Contents

1 Contest

1.1 Template

template.h, 18 lines

```cpp
#include <bits/stdc++.h>
using namespace std;

#ifdef LOCAL
#include "cp/debug.h"
#else
#define debug(...)
#endif

mt19937 rng(chrono::steady_clock::now().time_since_epoch().count());

int main() {
    cin.tie(nullptr)->sync_with_stdio(false);
    // freopen("input.txt", "r", stdin);
    // freopen("output.txt", "w", stdout);

    return 0;
}
```

1.2 Debug

Description: c++17 debug template, does not support: arrays (e.g. int arr[N], vector<int> dp[N]).

debug-cpp17.h, 137 lines

```cpp
template<typename T, typename G>
ostream& operator<<(ostream &os, pair<T, G> p);

template<size_t N>
ostream& operator<<(ostream &os, bitset<N> bs);

template<typename... Ts>
ostream &operator<<(ostream &os, tuple<Ts...> tup);

template<typename T, typename = void>
struct iterable_std_DA : false_type {};

template<typename T>
struct iterable_std_DA<T, void_t<decltype(declval<T>().begin(),
    declval<T>().end())>> : true_type {};

template<typename T, typename = void>
struct non_iterable_std_DA : false_type {};

template<typename T>
struct non_iterable_std_DA<T, void_t<decltype(declval<T>().pop())>> : true_type
    {};

template<typename T, typename = void>
struct stack_like : false_type {};

template<typename T>
struct stack_like<T, void_t<decltype(declval<T>().top())>> : true_type {};

template<typename T, typename = void>
struct queue_like : false_type {};

template<typename T>
struct queue_like<T, void_t<decltype(declval<T>().front())>> : true_type {};

template<typename Container>
typename enable_if<iterable_std_DA<Container>::value && !is_same<Container,
    string>::value,ostream&>::type
operator<<(ostream &os, Container container);

template<typename Container>
typename enable_if<non_iterable_std_DA<Container>::value && !is_same<Container,
    string>::value,ostream&>::type
operator<<(ostream &os, Container container);

template<typename Container>
typename enable_if<iterable_std_DA<Container>::value && !is_same<Container,
    string>::value,ostream&>::type
operator<<(ostream &os, Container container) {
    os << "{";
    for (auto it = container.begin(); it != container.end(); ++it) {
        os << (it == container.begin() ? "" : ", ") << *it;
    }
    return os << "}";
}

template<typename Container>
typename enable_if<non_iterable_std_DA<Container>::value && !is_same<Container,
    string>::value,ostream&>::type
operator<<(ostream &os, Container container) {
    os << "{";
    if constexpr (stack_like<Container>::value) {
        bool first = true;
        while (!container.empty()) {
            if (!first) os << ", ";
            first = false;
            os << container.top(), container.pop();
        }
    }
    else if constexpr (queue_like<Container>::value) {
        bool first = true;
        while (!container.empty()) {
            if (!first) os << ", ";
            first = false;
            os << container.front(), container.pop();
        }
    }
    else {
        // maybe throw an error
    }
    return os << "}";
}

template<typename T, typename G>
ostream& operator<<(ostream &os, pair<T, G> p) {
    return os << "(" << p.first << ", " << p.second << ")";
}

template<size_t N>
ostream& operator<<(ostream &os, bitset<N> bs) {
    for (size_t i = 0; i < N; ++i) {
        os << (char) (bs[i] + '0');
    }
    return os;
}

// https://en.cppreference.com/w/cpp/utility/integer_sequence
template<typename Tup, size_t... Is>
void print_tuple_impl(ostream &os, const Tup &tup, index_sequence<Is...>) {
    ((os << (Is == 0 ? "" : ", ") << get<Is>(tup)),...);
}

template<typename... Ts>
ostream &operator<<(ostream &os, tuple<Ts...> tup) {
    os << "(";
    print_tuple_impl(os, tup, index_sequence_for<Ts...>{});
    return os << ")";
```

```cpp
}

// https://codeforces.com/blog/entry/125435
template<typename H, typename... T>
void debug(const char *names, H &&head, T &&...tail) {
    int i = 0;
    for (size_t bracket = 0; names[i] != '\0' && (names[i] != ',' || bracket != 0); i++) {
        if (names[i] == '(' || names[i] == '<' || names[i] == '{') {
            bracket++;
        }
        else if (names[i] == ')' || names[i] == '>' || names[i] == '}') {
            bracket--;
        }
    }
    cerr << "[", cerr.write(names, i) << " = " << head << "]";
    if constexpr (sizeof...(tail)) {
        while (names[i] != '\0' && names[i + 1] == ' ') ++i;
        cerr << " "; debug(names + i + 1, tail...);
    }
    else {
        cerr << '\n';
    }
}

using high_clock = chrono::high_resolution_clock;
auto start_time = high_clock::now();
int elapsed_time() {
    auto elapsed = high_clock::now() - start_time;
    start_time = high_clock::now();
    return chrono::duration_cast<chrono::milliseconds>(elapsed).count();
}

#define debug(...) { \
    cerr << __FUNCTION__ << ":" << __LINE__ << ": "; \
    debug(#__VA_ARGS__, __VA_ARGS__); \
}
```

1.3 Java

template.java, 50 lines

```java
import java.io.BufferedReader;
import java.util.StringTokenizer;
import java.io.IOException;
import java.io.InputStreamReader;
import java.io.PrintWriter;
import java.util.ArrayList;
import java.util.Arrays;
import java.util.Collections;
import java.util.Random;

public class Main {
    public static void main(String[] args) {
        FastScanner fs = new FastScanner();
        PrintWriter out = new PrintWriter(System.out);
        int n = fs.nextInt();
        out.println(n);
        out.close(); // don't forget this line.
    }
    static class FastScanner {
        BufferedReader br;
        StringTokenizer st;
        public FastScanner() {
            br = new BufferedReader(new InputStreamReader(System.in));
            st = null;
        }
        public String next() {
            while (st == null || st.hasMoreTokens() == false) {
                try {
                    st = new StringTokenizer(br.readLine());
                }
                catch (IOException e) {
                    throw new RuntimeException(e);
                }
            }
            return st.nextToken();
        }

        public int nextInt() {
            return Integer.parseInt(next());
        }

        public long nextLong() {
            return Long.parseLong(next());
        }

        public double nextDouble() {
            return Double.parseDouble(next());
        }
    }
}
```

1.4 sublime-build

c++17.sublime-build, 14 lines

```
// location: ~/.config/sublime-text/Packages/User/
// tip: sample file can be found at Tools > Developer > View Package File > 'C++ Single File.sublime-build'
{
    "shell_cmd": "g++ -std=c++17 -DLOCAL -Wall -Wextra -Wfloat-equal -Wconversion -fmax-errors=3 \"${file}\" -o \"${file_path}/${file_base_name}.out\"",
    "file_regex": "^(..[^:]*):([0-9]+):?([0-9]+)?:? (.*)$",
    "working_dir": "${file_path}",
    "selector": "source.cpp, source.c++",
    "variants": [
        {
            "name": "build and run",
            "shell_cmd": "g++ -std=c++17 -DLOCAL -Wall -Wextra -Wfloat-equal -fmax-errors=3 \"${file}\" -o \"${file_path}/a.out\"; \"${file_path}/a.out\" < input > output 2> err"
        }
    ]
}
```

1.5 vscode

tasks.json, 25 lines

```
// location: ~/.vscode or ~/.config/Code/User/
{
    "version": "2.0.0",
    "tasks": [
        {
            "type": "shell",
            "label": "c++17 build",
            "command": "g++ -std=c++17 -DLOCAL -Wall -Wextra -Wfloat-equal -Wconversion -fmax-errors=3 \"${file}\" -o \"${fileDirname}/${fileBasenameNoExtension}.out\"",
            "group": {
                "kind": "build"
                // "isDefault": true
            },
        },
```

```
        {
            "type": "shell",
            "label": "c++17 build and run",
            "dependsOn": ["c++17 build"],
            "command": "\"${fileDirname}/${fileBasenameNoExtension}.out\" <
    input > output 2> err",
            "group": {
                "kind": "build"
                // "isDefault": true
            },
        }
    ]
}
```

2 Data structures

2.1 Sparse table

sparse_table.h, 25 lines

```
int st[MAXN][K + 1];
for (int i = 0; i < N; i++) {
    st[i][0] = f(array[i]);
}
for (int j = 1; j <= K; j++) {
    for (int i = 0; i + (1 << j) <= N; i++) {
        st[i][j] = f(st[i][j - 1], st[i + (1 << (j - 1))][j - 1]);
    }
}
// Range Minimum Queries.
int lg[MAXN + 1];
lg[1] = 0;
for (int i = 2; i <= MAXN; i++) {
    lg[i] = lg[i / 2] + 1;
}
int j = lg[R - L + 1];
int minimum = min(st[L][j], st[R - (1 << j) + 1][j]);
// Range Sum Queries.
long long sum = 0;
for (int j = K; j >= 0; j--) {
    if ((1 << j) <= R - L + 1) {
        sum += st[L][j];
        L += 1 << j;
    }
}
```

