<seg>::iterator nxt = s.lower_bound(a[id]), prv
                = prev(nxt);
            if (nxt != s.end() && intersect(*nxt, a[id])) {
                return make_pair(nxt->id, id);
            }
            if (prv != s.end() && intersect(*prv, a[id])) {
                return make_pair(prv->id, id);
            }
            where[id] = s.insert(nxt, a[id]);
        } else {
            set<seg>::iterator nxt = next(where[id]), prv =
                prev(where[id]);
            if (nxt != s.end() && prv != s.end() && intersect
                (*nxt, *prv)) {
                return make_pair(prv->id, nxt->id);
            }
            s.erase(where[id]);
        }
    }
    return make_pair(-1, -1);
}

```

3.4 Nearest Points

```

struct pt {
    ll x, y, id;
};
struct cmp_x {
    bool operator()(const pt & a, const pt & b) const {
        return a.x < b.x || (a.x == b.x && a.y < b.y);
    }
};
struct cmp_y {
    bool operator()(const pt & a, const pt & b) const {
        return a.y < b.y;
    }
};
ll n;
vector<pt> a;
double mindist;
pair<ll, ll> best_pair;
void upd_ans(const pt & a, const pt & b) {
    double dist = sqrt((a.x - b.x) * (a.x - b.x) + (a.y -
        b.y) * (a.y - b.y));
    if (dist < mindist) {
        mindist = dist;
        best_pair = {a.id, b.id};
    }
}
vector<pt> t;
void rec(ll l, ll r) {
    if (r - l <= 3) {
        for (ll i = l; i < r; ++i) {
            for (ll j = i + 1; j < r; ++j) {
                upd_ans(a[i], a[j]);
            }
        }
        sort(a.begin() + l, a.begin() + r, cmp_y());
        return;
    }
    ll m = (l + r) >> 1, midx = a[m].x;
    rec(l, m);
    rec(m, r);
    merge(a.begin() + l, a.begin() + m, a.begin() + m, a.
        begin() + r, t.begin(), cmp_y());
    copy(t.begin(), t.begin() + r - l, a.begin() + l);
    ll tsz = 0;
    for (ll i = l; i < r; ++i) {
        if (abs(a[i].x - midx) < mindist) {
            for (ll j = tsz - 1; j >= 0 && a[i].y - t[j].y <
                mindist; --j) {

```

```

        upd_ans(a[i], t[j]);
    }
    t[tsz++] = a[i];
}
}
t.resize(n);
sort(a.begin(), a.end(), cmp_x());
mindist = 1E20;
rec(0, n);

```

4 Graph Theory

4.1 Articulation Point

```

void APUtil(vector<vector<ll>> &adj, ll u, vector<bool>
    &visited,
vector<ll> &disc, vector<ll> &low, ll &time, ll parent,
vector<bool> &isAP) {
    ll children = 0;
    visited[u] = true;
    disc[u] = low[u] = ++time;
    for (auto v : adj[u]) {
        if (!visited[v]) {
            children++;
            APUtil(adj, v, visited, disc, low, time, u, isAP);
            low[u] = min(low[u], low[v]);
            if (parent != -1 && low[v] >= disc[u]) {
                isAP[u] = true;
            }
        } else if (v != parent) {
            low[u] = min(low[u], disc[v]);
        }
    }
    if (parent == -1 && children > 1) {
        isAP[u] = true;
    }
}

void AP(vector<vector<ll>> &adj, ll n) {
    vector<ll> disc(n), low(n);
    vector<bool> visited(n), isAP(n);
    ll time = 0, par = -1;
    for (ll u = 0; u < n; u++) {
        if (!visited[u]) {
            APUtil(adj, u, visited, disc, low, time, par, isAP);
        }
    }
    for (ll u = 0; u < n; u++) {

```

```

        if (isAP[u]) {
            cout << u << " ";
        }
    }
}

```

4.2 Bellman Ford

```

void bellman_ford(vector<vector<ll>> &edges, ll n, ll m,
    ll src, vector<ll> &dis) {
    for (ll i = 0; i < n; i++) {
        dis[i] = INF;
    }
    for (ll i = 0; i < n - 1; i++) {
        for (ll j = 0; j < m; j++) {
            ll u = edges[j][0], v = edges[j][1], w = edges[j][2];
            if (dis[u] < INF) {
                dis[v] = min(dis[v], dis[u] + w);
            }
        }
    }
    for (ll i = 0; i < m; i++) {
        ll u = edges[i][0], v = edges[i][1], w = edges[i][2];
        if (dis[u] < INF && dis[u] + w < dis[v]) {
            cout << "The graph contains a negative cycle." <<
                '\n';
        }
    }
}

```

4.3 Bridge

```

void bridge_util(vector<vector<ll>> &adj, ll u, vector<
    bool> &visited, vector<ll> &disc, vector<ll> &low,
vector<ll> &parent) {
    static ll time = 0;
    visited[u] = true;
    disc[u] = low[u] = ++time;
    list<ll>::iterator i;
    for (auto v : adj[u]) {
        if (!visited[v]) {
            parent[v] = u;
            bridge_util(adj, v, visited, disc, low, parent);
            low[u] = min(low[u], low[v]);
            if (low[v] > disc[u]) {
                cout << u << ' ' << v << '\n';
            }
        }
    }
}

```



```

    }
    } else if (v != parent[u]) {
        low[u] = min(low[u], disc[v]);
    }
}
}
void bridge(vector<vector<ll>> &adj, ll n) {
    vector<bool> visited(n, false);
    vector<ll> disc(n), low(n), parent(n, -1);
    for (ll i = 0; i < n; i++) {
        if (!visited[i]) {
            bridge_util(adj, i, visited, disc, low, parent);
        }
    }
}
}

```

4.4 Dijkstra

```

void dijkstra(ll n, vector<vector<pair<ll, ll>>> &adj,
    vector<ll> &dis) {
    priority_queue<pair<ll, ll>, vector<pair<ll, ll>>,
        greater<pair<ll, ll>>> pq;
    for (int i = 0; i < n; i++) {
        dis[i] = INF;
    }
    dis[0] = 0;
    pq.push({0, 0});
    while (!pq.empty()) {
        auto p = pq.top();
        pq.pop();
        ll u = p.second;
        if (dis[u] != p.first) {
            continue;
        }
        for (auto x : adj[u]) {
            ll v = x.first, w = x.second;
            if (dis[v] > dis[u] + w) {
                dis[v] = dis[u] + w;
                pq.push({dis[v], v});
            }
        }
    }
}
}

```

4.5 Find Cycle

```

bool dfs(ll v) {
    color[v] = 1;

```

```

    for (ll u : adj[v]) {
        if (color[u] == 0) {
            parent[u] = v;
            if (dfs(u)) {
                return true;
            }
        } else if (color[u] == 1) {
            cycle_end = v;
            cycle_start = u;
            return true;
        }
    }
    color[v] = 2;
    return false;
}
void find_cycle() {
    color.assign(n, 0);
    parent.assign(n, -1);
    cycle_start = -1;
    for (ll v = 0; v < n; v++) {
        if (color[v] == 0 && dfs(v)) {
            break;
        }
    }
    if (cycle_start == -1) {
        cout << "Acyclic" << endl;
    } else {
        vector<ll> cycle;
        cycle.push_back(cycle_start);
        for (ll v = cycle_end; v != cycle_start; v = parent[v]) {
            cycle.push_back(v);
        }
        cycle.push_back(cycle_start);
        reverse(cycle.begin(), cycle.end());
        cout << "Cycle found: ";
        for (ll v : cycle) {
            cout << v << ' ';
        }
        cout << '\n';
    }
}
}

```

4.6 Floyd Warshall

