Listings

Listing 1: **Contest**

Listing 2: Hash codes

```
#!/usr/bin/env bash
#Hashes a file, ignoring all:
#   - whitespace
#   - comments
#   - asserts
#   - includes
#   - pragmas
#Use to verify that code was correctly typed.

#usage:
#   chmod +x hash.sh
#   cat <file> | ./hash.sh
#or just copy this command:
#   cat <file> | sed -r '/(assert|include|pragma)/d' | cpp -fpreprocessed -P | tr -d
    ↪ '[:space:]' | md5sum | cut -c-6
sed -r '/(assert|include|pragma)/d' | cpp -fpreprocessed -P | tr -d '[:space:]' | md5sum
    ↪ | cut -c-6
```

Listing 3: Test on random inputs

```
#!/usr/bin/env bash
#runs 2 programs against each other on random inputs until they output different results
#usage:
#   chmod +x test.sh
#   ./test.sh
for((i = 1; ; ++i)); do
    echo $i
    ./test.out > in
    diff --ignore-all-space <(./a.out < in) <(./brute.out < in) || break
done
```

Listing 4: **GRAPHS**

Listing 5: Bridges and Cuts

```
//cat bridges_and_cuts.h | ./hash.sh
//34dc49
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/biconnected_components,
    ↪ https://judge.yosupo.jp/problem/two_edge_connected_components
//with asserts checking correctness of is_bridge and is_cut
//O(n+m) time & space
//2 edge cc and bcc stuff doesn't depend on each other, so delete whatever is not needed
//handles multiple edges
//
//example initialization of `adj`:
//for (int i = 0; i < m; i++) {
//  int u, v;
//  cin >> u >> v;
//  u--, v--;
//  adj[u].emplace_back(v, i);
//  adj[v].emplace_back(u, i);
//}
struct info {
    //2 edge connected component stuff (e.g. components split by bridge edges)
        ↪ https://cp-algorithms.com/graph/bridge-searching.html
    int num_2_edge_ccs;
    vector<bool> is_bridge;//edge id -> true iff bridge edge
    vector<int> two_edge_ccid;//node -> id of 2 edge component (which are labeled 0, 1,
        ↪ ..., `num_2_edge_ccs`-1)
    //bi connected component stuff (e.g. components split by cut/articulation nodes)
        ↪ https://cp-algorithms.com/graph/cutpoints.html
    int num_bccs;
    vector<bool> is_cut;//node -> true iff cut node
    vector<int> bcc_id;//edge id -> id of bcc (which are labeled 0, 1, ..., `num_bccs`-1)
};
info bridge_and_cut(const vector<vector<pair<int/*neighbor*/, int/*edge id*/>>>&
    ↪ adj/*undirected graph*/, int m/*number of edges*/) {
    //stuff for both (always keep)
    int n = adj.size(), timer = 1;
    vector<int> tin(n, 0);
    //2 edge cc stuff (delete if not needed)
    int num_2_edge_ccs = 0;
    vector<bool> is_bridge(m, false);
    vector<int> two_edge_ccid(n), node_stack;
    //bcc stuff (delete if not needed)
    int num_bccs = 0;
    vector<bool> is_cut(n, false);
    vector<int> bcc_id(m), edge_stack;
    auto dfs = [&](auto self, int v, int p_id) -> int {
        int low = tin[v] = timer++, deg = 0;
        node_stack.push_back(v);
        for (auto [to, e_id] : adj[v]) {
            if (e_id == p_id) continue;
            if (!tin[to]) {
                edge_stack.push_back(e_id);
                int low_ch = self(self, to, e_id);
                if (low_ch >= tin[v]) {
                    is_cut[v] = true;
                    while (true) {
                        int edge = edge_stack.back();
                        edge_stack.pop_back();
                        bcc_id[edge] = num_bccs;
                        if (edge == e_id) break;
                    }
                    num_bccs++;
                }
                low = min(low, low_ch);
                deg++;
            } else if (tin[to] < tin[v]) {
                edge_stack.push_back(e_id);
                low = min(low, tin[to]);
            }
        }
        if (p_id == -1) is_cut[v] = (deg > 1);
        if (tin[v] == low) {
            if (p_id != -1) is_bridge[p_id] = true;
            while (true) {
                int node = node_stack.back();
                node_stack.pop_back();
                two_edge_ccid[node] = num_2_edge_ccs;
                if (node == v) break;
            }
```

```
            num_2_edge_ccs++;
        }
        return low;
    };
    for (int i = 0; i < n; i++)
        if (!tin[i])
            dfs(dfs, i, -1);
    return {num_2_edge_ccs, is_bridge, two_edge_ccid, num_bccs, is_cut, bcc_id};
}
```

Listing 6: Block Vertex Tree

```
//cat block_vertex_tree.h | ./hash.sh
//a28ab2
#pragma once
#include "bridges_and_cuts.h"
//library checker tests: https://judge.yosupo.jp/problem/biconnected_components
//(asserts checking correctness of commented-example-usage-loops)
//returns adjacency list of block vertex tree
//usage:
//  info cc = bridge_and_cut(adj, m);
//  vector<vector<int>> bvt = block_vertex_tree(adj, cc);
//to loop over each *unique* bcc containing a node v:
//  for(int bccid : bvt[v]) {
//      bccid -= n;
//      ...
//  }
//to loop over each *unique* node inside a bcc:
//  for(int v : bvt[bccid + n]) {
//      ...
//  }
vector<vector<int>> block_vertex_tree(const vector<vector<pair<int, int>>>& adj, const
    ↪ info& cc) {
    int n = adj.size();
    vector<vector<int>> tree(n + cc.num_bccs);
    vector<int> cnt(cc.num_bccs, 0);
    for (int v = 0; v < n; v++) {
        for (auto [_, e_id] : adj[v]) {
            int bccid = cc.bcc_id[e_id];
            if (cnt[bccid]++ == 0) {
                tree[v].push_back(bccid + n);// add edge between original node, and bcc
                    ↪ node
                tree[bccid + n].push_back(v);
            }
        }
        for (auto [_, e_id] : adj[v])
            cnt[cc.bcc_id[e_id]]--;
    }
    return tree;
}
```

Listing 7: Bridge Tree

```
//cat bridge_tree.h | ./hash.sh
//85f56b
#pragma once
#include "bridges_and_cuts.h"
//library checker tests: https://judge.yosupo.jp/problem/two_edge_connected_components
//never adds multiple edges as bridges_and_cuts.h correctly marks them as non-bridges
//usage:
//  info cc = bridge_and_cut(adj, m);
//  vector<vector<int>> bt = bridge_tree(adj, cc);
vector<vector<int>> bridge_tree(const vector<vector<pair<int, int>>>& adj, const info&
    ↪ cc) {
    vector<vector<int>> tree(cc.num_2_edge_ccs);
    for (int i = 0; i < (int)adj.size(); i++)
        for (auto [to, e_id] : adj[i])
            if (cc.is_bridge[e_id])
                tree[cc.two_edge_ccid[i]].push_back(cc.two_edge_ccid[to]);
    return tree;
}
```

Listing 8: Centroid

```
//cat centroid.h | ./hash.sh
//4ba5e4
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/frequency_table_of_tree_distance
//with asserts checking depth of tree <= log2(n)
//returns array ‘par‘ where ‘par[i]‘ = parent of node ‘i‘ in centroid tree
//‘par[root]‘ is -1
//0-based nodes
//O(n log n)
//example usage:
//  vector<int> parent = get_centroid_tree(adj);
//  vector<vector<int>> childs(n);
//  int root;
//  for (int i = 0; i < n; i++) {
//      if (parent[i] == -1)
//          root = i;
//      else
//          childs[parent[i]].push_back(i);
//  }
vector<int> get_centroid_tree(const vector<vector<int>>& adj/*unrooted tree*/) {
    int n = adj.size();
    vector<int> sizes(n);
    vector<bool> vis(n, false);
    auto dfs_sz = [&](auto self, int node, int par) -> void {
        sizes[node] = 1;
        for (int to : adj[node]) {
            if (to != par && !vis[to]) {
                self(self, to, node);
                sizes[node] += sizes[to];
            }
        }
    };
    auto find_centroid = [&](int node) -> int {
        dfs_sz(dfs_sz, node, node);
        int size_cap = sizes[node] / 2, par = -1;
        while (true) {
            bool found = false;
            for (int to : adj[node]) {
                if (to != par && !vis[to] && sizes[to] > size_cap) {
                    found = true;
                    par = node;
                    node = to;
                    break;
                }
            }
```

```
            if (!found) return node;
        }
    };
    vector<int> parent(n);
    auto dfs = [&](auto self, int node, int par) -> void {
        node = find_centroid(node);
        parent[node] = par;
        vis[node] = true;
        for (int to : adj[node]) {
            if (!vis[to])
                self(self, to, node);
        }
    };
    dfs(dfs, 0, -1);
    return parent;
}
```

Listing 9: Dijkstra

```
//cat dijkstra.h | ./hash.sh
//6b6195
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/shortest_path
//returns array `len` where `len[i]` = shortest path from node v to node i
//For example len[v] will always = 0
const long long inf = 1e18;
vector<long long> dijkstra(const vector<vector<pair<int, long long>>>& adj /*directed or
    ↪ undirected, weighted graph*/, int v) {
    vector<long long> len(adj.size(), inf);
    len[v] = 0;
    set<pair<long long/*weight*/, int/*node*/>> q;
    q.insert({0LL, v});
    while (!q.empty()) {
        auto it = q.begin();
        int node = it->second;
        q.erase(it);
        for (auto [to, weight] : adj[node])
            if (len[to] > weight + len[node]) {
                q.erase({len[to], to});
                len[to] = weight + len[node];
                q.insert({len[to], to});
            }
    }
    return len;
}
```

Listing 10: Floyd Warshall

```
//cat floyd_warshall.h | ./hash.sh
//84799a
#pragma once
//status: not tested
//**for directed graphs only** if you initialize len[i][i] to infinity, then
//afterward floyds, len[i][i] = length of shortest cycle including node `i`
//
//another trick: change `len` to 2d array of *bools* where len[i][j] = true if
//there exists an edge from i -> j in initial graph. Also do:
//`len[i][j] = len[i][j] | (len[i][k] & len[k][j])`
//Then after floyds, len[i][j] = true iff there's exists some path from node
//`i` to node `j`
//
//Changing the order of for-loops to i-j-k (instead of the current k-i-j)
//results in min-plus matrix multiplication. If adjacency matrix is `mat`, then
//after computing mat^k (with binary exponentiation), mat[i][j] = min length path
//from i to j with at most k edges.
for (int k = 0; k < n; k++)
    for (int i = 0; i < n; i++)
        for (int j = 0; j < n; j++)
            len[i][j] = min(len[i][j], len[i][k] + len[k][j]);
```