2.2 Ordered set

ordered_set.h, 23 lines

```
#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/tree_policy.hpp>
using namespace __gnu_pbds;

template<typename key_type>
using set_t = tree<key_type, null_type, less<key_type>, rb_tree_tag,
    tree_order_statistics_node_update>;

const int INF = 0x3f3f3f3f;
void example() {
    vector<int> nums = {1, 2, 3, 5, 10};
    set_t<int> st(nums.begin(), nums.end());

    cout << *st.find_by_order(0) << '\n'; // 1
    assert(st.find_by_order(-INF) == st.end());
    assert(st.find_by_order(INF) == st.end());

    cout << st.order_of_key(2) << '\n'; // 1
    cout << st.order_of_key(4) << '\n'; //  3
    cout << st.order_of_key(9) << '\n'; // 4
    cout << st.order_of_key(-INF) << '\n'; // 0
    cout << st.order_of_key(INF) << '\n'; // 5
}
```

2.3 Dsu

dsu.h, 44 lines

```
struct Dsu {
    int n;
    vector<int> par, sz;
    Dsu(int _n) : n(_n) {
        sz.resize(n, 1);
        par.resize(n);
        iota(par.begin(), par.end(), 0);
    }
    int find(int v) {
        // finding leader/parrent of set that contains the element v.
        // with {path compression optimization}.
        return (v == par[v] ? v : par[v] = find(par[v]));
    }
    bool same(int u, int v) {
        return find(u) == find(v);
    }
    bool unite(int u, int v) {
        u = find(u); v = find(v);
        if (u == v) return false;
        if (sz[u] < sz[v]) swap(u, v);
        par[v] = u;
        sz[u] += sz[v];
        return true;
    }
    vector<vector<int>> groups() {
        // returns the list of the "list of the vertices in a connected
    component".
        vector<int> leader(n);
        for (int i = 0; i < n; ++i) {
            leader[i] = find(i);
        }
        vector<int> id(n, -1);
        int count = 0;
        for (int i = 0; i < n; ++i) {
            if (id[leader[i]] == -1) {
                id[leader[i]] = count++;
            }
        }
        vector<vector<int>> result(count);
        for (int i = 0; i < n; ++i) {
            result[id[leader[i]]].push_back(i);
        }
        return result;
    }
};
```

2.4 MinQueue

Description: acts like normal std::queue except it supports get minimum value in current queue.

min_queue.h, 35 lines

```
template <typename T>
struct MinQueue {
    vector<T> vals;
    int ptr = 0;
    vector<int> st;
```

```
    int ptr_idx = 0;
    void push(T val) {
        while ((int) st.size() > ptr_idx && vals[st.back()] >= val) {
            st.pop_back();
        }
        st.push_back((int) vals.size());
        vals.push_back(val);
    }
    void pop() {
        assert(ptr < (int) vals.size());
        if (ptr_idx < (int) st.size() && st[ptr_idx] == ptr) ptr_idx++;
        ptr++;
    }
    T get() {
        assert(ptr_idx < (int) st.size());
        return vals[st[ptr_idx]];
    }
    int front() {
        assert(!empty()); return vals[ptr];
    }
    int back() {
        assert(!empty()); return vals.back();
    }
    bool empty() {
        return (ptr == (int) vals.size());
    }
    int size() {
        return ((int) vals.size() - ptr);
    }
};
```

2.5 Segment tree

Description: A segment tree with range updates and sum queries that supports three types of operations:

- Increase each value in range [l, r] by x (i.e. a[i] += x).
- Set each value in range [l, r] to x (i.e. a[i] = x).
- Determine the sum of values in range [l, r].

segment_tree.h, 71 lines

```
struct SegmentTree {
    int n;
    vector<long long> tree, lazy_add, lazy_set;
    SegmentTree(int _n) : n(_n) {
        int p = 1;
        while (p < n) p *= 2;
        tree.resize(p * 2);
        lazy_add.resize(p * 2);
        lazy_set.resize(p * 2);
    }
    long long merge(const long long &left, const long long &right) {
        return left + right;
    }
    void build(int id, int l, int r, const vector<int> &arr) {
        if (l == r) {
            tree[id] += arr[l];
            return;
        }
        int mid = (l + r) >> 1;
        build(id * 2, l, mid, arr);
        build(id * 2 + 1, mid + 1, r, arr);
        tree[id] = merge(tree[id * 2], tree[id * 2 + 1]);
    }
    void push(int id, int l, int r) {
        if (lazy_set[id] == 0 && lazy_add[id] == 0) return;
        int mid = (l + r) >> 1;
        for (int child : {id * 2, id * 2 + 1}) {
            int range = (child == id * 2 ? mid - l + 1 : r - mid);
            if (lazy_set[id] != 0) {
                lazy_add[child] = 0;
                lazy_set[child] = lazy_set[id];
                tree[child] = range * lazy_set[id];
            }
            lazy_add[child] += lazy_add[id];
            tree[child] += range * lazy_add[id];
        }
        lazy_add[id] = lazy_set[id] = 0;

    }
    void update(int id, int l, int r, int u, int v, int amount, bool set_value
    = false) {
        if (r < u || l > v) return;
        if (u <= l && r <= v) {
            if (set_value) {
                tree[id] = 1LL * amount * (r - l + 1);
                lazy_set[id] = amount;
                lazy_add[id] = 0; // clear all previous updates.
            }
            else {
                tree[id] += 1LL * amount * (r - l + 1);
                lazy_add[id] += amount;
            }
            return;
        }
        push(id, l, r);
        int mid = (l + r) >> 1;
        update(id * 2, l, mid, u, v, amount, set_value);
        update(id * 2 + 1, mid + 1, r, u, v, amount, set_value);
        tree[id] = merge(tree[id * 2], tree[id * 2 + 1]);
    }
    long long get(int id, int l, int r, int u, int v) {
        if (r < u || l > v) return 0;
        if (u <= l && r <= v) {
            return tree[id];
        }
        push(id, l, r);
        int mid = (l + r) >> 1;
        long long left = get(id * 2, l, mid, u, v);
        long long right = get(id * 2 + 1, mid + 1, r, u, v);
        return merge(left, right);
    }
};
```

2.6 Efficient segment tree

efficient_segment_tree.h, 33 lines

```
template<typename T> struct SegmentTree {
    int n;
    vector<T> tree;
    SegmentTree(int _n) : n(_n), tree(2 * n) {}
    T merge(const T &left, const T &right) {
        return left + right;
    }
    template<typename G>
    void build(const vector<G> &initial) {
        assert((int) initial.size() == n);
        for (int i = 0; i < n; ++i) {
            tree[i + n] = initial[i];
        }
        for (int i = n - 1; i > 0; --i) {
            tree[i] = merge(tree[i * 2], tree[i * 2 + 1]);
        }
```

```
    }
    void modify(int i, int v) {
        tree[i += n] = v;
        for (i /= 2; i > 0; i /= 2) {
            tree[i] = merge(tree[i * 2], tree[i * 2 + 1]);
        }
    }
    T get_sum(int l, int r) {
        // sum of elements from l to r - 1.
        T ret{};
        for (l += n, r += n; l < r; l /= 2, r /= 2) {
            if (l & 1) ret = merge(ret, tree[l++]);
            if (r & 1) ret = merge(ret, tree[--r]);
        }
        return ret;
    }
};
```

2.7 Persistent lazy segment tree

persistent_lazy_segment_tree.h, 63 lines

```
struct Vertex {
    int l, r;
    long long val, lazy;
    bool has_changed = false;
    Vertex() {}
    Vertex(int _l, int _r, long long _val, int _lazy = 0) : l(_l), r(_r),
    val(_val), lazy(_lazy) {}
};
struct PerSegmentTree {
    vector<Vertex> tree;
    vector<int> root;
    int build(const vector<int> &arr, int l, int r) {
        if (l == r) {
            tree.emplace_back(-1, -1, arr[l]);
            return tree.size() - 1;
        }
        int mid = (l + r) / 2;
        int left = build(arr, l, mid);
        int right = build(arr, mid + 1, r);
        tree.emplace_back(left, right, tree[left].val + tree[right].val);
        return tree.size() - 1;
    }
    int add(int x, int l, int r, int u, int v, int amt) {
        if (l > v || r < u) return x;
        if (u <= l && r <= v) {
            tree.emplace_back(tree[x].l, tree[x].r, tree[x].val + 1LL * amt *
    (r - l + 1), tree[x].lazy + amt);
            tree.back().has_changed = true;
            return tree.size() - 1;
        }
        int mid = (l + r) >> 1;
        push(x, l, mid, r);
        int left = add(tree[x].l, l, mid, u, v, amt);
        int right = add(tree[x].r, mid + 1, r, u, v, amt);
        tree.emplace_back(left, right, tree[left].val + tree[right].val, 0);
        return tree.size() - 1;
    }
    long long get_sum(int x, int l, int r, int u, int v) {
        if (r < u || l > v) return 0;
        if (u <= l && r <= v) return tree[x].val;
        int mid = (l + r) / 2;
        push(x, l, mid, r);
        return get_sum(tree[x].l, l, mid, u, v) + get_sum(tree[x].r, mid + 1,
    r, u, v);
    }
    void push(int x, int l, int mid, int r) {
        if (!tree[x].has_changed) return;
        Vertex left = tree[tree[x].l];
        Vertex right = tree[tree[x].r];
        tree.emplace_back(left);
        tree[x].l = tree.size() - 1;
        tree.emplace_back(right);
        tree[x].r = tree.size() - 1;

        tree[tree[x].l].val += tree[x].lazy * (mid - l + 1);
        tree[tree[x].l].lazy += tree[x].lazy;

        tree[tree[x].r].val += tree[x].lazy * (r - mid);
        tree[tree[x].r].lazy += tree[x].lazy;

        tree[tree[x].l].has_changed = true;
        tree[tree[x].r].has_changed = true;
        tree[x].lazy = 0;
        tree[x].has_changed = false;
    }
};
```

2.8 Lichao tree

Description: A segment tree that allows insert a new line and query for minimum value over all lines at point x.