```

void floyd_warshall(vector<vector<ll>> &dis, ll n) {
    for (ll i = 0; i < n; i++) {
        for (ll j = 0; j < n; j++) {
            dis[i][j] = (i == j ? 0 : INF);
        }
    }
}

```

```

}
for (ll k = 0; k < n; k++) {
    for (ll i = 0; i < n; i++) {
        for (ll j = 0; j < n; j++) {
            if (dis[i][k] < INF && dis[k][j] < INF) {
                dis[i][j] = min(dis[i][j], dis[i][k] + dis[k][j]);
            }
        }
    }
}
for (ll i = 0; i < n; i++) {
    for (ll j = 0; j < n; j++) {
        for (ll k = 0; k < n; k++) {
            if (dis[k][k] < 0 && dis[i][k] < INF && dis[k][j] < INF) {
                dis[i][j] = -INF;
            }
        }
    }
}
}
}

```

4.7 Hierholzer

```

void print_circuit(vector<vector<ll>> &adj) {
    map<ll, ll> edge_count;
    for (ll i = 0; i < adj.size(); i++) {
        edge_count[i] = adj[i].size();
    }
    if (!adj.size()) {
        return;
    }
    stack<ll> curr_path;
    vector<ll> circuit;
    curr_path.push(0);
    ll curr_v = 0;
    while (!curr_path.empty()) {
        if (edge_count[curr_v]) {
            curr_path.push(curr_v);
            ll next_v = adj[curr_v].back();
            edge_count[curr_v]--;
            adj[curr_v].pop_back();
            curr_v = next_v;
        } else {
            circuit.push_back(curr_v);
            curr_v = curr_path.top();
            curr_path.pop();
        }
    }
}

```

```

for (ll i = circuit.size() - 1; i >= 0; i--) {
    cout << circuit[i] << ' ';
}
}

```

4.8 Is Bipartite

```

bool is_bipartite(vector<ll> &col, vector<vector<ll>> &adj, ll n) {
    queue<pair<ll, ll>> q;
    for (ll i = 0; i < n; i++) {
        if (col[i] == -1) {
            q.push({i, 0});
            col[i] = 0;
            while (!q.empty()) {
                pair<ll, ll> p = q.front();
                q.pop();
                ll v = p.first, c = p.second;
                for (ll j : adj[v]) {
                    if (col[j] == c) {
                        return false;
                    }
                    if (col[j] == -1) {
                        col[j] = (c ? 0 : 1);
                        q.push({j, col[j]});
                    }
                }
            }
        }
    }
    return true;
}

```

4.9 Is Cyclic

```

bool is_cyclic_util(int u, vector<vector<int>> &adj, vector<bool> &vis, vector<bool> &rec) {
    vis[u] = true;
    rec[u] = true;
    for (auto v : adj[u]) {
        if (!vis[v] && is_cyclic_util(v, adj, vis, rec)) {
            return true;
        } else if (rec[v]) {
            return true;
        }
    }
    rec[u] = false;
    return false;
}

```

```

}
bool is_cyclic(int n, vector<vector<int>> &adj) {
    vector<bool> vis(n, false), rec(n, false);
    for (int i = 0; i < n; i++) {
        if (!vis[i] && is_cyclic_util(i, adj, vis, rec)) {
            return true;
        }
    }
    return false;
}

```

4.10 Kahn

```

void kahn(vector<vector<ll>> &adj) {
    ll n = adj.size();
    vector<ll> in_degree(n, 0);
    for (ll u = 0; u < n; u++) {
        for (ll v: adj[u]) {
            in_degree[v]++;
        }
    }
    queue<ll> q;
    for (ll i = 0; i < n; i++) {
        if (in_degree[i] == 0) {
            q.push(i);
        }
    }
    ll cnt = 0;
    vector<ll> top_order;
    while (!q.empty()) {
        ll u = q.front();
        q.pop();
        top_order.push_back(u);
        for (ll v: adj[u]) {
            if (--in_degree[v] == 0) {
                q.push(v);
            }
        }
        cnt++;
    }
    if (cnt != n) {
        cout << -1 << '\n';
        return;
    }
    for (ll i = 0; i < (ll) top_order.size(); i++) {
        cout << top_order[i] << ' ';
    }
    cout << '\n';
}

```

4.11 Kruskal Mst

```

struct Edge {
    ll u, v, weight;
    bool operator<(Edge const& other) {
        return weight < other.weight;
    }
};
ll n;
vector<Edge> edges;
ll cost = 0;
vector<ll> tree_id(n);
vector<Edge> result;
for (ll i = 0; i < n; i++) {
    tree_id[i] = i;
}
sort(edges.begin(), edges.end());
for (Edge e: edges) {
    if (tree_id[e.u] != tree_id[e.v]) {
        cost += e.weight;
        result.push_back(e);
        ll old_id = tree_id[e.u], new_id = tree_id[e.v];
        for (ll i = 0; i < n; i++) {
            if (tree_id[i] == old_id) {
                tree_id[i] = new_id;
            }
        }
    }
}

```

4.12 Lowest Common Ancestor

```

struct LCA {
    vector<ll> height, euler, first, segtree;
    vector<bool> visited;
    ll n;
    LCA(vector<vector<ll>> &adj, ll root = 0) {
        n = adj.size();
        height.resize(n);
        first.resize(n);
        euler.reserve(n * 2);
        visited.assign(n, false);
        dfs(adj, root);
        ll m = euler.size();
        segtree.resize(m * 4);
        build(1, 0, m - 1);
    }
    void dfs(vector<vector<ll>> &adj, ll node, ll h = 0) {

```

```

visited[node] = true;
height[node] = h;
first[node] = euler.size();
euler.push_back(node);
for (auto to : adj[node]) {
    if (!visited[to]) {
        dfs(adj, to, h + 1);
        euler.push_back(node);
    }
}
}

void build(ll node, ll b, ll e) {
    if (b == e) {
        segtree[node] = euler[b];
    } else {
        ll mid = (b + e) / 2;
        build(node << 1, b, mid);
        build(node << 1 | 1, mid + 1, e);
        ll l = segtree[node << 1], r = segtree[node << 1 | 1];
        segtree[node] = (height[l] < height[r]) ? l : r;
    }
}

ll query(ll node, ll b, ll e, ll L, ll R) {
    if (b > R || e < L) {
        return -1;
    }
    if (b >= L && e <= R) {
        return segtree[node];
    }
    ll mid = (b + e) >> 1;
    ll left = query(node << 1, b, mid, L, R);
    ll right = query(node << 1 | 1, mid + 1, e, L, R);
    if (left == -1) return right;
    if (right == -1) return left;
    return height[left] < height[right] ? left : right;
}

ll lca(ll u, ll v) {
    ll left = first[u], right = first[v];
    if (left > right) {
        swap(left, right);
    }
    return query(1, 0, euler.size() - 1, left, right);
}
};

```

4.13 Maximum Bipartite Matching