Listing 11: HLD

```
//cat hld.h | ./hash.sh
//103dab
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/lca,
    ↪ https://judge.yosupo.jp/problem/vertex_add_path_sum,
    ↪ https://judge.yosupo.jp/problem/vertex_add_subtree_sum
//source: https://codeforces.com/blog/entry/53170
//assumes a single tree, 1-based nodes is possible by passing in `root` in range [1, n]
//mnemonic: Heavy Light Decomposition
//NOLINTNEXTLINE(readability-identifier-naming)
struct HLD {
    int n;
    vector<int> sub_sz, par, time_in, next;
    HLD(vector<vector<int>>& adj /*single unrooted tree*/, int root) :
        n(adj.size()), sub_sz(n, 1), par(n, root), time_in(n), next(n, root) {
        dfs1(root, adj);
        int timer = 0;
        dfs2(root, adj, timer);
    }
    void dfs1(int node, vector<vector<int>>& adj) {
        for (int& to : adj[node]) {
            if (to == par[node]) continue;
            par[to] = node;
            dfs1(to, adj);
            sub_sz[node] += sub_sz[to];
            if (sub_sz[to] > sub_sz[adj[node][0]] || adj[node][0] == par[node])
                swap(to, adj[node][0]);
        }
    }
    void dfs2(int node, const vector<vector<int>>& adj, int& timer) {
        time_in[node] = timer++;
        for (int to : adj[node]) {
            if (to == par[node]) continue;
            next[to] = (timer == time_in[node] + 1 ? next[node] : to);
            dfs2(to, adj, timer);
        }
    }
    // Returns intervals (of time_in's) corresponding to the path between u and v, not
        ↪ necessarily in order
    // This can answer queries for "is some node `x` on some path" by checking if the
        ↪ time_in[x] is in any of these intervals
    vector<pair<int, int>> path(int u, int v) const {
        vector<pair<int, int>> res;
        for (;; v = par[next[v]]) {
            if (time_in[v] < time_in[u]) swap(u, v);
            if (time_in[next[v]] <= time_in[u]) {
                res.emplace_back(time_in[u], time_in[v]);
```

```
                return res;
            }
            res.emplace_back(time_in[next[v]], time_in[v]);
        }
    }
    // Returns interval (of time_in's) corresponding to the subtree of node i
    // This can answer queries for "is some node `x` in some other node's subtree" by
        ↪ checking if time_in[x] is in this interval
    pair<int, int> subtree(int i) const {
        return {time_in[i], time_in[i] + sub_sz[i] - 1};
    }
    // Returns lca of nodes u and v
    int lca(int u, int v) const {
        for (;; v = par[next[v]]) {
            if (time_in[v] < time_in[u]) swap(u, v);
            if (time_in[next[v]] <= time_in[u]) return u;
        }
    }
};
```

Listing 12: Hopcroft Karp

```
//cat hopcroft_karp.h | ./hash.sh
//8b3f52
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/bipartitematching
//with asserts checking correctness of min vertex cover
//source:
    ↪ https://github.com/foreverbell/acm-icpc-cheat-sheet/blob/master/src/graph-algorithm/hopcroft-karp.cpp
//Worst case O(E*sqrt(V)) but faster in practice
struct match {
    //# of edges in matching (which = size of min vertex cover by öKnig's theorem)
    int size_of_matching;
    //an arbitrary max matching is found. For this matching:
    //if l_to_r[node_left] == -1:
    //  node_left is not in matching
    //else:
    //  the edge `node_left` <=> l_to_r[node_left] is in the matching
    //
    //similarly for r_to_l with edge r_to_l[node_right] <=> node_right in matching if
        ↪ r_to_l[node_right] != -1
    //matchings stored in l_to_r and r_to_l are the same matching
    //provides way to check if any node is in matching
    vector<int> l_to_r, r_to_l;
    //an arbitrary min vertex cover is found. For this mvc: mvc_l[node_left] is true iff
        ↪ node_left is in the min vertex cover (same for mvc_r)
    //if mvc_l[node_left] is false, then node_left is in the corresponding maximal
        ↪ independent set
    vector<bool> mvc_l, mvc_r;
};
//Think of the bipartite graph as having a left side (with size lsz) and a right side
    ↪ (with size rsz).
//Nodes on left side are indexed 0,1,...,lsz-1
//Nodes on right side are indexed 0,1,...,rsz-1
//
//`adj` is like a directed adjacency list containing edges from left side -> right side:
//To initialize `adj`: For every edge node_left <=> node_right, do:
    ↪ adj[node_left].push_back(node_right)
match hopcroft_karp(const vector<vector<int>>& adj/*bipartite graph*/, int rsz/*number
    ↪ of nodes on right side*/) {
    int size_of_matching = 0, lsz = adj.size();
    vector<int> l_to_r(lsz, -1), r_to_l(rsz, -1);
    while (true) {
        queue<int> q;
        vector<int> level(lsz, -1);
        for (int i = 0; i < lsz; i++) {
            if (l_to_r[i] == -1) level[i] = 0, q.push(i);
        }
        bool found = false;
        vector<bool> mvc_l(lsz, true), mvc_r(rsz, false);
        while (!q.empty()) {
            int u = q.front();
            q.pop();
            mvc_l[u] = false;
            for (int x : adj[u]) {
                mvc_r[x] = true;
                int v = r_to_l[x];
                if (v == -1) found = true;
                else if (level[v] < 0) {
                    level[v] = level[u] + 1;
                    q.push(v);
                }
            }
        }
        if (!found) return {size_of_matching, l_to_r, r_to_l, mvc_l, mvc_r};
        auto dfs = [&](auto self, int u) -> bool {
            for (int x : adj[u]) {
                int v = r_to_l[x];
                if (v == -1 || (level[u] + 1 == level[v] && self(self, v))) {
                    l_to_r[u] = x;
                    r_to_l[x] = u;
                    return true;
                }
            }
            level[u] = 1e9; //acts as visited array
            return false;
        };
        for (int i = 0; i < lsz; i++)
            size_of_matching += (l_to_r[i] == -1 && dfs(dfs, i));
    }
}
```

Listing 13: LCA

```
//cat lca.h | ./hash.sh
//90ab04
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/lca
//https://codeforces.com/blog/entry/74847
//assumes a single tree, 1-based nodes is possible by passing in `root` in range [1, n]
//mnemonic: Least/Lowest Common Ancestor
//NOLINTNEXTLINE(readability-identifier-naming)
struct LCA {
    int n;
    vector<int> jmp, jmp_edges, par, depth;
    vector<long long> dist;
    LCA(const vector<vector<pair<int, long long>>>& adj, int root) :
        n(adj.size()), jmp(n, root), jmp_edges(n, 1), par(n, root), depth(n, 0), dist(n,
            ↪ 0LL) {
        dfs(root, adj);
```

```
    }
    void dfs(int node, const vector<vector<pair<int, long long>>>& adj) {
        for (auto [ch, w] : adj[node]) {
            if (ch == par[node]) continue;
            par[ch] = node;
            depth[ch] = 1 + depth[node];
            dist[ch] = w + dist[node];
            if (depth[node] > 0 && jmp_edges[node] == jmp_edges[jmp[node]])
                jmp[ch] = jmp[jmp[node]], jmp_edges[ch] = 2 * jmp_edges[node] + 1;
            else
                jmp[ch] = node;
            dfs(ch, adj);
        }
    }
    //traverse up k edges in O(log(k)). So with k=1 this returns `node`'s parent
    int kth_par(int node, int k) const {
        k = min(k, depth[node]);
        while (k > 0) {
            if (jmp_edges[node] <= k) {
                k -= jmp_edges[node];
                node = jmp[node];
            } else {
                k--;
                node = par[node];
            }
        }
        return node;
    }
    int get_lca(int x, int y) const {
        if (depth[x] < depth[y]) swap(x, y);
        x = kth_par(x, depth[x] - depth[y]);
        while (x != y) {
            if (jmp[x] != jmp[y])
                x = jmp[x], y = jmp[y];
            else
                x = par[x], y = par[y];
        }
        return x;
    }
    int dist_edges(int x, int y) const {
        return depth[x] + depth[y] - 2 * depth[get_lca(x, y)];
    }
    long long dist_weight(int x, int y) const {
        return dist[x] + dist[y] - 2 * dist[get_lca(x, y)];
    }
};
```

Listing 14: SCC

```
//cat scc.h | ./hash.sh
//8fa337
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/scc
//source:
    ↪ https://github.com/kth-competitive-programming/kactl/blob/main/content/graph/SCC.h
//mnemonic: Strongly Connected Component
struct scc_info {
    int num_sccs;
    //scc's are labeled 0,1,...,`num_sccs-1`
    //scc_id[i] is the id of the scc containing node `i`
    //for each edge i -> j: scc_id[i] >= scc_id[j] (topo order of scc's)
    vector<int> scc_id;
};
//NOLINTNEXTLINE(readability-identifier-naming)
scc_info SCC(const vector<vector<int>>& adj /*directed, unweighted graph*/) {
    int n = adj.size(), timer = 1, num_sccs = 0;
    vector<int> tin(n, 0), scc_id(n, -1), node_stack;
    auto dfs = [&](auto self, int v) -> int {
        int low = tin[v] = timer++;
        node_stack.push_back(v);
        for (int to : adj[v]) {
            if (scc_id[to] < 0)
                low = min(low, tin[to] ? tin[to] : self(self, to));
        }
        if (tin[v] == low) {
            while (true) {
                int node = node_stack.back();
                node_stack.pop_back();
                scc_id[node] = num_sccs;
                if (node == v) break;
            }
            num_sccs++;
        }
        return low;
    };
    for (int i = 0; i < n; i++) {
        if (!tin[i])
            dfs(dfs, i);
    }
    return {num_sccs, scc_id};
}
```