Usage: useful in convex hull trick.

lichao_tree.h, 37 lines

```
const long long INF_LL = (long long) 4e18;

struct Line {
    long long a, b;
    Line(long long _a = 0, long long _b = INF_LL): a(_a), b(_b) {}
    long long operator()(long long x) {
        return a * x + b;
    }
};

struct SegmentTree { // min query
    int n;
    vector<Line> tree;
    SegmentTree() {}
    SegmentTree(int _n): n(1) {
        while (n < _n) n *= 2;
        tree.resize(n * 2);
    }
    void insert(int x, int l, int r, Line line) {
        if (l == r) {
            if (line(l) < tree[x](l)) tree[x] = line;
            return;
        }
        int mid = (l + r) >> 1;
        bool b_left = line(l) < tree[x](l);
        bool b_mid = line(mid) < tree[x](mid);
        if (b_mid) swap(tree[x], line);
        if (b_left != b_mid) insert(x * 2, l, mid, line);
        else insert(x * 2 + 1, mid + 1, r, line);
    }
    long long query(int x, int l, int r, int at) {
        if (l == r) return tree[x](at);
        int mid = (l + r) >> 1;
        if (at <= mid) return min(tree[x](at), query(x * 2, l, mid, at));
        else return min(tree[x](at), query(x * 2 + 1, mid + 1, r, at));
    }
};
```

2.9 Old driver tree (Chtholly tree)

Description: An optimized brute-force approach to deal with problems that have operation of setting an interval to the same number.
Note: only works when inputs are random, otherwise it will TLE.

old_driver_tree.h, 58 lines

```
struct ODT {
    map<int, long long> tree;
    using It = map<int, long long>::iterator;

    It split(int x) {
        It it = tree.upper_bound(x);
        assert(it != tree.begin());
        --it;
        if (it->first == x) return it;
        return tree.emplace(x, it->second).first;
    }

    void add(int l, int r, int amt) {
        It it_l = split(l);
        It it_r = split(r + 1);
        while (it_l != it_r) {
            it_l->second += amt;
            ++it_l;
        }
    }

    void set(int l, int r, int v) {
        It it_l = split(l);
        It it_r = split(r + 1);
        while (it_l != it_r) {
            tree.erase(it_l++);
        }
        tree[l] = v;
    }

    long long kth_smallest(int l, int r, int k) {
        // return the k-th smallest value in range [l..r]
        vector<pair<long long, int>> values; // pair(value, count)
        It it_l = split(l);
        It it_r = split(r + 1);
        while (it_l != it_r) {
            It prev = it_l++;
            values.emplace_back(prev->second, it_l->first - prev->first);
        }
        sort(values.begin(), values.end());
        for (auto [value, cnt] : values) {
            if (k <= cnt) return value;
            k -= cnt;
        }
        return -1;
    }
    int powmod(long long a, long long n, int mod);
    int sum_of_xth_power(int l, int r, int x, int mod) {
        It it_l = split(l);
        It it_r = split(r + 1);
        int res = 0;
        while (it_l != it_r) {
            It prev = it_l++;
            res = (res + 1LL * (it_l->first - prev->first) *
 powmod(prev->second, x, mod)) % mod;
        }
        return res;
    }
};
```

2.10 Disjoint sparse table

Description: range query on a static array.
Time: $O(1)$ per query.

disjoint_sparse_table.h, 40 lines

```
const int MOD = (int) 1e9 + 7;
struct DisjointSparseTable { // product queries.
    int n, h;
    vector<vector<int>> dst;
    vector<int> lg;
    DisjointSparseTable(int _n) : n(_n) {
        h = 1; // in case n = 1: h = 0 !!.
        int p = 1;
        while (p < n) p *= 2, h++;
        lg.resize(p); lg[1] = 0;
        for (int i = 2; i < p; ++i) {
            lg[i] = 1 + lg[i / 2];
        }
        dst.resize(h, vector<int>(n));
    }
    void build(const vector<int> &A) {
        for (int lv = 0; lv < h; ++lv) {
            int len = (1 << lv);
            for (int k = 0; k < n; k += len * 2) {
                int mid = min(k + len, n);
                dst[lv][mid - 1] = A[mid - 1] % MOD;
                for (int i = mid - 2; i >= k; --i) {
                    dst[lv][i] = 1LL * A[i] * dst[lv][i + 1] % MOD;
                }
                if (mid == n) break;
                dst[lv][mid] = A[mid] % MOD;
                for (int i = mid + 1; i < min(mid + len, n); ++i) {
                    dst[lv][i] = 1LL * A[i] * dst[lv][i - 1] % MOD;
                }
            }
        }
    }
    int get(int l, int r) {
        if (l == r) {
            return dst[0][l];
        }
        int i = lg[l ^ r];
        return 1LL * dst[i][l] * dst[i][r] % MOD;
    }
};
```

2.11 Fenwick tree

Description: range update and range sum query.

fenwick_tree.h, 58 lines

```
using tree_type = long long;
struct FenwickTree {
    int n;
    vector<tree_type> fenw_coeff, fenw;
    FenwickTree() {}
    FenwickTree(int _n) : n(_n) {
        fenw_coeff.assign(n, 0); // fenwick tree with coefficient (n - i).
        fenw.assign(n, 0); // normal fenwick tree.
    }
    template<typename G>
    void build(const vector<G> &A) {
        assert((int) A.size() == n);
        vector<int> diff(n);
        diff[0] = A[0];
        for (int i = 1; i < n; ++i) {
```

```
            diff[i] = A[i] - A[i - 1];
        }
        fenw_coeff[0] = (long long) diff[0] * n;
        fenw[0] = diff[0];
        for (int i = 1; i < n; ++i) {
            fenw_coeff[i] = fenw_coeff[i - 1] + (long long) diff[i] * (n - i);
            fenw[i] = fenw[i - 1] + diff[i];
        }
        for (int i = n - 1; i >= 0; --i) {
            int j = (i & (i + 1)) - 1;
            if (j >= 0) {
                fenw_coeff[i] -= fenw_coeff[j];
                fenw[i] -= fenw[j];
            }
        }
    }
    void add(vector<tree_type> &fenw, int i, tree_type val) {
        while (i < n) {
            fenw[i] += val;
            i |= (i + 1);
        }
    }
    tree_type __prefix_sum(vector<tree_type> &fenw, int i) {
        tree_type res{};
        while (i >= 0) {
            res += fenw[i];
            i = (i & (i + 1)) - 1;
        }
        return res;
    }
    tree_type prefix_sum(int i) {
        return __prefix_sum(fenw_coeff, i) - __prefix_sum(fenw, i) * (n - i - 1);
    }
    void range_add(int l, int r, tree_type val) {
        add(fenw_coeff, l, (n - l) * val);
        add(fenw_coeff, r + 1, (n - r - 1) * (-val));
        add(fenw, l, val);
        add(fenw, r + 1, -val);
    }
    tree_type range_sum(int l, int r) {
        return prefix_sum(r) - prefix_sum(l - 1);
    }
};
```

2.12 Fenwick tree 2D

Description: range update and range sum query on a 2D array.

fenwick_tree_2d.h, 41 lines

```
using tree_type = long long;
struct FenwickTree2D {
    int n, m;
    vector<vector<tree_type> > fenw[4];
    FenwickTree2D(int _n, int _m) : n(_n), m(_m) {
        for (int i = 0; i < 4; i++) {
            fenw[i].resize(n, vector<tree_type>(m));
        }
    }
    void add(int u, int v, tree_type val) {
        for (int i = u; i < n; i |= (i + 1)) {
          for (int j = v; j < m; j |= (j + 1)) {
            fenw[0][i][j] += val;
            fenw[1][i][j] += (u + 1) * val;
            fenw[2][i][j] += (v + 1) * val;
            fenw[3][i][j] += (u + 1) * (v + 1) * val;
          }
        }
    }
    void range_add(int r, int c, int rr, int cc, tree_type val) { // [r, rr] x [c, cc].
        add(r, c, val);
        add(r, cc + 1, -val);
        add(rr + 1, c, -val);
        add(rr + 1, cc + 1, val);
    }
    tree_type prefix_sum(int u, int v) {
        tree_type res{};
        for (int i = u; i >= 0; i = (i & (i + 1)) - 1) {
          for (int j = v; j >= 0; j = (j & (j + 1)) - 1) {
            res += (u + 2) * (v + 2) * fenw[0][i][j];
            res -= (v + 2) * fenw[1][i][j];
            res -= (u + 2) * fenw[2][i][j];
            res += fenw[3][i][j];
          }
        }
        return res;
    }
    tree_type range_sum(int r, int c, int rr, int cc) { // [r, rr] x [c, cc].
        return prefix_sum(rr, cc) - prefix_sum(r - 1, cc) - prefix_sum(rr, c - 1) + prefix_sum(r - 1, c - 1);
    }
};
```