```

bool bpm(ll n, ll m, vector<vector<bool>> &bpGraph, ll u
, vector<bool> &seen, vector<ll> &matchR) {

```

```

    for (ll v = 0; v < m; v++) {
        if (bpGraph[u][v] && !seen[v]) {
            seen[v] = true;
            if (matchR[v] < 0 || bpm(n, m, bpGraph, matchR[v],
                seen, matchR)) {
                matchR[v] = u;
                return true;
            }
        }
    }
    return false;
}

ll maxBPM(ll n, ll m, vector<vector<bool>> &bpGraph) {
    vector<ll> matchR(m, -1);
    ll result = 0;
    for (ll u = 0; u < n; u++) {
        vector<bool> seen(m, false);
        if (bpm(n, m, bpGraph, u, seen, matchR)) {
            result++;
        }
    }
    return result;
}

```

4.14 Max Flow

```

bool bfs(ll n, vector<vector<ll>> &r_graph, ll s, ll t,
    vector<ll> &parent) {
    vector<bool> visited(n, false);
    queue<ll> q;
    q.push(s);
    visited[s] = true;
    parent[s] = -1;
    while (!q.empty()) {
        ll u = q.front();
        q.pop();
        for (ll v = 0; v < n; v++) {
            if (!visited[v] && r_graph[u][v] > 0) {
                if (v == t) {
                    parent[v] = u;
                    return true;
                }
                q.push(v);
                parent[v] = u;
                visited[v] = true;
            }
        }
    }
    return false;
}

```

```

11 fordFulkerson(11 n, vector<vector<11>> graph, 11 s,
    11 t) {
    11 u, v;
    vector<vector<11>> r_graph;
    for (u = 0; u < n; u++) {
        for (v = 0; v < n; v++) {
            r_graph[u][v] = graph[u][v];
        }
    }
    vector<11> parent;
    11 max_flow = 0;
    while (bfs(n, r_graph, s, t, parent)) {
        11 path_flow = INF;
        for (v = t; v != s; v = parent[v]) {
            u = parent[v];
            path_flow = min(path_flow, r_graph[u][v]);
        }
        for (v = t; v != s; v = parent[v]) {
            u = parent[v];
            r_graph[u][v] -= path_flow;
            r_graph[v][u] += path_flow;
        }
        max_flow += path_flow;
    }
    return max_flow;
}

```

4.15 Prim Mst

```

vector<11> prim_mst(11 n, vector<vector<pair<11, 11>>> &
    adj) {
    priority_queue<pair<11, 11>, vector<pair<11, 11>>,
        greater<pair<11, 11>>> pq;
    11 src = 0;
    vector<11> key(n, INF), parent(n, -1);
    vector<bool> in_mst(n, false);
    pq.push(make_pair(0, src));
    key[src] = 0;
    while (!pq.empty()) {
        11 u = pq.top().second;
        pq.pop();
        if (in_mst[u]) {
            continue;
        }
        in_mst[u] = true;
        for (auto p : adj[u]) {
            11 v = p.first, w = p.second;
            if (in_mst[v] == false && w < key[v]) {
                key[v] = w;
                pq.push(make_pair(key[v], v));
            }
        }
    }
}

```

```

        parent[v] = u;
    }
}
return parent;
}

```

4.16 Strongly Connected Component

```

void dfs(11 u, vector<vector<11>> &adj, vector<bool> &
    visited) {
    visited[u] = true;
    cout << u + 1 << ' ';
    for (11 v : adj[u]) {
        if (!visited[v]) {
            dfs(v, adj, visited);
        }
    }
}

vector<vector<11>> get_transpose(11 n, vector<vector<11>>
    >> &adj) {
    vector<vector<11>> res(n);
    for (11 u = 0; u < n; u++) {
        for (11 v : adj[u]) {
            res[v].push_back(u);
        }
    }
    return res;
}

void fill_order(11 u, vector<vector<11>> &adj, vector<
    bool> &visited, stack<11> &stk) {
    visited[u] = true;
    for (auto v : adj[u]) {
        if (!visited[v]) {
            fill_order(v, adj, visited, stk);
        }
    }
    stk.push(u);
}

void get_scc(11 n, vector<vector<11>> &adj) {
    stack<11> stk;
    vector<bool> visited(n, false);
    for (11 i = 0; i < n; i++) {
        if (!visited[i]) {
            fill_order(i, adj, visited, stk);
        }
    }
    vector<vector<11>> transpose = get_transpose(n, adj);
    for (11 i = 0; i < n; i++) {
        visited[i] = false;
    }
}

```

```

    }
    while (!stk.empty()) {
        ll u = stk.top();
        stk.pop();
        if (!visited[u]) {
            dfs(u, transpose, visited);
            cout << '\n';
        }
    }
}

```

4.17 Topological Sort

```

void dfs(ll v) {
    visited[v] = true;
    for (ll u : adj[v]) {
        if (!visited[u]) {
            dfs(u);
        }
    }
    ans.push_back(v);
}

void topological_sort() {
    visited.assign(n, false);
    ans.clear();
    for (ll i = 0; i < n; ++i) {
        if (!visited[i]) {
            dfs(i);
        }
    }
    reverse(ans.begin(), ans.end());
}

```

5 Miscellaneous

5.1 Gauss

```

const double EPS = 1e-9;
const ll INF = 2;
ll gauss(vector<vector<double>> a, vector<double> &ans)
{
    ll n = (ll) a.size(), m = (ll) a[0].size() - 1;
    vector<ll> where(m, -1);
    for (ll col = 0, row = 0; col < m && row < n; ++col) {
        ll sel = row;
        for (ll i = row; i < n; ++i) {
            if (abs(a[i][col]) > abs(a[sel][col])) {
                sel = i;
            }
        }
        swap(a[sel][col], a[row][col]);
        if (abs(a[sel][col]) < EPS) {
            continue;
        }
        for (ll i = col; i <= m; ++i) {
            swap(a[sel][i], a[row][i]);
        }
        where[col] = row;
        for (ll i = 0; i < n; ++i) {
            if (i != row) {
                double c = a[i][col] / a[row][col];
                for (ll j = col; j <= m; ++j) {
                    a[i][j] -= a[row][j] * c;
                }
            }
        }
        ++row;
    }
    ans.assign(m, 0);
    for (ll i = 0; i < m; ++i) {
        if (where[i] != -1) {
            ans[i] = a[where[i]][m] / a[where[i]][i];
        }
    }
    for (ll i = 0; i < n; ++i) {
        double sum = 0;
        for (ll j = 0; j < m; ++j) {
            sum += ans[j] * a[i][j];
        }
        if (abs(sum - a[i][m]) > EPS) {
            return 0;
        }
    }
    for (ll i = 0; i < m; ++i) {
        if (where[i] == -1) {
            return INF;
        }
    }
    return 1;
}

```

```

    }
    while (!stk.empty()) {
        ll u = stk.top();
        stk.pop();
        if (!visited[u]) {
            dfs(u, transpose, visited);
            cout << '\n';
        }
    }
}

```

5.2 Ternary Search