Listing 15: **RANGE DATA STRUCTURES**

Listing 16: Segment Tree

```
//cat seg_tree.h | ./hash.sh
//7adf63
#pragma once
//stress tests: tests/stress_tests/range_data_structures/seg_tree.cpp
const long long inf = 1e18;
struct seg_tree {
    using dt /*data type*/ = array<long long, 3>; //sum, max, min
    struct node {
        dt val;
        long long lazy;
        int l, r;
        int len() const {
            return r - l + 1;
        }
        //returns 1 + (# of nodes in left child's subtree)
        //https://cp-algorithms.com/data_structures/segment_tree.html#memory-efficient-imple
        int rch() const { //right child
            return (r - l + 2) & ~1;
        }
    };
    vector<node> tree;
    //RTE's when `arr` is empty
```

```
    seg_tree(const vector<long long>& arr) : tree(2 * (int)arr.size() - 1) {
        int timer = 0;
        build(arr, timer, 0, (int)arr.size() - 1);
    }
    dt build(const vector<long long>& arr, int& timer, int tl, int tr) {
        node& curr = tree[timer++];
        curr.lazy = 0, curr.l = tl, curr.r = tr;
        if (tl == tr) {
            curr.val = {arr[tl], arr[tl], arr[tl]};
        } else {
            int tm = tl + (tr - tl) / 2;
            dt l = build(arr, timer, tl, tm);
            dt r = build(arr, timer, tm + 1, tr);
            curr.val = pull(l, r);
        }
        return curr.val;
    }
    //what happens when `add` is applied to every index in range [tree[v].l, tree[v].r]?
    void apply(int v, long long add) {
        tree[v].val[0] += tree[v].len() * add;
        tree[v].val[1] += add;
        tree[v].val[2] += add;
        if (tree[v].len() > 1) {
            tree[v + 1].lazy += add;
            tree[v + tree[v].rch()].lazy += add;
        }
    }
    void push(int v) {
        if (tree[v].lazy) {
            apply(v, tree[v].lazy);
            tree[v].lazy = 0;
        }
    }
    static dt pull(const dt& l, const dt& r) {
        return {
            l[0] + r[0],
            max(l[1], r[1]),
            min(l[2], r[2])
        };
    }
    //update range [l,r] with `add`
    void update(int l, int r, long long add) {
        update(0, l, r, add);
    }
    void update(int v, int l, int r, long long add) {
        push(v);
        if (tree[v].r < l || r < tree[v].l)
            return;
        if (l <= tree[v].l && tree[v].r <= r)
            return apply(v, add);
        update(v + 1, l, r, add);
        update(v + tree[v].rch(), l, r, add);
        tree[v].val = pull(tree[v + 1].val, tree[v + tree[v].rch()].val);
    }
    //query range [l,r]
    dt query(int l, int r) {
        return query(0, l, r);
    }
    dt query(int v, int l, int r) {
        if (tree[v].r < l || r < tree[v].l)
            return {0, -inf, inf};
        push(v);
        if (l <= tree[v].l && tree[v].r <= r)
            return tree[v].val;
        return pull(query(v + 1, l, r),
                    query(v + tree[v].rch(), l, r));
    }
};
```

Listing 17: BIT

```
//cat bit.h | ./hash.sh
//516197
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/point_add_range_sum,
    ↪ https://judge.yosupo.jp/problem/vertex_add_path_sum,
    ↪ https://judge.yosupo.jp/problem/vertex_add_subtree_sum,
    ↪ https://judge.yosupo.jp/problem/predecessor_problem
//mnemonic: Binary Indexed Tree
//NOLINTNEXTLINE(readability-identifier-naming)
template<class T> struct BIT {
    vector<T> bit;
    BIT(int n) : bit(n, 0) {}
    BIT(const vector<T>& a) : bit(a.size()) {
        if (a.empty()) return;
        bit[0] = a[0];
        for (int i = 1; i < (int)a.size(); i++)
            bit[i] = bit[i - 1] + a[i];
        for (int i = (int)a.size() - 1; i > 0; i--) {
            int lower_i = (i & (i + 1)) - 1;
            if (lower_i >= 0)
                bit[i] -= bit[lower_i];
        }
    }
    void update(int idx, const T& d) {
        for (; idx < (int)bit.size(); idx = idx | (idx + 1))
            bit[idx] += d;
    }
    T sum(int r) const {
        T ret = 0;
        for (; r >= 0; r = (r & (r + 1)) - 1)
            ret += bit[r];
        return ret;
    }
    T sum(int l, int r) const {
        return sum(r) - sum(l - 1);
    }
    //Returns min pos such that sum of [0, pos] >= sum
    //Returns bit.size() if no sum is >= sum, or -1 if empty sum is.
    //Doesn't work with negatives (since it's greedy), counterexample: array: {1, -1},
        ↪ sum: 1, this returns 2, but should return 0
    int lower_bound(T sum) const {
        if (sum <= 0) return -1;
        int pos = 0;
        for (int pw = 1 << (31 - __builtin_clz(bit.size() | 1)); pw; pw >>= 1) {
            if (pos + pw <= (int)bit.size() && bit[pos + pw - 1] < sum)
                pos += pw, sum -= bit[pos - 1];
        }
        return pos;
    }
};
```

Listing 18: RMQ

```
//cat rmq.h | ./hash.sh
//43c762
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/staticrmq,
    ↪ https://judge.yosupo.jp/problem/zalgorithm,
    ↪ https://judge.yosupo.jp/problem/enumerate_palindromes,
    ↪ https://judge.yosupo.jp/problem/cartesian_tree
//usage:
//  vector<long long> arr;
//  ...
//  RMQ<long long> st(arr, [&](auto x, auto y) { return min(x,y); });
//
//to also get index of min element, do:
//  RMQ<pair<T, int>> st(arr, [&](auto x, auto y) { return min(x,y); });
//and initialize arr[i].second = i (0<=i<n)
//If there are multiple indexes of min element, it'll return the smallest
//(left-most) one
//mnemonic: Range Min/Max Query
//NOLINTNEXTLINE(readability-identifier-naming)
template <class T> struct RMQ {
    vector<vector<T>> dp;
    function<T(const T&, const T&)> func;
    RMQ(const vector<T>& arr, const function<T(const T&, const T&)>& a_func) : dp(1,
        ↪ arr), func(a_func) {
        for (int pw = 1, k = 1, n = arr.size(); 2 * pw <= n; pw *= 2, k++) {
            dp.emplace_back(n - 2 * pw + 1);
            for (int j = 0; j < n - 2 * pw + 1; j++)
                dp[k][j] = func(dp[k - 1][j], dp[k - 1][j + pw]);
        }
    }
    //inclusive range [l, r]
    T query(int l, int r) const {
        int lg = 31 - __builtin_clz(r - l + 1);
        return func(dp[lg][l], dp[lg][r - (1 << lg) + 1]);
    }
};
```

Listing 19: Implicit Lazy Segment Tree

```
//cat implicit_seg_tree.h | ./hash.sh
//ad662a
#pragma once
//stress tests: tests/stress_tests/range_data_structures/implicit_seg_tree.cpp
//see TODO for lines of code which usually need to change (not a complete list)
using dt = array<long long, 3>; //sum, max, min
const long long inf = 1e18;
const int sz = 1.5e7; //TODO
struct node {
    dt val;
    long long lazy;
    int lch, rch; // children, indexes into 'tree', -1 for null
    node() {}
    node(dt a_val) : val(a_val) {
        lazy = 0, lch = rch = -1;
    }
} tree[sz];
struct implicit_seg_tree {
    int ptr, root_l, root_r;//[root_l, root_r] defines range of root node; handles
        ↪ negatives
    //RTE's when 'arr' is empty
    implicit_seg_tree(int l, int r) : ptr(0), root_l(l), root_r(r) {
        tree[ptr++] = node({0, 0, 0}); //TODO
    }
    //what happens when 'add' is applied to every index in range [tree[v].l, tree[v].r]?
    void apply(int v, int tl, int tr, long long add) {
        tree[v].val[0] += (tr - tl + 1) * add;
        tree[v].val[1] += add;
        tree[v].val[2] += add;
        if (tl != tr) {
            tree[tree[v].lch].lazy += add;
            tree[tree[v].rch].lazy += add;
        }
    }
    void push(int v, int tl, int tr) {
        if (tl != tr && tree[v].lch == -1) {
            assert(ptr + 1 < sz);
            tree[v].lch = ptr;
            tree[ptr++] = node(dt{0, 0, 0}); //TODO
            tree[v].rch = ptr;
            tree[ptr++] = node(dt{0, 0, 0});
        }
        if (tree[v].lazy) {
            apply(v, tl, tr, tree[v].lazy);
            tree[v].lazy = 0;
        }
    }
    static dt pull(const dt& l, const dt& r) {
        return {
            l[0] + r[0],
            max(l[1], r[1]),
            min(l[2], r[2])
        };
    }
    //update range [l,r] with 'add'
    void update(int l, int r, long long add) {
        update(0, root_l, root_r, l, r, add);
    }
    void update(int v, int tl, int tr, int l, int r, long long add) {
        push(v, tl, tr);
        if (tr < l || r < tl)
            return;
        if (l <= tl && tr <= r)
            return apply(v, tl, tr, add);
        int tm = tl + (tr - tl) / 2;
        update(tree[v].lch, tl, tm, l, r, add);
        update(tree[v].rch, tm + 1, tr, l, r, add);
        tree[v].val = pull(tree[tree[v].lch].val, tree[tree[v].rch].val);
    }
    //query range [l,r]
    dt query(int l, int r) {
        return query(0, root_l, root_r, l, r);
    }
    dt query(int v, int tl, int tr, int l, int r) {
        if (tr < l || r < tl)
            return {0, -inf, inf}; //TODO
        push(v, tl, tr);
        if (l <= tl && tr <= r)
            return tree[v].val;
        int tm = tl + (tr - tl) / 2;
        return pull(query(tree[v].lch, tl, tm, l, r),
```

```
            query(tree[v].rch, tm + 1, tr, l, r));
    }
};
```

Listing 20: Range Updates, Point Queries

```
//cat fenwick_inv.h | ./hash.sh
//e1114e
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/vertex_add_subtree_sum,
    ↪ https://judge.yosupo.jp/problem/point_add_range_sum
#include "../bit.h"
template<class T> struct fenwick_inv {
    BIT<T> ft;
    fenwick_inv(int n) : ft(n) {}
    fenwick_inv(const vector<T>& arr) : ft(init(arr)) {}
    BIT<T> init(vector<T> arr/*intentional pass by value*/) const {
        for (int i = (int)arr.size() - 1; i >= 1; i--)
            arr[i] -= arr[i - 1];
        return BIT<T>(arr);
    }
    //add 'add' to inclusive range [l, r]
    void update(int l, int r, const T& add) {
        ft.update(l, add);
        if (r + 1 < (int)ft.bit.size())
            ft.update(r + 1, -add);
    }
    //get value at index 'idx'
    T query(int idx) const {
        return ft.sum(idx);
    }
};
```