2.13 Implicit treap

implicit_treap.h, 90 lines

```
struct Node {
    int val, prior, cnt;
    bool rev;
    Node *left, *right;
    Node() {}
    Node(int _val) : val(_val), prior(rng()), cnt(1), rev(false), left(nullptr), right(nullptr) {}
};
// Binary search tree + min-heap.
struct Treap {
    Node *root;
    Treap() : root(nullptr) {}
    int get_cnt(Node *n) { return n ? n->cnt : 0; }
    void upd_cnt(Node *&n) {
        if (n) n->cnt = get_cnt(n->left) + get_cnt(n->right) + 1;
    }
    void push_rev(Node *treap) {
        if (!treap || !treap->rev) return;
        treap->rev = false;
        swap(treap->left, treap->right);
        if (treap->left) treap->left->rev ^= true;
        if (treap->right) treap->right->rev ^= true;
    }
    pair<Node*, Node*> split(Node *treap, int x, int smaller = 0) {
        if (!treap) return {};
        push_rev(treap);
        int idx = smaller + get_cnt(treap->left); // implicit val.
        if (idx <= x) {
            auto pr = split(treap->right, x, idx + 1);
            treap->right = pr.first;
            upd_cnt(treap);
            return {treap, pr.second};
        }
        else {
```

```
            auto pl = split(treap->left, x, smaller);
            treap->left = pl.second;
            upd_cnt(treap);
            return {pl.first, treap};
        }
    }
    Node* merge(Node *l, Node *r) {
        push_rev(l); push_rev(r);
        if (!l || !r) return (l ? l : r);
        if (l->prior < r->prior) {
            l->right = merge(l->right, r);
            upd_cnt(l);
            return l;
        }
        else {
            r->left = merge(l, r->left);
            upd_cnt(r);
            return r;
        }
    }
    void insert(int pos, int val) {
        if (!root) {
            root = new Node(val);
            return;
        }
        Node *l, *m, *r;
        m = new Node(val);
        tie(l, r) = split(root, pos - 1);
        root = merge(l, merge(m, r));
    }
    void erase(int pos_l, int pos_r) {
        Node *l, *m, *r;
        tie(l, r) = split(root, pos_l - 1);
        tie(m, r) = split(r, pos_r - pos_l);
        root = merge(l, r);
    }
    void reverse(int pos_l, int pos_r) {
        Node *l, *m, *r;
        tie(l, r) = split(root, pos_l - 1);
        tie(m, r) = split(r, pos_r - pos_l);
        m->rev ^= true;
        root = merge(l, merge(m, r));
    }
    int query(int pos_l, int pos_r);
         // returns answer for corresponding types of query.
    void inorder(Node *n) {
        if (!n) return;
        push_rev(n);
        inorder(n->left);
        cout << n->val << ' ';
        inorder(n->right);
    }
    void print() {
        inorder(root);
        cout << '\n';
    }
};
```

2.14 Line container

Description: container that allow you can add lines in form $ax + b$ and query maximum value at x.

line_container.h, 45 lines

```
using num_t = int;
struct Line {
    num_t a, b; // ax + b
    mutable num_t x; // x-intersect with the next line in the hull
    bool operator<(const Line &other) const {
        return a < other.a;
    }
    bool operator<(num_t other_x) const {
        return x < other_x;
    }
};

struct LineContainer : multiset<Line, less<>> { // max-query
    // for doubles, use INF = 1 / 0.0
    static const num_t INF = numeric_limits<num_t>::max();

    num_t floor_div(num_t a, num_t b) {
        return a / b - ((a ^ b) < 0 && a % b != 0);
    }
    bool isect(iterator u, iterator v) {
        if (v == end()) {
            u->x = INF;
            return false;
        }
        if (u->a == v->a) u->x = (u->b > v->b ? INF : -INF);
        else u->x = floor_div(v->b - u->b, u->a - v->a);
        return u->x >= v->x;
    }
    void add(num_t a, num_t b) {
        auto z = insert({a, b, 0}), y = z++, x = y;
        while (isect(y, z)) z = erase(z);
        if (x != begin() && isect(--x, y)) {
            y = erase(y);
            isect(x, y);
        }
        while ((y = x) != begin() && (--x)->x >= y->x) {
            isect(x, erase(y));
        }
    }
    num_t query(num_t x) {
        assert(!empty());
        auto it = *lower_bound(x);
        return it.a * x + it.b;
    }
};
```

3 Mathematics

3.1 Trigonometry

3.1.1 Sum - difference identities

$$\sin(u \pm v) = \sin(u)\cos(v) \pm \cos(u)\sin(v)$$
$$\cos(u \pm v) = \cos(u)\cos(v) \mp \sin(u)\sin(v)$$
$$\tan(u \pm v) = \frac{\tan(u) \pm \tan(v)}{1 \mp \tan(u)\tan(v)}$$

3.1.2 Sum to product identities

$$\cos(u) + \cos(v) = 2\cos(\frac{u+v}{2})\cos(\frac{u-v}{2}) \qquad \sin(u) + \sin(v) = 2\sin(\frac{u+v}{2})\cos(\frac{u-v}{2})$$
$$\cos(u) - \cos(v) = -2\sin(\frac{u+v}{2})\sin(\frac{u-v}{2}) \qquad \sin(u) - \sin(v) = 2\cos(\frac{u+v}{2})\sin(\frac{u-v}{2})$$

3.1.3 Product identities

$$\cos(u)\cos(v) = \frac{1}{2}[\cos(u+v) + \cos(u-v)]$$
$$\sin(u)\sin(v) = -\frac{1}{2}[\cos(u+v) - \cos(u-v)]$$
$$\sin(u)\cos(v) = \frac{1}{2}[\sin(u+v) + \sin(u-v)]$$

3.1.4 Double - triple angle identities

$$\sin(2u) = 2\sin(u)\cos(u) \qquad \sin(3u) = 3\sin(u) - 4\sin^3(u)$$
$$\cos(2u) = 2\cos^2(u) - 1 = 1 - 2\sin^2(u) \qquad \cos(3u) = 4\cos^3(u) - 3\cos(u)$$
$$\tan(2u) = \frac{2\tan(u)}{1-\tan^2(u)} \qquad \tan(3u) = \frac{3\tan(u) - \tan^3(u)}{1 - 3\tan^2(u)}$$

3.2 Sums

$$\sum_{i=a}^{b} c^i = \frac{c^{b+1} - c^a}{c-1},\ c \neq 1 \qquad \sum_{i=1}^{n} i^6 = \frac{n(n+1)(2n+1)(3n^4+6n^3-3n+1)}{42}$$
$$\sum_{i=0}^{n} ic^i = \frac{nc^{n+2} - (n+1)c^{n+1} + c}{(c-1)^2},\ c \neq 1 \qquad \sum_{i=1}^{n} i^7 = \frac{n^2(n+1)^2(3n^4+6n^3-n^2-4n+2)}{24}$$
$$\sum_{i=1}^{n} i = \frac{n(n+1)}{2} \qquad \sum_{i=0}^{n} \binom{n}{i} a^{n-i} b^i = (a+b)^n$$
$$\sum_{i=1}^{n} i^2 = \frac{n(n+1)(2n+1)}{6} \qquad \sum_{i=0}^{n} i\binom{n}{i} = n2^{n-1}$$
$$\sum_{i=1}^{n} i^3 = \left(\frac{n(n+1)}{2}\right)^2 \qquad \sum_{i=0}^{n} \frac{\binom{n}{i}}{i+1} = \frac{2^{n+1}-1}{n+1}$$
$$\sum_{i=1}^{n} i^4 = \frac{n(n+1)(2n+1)(3n^2+3n-1)}{30} \qquad \sum_{k=0}^{m} \binom{n+k}{n} = \binom{n+m+1}{n+1}$$
$$\sum_{i=1}^{n} i^5 = \frac{n^2(n+1)^2(2n^2+2n-1)}{12} \qquad \sum_{i=k}^{n} \binom{i}{k} = \binom{n+1}{k+1}$$

3.3 Pythagorean triple

- A Pythagorean triple is a triple of positive integers a, b, and c such that $a^2 + b^2 = c^2$.
- If (a, b, c) is a Pythagorean triple, then so is (ka, kb, kc) for any positive integer k.
- A primitive Pythagorean triple is one in which a, b, and c are coprime.
- Generating Pythagorean triple
  - Euclid's formula: with arbitrary $0 < n < m$, then:
  $$a = m^2 - n^2, \quad b = 2mn, \quad c = m^2 + n^2$$
  form a Pythagorean triple.
  - To obtain primitive Pythagorean triple, this condition must hold: m and n are coprime, m and n have opposite parity.