```

double ternary_search(double l, double r) {
    double eps = 1e-9;
    while (r - l > eps) {
        double m1 = l + (r - l) / 3;
        double m2 = r - (r - l) / 3;
        double f1 = f(m1);
        double f2 = f(m2);
        if (f1 < f2) {
            r = m2;
        } else {
            l = m1;
        }
    }
    return (l + r) / 2;
}

```

```

    double f2 = f(m2);
    if (f1 < f2) {
        l = m1;
    } else {
        r = m2;
    }
}
return f(l);
}

```

6 Number Theory

6.1 Extended Euclidean

```

ll gcd_extended(ll a, ll b, ll &x, ll &y) {
    if (b == 0) {
        x = 1;
        y = 0;
        return a;
    }
    ll x1, y1, g = gcd_extended(b, a % b, x1, y1);
    x = y1;
    y = x1 - (a / b) * y1;
    return g;
}

```

6.2 Find All Solutions

```

bool find_any_solution(ll a, ll b, ll c, ll &x0, ll &y0,
    ll &g) {
    g = gcd_extended(abs(a), abs(b), x0, y0);
    if (c % g) {
        return false;
    }
    x0 *= c / g;
    y0 *= c / g;
    if (a < 0) {
        x0 = -x0;
    }
    if (b < 0) {
        y0 = -y0;
    }
    return true;
}

void shift_solution(ll & x, ll & y, ll a, ll b, ll cnt)
{
    x += cnt * b;
    y -= cnt * a;
}

```

```

}
ll find_all_solutions(ll a, ll b, ll c, ll minx, ll maxx,
    ll miny, ll maxy) {
    ll x, y, g;
    if (!find_any_solution(a, b, c, x, y, g)) {
        return 0;
    }
    a /= g;
    b /= g;
    ll sign_a = a > 0 ? +1 : -1;
    ll sign_b = b > 0 ? +1 : -1;
    shift_solution(x, y, a, b, (minx - x) / b);
    if (x < minx) {
        shift_solution(x, y, a, b, sign_b);
    }
    if (x > maxx) {
        return 0;
    }
    ll lx1 = x;
    shift_solution(x, y, a, b, (maxx - x) / b);
    if (x > maxx) {
        shift_solution(x, y, a, b, -sign_b);
    }
    ll rx1 = x;
    shift_solution(x, y, a, b, -(miny - y) / a);
    if (y < miny) {
        shift_solution(x, y, a, b, -sign_a);
    }
    if (y > maxy) {
        return 0;
    }
    ll lx2 = x;
    shift_solution(x, y, a, b, -(maxy - y) / a);
    if (y > maxy) {
        shift_solution(x, y, a, b, sign_a);
    }
    ll rx2 = x;
    if (lx2 > rx2) {
        swap(lx2, rx2);
    }
    ll lx = max(lx1, lx2), rx = min(rx1, rx2);
    if (lx > rx) {
        return 0;
    }
    return (rx - lx) / abs(b) + 1;
}

```

6.3 Linear Sieve

```

void linear_sieve(ll N, vector<ll> &lowest_prime, vector

```

```

<ll> &prime) {
for (ll i = 2; i <= N; i++) {
    if (lowest_prime[i] == 0) {
        lowest_prime[i] = i;
        prime.push_back(i);
    }
    for (ll j = 0; i * prime[j] <= N; j++) {
        lowest_prime[i * prime[j]] = prime[j];
        if (prime[j] == lowest_prime[i]) {
            break;
        }
    }
}
}
}

```

6.4 Miller Rabin

```

bool check_composite(u64 n, u64 a, u64 d, ll s) {
    u64 x = binpower(a, d, n);
    if (x == 1 || x == n - 1) {
        return false;
    }
    for (ll r = 1; r < s; r++) {
        x = (u128) x * x % n;
        if (x == n - 1) {
            return false;
        }
    }
    return true;
}

bool miller_rabin(u64 n) {
    if (n < 2) {
        return false;
    }
    ll r = 0;
    u64 d = n - 1;
    while ((d & 1) == 0) {
        d >>= 1;
        r++;
    }
    for (ll a : {2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37}) {
        if (n == a) {
            return true;
        }
        if (check_composite(n, a, d, r)) {
            return false;
        }
    }
    return true;
}

```

6.5 Modulo Inverse

```

ll mod_inv(ll a, ll m) {
    if (m == 1) {
        return 0;
    }
    ll m0 = m, x = 1, y = 0;
    while (a > 1) {
        ll q = a / m, t = m;
        m = a % m;
        a = t;
        t = y;
        y = x - q * y;
        x = t;
    }
    if (x < 0) {
        x += m0;
    }
    return x;
}

```

6.6 Pollard Rho Brent

```

ll mult(ll a, ll b, ll mod) {
    return (__int128_t) a * b % mod;
}

ll f(ll x, ll c, ll mod) {
    return (mult(x, x, mod) + c) % mod;
}

ll pollard_rho_brent(ll n, ll x0 = 2, ll c = 1) {
    ll x = x0, g = 1, q = 1, xs, y, m = 128, l = 1;
    while (g == 1) {
        y = x;
        for (ll i = 1; i < l; i++) {
            x = f(x, c, n);
        }
        ll k = 0;
        while (k < l && g == 1) {
            xs = x;
            for (ll i = 0; i < m && i < l - k; i++) {
                x = f(x, c, n);
                q = mult(q, abs(y - x), n);
            }
            g = __gcd(q, n);
            k += m;
        }
    }
}

```



```

    l *= 2;
}
if (g == n) {
    do {
        xs = f(xs, c, n);
        g = __gcd(abs(xs - y), n);
    } while (g == 1);
}
return g;
}

```

6.7 Range Sieve

```

vector<bool> range_sieve(ll l, ll r) {
    ll n = sqrt(r);
    vector<bool> is_prime(n + 1, true);
    vector<ll> prime;
    is_prime[0] = is_prime[1] = false;
    prime.push_back(2);
    for (ll i = 4; i <= n; i += 2) {
        is_prime[i] = false;
    }
    for (ll i = 3; i <= n; i += 2) {
        if (is_prime[i]) {
            prime.push_back(i);
            for (ll j = i * i; j <= n; j += i) {
                is_prime[j] = false;
            }
        }
    }
    vector<bool> result(r - l + 1, true);
    for (ll i : prime) {
        for (ll j = max(i * i, (l + i - 1) / i * i); j <= r;
              j += i) {
            result[j - l] = false;
        }
    }
    if (l == 1) {
        result[0] = false;
    }
    return result;
}

```

6.8 Segmented Sieve

```

vector<ll> segmented_sieve(ll n) {
    const ll S = 10000;
    ll nsqrt = sqrt(n);

```

```

    vector<char> is_prime(nsqrt + 1, true);
    vector<ll> prime;
    is_prime[0] = is_prime[1] = false;
    prime.push_back(2);
    for (ll i = 4; i <= nsqrt; i += 2) {
        is_prime[i] = false;
    }
    for (ll i = 3; i <= nsqrt; i += 2) {
        if (is_prime[i]) {
            prime.push_back(i);
            for (ll j = i * i; j <= nsqrt; j += i) {
                is_prime[j] = false;
            }
        }
    }
    vector<ll> result;
    vector<char> block(S);
    for (ll k = 0; k * S <= n; k++) {
        fill(block.begin(), block.end(), true);
        for (ll p : prime) {
            for (ll j = max((k * S + p - 1) / p, p) * p - k *
                          S; j < S; j += p) {
                block[j] = false;
            }
        }
        if (k == 0) {
            block[0] = block[1] = false;
        }
        for (ll i = 0; i < S && k * S + i <= n; i++) {
            if (block[i]) {
                result.push_back(k * S + i);
            }
        }
    }
    return result;
}

```

6.9 Tonelli Shanks