Listing 21: Kth Smallest

```
//cat kth_smallest.h | ./hash.sh
//4e859c
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/range_kth_smallest
//source:
    ↪ https://cp-algorithms.com/data_structures/segment_tree.html#preserving-the-history-of-its-values-persistent-segment-tree
struct kth_smallest {
    struct node {
        int sum;
        int lch, rch;//children, indexes into 'tree'
    };
    int mn, mx;
    vector<int> roots;
    deque<node> tree;
    kth_smallest(const vector<int>& arr) : mn(INT_MAX), mx(INT_MIN), roots(arr.size() +
        ↪ 1, 0) {
        tree.push_back({0, 0, 0}); //acts as null
        for (int val : arr) mn = min(mn, val), mx = max(mx, val);
        for (int i = 0; i < (int)arr.size(); i++)
            roots[i + 1] = update(roots[i], mn, mx, arr[i]);
    }
    int update(int v, int tl, int tr, int idx) {
        if (tl == tr) {
            tree.push_back({tree[v].sum + 1, 0, 0});
            return tree.size() - 1;
        }
        int tm = tl + (tr - tl) / 2;
        int lch = tree[v].lch;
        int rch = tree[v].rch;
        if (idx <= tm)
            lch = update(lch, tl, tm, idx);
        else
            rch = update(rch, tm + 1, tr, idx);
        tree.push_back({tree[lch].sum + tree[rch].sum, lch, rch});
        return tree.size() - 1;
    }
    /* find (k+1)th smallest number among arr[l], arr[l+1], ..., arr[r]
     * k is 0-based, so query(l,r,0) returns the min
     */
    int query(int l, int r, int k) const {
        assert(0 <= k && k < r - l + 1); //note this condition implies l <= r
        assert(0 <= l && r + 1 < (int)roots.size());
        return query(roots[l], roots[r + 1], mn, mx, k);
    }
    int query(int vl, int vr, int tl, int tr, int k) const {
        if (tl == tr)
            return tl;
        int tm = tl + (tr - tl) / 2;
        int left_count = tree[tree[vr].lch].sum - tree[tree[vl].lch].sum;
        if (left_count > k) return query(tree[vl].lch, tree[vr].lch, tl, tm, k);
        return query(tree[vl].rch, tree[vr].rch, tm + 1, tr, k - left_count);
    }
};
```

Listing 22: Number Distinct Elements

```
//cat distinct_query.h | ./hash.sh
//6bdf2f
#pragma once
//stress tests: tests/stress_tests/range_data_structures/distinct_query.cpp
//source:
    ↪ https://cp-algorithms.com/data_structures/segment_tree.html#preserving-the-history-o
//works with negatives
//O(n log n) time and space
struct distinct_query {
    struct node {
        int sum;
        int lch, rch;//children, indexes into 'tree'
    };
    vector<int> roots;
    deque<node> tree;
    distinct_query(const vector<int>& arr) : roots(arr.size() + 1, 0) {
        tree.push_back({0, 0, 0}); //acts as null
        map<int, int> last_idx;
        for (int i = 0; i < (int)arr.size(); i++) {
            roots[i + 1] = update(roots[i], 0, arr.size(), last_idx[arr[i]]);
            last_idx[arr[i]] = i + 1;
        }
    }
    int update(int v, int tl, int tr, int idx) {
        if (tl == tr) {
            tree.push_back({tree[v].sum + 1, 0, 0});
            return tree.size() - 1;
        }
```

```
        int tm = (tl + tr) / 2;
        int lch = tree[v].lch;
        int rch = tree[v].rch;
        if (idx <= tm)
            lch = update(lch, tl, tm, idx);
        else
            rch = update(rch, tm + 1, tr, idx);
        tree.push_back({tree[lch].sum + tree[rch].sum, lch, rch});
        return tree.size() - 1;
    }
    //returns number of distinct elements in range [l,r]
    int query(int l, int r) const {
        return query(roots[l], roots[r + 1], 0, (int)roots.size() - 1, l + 1);
    }
    int query(int vl, int vr, int tl, int tr, int idx) const {
        if (tree[vr].sum == 0 || idx <= tl)
            return 0;
        if (tr < idx)
            return tree[vr].sum - tree[vl].sum;
        int tm = (tl + tr) / 2;
        return query(tree[vl].lch, tree[vr].lch, tl, tm, idx) +
               query(tree[vl].rch, tree[vr].rch, tm + 1, tr, idx);
    }
};
```

Listing 23: Buckets

```
//cat buckets.h | ./hash.sh
//435b76
#pragma once
//stress tests: tests/stress_tests/range_data_structures/buckets.cpp
//this code isn't the best. It's meant as a rough start for sqrt_decomposition, and to
    ↪ be modified
//doesn't handle overflow
struct buckets {
    const int bucket_size = 300;//TODO
    struct node {
        int sum_lazy = 0;
        int sum_bucket = 0;
        int l, r;//inclusive range of bucket
        int len() const {
            return r - l + 1;
        }
    };
    vector<int> values;
    vector<node> bucket;
    buckets(const vector<int>& initial) : values(initial) {
        int numbucket = ((int)values.size() + bucket_size - 1) / bucket_size;
        bucket.resize(numbucket);
        for (int i = 0; i < numbucket; i++) {
            bucket[i].sum_lazy = 0;
            bucket[i].sum_bucket = 0;
            bucket[i].l = i * bucket_size;
            bucket[i].r = min((i + 1) * bucket_size, (int)values.size()) - 1;
            for (int j = bucket[i].l; j <= bucket[i].r; j++)
                bucket[i].sum_bucket += values[j];
        }
    }
    void push(int b_idx) {
        node& b = bucket[b_idx];
        if (!b.sum_lazy) return;
        for (int i = b.l; i <= b.r; i++)
            values[i] += b.sum_lazy;
        b.sum_lazy = 0;
    }
    //update range [l,r]
    void update(int l, int r, int diff) {
        int start_bucket = l / bucket_size;
        int end_bucket = r / bucket_size;
        if (start_bucket == end_bucket) { //range contained in same bucket case
            for (int i = l; i <= r; i++) {
                values[i] += diff;
                bucket[start_bucket].sum_bucket += diff;
            }
            return;
        }
        for (int b_idx : {
                    start_bucket, end_bucket
                }) { //handle "endpoint" buckets
            node& b = bucket[b_idx];
            for (int i = max(b.l, l); i <= min(b.r, r); i++) {
                values[i] += diff;
                b.sum_bucket += diff;
            }
        }
        for (int i = start_bucket + 1; i < end_bucket; i++) { //handle all n/bucket_size
            ↪ buckets in middle
            node& b = bucket[i];
            b.sum_lazy += diff;
            b.sum_bucket += b.len() * diff;
        }
    }
    //sum of range [l,r]
    int query(int l, int r) {
        int start_bucket = l / bucket_size;
        int end_bucket = r / bucket_size;
        if (start_bucket == end_bucket) { //range contained in same bucket case
            push(start_bucket);
            int sum = 0;
            for (int i = l; i <= r; i++)
                sum += values[i];
            return sum;
        }
        int sum = 0;
        for (int b_idx : {
                    start_bucket, end_bucket
                }) { //handle "endpoint" buckets
            node& b = bucket[b_idx];
            push(b_idx);
            for (int i = max(b.l, l); i <= min(b.r, r); i++)
                sum += values[i];
        }
        for (int i = start_bucket + 1; i < end_bucket; i++) //handle all n/bucket_size
            ↪ buckets in middle
            sum += bucket[i].sum_bucket;
        return sum;
    }
};
```

Listing 24: Persistent Lazy Segment Tree

```
//cat persistent_lazy_seg_tree.h | ./hash.sh
//5f187b
#pragma once
//status: not tested
struct persistent_lazy_seg_tree {
    struct node {
        int lch, rch;//children, indexes into 'tree'
        int sum;
        bool lazy_tog;
    };
    int sz;
    deque<node> tree;
    vector<int> roots;
    //implicit
    persistent_lazy_seg_tree(int a_sz) : sz(a_sz) {
        tree.push_back({0, 0, 0, 0}); //acts as null
        roots.push_back(0);
    }
    void push(int v, int tl, int tr) {
        if (tl != tr) {
            tree.push_back(tree[tree[v].lch]);
            tree[v].lch = tree.size() - 1;
            tree.push_back(tree[tree[v].rch]);
            tree[v].rch = tree.size() - 1;
        }
        if (tree[v].lazy_tog) {
            tree[v].sum = (tr - tl + 1) - tree[v].sum;
            tree[v].lazy_tog = false;
            if (tl != tr) {
                tree[tree[v].lch].lazy_tog ^= 1;
                tree[tree[v].rch].lazy_tog ^= 1;
            }
        }
    }
    void set(int idx, int new_val) {
        tree.push_back(tree[roots.back()]);//allocate top down
        roots.push_back(tree.size() - 1);
        set(roots.back(), 0, sz - 1, idx, new_val);
    }
    void set(int v, int tl, int tr, int idx, int new_val) {
        push(v, tl, tr);
        if (tr < idx || idx < tl)
            return;
        if (idx <= tl && tr <= idx) {
            tree[v].sum = new_val;
            return;
        }
        int tm = (tl + tr) / 2;
        int lch = tree[v].lch;
        int rch = tree[v].rch;
        set(lch, tl, tm, idx, new_val);
        set(rch, tm + 1, tr, idx, new_val);
        tree[v].sum = tree[lch].sum + tree[rch].sum;
    }
    void toggle_range(int l, int r) {
        tree.push_back(tree[roots.back()]);//allocate top down
        roots.push_back(tree.size() - 1);
        toggle_range(roots.back(), 0, sz - 1, l, r);
    }
    void toggle_range(int v, int tl, int tr, int l, int r) {
        push(v, tl, tr);
        if (tr < l || r < tl)
            return;
        int lch = tree[v].lch;
        int rch = tree[v].rch;
        if (l <= tl && tr <= r) {
            tree[v].sum = (tr - tl + 1) - tree[v].sum;
            if (tl != tr) {
                tree[lch].lazy_tog ^= 1;
                tree[rch].lazy_tog ^= 1;
            }
            return;
        }
        int tm = (tl + tr) / 2;
        toggle_range(lch, tl, tm, l, r);
        toggle_range(rch, tm + 1, tr, l, r);
        tree[v].sum = tree[lch].sum + tree[rch].sum;
    }
    //let's use implementation trick described here
        ↪ https://codeforces.com/blog/entry/72626
    //so that we don't have to propagate lazy vals and thus we don't have to allocate
        ↪ new nodes
    int query(int l, int r) const {
        int version = roots.size() - 1;
        int root = roots[version];
        return query(root, 0, sz - 1, l, r, tree[root].lazy_tog);
    }
    int query(int v, int tl, int tr, int l, int r, bool tog) const {
        if (v == 0 || tr < l || r < tl)
            return 0;
        if (l <= tl && tr <= r) {
            int sum = tree[v].sum;
            if (tree[v].lazy_tog) sum = (tr - tl + 1) - sum;
            return sum;
        }
        int tm = (tl + tr) / 2;
        tog ^= tree[v].lazy_tog;
        return query(tree[v].lch, tl, tm, l, r, tog) +
               query(tree[v].rch, tm + 1, tr, l, r, tog);
    }
};
```