4 String

4.1 Prefix function

Description: the prefix function of a string s is defined as an array pi of length n, where pi[i] is the length of the longest proper prefix of the sub-string s[0..i] which is also a suffix of this sub-string.
Time: $O(|S|)$.

prefix_function.h, 15 lines

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

4.2 Z function

Description: for a given string 's', z[i] = longest common prefix of 's' and suffix starting at 'i'. z[0] is generally not well defined (this implementation below assume z[0] = 0).
Time: $O(n)$.

z_function.h, 15 lines

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

4.3 Counting occurrences of each prefix

Description: count the number of occurrences of each prefix in the given string.
Time: $O(n)$.

counting_occur_of_prefix.h, 18 lines

```
#include "prefix_function.h"
vector<int> count_occurrences(const string &s) {
    vector<int> pi = prefix_function(s);
    int n = (int) s.size();
    vector<int> ans(n + 1);
    for (int i = 0; i < n; ++i) {
        ans[pi[i]]++;
```

```
    }
    for (int i = n - 1; i > 0; --i) {
        ans[pi[i - 1]] += ans[i];
    }
    for (int i = 0; i <= n; ++i) {
        ans[i]++;
    }
    return ans;
    // Input: ABACABA
    // Output: 4 2 2 1 1 1 1
}
```

4.4 Knuth–Morris–Pratt algorithm

Description: searching for a sub-string in a string.
Time: $O(N + M)$.

KMP.h, 14 lines

```
#include "prefix_function.h"
vector<int> KMP(const string &text, const string &pattern) {
    int n = (int) text.length();
    int m = (int) pattern.length();
    string s = pattern + '$' + text;
    vector<int> pi = prefix_function(s);
    vector<int> indices;
    for (int i = 0; i < (int) s.length(); ++i) {
        if (pi[i] == m) {
            indices.push_back(i - 2 * m);
        }
    }
    return indices;
}
```

4.5 Suffix array

Description: suffix array is a sorted array of all the suffixes of a given string.
Usage:

- sa[i] = starting index of the i-th smallest suffix.
- rank[i] = rank of the suffix starting at 'i'.
- lcp[i] = longest common prefix between 'sa[i - 1]' and 'sa[i]'
- for arbitrary 'u v', let i = rank[u] - 1, j = rank[v] - 1 (assume i < j), then longest_common_prefix(u, v) = min(lcp[i + 1], lcp[i + 2], ..., lcp[j])

Time: $O(N \log N)$.

suffix_array.h, 42 lines

```
struct SuffixArray {
    string s;
    int n, lim;
    vector<int> sa, lcp, rank;
    SuffixArray(const string &_s, int _lim = 256) : s(_s), n(s.length() + 1),
        lim(_lim), sa(n), lcp(n), rank(n) {
        s += '$';
        build(); kasai();
        sa.erase(sa.begin()); lcp.erase(lcp.begin());
        rank.pop_back(); s.pop_back();
    }
    void build() {
        vector<int> nrank(n), norder(n), cnt(max(n, lim));
        for (int i = 0; i < n; ++i) {
            sa[i] = i; rank[i] = s[i];
        }
        for (int k = 0, rank_cnt = 0; rank_cnt < n - 1; k = max(1, k * 2), lim
    = rank_cnt + 1) {
            for (int i = 0; i < n; ++i) {
                norder[i] = (sa[i] - k + n) % n;
                cnt[rank[i]]++;
            }
            for (int i = 1; i < lim; ++i) cnt[i] += cnt[i - 1];
            for (int i = n - 1; i >= 0; --i) sa[--cnt[rank[norder[i]]]] =
    norder[i];
            rank[sa[0]] = rank_cnt = 0;
            for (int i = 1; i < n; ++i) {
                int u = sa[i], v = sa[i - 1];
                int nu = (u + k) % n, nv = (v + k) % n;
                if (rank[u] != rank[v] || rank[nu] != rank[nv]) ++rank_cnt;
                nrank[sa[i]] = rank_cnt;
            }
            for (int i = 0; i < rank_cnt + 1; ++i) cnt[i] = 0;
            rank.swap(nrank);
        }
    }
    void kasai() {
        for (int i = 0, k = 0; i < n - 1; ++i, k = max(0, k - 1)) {
            int j = sa[rank[i] - 1];
            while (s[i + k] == s[j + k]) k++;
            lcp[rank[i]] = k;
        }
    }
};
```

4.6 Suffix array slow

Description: an easier and shorter implementation of suffix array but run a bit slower.
Time: $O(N \log^2 N)$.

suffix_array_slow.h, 37 lines

```
struct SuffixArraySlow {
    string s;
    int n;
    vector<int> sa, lcp, rank;
    SuffixArraySlow(const string &_s): s(_s), n((int) s.size() + 1), sa(n),
    lcp(n), rank(n) {
        s += '$';
        build(); kasai();
        sa.erase(sa.begin()); lcp.erase(lcp.begin());
        rank.pop_back(); s.pop_back();
    }
    bool comp(int i, int j, int k) {
        return make_pair(rank[i], rank[(i + k) % n]) < make_pair(rank[j],
    rank[(j + k) % n]);
    }
    void build() {
        vector<int> nrank(n);
        for (int i = 0; i < n; ++i) {
            sa[i] = i; rank[i] = s[i];
        }
        for (int k = 0; k < n; k = max(1, k * 2)) {
            stable_sort(sa.begin(), sa.end(), [&](int i, int j) {
                return comp(i, j, k);
            });
            for (int i = 0, cnt = 0; i < n; ++i) {
                if (i > 0 && comp(sa[i - 1], sa[i], k)) ++cnt;
                nrank[sa[i]] = cnt;
            }
            rank.swap(nrank);
        }
    }
    void kasai() {
        for (int i = 0, k = 0; i < n - 1; ++i, k = max(0, k - 1)) {
            int j = sa[rank[i] - 1];
            while (s[i + k] == s[j + k]) ++k;
            lcp[rank[i]] = k;
        }
```

```
    }
};
```

4.7 Manacher's algorithm

Description: for each position, computes d[0][i] = half length of longest palindrome centered on i (rounded up), d[1][i] = half length of longest palindrome centered on i and i - 1.
Time: $O(N)$.

manacher.h, 20 lines

```
array<vector<int>, 2> manacher(const string &s) {
    int n = (int) s.size();
    array<vector<int>, 2> d;
    for (int z = 0; z < 2; ++z) {
        d[z].resize(n);
        int l = 0, r = 0;
        for (int i = 0; i < n; ++i) {
            int mirror = l + r - i + z;
            d[z][i] = (i > r ? 0 : min(d[z][mirror], r - i));
            int L = i - d[z][i] - z, R = i + d[z][i];
            while (L >= 0 && R < n && s[L] == s[R]) {
                d[z][i]++; L--; R++;
            }
            if (R > r) {
                l = L; r = R;
            }
        }
    }
    return d;
}
```

4.8 Trie

Description: a rooted tree in which each edge is labeled with a character.
Usage:

- Check if a string exists in the set of strings.

Time: $O(N)$ for each operation where N is the length of the string.

trie.h, 38 lines

```
struct Trie {
    const static int ALPHABET = 26;
    const static char minChar = 'a';
    struct Vertex {
        int next[ALPHABET];
        bool leaf;
        Vertex() {
            leaf = false;
            fill(next, next + ALPHABET, -1);
        }
    };
    vector<Vertex> trie;
    Trie() { trie.emplace_back(); }

    void insert(const string &s) {
        int i = 0;
        for (const char &ch : s) {
            int j = ch - minChar;
            if (trie[i].next[j] == -1) {
                trie[i].next[j] = trie.size();
                trie.emplace_back();
            }
            i = trie[i].next[j];
        }
        trie[i].leaf = true;
    }
    bool find(const string &s) {
        int i = 0;
        for (const char &ch : s) {
            int j = ch - minChar;
            if (trie[i].next[j] == -1) {
                return false;
            }
            i = trie[i].next[j];
        }
        return (trie[i].leaf ? true : false);
    }
};
```