```

ll legendre(ll a, ll p) {
    return bin_pow_mod(a, (p - 1) / 2, p);
}
ll tonelli_shanks(ll n, ll p) {
    if (legendre(n, p) == p - 1) {
        return -1;
    }
    if (p % 4 == 3) {
        return bin_pow_mod(n, (p + 1) / 4, p);
    }
    ll Q = p - 1, S = 0;

```

```

while (Q % 2 == 0) {
    Q /= 2;
    S++;
}
ll z = 2;
for (; z < p; z++) {
    if (legendre(z, p) == p - 1) {
        break;
    }
}
ll M = S, c = bin_pow_mod(z, Q, p), t = bin_pow_mod(n,
    Q, p), R = bin_pow_mod(n, (Q + 1) / 2, p);
while (t % p != 1) {
    if (t % p == 0) {
        return 0;
    }
    ll i = 1, t2 = t * t % p;
    for (; i < M; i++) {
        if (t2 % p == 1) {
            break;
        }
        t2 = t2 * t2 % p;
    }
    ll b = bin_pow_mod(c, bin_pow_mod(2, M - i - 1, p),
        p);
    M = i;
    c = b * b % p;
    t = t * c % p;
    R = R * b % p;
}
return R;
}

```

7 Strings

7.1 Hashing

```

ll compute_hash(string const& s) {
    const ll p = 31, m = 1e9 + 9;
    ll hash_value = 0, p_pow = 1;
    for (char c : s) {
        hash_value = (hash_value + (c - 'a' + 1) * p_pow) %
            m;
        p_pow = (p_pow * p) % m;
    }
    return hash_value;
}

```

7.2 Knuth Morris Pratt

```

vector<ll> prefix_function(string s) {
    ll n = (ll) s.length();
    vector<ll> pi(n);
    for (ll i = 1; i < n; i++) {
        ll j = pi[i - 1];
        while (j > 0 && s[i] != s[j]) {
            j = pi[j - 1];
        }
        if (s[i] == s[j]) {
            j++;
        }
        pi[i] = j;
    }
    return pi;
}

```

7.3 Rabin Karp

```

vector<ll> rabin_karp(string const& s, string const& t)
{
    const ll p = 31, m = 1e9 + 9;
    ll S = s.size(), T = t.size();
    vector<ll> p_pow(max(S, T));
    p_pow[0] = 1;
    for (ll i = 1; i < (ll) p_pow.size(); i++) {
        p_pow[i] = (p_pow[i-1] * p) % m;
    }
    vector<ll> h(T + 1, 0);
    for (ll i = 0; i < T; i++) {
        h[i + 1] = (h[i] + (t[i] - 'a' + 1) * p_pow[i]) % m;
    }
    ll h_s = 0;
    for (ll i = 0; i < S; i++) {
        h_s = (h_s + (s[i] - 'a' + 1) * p_pow[i]) % m;
    }
    vector<ll> occurrences;
    for (ll i = 0; i + S - 1 < T; i++) {
        ll cur_h = (h[i + S] + m - h[i]) % m;
        if (cur_h == h_s * p_pow[i] % m) {
            occurrences.push_back(i);
        }
    }
    return occurrences;
}

```

7.4 Suffix Array

```

vector<ll> sort_cyclic_shifts(string const& s) {
    ll n = s.size();
    const ll alphabet = 256;
    vector<ll> p(n), c(n), cnt(max(alphabet, n), 0);
    for (ll i = 0; i < n; i++) {
        cnt[s[i]]++;
    }
    for (ll i = 1; i < alphabet; i++) {
        cnt[i] += cnt[i - 1];
    }
    for (ll i = 0; i < n; i++) {
        p[--cnt[s[i]]] = i;
    }
    c[p[0]] = 0;
    ll classes = 1;
    for (ll i = 1; i < n; i++) {
        if (s[p[i]] != s[p[i - 1]]) {
            classes++;
        }
        c[p[i]] = classes - 1;
    }
    vector<ll> pn(n), cn(n);
    for (ll h = 0; (1 << h) < n; ++h) {
        for (ll i = 0; i < n; i++) {
            pn[i] = p[i] - (1 << h);
            if (pn[i] < 0) {
                pn[i] += n;
            }
        }
        fill(cnt.begin(), cnt.begin() + classes, 0);
        for (ll i = 0; i < n; i++) {
            cnt[c[pn[i]]]++;
        }
        for (ll i = 1; i < classes; i++) {
            cnt[i] += cnt[i - 1];
        }
        for (ll i = n - 1; i >= 0; i--) {
            p[--cnt[c[pn[i]]]] = pn[i];
        }
        cn[p[0]] = 0;

```

```

        classes = 1;
        for (ll i = 1; i < n; i++) {
            pair<ll, ll> cur = {c[p[i]], c[(p[i] + (1 << h)) %
                n]};
            pair<ll, ll> prev = {c[p[i - 1]], c[(p[i - 1] + (1
                << h)) % n]};
            if (cur != prev) {
                ++classes;
            }
            cn[p[i]] = classes - 1;
        }
        c.swap(cn);
    }
    return p;
}

vector<ll> build_suff_arr(string s) {
    s += (char) 0;
    vector<ll> sorted_shifts = sort_cyclic_shifts(s);
    sorted_shifts.erase(sorted_shifts.begin());
    return sorted_shifts;
}

```

7.5 Z Function