Listing 25: Merge Sort Tree

```
//cat merge_sort_tree.h | ./hash.sh
//b40eaf
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/static_range_frequency,
    ↪ https://judge.yosupo.jp/problem/range_kth_smallest
//For point updates: either switch to policy based BST, or use sqrt decomposition
struct merge_sort_tree {
    struct node {
        vector<int> val; //sorted list of values
        int l, r;
        //returns 1 + (# of nodes in left child's subtree)
        //https://cp-algorithms.com/data_structures/segment_tree.html#memory-efficient-imple
        int rch() const { //right child
            return (r - l + 2) & ~1;
        }
```

```
    };
    vector<node> tree;
    //RTE's when `arr` is empty
    merge_sort_tree(const vector<int>& arr) : tree(2 * (int)arr.size() - 1) {
        int timer = 0;
        build(arr, timer, 0, (int)arr.size() - 1);
    }
    void build(const vector<int>& arr, int& timer, int tl, int tr) {
        node& curr = tree[timer++];
        if (tl == tr) {
            curr.val = {arr[tl]};
        } else {
            int tm = tl + (tr - tl) / 2;
            const auto& l = tree[timer].val;
            build(arr, timer, tl, tm);
            const auto& r = tree[timer].val;
            build(arr, timer, tm + 1, tr);
            merge(l.begin(), l.end(), r.begin(), r.end(), back_inserter(curr.val));
        }
        curr.l = tl, curr.r = tr;
    }
    //How many of arr[l], arr[l+1], ..., arr[r] are < x?
    //O(log^2(n))
    int query(int l, int r, int x) const {
        return query(0, l, r, x);
    }
    int query(int v, int l, int r, int x) const {
        if (tree[v].r < l || r < tree[v].l)
            return 0;
        if (l <= tree[v].l && tree[v].r <= r) {
            const vector<int>& val = tree[v].val;
            return lower_bound(val.begin(), val.end(), x) - val.begin();
        }
        return query(v + 1, l, r, x) +
               query(v + tree[v].rch(), l, r, x);
    }
};
```

Listing 26: **STRINGS**

Listing 27: Suffix Array

```
//cat suffix_array.h | ./hash.sh
//46840a
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/suffixarray,
    ↪ https://judge.yosupo.jp/problem/zalgorithm,
    ↪ https://judge.yosupo.jp/problem/number_of_substrings,
    ↪ https://judge.yosupo.jp/problem/enumerate_palindromes
//source: https://judge.yosupo.jp/submission/37410
//O(n)
//mnemonic: Suffix Array Induced Sorting
template<class T> vector<int> sa_is(const T& s, int upper/*max element of `s`; for
    ↪ std::string, pass in 255*/) {
    int n = (int)s.size();
    if (n == 0) return {};
    if (n == 1) return {0};
    if (n == 2) {
        if (s[0] < s[1]) {
            return {0, 1};
        } else {
            return {1, 0};
        }
    }
    vector<int> sa(n);
    vector<bool> ls(n);
    for (int i = n - 2; i >= 0; i--)
        ls[i] = (s[i] == s[i + 1]) ? ls[i + 1] : (s[i] < s[i + 1]);
    vector<int> sum_l(upper + 1), sum_s(upper + 1);
    for (int i = 0; i < n; i++) {
        if (!ls[i])
            sum_s[s[i]]++;
        else
            sum_l[s[i] + 1]++;
    }
    for (int i = 0; i <= upper; i++) {
        sum_s[i] += sum_l[i];
        if (i < upper) sum_l[i + 1] += sum_s[i];
    }
    vector<int> buf(upper + 1);
    auto induce = [&](const vector<int>& lms) {
        fill(sa.begin(), sa.end(), -1);
        fill(buf.begin(), buf.end(), 0);
        copy(sum_s.begin(), sum_s.end(), buf.begin());
        for (auto d : lms) {
            if (d == n) continue;
            sa[buf[s[d]]++] = d;
        }
        copy(sum_l.begin(), sum_l.end(), buf.begin());
        sa[buf[s[n - 1]]++] = n - 1;
        for (int i = 0; i < n; i++) {
            int v = sa[i];
            if (v >= 1 && !ls[v - 1])
                sa[buf[s[v - 1]]++] = v - 1;
        }
        copy(sum_l.begin(), sum_l.end(), buf.begin());
        for (int i = n - 1; i >= 0; i--) {
            int v = sa[i];
            if (v >= 1 && ls[v - 1])
                sa[--buf[s[v - 1] + 1]] = v - 1;
        }
    };
    vector<int> lms_map(n + 1, -1);
    int m = 0;
    for (int i = 1; i < n; i++) {
        if (!ls[i - 1] && ls[i])
            lms_map[i] = m++;
    }
    vector<int> lms;
    lms.reserve(m);
    for (int i = 1; i < n; i++) {
        if (!ls[i - 1] && ls[i])
            lms.push_back(i);
    }
    induce(lms);
    if (m) {
        vector<int> sorted_lms;
        sorted_lms.reserve(m);
        for (int v : sa) {
```

```
            if (lms_map[v] != -1) sorted_lms.push_back(v);
        }
        vector<int> rec_s(m);
        int rec_upper = 0;
        rec_s[lms_map[sorted_lms[0]]] = 0;
        for (int i = 1; i < m; i++) {
            int l = sorted_lms[i - 1], r = sorted_lms[i];
            int end_l = (lms_map[l] + 1 < m) ? lms[lms_map[l] + 1] : n;
            int end_r = (lms_map[r] + 1 < m) ? lms[lms_map[r] + 1] : n;
            bool same = true;
            if (end_l - l != end_r - r)
                same = false;
            else {
                while (l < end_l) {
                    if (s[l] != s[r])
                        break;
                    l++;
                    r++;
                }
                if (l == n || s[l] != s[r]) same = false;
            }
            if (!same) rec_upper++;
            rec_s[lms_map[sorted_lms[i]]] = rec_upper;
        }
        auto rec_sa =
            sa_is(rec_s, rec_upper);
        for (int i = 0; i < m; i++)
            sorted_lms[i] = lms[rec_sa[i]];
        induce(sorted_lms);
    }
    return sa;
}
```

Listing 28: LCP

```
//cat lcp.h | ./hash.sh
//064842
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/zalgorithm,
    ↪ https://judge.yosupo.jp/problem/number_of_substrings,
    ↪ https://judge.yosupo.jp/problem/enumerate_palindromes
//source: https://judge.yosupo.jp/submission/37410
//mnemonic: Longest Common Prefix
//NOLINTNEXTLINE(readability-identifier-naming)
template<class T> vector<int> LCP(const T& s, const vector<int>& sa) {
    int n = s.size(), k = 0;
    vector<int> lcp(n, 0);
    vector<int> rank(n, 0);
    for (int i = 0; i < n; i++) rank[sa[i]] = i;
    for (int i = 0; i < n; i++, k ? k-- : 0) {
        if (rank[i] == n - 1) {
            k = 0;
            continue;
        }
        int j = sa[rank[i] + 1];
        while (i + k < n && j + k < n && s[i + k] == s[j + k]) k++;
        lcp[rank[i]] = k;
    }
    return lcp;
}
```

Listing 29: Prefix Function

```
//cat prefix_function.h | ./hash.sh
//aa0518
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/zalgorithm
//stress tests: tests/stress_tests/strings/kmp.cpp
//source: https://cp-algorithms.com/string/prefix-function.html#implementation
template <class T> vector<int> prefix_function(const T& s) {
    int n = s.size();
    vector<int> pi(n, 0);
    for (int i = 1; i < n; i++) {
        int j = pi[i - 1];
        while (j > 0 && s[i] != s[j]) j = pi[j - 1];
        pi[i] = j + (s[i] == s[j]);
    }
    return pi;
}
```

Listing 30: KMP

```
//cat kmp.h | ./hash.sh
//9d70ad
#pragma once
//stress tests: tests/stress_tests/strings/kmp.cpp
//mnemonic: Knuth Morris Pratt
#include "prefix_function.h"
//usage:
//  string needle;
//  ...
//  KMP kmp(needle);
//or
//  vector<int> needle;
//  ...
//  KMP kmp(needle);
//kmp doubling trick: to check if 2 arrays are rotationally equivalent: run kmp
//with one array as the needle and the other array doubled (excluding the first
//& last characters) as the haystack or just use kactl's min rotation code
//NOLINTNEXTLINE(readability-identifier-naming)
template <class T> struct KMP {
    KMP(const T& a_needle) : pi(prefix_function(a_needle)), needle(a_needle) {}
    // if haystack = "bananas"
    // needle = "ana"
    //
    // then we find 2 matches:
    // bananas
    // _ana___
    // ___ana_
    // 0123456 (indexes)
    // and KMP::find returns {1,3} - the indexes in haystack where
    // each match starts.
    //
    // You can also pass in false for "all" and KMP::find will only
    // return the first match: {1}. Useful for checking if there exists
    // some match:
    //
    // KMP::find(<haystack>,false).size() > 0
    vector<int> find(const T& haystack, bool all = true) const {
        vector<int> matches;
        for (int i = 0, j = 0; i < (int)haystack.size(); i++) {
            while (j > 0 && needle[j] != haystack[i]) j = pi[j - 1];
```

```
            if (needle[j] == haystack[i]) j++;
            if (j == (int)needle.size()) {
                matches.push_back(i - (int)needle.size() + 1);
                if (!all) return matches;
                j = pi[j - 1];
            }
        }
        return matches;
    }
    vector<int> pi;//prefix function
    T needle;
};
```

Listing 31: Trie

```
//cat trie.h | ./hash.sh
//6c97ea
#pragma once
//status: not tested
//source: https://cp-algorithms.com/string/aho_corasick.html#construction-of-the-trie
//intended to be a base template and to be modified
const int k = 26;//alphabet size
struct trie {
    const char min_ch = 'a';//'A' for uppercase, '0' for digits
    struct node {
        int next[k], id, p = -1;
        char ch;
        bool leaf = 0;
        node(int a_p = -1, char a_ch = '#') : p(a_p), ch(a_ch) {
            fill(next, next + k, -1);
        }
    };
    vector<node> t;
    trie() : t(1) {}
    void add_string(const string& s, int id) {
        int c = 0;
        for (char ch : s) {
            int v = ch - min_ch;
            if (t[c].next[v] == -1) {
                t[c].next[v] = t.size();
                t.emplace_back(c, ch);
            }
            c = t[c].next[v];
        }
        t[c].leaf = 1;
        t[c].id = id;
    }
    void remove_string(const string& s) {
        int c = 0;
        for (char ch : s) {
            int v = ch - min_ch;
            if (t[c].next[v] == -1)
                return;
            c = t[c].next[v];
        }
        t[c].leaf = 0;
    }
    int find_string(const string& s) const {
        int c = 0;
        for (char ch : s) {
            int v = ch - min_ch;
            if (t[c].next[v] == -1)
                return -1;
            c = t[c].next[v];
        }
        if (!t[c].leaf) return -1;
        return t[c].id;
    }
};
```