4.9 Hashing

hash61.h, 57 lines

```
struct Hash61 {
    static const uint64_t MOD = (1LL << 61) - 1;
    static uint64_t BASE;
    static vector<uint64_t> pw;
    uint64_t addmod(uint64_t a, uint64_t b) const {
        a += b;
        if (a >= MOD) a -= MOD;
        return a;
    }
    uint64_t submod(uint64_t a, uint64_t b) const {
        a += MOD - b;
        if (a >= MOD) a -= MOD;
        return a;
    }
    uint64_t mulmod(uint64_t a, uint64_t b) const {
        uint64_t low1 = (uint32_t) a, high1 = (a >> 32);
        uint64_t low2 = (uint32_t) b, high2 = (b >> 32);

        uint64_t low = low1 * low2;
        uint64_t mid = low1 * high2 + low2 * high1;
        uint64_t high = high1 * high2;

        uint64_t ret = (low & MOD) + (low >> 61) + (high << 3) + (mid >> 29) + (mid << 35 >> 3) + 1;
        // ret %= MOD:
        ret = (ret >> 61) + (ret & MOD);
        ret = (ret >> 61) + (ret & MOD);
        return ret - 1;
    }
    void ensure_pw(int m) {
        int sz = (int) pw.size();
        if (sz >= m) return;
        pw.resize(m);
        for (int i = sz; i < m; ++i) {
            pw[i] = mulmod(pw[i - 1], BASE);
        }
    }

    vector<uint64_t> pref;
    int n;
    template<typename T> Hash61(const T &s) { // strings or arrays.
        n = (int) s.size();
        ensure_pw(n);
        pref.resize(n + 1);
        pref[0] = 0;
        for (int i = 0; i < n; ++i) {
            pref[i + 1] = addmod(mulmod(pref[i], BASE), s[i]);
        }
    }
    inline uint64_t operator()(const int from, const int to) const {
        assert(0 <= from && from <= to && to < n);
        // pref[to + 1] - pref[from] * pw[to - from + 1]
```

```
        return submod(pref[to + 1], mulmod(pref[from], pw[to - from + 1]));
    }
};
mt19937 rnd((unsigned int)
    chrono::steady_clock::now().time_since_epoch().count());
uint64_t Hash61::BASE = (MOD >> 2) + rnd() % (MOD >> 1);
vector<uint64_t> Hash61::pw = vector<uint64_t>(1, 1);
```

4.10 Minimum rotation

Description: finds the lexicographically smallest rotation of a string.
Usage: rotate(v.begin(), v.begin() + minRotation(v), v.end())
Time: $O(N)$.

min_rotation.h, 10 lines

```
#pragma once

int minRotation(string s) {
  int a = 0, N = (int) s.size(); s += s;
  rep(b, 0, N) rep(k, 0, N) {
    if (a + k == b || s[a + k] < s[b + k]) {b += max(0, k - 1); break;}
    if (s[a + k] > s[b + k]) { a = b; break; }
  }
  return a;
}
```

5 Numerical

5.1 Fast Fourier transform

Description: a fast algorithm for multiplying two polynomials.
Time: $O(N \log N)$.

fast_fourier_transform.h, 51 lines

```
const double PI = acos(-1);
using Comp = complex<double>;
int reverse_bit(int n, int lg) {
    int res = 0;
    for (int i = 0; i < lg; ++i) {
        if (n & (1 << i)) {
            res |= (1 << (lg - i - 1));
        }
    }
    return res;
}
void fft(vector<Comp> &a, bool invert = false) {
    int n = (int) a.size();
    int lg = 0;
    while (1 << (lg) < n) ++lg;
    for (int i = 0; i < n; ++i) {
        int rev_i = reverse_bit(i, lg);
        if (i < rev_i) swap(a[i], a[rev_i]);
    }
    for (int len = 2; len <= n; len *= 2) {
        double angle = 2 * PI / len * (invert ? -1 : 1);
        Comp w_base(cos(angle), sin(angle));
        for (int i = 0; i < n; i += len) {
            Comp w(1);
            for (int j = i; j < i + len / 2; ++j) {
                Comp u = a[j], v = a[j + len / 2];
                a[j] = u + w * v;
                a[j + len / 2] = u - w * v;
                w *= w_base;
            }
        }
    }
    if (invert) for (int i = 0; i < n; ++i) a[i] /= n;
}
vector<int> mult(vector<int> &a, vector<int> &b) {
    vector<Comp> A(a.begin(), a.end()), B(b.begin(), b.end());
    int n = (int) a.size(), m = (int) b.size(), p = 1;
    while (p < n + m) p *= 2;
    A.resize(p), B.resize(p);
    fft(A, false);
    fft(B, false);
    for (int i = 0; i < p; ++i) {
        A[i] *= B[i];
    }
    fft(A, true);
    vector<int> res(n + m - 1);
    for (int i = 0; i < n + m - 1; ++i) {
        res[i] = (int) round(A[i].real());
    }
    return res;
}
```

6 Number Theory

6.1 Euler's totient function

- Euler's totient function, also known as **phi-function** $\phi(n)$ counts the number of integers between 1 and n inclusive, that are **coprime to** n.
- Properties:
  - Divisor sum property: $\sum_{d|n} \phi(d) = n$.
  - $\phi(n)$ is a **prime number** when $n = 3, 4, 6$.
  - If p is a prime number, then $\phi(p) = p - 1$.
  - If p is a prime number and $k \geq 1$, then $\phi(p^k) = p^k - p^{k-1}$.
  - If a and b are **coprime**, then $\phi(ab) = \phi(a) \cdot \phi(b)$.
  - In general, for **not coprime** a and b, with $d = gcd(a, b)$ this equation holds: $\phi(ab) = \phi(a) \cdot \phi(b) \cdot \dfrac{d}{\phi(d)}$.
  - With $n = p_1^{k_1} \cdot p_2^{k_2} \cdots p_m^{k_m}$:

$$\begin{aligned}\phi(n) &= \phi(p_1^{k_1}) \cdot \phi(p_2^{k_2}) \cdots \phi(p_m^{k_m}) \\ &= n \cdot \left(1 - \frac{1}{p_1}\right) \cdot \left(1 - \frac{1}{p_2}\right) \cdots \left(1 - \frac{1}{p_m}\right)\end{aligned}$$

- Application in Euler's theorem:
  - If $\gcd(a, M) = 1$, then:

$$a^{\phi(M)} \equiv 1 \pmod M \Rightarrow a^n \equiv a^{n \bmod \phi(M)} \pmod M$$

– In general, for arbitrary a, M and $n \geq \log_2 M$:

$$a^n \equiv a^{\phi(M)+[n \bmod \phi(M)]} \pmod M$$

Time: $O(N \log N)$.

phi_euler_totient_function.h, 14 lines

```
const int MAXN = (int) 2e5;
int etf[MAXN + 1];
void sieve(int n) {
    for (int i = 0; i <= n; ++i) {
        etf[i] = i;
    }
    for (int i = 2; i <= n; ++i) {
        if (etf[i] == i) {
            for (int j = i; j <= n; j += i) {
                etf[j] -= etf[j] / i;
            }
        }
    }
}
```

6.2 Mobius function

- For a positive integer $n = p_1^{k_1} \cdot p_2^{k_2} \cdots p_m^{k_m}$:

$$\mu(n) = \begin{cases} 1, & \text{if } n = 1 \\ 0, & \text{if } \exists k_i > 1 \\ (-1)^m & \text{otherwise} \end{cases}$$

- Properties:
  – $\sum_{d|n} \mu(d) = [n = 1]$.
  – If a and b are **coprime**, then $\mu(ab) = \mu(a) \cdot \mu(b)$.
  – Mobius inversion: let f and g be arithmetic functions:

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

.

Time: $O(N \log N)$.

mobius_function.h, 10 lines

```
const int MAXN = (int) 2e5;
int mu[MAXN + 1];
void sieve(int n) {
    mu[1] = 1;
    for (int i = 1; i <= n; ++i) {
        for (int j = 2 * i; j <= n; j += i) {
            mu[j] -= mu[i];
        }
    }
}
```

6.3 Primes

Approximating the number of primes up to n:

n	$\pi(n)$	$\frac{n}{\ln n - 1}$
100 ($1e^2$)	25	28
500 ($5e^2$)	95	96
1000 ($1e^3$)	168	169
5000 ($5e^3$)	669	665
10000 ($1e^4$)	1229	1218
50000 ($5e^4$)	5133	5092
100000 ($1e^5$)	9592	9512
500000 ($5e^5$)	41538	41246
1000000 ($1e^6$)	78498	78030
5000000 ($5e^6$)	348513	346622

($\pi(n)$ = the number of primes less than or equal to n, $\frac{n}{\ln n - 1}$ is used to approximate $\pi(n)$).