```

vector<ll> z_function(string s) {
    ll n = (ll) s.length();
    vector<ll> z(n);
    for (ll i = 1, l = 0, r = 0; i < n; ++i) {
        if (i <= r) {
            z[i] = min(r - i + 1, z[i - l]);
        }
        while (i + z[i] < n && s[z[i]] == s[i + z[i]]) {
            ++z[i];
        }
        if (i + z[i] - 1 > r) {
            l = i, r = i + z[i] - 1;
        }
    }
    return z;
}

```

$f(n) = O(g(n))$	iff \exists positive c, n_0 such that $0 \leq f(n) \leq cg(n) \forall n \geq n_0$.	$\sum_{i=1}^n i = \frac{n(n+1)}{2}, \quad \sum_{i=1}^n i^2 = \frac{n(n+1)(2n+1)}{6}, \quad \sum_{i=1}^n i^3 = \frac{n^2(n+1)^2}{4}.$
$f(n) = \Omega(g(n))$	iff \exists positive c, n_0 such that $f(n) \geq cg(n) \geq 0 \forall n \geq n_0$.	In general:
$f(n) = \Theta(g(n))$	iff $f(n) = O(g(n))$ and $f(n) = \Omega(g(n))$.	$\sum_{i=1}^n i^m = \frac{1}{m+1} \left[(n+1)^{m+1} - 1 - \sum_{i=1}^n ((i+1)^{m+1} - i^{m+1} - (m+1)i^m) \right]$
$f(n) = o(g(n))$	iff $\lim_{n \rightarrow \infty} f(n)/g(n) = 0$.	$\sum_{i=1}^{n-1} i^m = \frac{1}{m+1} \sum_{k=0}^m \binom{m+1}{k} B_k n^{m+1-k}.$
$\lim_{n \rightarrow \infty} a_n = a$	iff $\forall \epsilon > 0, \exists n_0$ such that $ a_n - a < \epsilon, \forall n \geq n_0$.	Geometric series:
$\sup S$	least $b \in \mathbb{R}$ such that $b \geq s, \forall s \in S$.	$\sum_{i=0}^n c^i = \frac{c^{n+1} - 1}{c - 1}, \quad c \neq 1, \quad \sum_{i=0}^{\infty} c^i = \frac{1}{1 - c}, \quad \sum_{i=1}^{\infty} c^i = \frac{c}{1 - c}, \quad c < 1,$
$\inf S$	greatest $b \in \mathbb{R}$ such that $b \leq s, \forall s \in S$.	$\sum_{i=0}^n i c^i = \frac{nc^{n+2} - (n+1)c^{n+1} + c}{(c-1)^2}, \quad c \neq 1, \quad \sum_{i=0}^{\infty} i c^i = \frac{c}{(1-c)^2}, \quad c < 1.$
$\liminf_{n \rightarrow \infty} a_n$	$\lim_{n \rightarrow \infty} \inf \{a_i \mid i \geq n, i \in \mathbb{N}\}.$	Harmonic series:
$\limsup_{n \rightarrow \infty} a_n$	$\lim_{n \rightarrow \infty} \sup \{a_i \mid i \geq n, i \in \mathbb{N}\}.$	$H_n = \sum_{i=1}^n \frac{1}{i}, \quad \sum_{i=1}^n i H_i = \frac{n(n+1)}{2} H_n - \frac{n(n-1)}{4}.$
$\binom{n}{k}$	Combinations: Size k sub-sets of a size n set.	$\sum_{i=1}^n H_i = (n+1)H_n - n, \quad \sum_{i=1}^n \binom{i}{m} H_i = \binom{n+1}{m+1} \left(H_{n+1} - \frac{1}{m+1} \right).$
$[n]$	Stirling numbers (1st kind): Arrangements of an n element set into k cycles.	1. $\binom{n}{k} = \frac{n!}{(n-k)!k!}, \quad 2. \sum_{k=0}^n \binom{n}{k} = 2^n, \quad 3. \binom{n}{k} = \binom{n}{n-k},$
$\left\{ \begin{smallmatrix} n \\ k \end{smallmatrix} \right\}$	Stirling numbers (2nd kind): Partitions of an n element set into k non-empty sets.	4. $\binom{n}{k} = \frac{n}{k} \binom{n-1}{k-1}, \quad 5. \binom{n}{k} = \binom{n-1}{k} + \binom{n-1}{k-1},$
$\langle \begin{smallmatrix} n \\ k \end{smallmatrix} \rangle$	1st order Eulerian numbers: Permutations $\pi_1 \pi_2 \dots \pi_n$ on $\{1, 2, \dots, n\}$ with k ascents.	6. $\binom{n}{m} \binom{m}{k} = \binom{n}{k} \binom{n-k}{m-k}, \quad 7. \sum_{k=0}^n \binom{r+k}{k} = \binom{r+n+1}{n},$
$\langle \langle \begin{smallmatrix} n \\ k \end{smallmatrix} \rangle \rangle$	2nd order Eulerian numbers.	8. $\sum_{k=0}^n \binom{k}{m} = \binom{n+1}{m+1}, \quad 9. \sum_{k=0}^n \binom{r}{k} \binom{s}{n-k} = \binom{r+s}{n},$
C_n	Catalan Numbers: Binary trees with $n+1$ vertices.	10. $\binom{n}{k} = (-1)^k \binom{k-n-1}{k}, \quad 11. \left\{ \begin{smallmatrix} n \\ 1 \end{smallmatrix} \right\} = \left\{ \begin{smallmatrix} n \\ n \end{smallmatrix} \right\} = 1,$
14. $\left[\begin{smallmatrix} n \\ 1 \end{smallmatrix} \right] = (n-1)!,$	15. $\left[\begin{smallmatrix} n \\ 2 \end{smallmatrix} \right] = (n-1)!H_{n-1},$	16. $\left[\begin{smallmatrix} n \\ n \end{smallmatrix} \right] = 1, \quad 17. \left[\begin{smallmatrix} n \\ k \end{smallmatrix} \right] \geq \left\{ \begin{smallmatrix} n \\ k \end{smallmatrix} \right\},$
18. $\left[\begin{smallmatrix} n \\ k \end{smallmatrix} \right] = (n-1) \left[\begin{smallmatrix} n-1 \\ k \end{smallmatrix} \right] + \left[\begin{smallmatrix} n-1 \\ k-1 \end{smallmatrix} \right],$	19. $\left\{ \begin{smallmatrix} n \\ n-1 \end{smallmatrix} \right\} = \left[\begin{smallmatrix} n \\ n-1 \end{smallmatrix} \right] = \binom{n}{2},$	20. $\sum_{k=0}^n \left[\begin{smallmatrix} n \\ k \end{smallmatrix} \right] = n!, \quad 21. C_n = \frac{1}{n+1} \binom{2n}{n},$
22. $\langle \begin{smallmatrix} n \\ 0 \end{smallmatrix} \rangle = \langle \begin{smallmatrix} n \\ n-1 \end{smallmatrix} \rangle = 1,$	23. $\langle \begin{smallmatrix} n \\ k \end{smallmatrix} \rangle = \langle \begin{smallmatrix} n \\ n-1-k \end{smallmatrix} \rangle,$	24. $\langle \begin{smallmatrix} n \\ k \end{smallmatrix} \rangle = (k+1) \langle \begin{smallmatrix} n-1 \\ k \end{smallmatrix} \rangle + (n-k) \langle \begin{smallmatrix} n-1 \\ k-1 \end{smallmatrix} \rangle,$
25. $\langle \begin{smallmatrix} 0 \\ k \end{smallmatrix} \rangle = \begin{cases} 1 & \text{if } k=0, \\ 0 & \text{otherwise} \end{cases}$	26. $\langle \begin{smallmatrix} n \\ 1 \end{smallmatrix} \rangle = 2^n - n - 1,$	27. $\langle \begin{smallmatrix} n \\ 2 \end{smallmatrix} \rangle = 3^n - (n+1)2^n + \binom{n+1}{2},$