Listing 32: Binary Trie

```
//cat binary_trie.h | ./hash.sh
//874a75
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/set_xor_min
struct binary_trie {
    const int mx_bit = 62;
    struct node {
        long long val = -1;
        int sub_sz = 0;//number of inserted values in subtree
        int next[2] = {-1, -1};
    };
    vector<node> t;
    binary_trie() : t(1) {}
    //delta = 1 to insert val, -1 to remove val, 0 to get the # of val's in this data
        ↪ structure
    int update(long long val, int delta) {
        int c = 0;
        t[0].sub_sz += delta;
        for (int bit = mx_bit; bit >= 0; bit--) {
            bool v = (val >> bit) & 1;
            if (t[c].next[v] == -1) {
                t[c].next[v] = t.size();
                t.emplace_back();
            }
            c = t[c].next[v];
            t[c].sub_sz += delta;
        }
        t[c].val = val;
        return t[c].sub_sz;
    }
    int size() const {
        return t[0].sub_sz;
    }
    //returns x such that:
    //  x is in this data structure
    //  value of (x ^ val) is minimum
    long long min_xor(long long val) const {
        assert(size() > 0);
        int c = 0;
        for (int bit = mx_bit; bit >= 0; bit--) {
            bool v = (val >> bit) & 1;
            int ch = t[c].next[v];
            if (ch != -1 && t[ch].sub_sz > 0)
                c = ch;
            else
                c = t[c].next[!v];
        }
        return t[c].val;
```

```
    }
};
```

Listing 33: Longest Common Prefix Query

```
//cat lcp_queries.h | ./hash.sh
//a4013c
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/zalgorithm,
    ↪ https://judge.yosupo.jp/problem/enumerate_palindromes
#include "suffix_array.h"
#include "lcp.h"
#include "../range_data_structures/rmq.h"
//computes suffix array, lcp array, and then sparse table over lcp array
//O(n log n)
struct lcp_queries {
    lcp_queries(const string& s) : sa(sa_is(s, 255)), inv_sa(s.size()), lcp(LCP(s, sa)),
        ↪ st(lcp, [](int x, int y) {
        return min(x, y);
    }) {
        for (int i = 0; i < (int)s.size(); i++)
            inv_sa[sa[i]] = i;
    }
    //length of longest common prefix of suffixes s[idx1 ... n-1], s[idx2 ... n-1],
        ↪ 0-based indexing
    //
    //You can check if two substrings s[l1..r1], s[l2..r2] are equal in O(1) by:
    //r2-l2 == r1-l1 && longest_common_prefix(l1, l2) >= r2-l2+1
    int longest_common_prefix(int idx1, int idx2) const {
        if (idx1 == idx2) return (int)sa.size() - idx1;
        idx1 = inv_sa[idx1];
        idx2 = inv_sa[idx2];
        if (idx1 > idx2) swap(idx1, idx2);
        return st.query(idx1, idx2 - 1);
    }
    //returns true if suffix s[idx1 ... n-1] < s[idx2 ... n-1]
    //(so false if idx1 == idx2)
    bool less(int idx1, int idx2) const {
        return inv_sa[idx1] < inv_sa[idx2];
    }
    vector<int> sa, inv_sa, lcp;
    RMQ<int> st;
};
```

Listing 34: **MATH**

Listing 35: BIN EXP MOD

```
//cat exp_mod.h | ./hash.sh
//3be256
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/system_of_linear_equations,
    ↪ https://judge.yosupo.jp/problem/binomial_coefficient,
    ↪ https://judge.yosupo.jp/problem/matrix_det,
    ↪ https://judge.yosupo.jp/problem/inverse_matrix
//stress tests: tests/stress_tests/math/exp_mod.cpp
//returns (base^pw)%mod in O(log(pw)), but returns 1 for 0^0
//
//What if base doesn't fit in long long?
//Since (base^pw)%mod == ((base%mod)^pw)%mod we can calculate base under mod of `mod`
//
//What if pw doesn't fit in long long?
//case 1: mod is prime
//(base^pw)%mod == (base^(pw%(mod-1)))%mod (from Fermat's little theorem)
//so calculate pw under mod of `mod-1`
//note `mod-1` is not prime, so you need to be able to calculate `pw%(mod-1)` without
    ↪ division
//
//case 2: non-prime mod
//let t = totient(mod)
//if pw >= log2(mod) then (base^pw)%mod == (base^(t+(pw%t)))%mod (proof
    ↪ https://cp-algorithms.com/algebra/phi-function.html#generalization)
//so calculate pw under mod of `t`
//incidentally, totient(p) = p - 1 for every prime p, making this a more generalized
    ↪ version of case 1
int pow(long long base, long long pw, int mod) {
    assert(0 <= pw && 0 <= base && 1 <= mod);
    int res = 1;
    base %= mod;
    while (pw > 0) {
        if (pw & 1) res = res * base % mod;
        base = base * base % mod;
        pw >>= 1;
    }
    return res;
}
```

Listing 36: Fibonacci

```
//cat fib.h | ./hash.sh
//9ac293
#pragma once
//stress tests: tests/stress_tests/math/fib_matrix_expo.cpp
//https://codeforces.com/blog/entry/14516
//O(log(n))
unordered_map<long long, int> table;
int fib(long long n, int mod) {
    if (n < 2) return 1;
    if (table.find(n) != table.end()) return table[n];
    table[n] = (1LL * fib((n + 1) / 2, mod) * fib(n / 2, mod) + 1LL * fib((n - 1) / 2,
        ↪ mod) * fib((n - 2) / 2, mod)) % mod;
    return table[n];
}
```

Listing 37: Matrix Mult and Pow

```
//cat matrix_expo.h | ./hash.sh
//2edd34
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/matrix_product
//stress tests: tests/stress_tests/math/fib_matrix_expo.cpp
//empty matrix -> RTE
vector<vector<int>> mult(const vector<vector<int>>& a, const vector<vector<int>>& b, int
    ↪ mod) {
    assert(a[0].size() == b.size());
    int n = a.size(), m = b[0].size(), inner = b.size();
```

```
    vector<vector<int>> prod(n, vector<int>(m, 0));
    for (int i = 0; i < n; i++) {
        for (int k = 0; k < inner; k++) {
            for (int j = 0; j < m; j++)
                prod[i][j] = (prod[i][j] + 1LL * a[i][k] * b[k][j]) % mod;
        }
    }
    return prod;
}
vector<vector<int>> power(vector<vector<int>> mat/*intentional pass by value*/, long
    ↪ long pw, int mod) {
    int n = mat.size();
    vector<vector<int>> prod(n, vector<int>(n, 0));
    for (int i = 0; i < n; i++)
        prod[i][i] = 1;
    while (pw > 0) {
        if (pw % 2 == 1) prod = mult(prod, mat, mod);
        mat = mult(mat, mat, mod);
        pw /= 2;
    }
    return prod;
}
```

Listing 38: N Choose K MOD

```
//cat n_choose_k_mod.h | ./hash.sh
//1e5548
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/binomial_coefficient
//only the tests with prime mod
//for mod inverse
#include "exp_mod.h"
// usage:
//     n_choose_k nk(n, 1e9+7) to use `choose`, `inv` with inputs < n
// or:
//     n_choose_k nk(mod, mod) to use `choose_with_lucas_theorem` with arbitrarily large
    ↪ inputs
struct n_choose_k {
    n_choose_k(int n, int a_mod) : mod(a_mod), fact(n, 1), inv_fact(n, 1) {
        //this implementation doesn't work if n > mod because n! % mod = 0 when n >=
            ↪ mod. So `inv_fact` array will be all 0's
        assert(max(n, 2) <= mod);
        //assert mod is prime. mod is intended to fit inside an int so that
        //multiplications fit in a longlong before being modded down. So this
        //will take sqrt(2^31) time
        for (int i = 2; i * i <= mod; i++) assert(mod % i);
        for (int i = 2; i < n; i++)
            fact[i] = 1LL * fact[i - 1] * i % mod;
        inv_fact.back() = pow(fact.back(), mod - 2, mod);
        for (int i = n - 2; i >= 2; i--)
            inv_fact[i] = 1LL * inv_fact[i + 1] * (i + 1) % mod;
    }
    //classic n choose k
    //fails when n >= mod
    int choose(int n, int k) const {
        if (k < 0 || k > n) return 0;
        //now we know 0 <= k <= n so 0 <= n
        return 1LL * fact[n] * inv_fact[k] % mod * inv_fact[n - k] % mod;
    }
    //lucas theorem to calculate n choose k in O(log(k))
    //need to calculate all factorials in range [0,mod), so O(mod) time&space, so need
        ↪ smallish prime mod (< 1e6 maybe)
    //handles n >= mod correctly
    int choose_with_lucas_theorem(long long n, long long k) const {
        if (k < 0 || k > n) return 0;
        if (k == 0 || k == n) return 1;
        return 1LL * choose_with_lucas_theorem(n / mod, k / mod) * choose(n % mod, k %
            ↪ mod) % mod;
    }
    //returns inverse of n in O(1)
    int inv(int n) const {
        assert(1 <= n); //don't divide by 0 :)
        return 1LL * fact[n - 1] * inv_fact[n] % mod;
    }
    int mod;
    vector<int> fact, inv_fact;
};
```

Listing 39: Partitions

```
//cat partitions.h | ./hash.sh
//3356f6
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/partition_function
//https://oeis.org/A000041
//O(n sqrt n) time, but small-ish constant factor (there does exist a O(n log n)
    ↪ solution too)
vector<int> partitions(int n/*size of dp array*/, int mod) {
    vector<int> dp(n, 1);
    for (int i = 1; i < n; i++) {
        long long sum = 0;
        for (int j = 1, pent = 1, sign = 1; pent <= i; j++, pent += 3 * j - 2, sign =
            ↪ -sign) {
            if (pent + j <= i) sum += dp[i - pent - j] * sign + mod;
            sum += dp[i - pent] * sign + mod;
        }
        dp[i] = sum % mod;
    }
    return dp;
}
```