6.4 Wilson's theorem

A positive integer n is a prime if and only if:

$$(n-1)! \equiv n - 1 \pmod n$$

6.5 Zeckendorf's theorem

The Zeckendorf's theorem states that every positive integer n can be represented uniquely as a sum of one or more distinct non-consecutive Fibonacci numbers. For example:

$$64 = 55 + 8 + 1$$
$$85 = 55 + 21 + 8 + 1$$

6.6 Bitwise operation

- $a + b = (a \oplus b) + 2(a \,\&\, b)$
- $a \mid b = (a \oplus b) + (a \,\&\, b)$
- $a \,\&\, (b \oplus c) = (a \,\&\, b) \oplus (a \,\&\, c)$
- $a \mid (b \,\&\, c) = (a \mid b) \,\&\, (a \mid c)$
- $a \,\&\, (b \mid c) = (a \,\&\, b) \mid (a \,\&\, c)$
- $a \mid (a \,\&\, b) = a$
- $a \,\&\, (a \mid b) = a$
- $n = 2^k \Leftrightarrow !(n \,\&\, (n-1)) = 1$
- $-a = {\sim}a + 1$
- $4i \oplus (4i+1) \oplus (4i+2) \oplus (4i+3) = 0$

- Iterating over all subsets of a set and iterating over all submasks of a mask:

mask.h, 18 lines

```
int n;
void mask_example() {
    for (int mask = 0; mask < (1 << n); ++mask) {
        for (int i = 0; i < n; ++i) {
            if (mask & (1 << i)) {
                // do something...
            }
        }
        // Time complexity: O(n * 2^n).
    }
    for (int mask = 0; mask < (1 << n); ++mask) {
        for (int submask = mask; ; submask = (submask - 1) & mask) {
            // do something...
            if (submask == 0) break;
        }
        // Time complexity: O(3^n).
    }
}
```

6.7 Pollard's rho algorithm

Description: Pollard's rho is an efficient algorithm for integer factorization. The algorithm can run smoothly with n upto 10^{18}, but be careful with overflow for larger n (e.g. 10^{19}).

pollard_rho.h, 84 lines

```cpp
using num_t = long long;
const int PRIME_MAX = (int) 4e4; // for handle numbers <= 1e9.
const int LIMIT = (int) 1e9;
vector<int> primes;
int small_primes[] = {2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 73, 113, 193,
    311, 313, 407521, 299210837};
void linear_sieve(int n);
num_t mulmod(num_t a, num_t b, num_t mod);
num_t powmod(num_t a, num_t n, num_t mod);
bool miller_rabin(num_t a, num_t d, int s, num_t mod) {
    num_t x = powmod(a, d, mod);
    if (x == mod - 1 || x == 1) {
        return true;
    }
    for (int i = 0; i < s - 1; ++i) {
        x = mulmod(x, x, mod);
        if (x == mod - 1) return true;
    }
    return false;
}
bool is_prime(num_t n, int tests = 10) {
    if (n < 4) return (n > 1);
    num_t d = n - 1;
    int s = 0;
    while (d % 2 == 0) { d >>= 1; s++; }
    for (int i = 0; i < tests; ++i) {
        int a = small_primes[i];
        if (n == a) return true;
        if (n % a == 0 || !miller_rabin(a, d, s, n)) return false;
    }
    return true;
}
num_t f(num_t x, int c, num_t mod) { // f(x) = (x^2 + c) % mod.
    x = mulmod(x, x, mod);
    x += c;
    if (x >= mod) x -= mod;
    return x;
}
num_t pollard_rho(num_t n, int c) {
    // algorithm to find a random divisor of `n`.
    // using random function: f(x) = (x^2 + c) % n.
    num_t x = 2, y = x, d;
    long long p = 1;
    int dist = 0;
    while (true) {
        y = f(y, c, n);
        dist++;
        d = __gcd(llabs(x - y), n);
        if (d > 1) break;
        if (dist == p) { dist = 0; p *= 2; x = y; }
    }
    return d;
}
void factorize(int n, vector<num_t> &factors);
void llfactorize(num_t n, vector<num_t> &factors) {
    if (n < 2) return;
    if (is_prime(n)) {
        factors.emplace_back(n);
        return;
    }
    if (n < LIMIT) {
        factorize(n, factors);
        return;
    }
    num_t d = n;
    for (int c = 2; d == n; c++) {
        d = pollard_rho(n, c);
    }
    llfactorize(d, factors);
    llfactorize(n / d, factors);
}
vector<num_t> gen_divisors(vector<pair<num_t, int>> &factors) {
    vector<num_t> divisors = {1};
    for (auto &x : factors) {
        int sz = (int) divisors.size();
        for (int i = 0; i < sz; ++i) {
            num_t cur = divisors[i];
            for (int j = 0; j < x.second; ++j) {
                cur *= x.first;
                divisors.push_back(cur);
            }
        }
    }
    return divisors; // this array is NOT sorted yet.
}
```

6.8 Segment divisor sieve

Description: computes the number of divisors for each number in range [L, R].

segment_divisor_sieve.h, 16 lines

```cpp
const int MAXN = (int) 1e6; // R - L + 1 <= N.
int divisor_count[MAXN + 3];
void segment_divisor_sieve(long long L, long long R) {
    for (long long i = 1; i <= (long long) sqrt(R); ++i) {
        long long start1 = ((L + i - 1) / i) * i;
        long long start2 = i * i;
        long long j = max(start1, start2);
        if (j == start2) {
            divisor_count[j - L] += 1;
            j += i;
        }
        for ( ; j <= R; j += i) {
            divisor_count[j - L] += 2;
        }
    }
}
```

6.9 Linear sieve

Description: finding primes and computing value for multiplicative function in $O(N)$.
Time: $O(N)$ (but the factor may be large).

linear_sieve.h, 43 lines

```cpp
const int N = (int) 1e6;
bool is_prime[N + 1];
int spf[N + 1]; // smallest prime factor
int phi[N + 1]; // euler's totient function
int mu[N + 1]; // mobius function
int func[N + 1]; // a multiplicative function, f(p^k) = k
int cnt[N + 1]; // cnt[i] = the power of the smallest prime factor of i
int pw[N + 1]; // pw[i] = p^cnt[i] where p is the smallest prime factor of i
vector<int> primes;

void sieve(int n = N) {
    spf[0] = spf[1] = -1;
    phi[1] = mu[1] = func[1] = 1;
```

```
    for (int x = 2; x <= n; ++x) {
        if (spf[x] == 0) {
            primes.push_back(spf[x] = x);
            is_prime[x] = true;
            phi[x] = x - 1;
            mu[x] = -1;
            func[x] = 1;
            cnt[x] = 1;
            pw[x] = x;
        }
        for (int p : primes) {
            if (p > spf[x] || x * p > n) break;
            spf[x * p] = p;
            if (p == spf[x]) {
                phi[x * p] = phi[x] * p;
                mu[x * p] = 0;
                func[x * p] = func[x / pw[x]] * (cnt[x] + 1);
                cnt[x * p] = cnt[x] + 1;
                pw[x * p] = pw[x] * p;
            }
            else {
                phi[x * p] = phi[x] * phi[p];
                mu[x * p] = mu[x] * mu[p]; // or -mu[x]
                func[x * p] = func[x] * func[p];
                cnt[x * p] = 1;
                pw[x * p] = p;
            }
        }
    }
}
```

6.10 Bitset sieve

Description: sieve of eratosthenes for large n (up to 10^9).
Time: time and space tested on codeforces:

- For $n = 10^8$: 200 ms, 6 MB.
- For $n = 10^9$: 4000 ms, 60 MB.

bitset_sieve.h, 23 lines

```
const int N = (int) 1e8;
bitset<N / 2 + 1> isPrime;
void sieve(int n = N) {
    isPrime.flip();
    isPrime[0] = false;
    for (int i = 3; i <= (int) sqrt(n); i += 2) {
        if (isPrime[i >> 1]) {
            for (int j = i * i; j <= n; j += 2 * i) {
                isPrime[j >> 1] = false;
            }
        }
    }
}
void example(int n) {
    sieve(n);
    int primeCnt = (n >= 2);
    for (int i = 3; i <= n; i += 2) {
        if (isPrime[i >> 1]) {
            primeCnt++;
        }
    }
    cout << primeCnt << '\n';
}
```

6.11 Block sieve

Description: a very fast sieve of eratosthenes for large n (up to 10^9).
Time: time and space tested on codeforces:

- For $n = 10^8$: 160 ms, 60 MB.
- For $n = 10^9$: 1600 ms, 505 MB.

block_sieve.h, 27 lines

```
const int N = (int) 1e8;
bitset<N + 1> is_prime;
vector<int> fast_sieve() {
    const int S = (int) sqrt(N), R = N / 2;
    vector<int> primes = {2};
    vector<bool> sieve(S + 1, true);
    vector<array<int, 2>> cp;
    for (int i = 3; i <= S; i += 2) {
        if (sieve[i]) {
            cp.push_back({i, i * i / 2});
            for (int j = i * i; j <= S; j += 2 * i) {
                sieve[j] = false;
            }
        }
    }
    for (int L = 1; L <= R; L += S) {
        array<bool, S> block{};
        for (auto &[p, idx] : cp) {
            for (; idx < S + L; idx += p) block[idx - L] = true;
        }
        for (int i = 0; i < min(S, R - L); ++i) {
            if (!block[i]) primes.push_back((L + i) * 2 + 1);
        }
    }
    for (int p : primes) is_prime[p] = true;
    return primes;
}
```

7 Combinatorics

7.1 Catalan numbers

$$C_n = \frac{1}{n+1}\binom{2n}{n} = \frac{(2n)!}{n!(n+1)!}$$

$$C_{n+1} = \sum_{i=0}^{n} C_i C_{n-i},\ C_0 = 1,\ C_n = \frac{4n-2}{n+1} C_{n-1}$$

- The first 12 Catalan numbers ($n = 0, 1, 2, \ldots, 11$):
$$C_n = 1, 1, 2, 5, 14, 42, 132, 429, 1430, 4862, 16796, 58786$$
- Applications of Catalan numbers:
  - difference binary search trees with n vertices from 1 to n.
  - rooted binary trees with $n+1$ leaves (vertices are not numbered).
  - correct bracket sequence of length $2 * n$.
  - permutation $[n]$ with no 3-term increasing subsequence (i.e. doesn't exist $i < j < k$ for which $a[i] < a[j] < a[k]$).
  - ways a convex polygon of $n+2$ sides can split into triangles by connecting vertices.