28. $x^n = \sum_{k=0}^n \langle \begin{smallmatrix} n \\ k \end{smallmatrix} \rangle \binom{x+k}{n},$	29. $\langle \begin{smallmatrix} n \\ m \end{smallmatrix} \rangle = \sum_{k=0}^m \binom{n+1}{k} (m+1-k)^n (-1)^k,$	30. $m! \left\{ \begin{smallmatrix} n \\ m \end{smallmatrix} \right\} = \sum_{k=0}^n \langle \begin{smallmatrix} n \\ k \end{smallmatrix} \rangle \binom{k}{n-m},$
31. $\langle \begin{smallmatrix} n \\ m \end{smallmatrix} \rangle = \sum_{k=0}^n \left\{ \begin{smallmatrix} n \\ k \end{smallmatrix} \right\} \binom{n-k}{m} (-1)^{n-k-m} k!,$	32. $\langle \langle \begin{smallmatrix} n \\ 0 \end{smallmatrix} \rangle \rangle = 1,$	33. $\langle \langle \begin{smallmatrix} n \\ n \end{smallmatrix} \rangle \rangle = 0 \quad \text{for } n \neq 0,$
34. $\langle \langle \begin{smallmatrix} n \\ k \end{smallmatrix} \rangle \rangle = (k+1) \langle \langle \begin{smallmatrix} n-1 \\ k \end{smallmatrix} \rangle \rangle + (2n-1-k) \langle \langle \begin{smallmatrix} n-1 \\ k-1 \end{smallmatrix} \rangle \rangle,$	35. $\sum_{k=0}^n \langle \langle \begin{smallmatrix} n \\ k \end{smallmatrix} \rangle \rangle = \frac{(2n)^n}{2^n},$	36. $\left\{ \begin{smallmatrix} x \\ x-n \end{smallmatrix} \right\} = \sum_{k=0}^n \langle \langle \begin{smallmatrix} n \\ k \end{smallmatrix} \rangle \rangle \binom{x+n-1-k}{2n},$
37. $\left\{ \begin{smallmatrix} n+1 \\ m+1 \end{smallmatrix} \right\} = \sum_k \binom{n}{k} \left\{ \begin{smallmatrix} k \\ m \end{smallmatrix} \right\} = \sum_{k=0}^n \left\{ \begin{smallmatrix} k \\ m \end{smallmatrix} \right\} (m+1)^{n-k},$		

The Chinese remainder theorem: There exists a number C such that:

$$C \equiv r_1 \pmod{m_1}$$

$$\vdots \quad \vdots \quad \vdots$$

$$C \equiv r_n \pmod{m_n}$$

if m_i and m_j are relatively prime for $i \neq j$.

Euler's function: $\phi(x)$ is the number of positive integers less than x relatively prime to x . If $\prod_{i=1}^n p_i^{e_i}$ is the prime factorization of x then

$$\phi(x) = \prod_{i=1}^n p_i^{e_i-1} (p_i - 1).$$

Euler's theorem: If a and b are relatively prime then

$$1 \equiv a^{\phi(b)} \pmod{b}.$$

Fermat's theorem:

$$1 \equiv a^{p-1} \pmod{p}.$$

The Euclidean algorithm: if $a > b$ are integers then

$$\gcd(a, b) = \gcd(a \bmod b, b).$$

If $\prod_{i=1}^n p_i^{e_i}$ is the prime factorization of x then

$$S(x) = \sum_{d|x} d = \prod_{i=1}^n \frac{p_i^{e_i+1} - 1}{p_i - 1}.$$

Perfect Numbers: x is an even perfect number iff $x = 2^{n-1}(2^n - 1)$ and $2^n - 1$ is prime.

Wilson's theorem: n is a prime iff

$$(n-1)! \equiv -1 \pmod{n}.$$

Möbius inversion:

$$\mu(i) = \begin{cases} 1 & \text{if } i = 1. \\ 0 & \text{if } i \text{ is not square-free.} \\ (-1)^r & \text{if } i \text{ is the product of } r \text{ distinct primes.} \end{cases}$$

If

$$G(a) = \sum_{d|a} F(d),$$

then

$$F(a) = \sum_{d|a} \mu(d) G\left(\frac{a}{d}\right).$$

Prime numbers:

$$p_n = n \ln n + n \ln \ln n - n + n \frac{\ln \ln n}{\ln n}$$

$$+ O\left(\frac{n}{\ln n}\right),$$

$$\pi(n) = \frac{n}{\ln n} + \frac{n}{(\ln n)^2} + \frac{2!n}{(\ln n)^3}$$

$$+ O\left(\frac{n}{(\ln n)^4}\right).$$

Definitions:

Loop An edge connecting a vertex to itself.

Directed Simple Each edge has a direction. Graph with no loops or multi-edges.

Walk A sequence $v_0 e_1 v_1 \dots e_\ell v_\ell$.

Trail A walk with distinct edges.

Path A trail with distinct vertices.

Connected A graph where there exists a path between any two vertices.

Component A maximal connected subgraph.

Tree A connected acyclic graph.

Free tree A tree with no root.

DAG Directed acyclic graph.

Eulerian Graph with a trail visiting each edge exactly once.

Hamiltonian Graph with a cycle visiting each vertex exactly once.

Cut A set of edges whose removal increases the number of components.

Cut-set A minimal cut.

Cut edge A size 1 cut.

k-Connected A graph connected with the removal of any $k-1$ vertices.

k-Tough $\forall S \subseteq V, S \neq \emptyset$ we have $k \cdot c(G-S) \leq |S|$.

k-Regular A graph where all vertices have degree k .

k-Factor A k -regular spanning subgraph.

Matching A set of edges, no two of which are adjacent.

Clique A set of vertices, all of which are adjacent.

Ind. set A set of vertices, none of which are adjacent.

Vertex cover A set of vertices which cover all edges.

Planar graph A graph which can be embedded in the plane.

Plane graph An embedding of a planar graph.

$$\sum_{v \in V} \deg(v) = 2m.$$

If G is planar then $n - m + f = 2$, so

$$f \leq 2n - 4, \quad m \leq 3n - 6.$$

Any planar graph has a vertex with degree ≤ 5 .

Notation:

$E(G)$ Edge set

$V(G)$ Vertex set

$c(G)$ Number of components

$G[S]$ Induced subgraph

$\deg(v)$ Degree of v

$\Delta(G)$ Maximum degree

$\delta(G)$ Minimum degree

$\chi(G)$ Chromatic number

$\chi_E(G)$ Edge chromatic number

G^c Complement graph