Listing 40: Derangements

```
//cat derangements.h | ./hash.sh
//c221bb
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/montmort_number_mod
//https://oeis.org/A000166
//
//for a permutation of size i:
//there are (i-1) places to move 0 to not be at index 0. Let's say we moved 0 to index j
    ↪ (j>0).
//If we move value j to index 0 (forming a cycle of length 2), then there are dp[i-2]
    ↪ derangements of the remaining i-2 elements
//else there are dp[i-1] derangements of the remaining i-1 elements (including j)
vector<int> derangements(int n/*size of dp array*/, int mod) {
    vector<int> dp(n, 0);
    dp[0] = 1;
    for (int i = 2; i < n; i++)
```

```
        dp[i] = 1LL * (i - 1) * (dp[i - 1] + dp[i - 2]) % mod;
    return dp;
}
```

Listing 41: Prime Sieve Mobius

```
//cat prime_sieve_mobius.h | ./hash.sh
//4986da
#pragma once
//stress tests: tests/stress_tests/math/prime_sieve_mobius.cpp
//mobius[i] = 0 iff there exists a prime p s.t. i%(p^2)=0
//mobius[i] = -1 iff i has an odd number of distinct prime factors
//mobius[i] = 1 iff i has an even number of distinct prime factors
const int sz = 2e6 + 10;
int mobius[sz];
void calc_mobius() {
    mobius[1] = 1;
    for (int i = 1; i < sz; i++)
        for (int j = i + i; j < sz; j += i)
            mobius[j] -= mobius[i];
}
//a_prime[val] = some random prime factor of `val`
//
//to check if `val` is prime:
//  if (a_prime[val] == val)
//
//to get all prime factors of a number `val` in O(log(val)):
//  while(val > 1) {
//      int p = a_prime[val];
//      //p is some prime factor of val
//      val /= p;
//  }
int a_prime[sz];
void calc_seive() {
    iota(a_prime, a_prime + sz, 0);
    for (int i = 2; i * i < sz; i++)
        if (a_prime[i] == i)
            for (int j = i * i; j < sz; j += i)
                a_prime[j] = i;
}
```

Listing 42: Row Reduce

```
//cat row_reduce.h | ./hash.sh
//1d7c3e
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/system_of_linear_equations,
     ↪ https://judge.yosupo.jp/problem/matrix_det,
     ↪ https://judge.yosupo.jp/problem/inverse_matrix
//for mod inverse
#include "exp_mod.h"
//First `cols` columns of mat represents a matrix to be left in reduced row echelon form
//Row operations will be performed to all later columns
//
//example usage:
//  row_reduce(mat, mat[0].size(), mod) //row reduce matrix with no extra columns
pair<int/*rank*/, int/*determinant*/> row_reduce(vector<vector<int>>& mat, int cols, int
     ↪ mod) {
    int n = mat.size(), m = mat[0].size(), rank = 0, det = 1;
    assert(cols <= m);
    for (int col = 0; col < cols && rank < n; col++) {
        //find arbitrary pivot and swap pivot to current row
        for (int i = rank; i < n; i++)
            if (mat[i][col] != 0) {
                if (rank != i) det = det == 0 ? 0 : mod - det;
                swap(mat[i], mat[rank]);
                break;
            }
        if (mat[rank][col] == 0) {
            det = 0;
            continue;
        }
        det = (1LL * det * mat[rank][col]) % mod;
        //make pivot 1 by dividing row by inverse of pivot
        int a_inv = pow(mat[rank][col], mod - 2, mod);
        for (int j = 0; j < m; j++)
            mat[rank][j] = (1LL * mat[rank][j] * a_inv) % mod;
        //zero-out all numbers above & below pivot
        for (int i = 0; i < n; i++)
            if (i != rank && mat[i][col] != 0) {
                int val = mat[i][col];
                for (int j = 0; j < m; j++) {
                    mat[i][j] -= 1LL * mat[rank][j] * val % mod;
                    if (mat[i][j] < 0) mat[i][j] += mod;
                }
            }
        rank++;
    }
    assert(rank <= min(n, cols));
    return {rank, det};
}
```

Listing 43: Solve Linear Equations MOD

```
//cat solve_linear_mod.h | ./hash.sh
//44cc6e
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/system_of_linear_equations
#include "row_reduce.h"
struct matrix_info {
    int rank, det;
    vector<int> x;
};
//Solves mat * x = b under prime mod.
//mat is a n (rows) by m (cols) matrix, b is a length n column vector, x is a length m
     ↪ vector.
//assumes n,m >= 1, else RTE
//Returns rank of mat, determinant of mat, and x (solution vector to mat * x = b).
//x is empty if no solution. If rank < m, there are multiple solutions and an arbitrary
     ↪ one is returned.
//Leaves mat in reduced row echelon form (unlike kactl) with b appended.
//O(n * m * min(n,m))
matrix_info solve_linear_mod(vector<vector<int>>& mat, const vector<int>& b, int mod) {
    assert(mat.size() == b.size());
    int n = mat.size(), m = mat[0].size();
    for (int i = 0; i < n; i++)
        mat[i].push_back(b[i]);
    auto [rank, det] = row_reduce(mat, m, mod);//row reduce not including the last column
    //check if solution exists
```

```
    for (int i = rank; i < n; i++) {
        if (mat[i].back() != 0) return {rank, det, {} }; //no solution exists
    }
    //initialize solution vector (`x`) from row-reduced matrix
    vector<int> x(m, 0);
    for (int i = 0, j = 0; i < rank; i++) {
        while (mat[i][j] == 0) j++; //find pivot column
        x[j] = mat[i].back();
    }
    return {rank, det, x};
}
```

Listing 44: Matrix Inverse

```
//cat matrix_inverse.h | ./hash.sh
//3056ad
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/inverse_matrix
#include "row_reduce.h"
//returns inverse of square matrix mat, empty if no inverse
vector<vector<int>> matrix_inverse(vector<vector<int>> mat/*intentional pass by value*/,
    ↪ int mod) {
    int n = mat.size();
    assert(n == (int)mat[0].size());
    //append identity matrix
    for (int i = 0; i < n; i++) {
        mat[i].resize(2 * n, 0);
        mat[i][i + n] = 1;
    }
    auto [rank, det] = row_reduce(mat, n, mod);//row reduce first n columns, leaving
        ↪ inverse in last n columns
    if (rank < n) return {}; //no inverse
    for (int i = 0; i < n; i++)
        mat[i].erase(mat[i].begin(), mat[i].begin() + n);
    return mat;
}
```

Listing 45: Euler's Totient Phi Function

```
//cat totient.h | ./hash.sh
//36bd41
#pragma once
//stress tests: tests/stress_tests/math/totient.cpp
//Euler's totient function counts the positive integers
//up to a given integer n that are relatively prime to n.
//
//To improve, use Pollard-rho to find prime factors
int totient(int n) {
    int res = n;
    for (int i = 2; i * i <= n; i++) {
        if (n % i == 0) {
            while (n % i == 0) n /= i;
            res -= res / i;
        }
    }
    if (n > 1) res -= res / n;
    return res;
}
```

Listing 46: MAX FLOW

Listing 47: Dinic

```
//cat dinic.h | ./hash.sh
//23e871
#pragma once
//status: not tested
struct max_flow {
    typedef long long ll;
    ll n, s, t;
    max_flow(int a_n, int a_s, int a_t) : n(a_n), s(a_s), t(a_t), d(n), ptr(n), q(n),
        ↪ g(n) {}
    void add_edge(ll a, ll b, ll cap) {
        edge_map[a * n + b] = e.size();
        edge e1 = { a, b, cap, 0 };
        edge e2 = { b, a, 0, 0 };
        g[a].push_back((ll) e.size());
        e.push_back(e1);
        g[b].push_back((ll) e.size());
        e.push_back(e2);
    }
    ll get_flow() {
        ll flow = 0;
        for (;;) {
            if (!bfs()) break;
            ptr.assign(ptr.size(), 0);
            while (ll pushed = dfs(s, inf))
                flow += pushed;
        }
        return flow;
    }
    ll get_flow_for_edge(ll a, ll b) {
        return e[edge_map[a * n + b]].flow;
    }
    const ll inf = 1e18;
    struct edge {
        ll a, b, cap, flow;
    };
    unordered_map<int, ll> edge_map;
    vector<ll> d, ptr, q;
    vector<edge> e;
    vector<vector<ll>> g;
    bool bfs() {
        ll qh = 0, qt = 0;
        q[qt++] = s;
        d.assign(d.size(), -1);
        d[s] = 0;
        while (qh < qt && d[t] == -1) {
            ll v = q[qh++];
            for (size_t i = 0; i < g[v].size(); i++) {
                ll id = g[v][i],
                   to = e[id].b;
                if (d[to] == -1 && e[id].flow < e[id].cap) {
                    q[qt++] = to;
                    d[to] = d[v] + 1;
                }
            }
        }
        return d[t] != -1;
```

```
    }
    ll dfs(ll v, ll flow) {
        if (!flow) return 0;
        if (v == t) return flow;
        for (; ptr[v] < (ll) g[v].size(); ptr[v]++) {
            ll id = g[v][ptr[v]];
            ll to = e[id].b;
            if (d[to] != d[v] + 1) continue;
            ll pushed = dfs(to, min(flow, e[id].cap - e[id].flow));
            if (pushed) {
                e[id].flow += pushed;
                e[id ^ 1].flow -= pushed;
                return pushed;
            }
        }
        return 0;
    }
};
```

Listing 48: Hungarian

```
//cat hungarian.h | ./hash.sh
//c1ba31
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/assignment
//source: https://e-maxx.ru/algo/assignment_hungary
//
//input: cost[1...n][1...m] with 1 <= n <= m
//n workers, indexed 1, 2, ..., n
//m jobs, indexed 1, 2, ..., m
//it costs `cost[i][j]` to assign worker i to job j (1<=i<=n, 1<=j<=m)
//this returns *min* total cost to assign each worker to some distinct job
//O(n^2 * m)
//
//trick 1: set `cost[i][j]` to inf to say: "worker `i` cannot be assigned job `j`"
//trick 2: `cost[i][j]` can be negative, so to instead find max total cost over all
    ↪ matchings: set all `cost[i][j]` to `-cost[i][j]`.
//Now max total cost = - hungarian(cost).min_cost
const long long inf = 1e18;
struct match {
    long long min_cost;
    vector<int> matching;//worker `i` (1<=i<=n) is assigned to job `matching[i]`
        ↪ (1<=matching[i]<=m)
};
match hungarian(const vector<vector<long long>>& cost) {
    int n = cost.size() - 1, m = cost[0].size() - 1;
    assert(n <= m);
    vector<int> p(m + 1), way(m + 1);
    vector<long long> u(n + 1), v(m + 1);
    for (int i = 1; i <= n; i++) {
        p[0] = i;
        int j0 = 0;
        vector<long long> minv(m + 1, inf);
        vector<bool> used(m + 1, false);
        do {
            used[j0] = true;
            int i0 = p[j0], j1 = 0;
            long long delta = inf;
            for (int j = 1; j <= m; j++)
                if (!used[j]) {
                    long long cur = cost[i0][j] - u[i0] - v[j];
                    if (cur < minv[j])
                        minv[j] = cur, way[j] = j0;
                    if (minv[j] < delta)
                        delta = minv[j], j1 = j;
                }
            for (int j = 0; j <= m; j++)
                if (used[j])
                    u[p[j]] += delta, v[j] -= delta;
                else
                    minv[j] -= delta;
            j0 = j1;
        } while (p[j0] != 0);
        do {
            int j1 = way[j0];
            p[j0] = p[j1];
            j0 = j1;
        } while (j0);
    }
    vector<int> ans(n + 1);
    for (int j = 1; j <= m; j++)
        ans[p[j]] = j;
    return {-v[0], ans};
}
```