K_n Complete graph

K_{n_1, n_2} Complete bipartite graph

$r(k, \ell)$ Ramsey number

Geometry

Projective coordinates: triples (x, y, z) , not all x, y and z zero.

$$(x, y, z) = (cx, cy, cz) \quad \forall c \neq 0.$$

Cartesian Projective

$$(x, y) \quad (x, y, 1)$$

$$y = mx + b \quad (m, -1, b)$$

$$x = c \quad (1, 0, -c)$$

Distance formula, L_p and L_∞ metric:

$$\sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2},$$

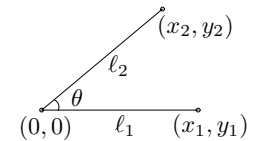
$$[|x_1 - x_0|^p + |y_1 - y_0|^p]^{1/p},$$

$$\lim_{p \rightarrow \infty} [|x_1 - x_0|^p + |y_1 - y_0|^p]^{1/p}.$$

Area of triangle $(x_0, y_0), (x_1, y_1)$ and (x_2, y_2) :

$$\frac{1}{2} \text{abs} \begin{vmatrix} x_1 - x_0 & y_1 - y_0 \\ x_2 - x_0 & y_2 - y_0 \end{vmatrix}.$$

Angle formed by three points:



$$\cos \theta = \frac{(x_1, y_1) \cdot (x_2, y_2)}{l_1 l_2}.$$

Line through two points (x_0, y_0) and (x_1, y_1) :

$$\begin{vmatrix} x & y & 1 \\ x_0 & y_0 & 1 \\ x_1 & y_1 & 1 \end{vmatrix} = 0.$$

Area of circle, volume of sphere:

$$A = \pi r^2, \quad V = \frac{4}{3} \pi r^3.$$

If I have seen farther than others, it is because I have stood on the shoulders of giants.

– Issac Newton

Taylor's series:

$$f(x) = f(a) + (x-a)f'(a) + \frac{(x-a)^2}{2}f''(a) + \dots = \sum_{i=0}^{\infty} \frac{(x-a)^i}{i!} f^{(i)}(a).$$

Expansions:

$$\begin{aligned} \frac{1}{1-x} &= 1 + x + x^2 + x^3 + x^4 + \dots = \sum_{i=0}^{\infty} x^i, \\ \frac{1}{1-cx} &= 1 + cx + c^2x^2 + c^3x^3 + \dots = \sum_{i=0}^{\infty} c^i x^i, \\ \frac{1}{1-x^n} &= 1 + x^n + x^{2n} + x^{3n} + \dots = \sum_{i=0}^{\infty} x^{ni}, \\ \frac{x}{(1-x)^2} &= x + 2x^2 + 3x^3 + 4x^4 + \dots = \sum_{i=0}^{\infty} ix^i, \\ x^k \frac{d^n}{dx^n} \left(\frac{1}{1-x} \right) &= x + 2^n x^2 + 3^n x^3 + 4^n x^4 + \dots = \sum_{i=0}^{\infty} i^n x^i, \\ e^x &= 1 + x + \frac{1}{2}x^2 + \frac{1}{6}x^3 + \dots = \sum_{i=0}^{\infty} \frac{x^i}{i!}, \\ \ln(1+x) &= x - \frac{1}{2}x^2 + \frac{1}{3}x^3 - \frac{1}{4}x^4 + \dots = \sum_{i=1}^{\infty} (-1)^{i+1} \frac{x^i}{i}, \\ \ln \frac{1}{1-x} &= x + \frac{1}{2}x^2 + \frac{1}{3}x^3 + \frac{1}{4}x^4 + \dots = \sum_{i=1}^{\infty} \frac{x^i}{i}, \\ \sin x &= x - \frac{1}{3!}x^3 + \frac{1}{5!}x^5 - \frac{1}{7!}x^7 + \dots = \sum_{i=0}^{\infty} (-1)^i \frac{x^{2i+1}}{(2i+1)!}, \\ \cos x &= 1 - \frac{1}{2!}x^2 + \frac{1}{4!}x^4 - \frac{1}{6!}x^6 + \dots = \sum_{i=0}^{\infty} (-1)^i \frac{x^{2i}}{(2i)!}, \\ \tan^{-1} x &= x - \frac{1}{3}x^3 + \frac{1}{5}x^5 - \frac{1}{7}x^7 + \dots = \sum_{i=0}^{\infty} (-1)^i \frac{x^{2i+1}}{(2i+1)}, \\ (1+x)^n &= 1 + nx + \frac{n(n-1)}{2}x^2 + \dots = \sum_{i=0}^{\infty} \binom{n}{i} x^i, \\ \frac{1}{(1-x)^{n+1}} &= 1 + (n+1)x + \binom{n+2}{2}x^2 + \dots = \sum_{i=0}^{\infty} \binom{i+n}{i} x^i, \\ \frac{x}{e^x - 1} &= 1 - \frac{1}{2}x + \frac{1}{12}x^2 - \frac{1}{720}x^4 + \dots = \sum_{i=0}^{\infty} \frac{B_i x^i}{i!}, \\ \frac{1}{2x}(1 - \sqrt{1-4x}) &= 1 + x + 2x^2 + 5x^3 + \dots = \sum_{i=0}^{\infty} \frac{1}{i+1} \binom{2i}{i} x^i, \\ \frac{1}{\sqrt{1-4x}} &= 1 + x + 2x^2 + 6x^3 + \dots = \sum_{i=0}^{\infty} \binom{2i}{i} x^i, \\ \frac{1}{\sqrt{1-4x}} \left(\frac{1 - \sqrt{1-4x}}{2x} \right)^n &= 1 + (2+n)x + \binom{4+n}{2}x^2 + \dots = \sum_{i=0}^{\infty} \binom{2i+n}{i} x^i, \\ \frac{1}{1-x} \ln \frac{1}{1-x} &= x + \frac{3}{2}x^2 + \frac{11}{6}x^3 + \frac{25}{12}x^4 + \dots = \sum_{i=1}^{\infty} H_i x^i, \\ \frac{1}{2} \left(\ln \frac{1}{1-x} \right)^2 &= \frac{1}{2}x^2 + \frac{3}{4}x^3 + \frac{11}{24}x^4 + \dots = \sum_{i=2}^{\infty} \frac{H_{i-1} x^i}{i}, \\ \frac{x}{1-x-x^2} &= x + x^2 + 2x^3 + 3x^4 + \dots = \sum_{i=0}^{\infty} F_i x^i, \\ \frac{F_n x}{1 - (F_{n-1} + F_{n+1})x - (-1)^n x^2} &= F_n x + F_{2n} x^2 + F_{3n} x^3 + \dots = \sum_{i=0}^{\infty} F_{ni} x^i. \end{aligned}$$

Ordinary power series:

$$A(x) = \sum_{i=0}^{\infty} a_i x^i.$$

Exponential power series:

$$A(x) = \sum_{i=0}^{\infty} a_i \frac{x^i}{i!}.$$

Dirichlet power series:

$$A(x) = \sum_{i=1}^{\infty} \frac{a_i}{i^x}.$$

Binomial theorem:

$$(x+y)^n = \sum_{k=0}^n \binom{n}{k} x^{n-k} y^k.$$

Difference of like powers:

$$x^n - y^n = (x-y) \sum_{k=0}^{n-1} x^{n-1-k} y^k.$$

For ordinary power series:

$$\alpha A(x) + \beta B(x) = \sum_{i=0}^{\infty} (\alpha a_i + \beta b_i) x^i,$$

$$x^k A(x) = \sum_{i=k}^{\infty} a_{i-k} x^i,$$

$$\frac{A(x) - \sum_{i=0}^{k-1} a_i x^i}{x^k} = \sum_{i=0}^{\infty} a_{i+k} x^i,$$

$$A(cx) = \sum_{i=0}^{\infty} c^i a_i x^i,$$

$$A'(x) = \sum_{i=0}^{\infty} (i+1) a_{i+1} x^i,$$

$$xA'(x) = \sum_{i=1}^{\infty} i a_i x^i,$$

$$\int A(x) dx = \sum_{i=1}^{\infty} \frac{a_{i-1}}{i} x^i,$$

$$\frac{A(x) + A(-x)}{2} = \sum_{i=0}^{\infty} a_{2i} x^{2i},$$

$$\frac{A(x) - A(-x)}{2} = \sum_{i=0}^{\infty} a_{2i+1} x^{2i+1}.$$

Summation: If $b_i = \sum_{j=0}^i a_j$ then

$$B(x) = \frac{1}{1-x} A(x).$$

Convolution:

$$A(x)B(x) = \sum_{i=0}^{\infty} \left(\sum_{j=0}^i a_j b_{i-j} \right) x^i.$$

God made the natural numbers;
all the rest is the work of man.
– Leopold Kronecker