Listing 49: Min Cost Max Flow

```
//cat min_cost_max_flow.h | ./hash.sh
//805596
#pragma once
//status: not tested
const long long inf = 1e18;
struct min_cost_max_flow {
    typedef long long ll;
    struct edge {
        ll a, b, cap, cost, flow;
        size_t back;
    };
    vector<edge> e;
    vector<vector<ll>> g;
    ll n, s, t;
    ll k = inf; // max amount of flow allowed
    min_cost_max_flow(int a_n, int a_s, int a_t) : n(a_n), s(a_s), t(a_t) {
        g.resize(n);
    }
    void add_edge(ll a, ll b, ll cap, ll cost) {
        edge e1 = {a, b, cap, cost, 0, g[b].size() };
        edge e2 = {b, a, 0, -cost, 0, g[a].size() };
        g[a].push_back((ll) e.size());
        e.push_back(e1);
        g[b].push_back((ll) e.size());
        e.push_back(e2);
    }
    // returns {flow, cost}
    pair<ll, ll> get_flow() {
        ll flow = 0, cost = 0;
        while (flow < k) {
            vector<ll> id(n, 0), d(n, inf), q(n), p(n);
            vector<size_t> p_edge(n);
            ll qh = 0, qt = 0;
```

```
            q[qt++] = s;
            d[s] = 0;
            while (qh != qt) {
                ll v = q[qh++];
                id[v] = 2;
                if (qh == n) qh = 0;
                for (size_t i = 0; i < g[v].size(); i++) {
                    edge& r = e[g[v][i]];
                    if (r.flow < r.cap && d[v] + r.cost < d[r.b]) {
                        d[r.b] = d[v] + r.cost;
                        if (id[r.b] == 0) {
                            q[qt++] = r.b;
                            if (qt == n) qt = 0;
                        } else if (id[r.b] == 2) {
                            if (--qh == -1) qh = n - 1;
                            q[qh] = r.b;
                        }
                        id[r.b] = 1;
                        p[r.b] = v;
                        p_edge[r.b] = i;
                    }
                }
            }
            if (d[t] == inf) break;
            ll addflow = k - flow;
            for (ll v = t; v != s; v = p[v]) {
                ll pv = p[v];
                size_t pr = p_edge[v];
                addflow = min(addflow, e[g[pv][pr]].cap - e[g[pv][pr]].flow);
            }
            for (ll v = t; v != s; v = p[v]) {
                ll pv = p[v];
                size_t pr = p_edge[v], r = e[g[pv][pr]].back;
                e[g[pv][pr]].flow += addflow;
                e[g[v][r]].flow -= addflow;
                cost += e[g[pv][pr]].cost * addflow;
            }
            flow += addflow;
        }
        return {flow, cost};
    }
};
```

Listing 50: **MISC**

Listing 51: DSU

```
//cat dsu.h | ./hash.sh
//9b3c97
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/unionfind,
    ↪ https://judge.yosupo.jp/problem/two_edge_connected_components
//stress tests: tests/stress_tests/misc/disjoint_set.cpp
//mnemonic: Disjoint Set Union
//NOLINTNEXTLINE(readability-identifier-naming)
struct DSU {
    int num_sets;
    vector<int> par;
    DSU(int n) : num_sets(n), par(n, -1) {}
    DSU(const DSU& rhs) : num_sets(rhs.num_sets), par(rhs.par) {}
    int find(int x) {
        return par[x] < 0 ? x : par[x] = find(par[x]);
    }
    int size_of_set(int x) {
        return -par[find(x)];
    }
    bool join(int x, int y) {
        if ((x = find(x)) == (y = find(y))) return false;
        if (par[y] < par[x]) swap(x, y);
        par[x] += par[y];
        par[y] = x;
        num_sets--;
        return true;
    }
};
```

Listing 52: PBDS

```
//cat policy_based_data_structures.h | ./hash.sh
//807de9
#pragma once
//status: not tested
//place these includes *before* the `#define int long long` else compile error
//not using <bits/extc++.h> as it compile errors on codeforces c++20 compiler
#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/tree_policy.hpp>
using namespace __gnu_pbds;
//BST with extra functions https://codeforces.com/blog/entry/11080
//order_of_key - # of elements *strictly* less than given element
//find_by_order - find kth largest element, k is 0 based so find_by_order(0) returns min
    ↪ element
template<class T> using indexed_set = tree<T, null_type, less<T>, rb_tree_tag,
    ↪ tree_order_statistics_node_update>;
//example initialization:
indexed_set<pair<long long, int>> is;
//hash table (apparently faster than unordered_map):
    ↪ https://codeforces.com/blog/entry/60737
//example initialization:
gp_hash_table<string, long long> ht;
```

Listing 53: Monotonic Stack

```
//cat monotonic_stack.h | ./hash.sh
//90f107
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/cartesian_tree
//stress tests: tests/stress_tests/misc/count_rectangles.cpp
//calculates array `left` with:
//for every index j with left[i] < j < i: arr[j] > arr[i]
//and
//arr[left[i]] <= arr[i] if left[i] != -1
//
//trick: pass in vector<pair<T/*value*/, int/*index*/>> with arr[i].second = i (0<=i<n)
    ↪ to simulate arr[j] >= arr[i]
//
//O(n)
template<class T> vector<int> monotonic_stack(const vector<T>& arr) {
```

```
    int n = arr.size();
    vector<int> left(n);
    for (int i = 0; i < n; i++) {
        int& j = left[i] = i - 1;
        while (j >= 0 && arr[j] > arr[i]) j = left[j];
    }
    return left;
}
```

Listing 54: Count Rectangles

```
//cat count_rectangles.h | ./hash.sh
//9873d2
#pragma once
#include "monotonic_stack.h"
//stress tests: tests/stress_tests/misc/count_rectangles.cpp
//given a 2D boolean matrix, calculate cnt[i][j]
//cnt[i][j] = the number of times an i-by-j rectangle appears in the matrix such that
    ↪ all i*j cells in the rectangle are true
//Note cnt[0][j] and cnt[i][0] will contain garbage values
//O(n*m)
vector<vector<int>> count_rectangles(const vector<vector<bool>>& grid) {
    int n = grid.size(), m = grid[0].size();
    vector<vector<int>> cnt(n + 1, vector<int>(m + 1, 0));
    vector<int> arr(m, 0);
    auto rv = [&](int j) -> int {//reverse
        return m - 1 - j;
    };
    for (int i = 0; i < n; i++) {
        vector<pair<int, int>> arr_rev(m);
        for (int j = 0; j < m; j++) {
            arr[j] = grid[i][j] * (arr[j] + 1);
            arr_rev[rv(j)] = {arr[j], j};
        }
        vector<int> left = monotonic_stack(arr);
        vector<int> right = monotonic_stack(arr_rev);
        for (int j = 0; j < m; j++) {
            int l = j - left[j] - 1, r = rv(right[rv(j)]) - j - 1;
            cnt[arr[j]][l + r + 1]++;
            cnt[arr[j]][l]--;
            cnt[arr[j]][r]--;
        }
    }
    for (int i = 1; i <= n; i++)
        for (int k = 0; k < 2; k++)
            for (int j = m; j > 1; j--)
                cnt[i][j - 1] += cnt[i][j];
    for (int j = 1; j <= m; j++)
        for (int i = n; i > 1; i--)
            cnt[i - 1][j] += cnt[i][j];
    return cnt;
}
```

Listing 55: LIS

```
//cat lis.h | ./hash.sh
//a243e1
#pragma once
//library checker tests: https://judge.yosupo.jp/problem/static_range_lis_query
//returns array of indexes representing the longest *strictly* increasing subsequence
//for non-decreasing: pass in a vector<pair<T, int>> with arr[i].second = i (0<=i<n)
//alternatively, there's this https://codeforces.com/blog/entry/13225
//mnemonic: Longest Increasing Subsequence
//NOLINTNEXTLINE(readability-identifier-naming)
template<class T> vector<int> LIS(const vector<T>& arr) {
    if (arr.empty()) return {};
    vector<int> dp{0}/*array of indexes into 'arr'*/, prev(arr.size(), -1);
    for (int i = 1; i < (int)arr.size(); i++) {
        auto it = lower_bound(dp.begin(), dp.end(), i, [&](int x, int y) -> bool {
            return arr[x] < arr[y];
        });
        if (it == dp.end()) {
            prev[i] = dp.back();
            dp.push_back(i);
        } else {
            prev[i] = it == dp.begin() ? -1 : *(it - 1);
            *it = i;
        }
        //here, dp.size() = length of LIS of prefix of arr ending at index i
    }
    vector<int> res(dp.size());
    for (int i = dp.back(), j = dp.size(); i != -1; i = prev[i])
        res[--j] = i;
    return res;
}
```

Listing 56: Safe Hash

```
//cat safe_hash.h | ./hash.sh
//e837ee
#pragma once
//status: not tested
//source: https://codeforces.com/blog/entry/62393
struct custom_hash {
    static uint64_t splitmix64(uint64_t x) {
        // http://xorshift.di.unimi.it/splitmix64.c
        x += 0x9e3779b97f4a7c15;
        x = (x ^ (x >> 30)) * 0xbf58476d1ce4e5b9;
        x = (x ^ (x >> 27)) * 0x94d049bb133111eb;
        return x ^ (x >> 31);
    }
    size_t operator()(uint64_t x) const {
        static const uint64_t fixed_random =
            ↪ chrono::steady_clock::now().time_since_epoch().count();
        return splitmix64(x + fixed_random);
    }
};
//usage:
unordered_map<long long, int, custom_hash> safe_map;
#include "policy_based_data_structures.h"
gp_hash_table<long long, int, custom_hash> safe_hash_table;
```