7.2 Fibonacci numbers

$$F_n = \begin{cases} 0, & \text{if } n = 0 \\ 1, & \text{if } n = 1 \\ F_{n-1} + F_{n-2}, & \text{otherwise} \end{cases}$$

- The first 20 Fibonacci numbers ($n = 0, 1, 2, \ldots, 19$):

$$F_n = 0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, 233, 377, 610, 987, 1597, 2584, 4181$$

- Binet's formula:

$$F_n = \frac{\varphi^n - \psi^n}{\varphi - \psi} = \frac{\varphi^n - \psi^n}{\sqrt{5}}$$

where $\varphi = \dfrac{1 + \sqrt{5}}{2}, \psi = \dfrac{1 - \sqrt{5}}{2}$

- Properties:

$$F_{2n+1} = F_n^2 + F_{n+1}^2$$
$$F_{2n} = F_{n-1} \cdot F_n + F_n \cdot F_{n+1}$$

$$F_{n+1} \cdot F_{n-1} - F_n^2 = (-1)^n$$
$$n \mid m \Leftrightarrow F_n \mid F_m$$
$$\gcd(F_n, F_m) = F_{\gcd(n,m)}$$

7.3 Stirling numbers of the first kind

Number of permutations of n elements which contain exactly k permutation cycles.

$$S(0,0) = 1$$

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

$$\sum_{k=0}^{n} S(n,k)x^k = x(x+1)(x+2)\ldots(x+n-1)$$

7.4 Stirling numbers of the second kind

Partitions of n distinct elements into exactly k non-empty groups.

$$S(n,1) = S(n,n) = 1$$

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

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

7.5 Derangements

Permutation of the elements of a set, such that no element appears in its original position (no fixied point). Recursive formulas:

$$D(n) = (n-1)[D(n-1) + D(n-2)] = nD(n-1) + (-1)^n$$

8 Geometry

8.1 Fundamentals

8.1.1 Point

point.h, 65 lines

```
#pragma once

const double PI = acos(-1);
const double EPS = 1e-9;
typedef double ftype;
struct Point {
    ftype x, y;
    Point(ftype _x = 0, ftype _y = 0): x(_x), y(_y) {}
    Point& operator+=(const Point& other) {
        x += other.x; y += other.y; return *this;
    }
    Point& operator-=(const Point& other) {
        x -= other.x; y -= other.y; return *this;
    }
    Point& operator*=(ftype t) {
        x *= t; y *= t; return *this;
    }
    Point& operator/=(ftype t) {
        x /= t; y /= t; return *this;
    }
    Point operator+(const Point& other) const {
        return Point(*this) += other;
    }
    Point operator-(const Point& other) const {
        return Point(*this) -= other;
    }
    Point operator*(ftype t) const {
        return Point(*this) *= t;
    }
    Point operator/(ftype t) const {
        return Point(*this) /= t;
    }
    Point rotate(double angle) const {
        return Point(x * cos(angle) - y * sin(angle), x * sin(angle) + y *
    cos(angle));
    }
    friend istream& operator>>(istream &in, Point &t);
    friend ostream& operator<<(ostream &out, const Point& t);
    bool operator<(const Point& other) const {
        if (fabs(x - other.x) < EPS)
            return y < other.y;
        return x < other.x;
    }
};

istream& operator>>(istream &in, Point &t) {
    in >> t.x >> t.y;
    return in;
}
ostream& operator<<(ostream &out, const Point& t) {
    out << t.x << ' ' << t.y;
    return out;
}

ftype dot(Point a, Point b) {return a.x * b.x + a.y * b.y;}
ftype norm(Point a) {return dot(a, a);}
ftype abs(Point a) {return sqrt(norm(a));}
ftype angle(Point a, Point b) {return acos(dot(a, b) / (abs(a) * abs(b)));}
ftype proj(Point a, Point b) {return dot(a, b) / abs(b);}
```

```
ftype cross(Point a, Point b) {return a.x * b.y - a.y * b.x;}
bool ccw(Point a, Point b, Point c) {return cross(b - a, c - a) > EPS;}
bool collinear(Point a, Point b, Point c) {return fabs(cross(b - a, c - a)) <
    EPS;}
Point intersect(Point a1, Point d1, Point a2, Point d2) {
    double t = cross(a2 - a1, d2) / cross(d1, d2);
    return a1 + d1 * t;
}
```

8.1.2 Line

line.h, 76 lines

```
#include "point.h"

struct Line {
    double a, b, c;
    Line (double _a = 0, double _b = 0, double _c = 0): a(_a), b(_b), c(_c) {}
    friend ostream & operator<<(ostream& out, const Line& l);
};
ostream & operator<<(ostream& out, const Line& l) {
    out << l.a << ' ' << l.b << ' ' << l.c;
    return out;
}
void PointsToLine(const Point& p1, const Point& p2, Line& l) {
    if (fabs(p1.x - p2.x) < EPS)
        l = {1.0, 0.0, -p1.x};
    else {
        l.a = - (double)(p1.y - p2.y) / (p1.x - p2.x);
        l.b = 1.0;
        l.c =  - l.a * p1.x - l.b * p1.y;
    }
}
void PointsSlopeToLine(const Point& p, double m, Line& l) {
    l.a = -m;
    l.b = 1;
    l.c = -l.a * p.x - l.b * p.y;
}
bool areParallel(const Line& l1, const Line& l2) {
    return fabs(l1.a - l2.a) < EPS && fabs(l1.b - l2.b) < EPS;
}
bool areSame(const Line& l1, const Line& l2) {
    return areParallel(l1, l2) && fabs(l1.c - l2.c) < EPS;
}
bool areIntersect(Line l1, Line l2, Point& p) {
    if (areParallel(l1, l2)) return false;
    p.x = - (l1.c * l2.b - l1.b * l2.c) / (l1.a * l2.b - l1.b * l2.a);
    if (fabs(l1.b) > EPS) p.y = - (l1.c + l1.a * p.x);
    else p.y = - (l2.c + l2.a * p.x);
    return 1;
}
double distToLine(Point p, Point a, Point b, Point& c) {
    double t = dot(p - a, b - a) / norm(b - a);
    c = a + (b - a) * t;
    return abs(c - p);
}
double distToSegment(Point p, Point a, Point b, Point& c) {
    double t = dot(p - a, b - a) / norm(b - a);
    if (t > 1.0)
        c = Point(b.x, b.y);
    else if (t < 0.0)
        c = Point(a.x, a.y);
    else
        c = a + (b - a) * t;
    return abs(c - p);
}
bool intersectTwoSegment(Point a, Point b, Point c, Point d) {
    ftype ABxAC = cross(b - a, c - a);
    ftype ABxAD = cross(b - a, d - a);
    ftype CDxCA = cross(d - c, a - c);
    ftype CDxCB = cross(d - c, b - c);
    if (ABxAC == 0 || ABxAD == 0 || CDxCA == 0 || CDxCB == 0) {
        if (ABxAC == 0 && dot(a - c, b - c) <= 0) return true;
        if (ABxAD == 0 && dot(a - d, b - d) <= 0) return true;
        if (CDxCA == 0 && dot(c - a, d - a) <= 0) return true;
        if (CDxCB == 0 && dot(c - b, d - b) <= 0) return true;
        return false;
    }
    return (ABxAC * ABxAD < 0 && CDxCA * CDxCB < 0);
}
void perpendicular(Line l1, Point p, Line& l2) {
    if (fabs(l1.a) < EPS)
        l2 = {1.0, 0.0, -p.x};
    else {
        l2.a = -l1.b / l1.a;
        l2.b = 1.0;
        l2.c = -l2.a * p.x - l2.b * p.y;
    }
}
```

8.1.3 Circle

circle.h, 16 lines

```
#include "point.h"

int insideCircle(const Point& p, const Point& center, ftype r) {
    ftype d = norm(p - center);
    ftype rSq = r * r;
    return fabs(d - rSq) < EPS ? 0 : (d - rSq >= EPS ? 1 : -1);
}
bool circle2PointsR(const Point& p1, const Point& p2, ftype r, Point& c) {
    double h = r * r - norm(p1 - p2) / 4.0;
    if (fabs(h) < 0) return false;
    h = sqrt(h);
    Point perp = (p2 - p1).rotate(PI / 2.0);
    Point m = (p1 + p2) / 2.0;
    c = m + perp * (h / abs(perp));
    return true;
}
```

8.1.4 Triangle

triangle.h, 33 lines

```
#include "point.h"
#include "line.h"

double areaTriangle(double ab, double bc, double ca) {
    double p = (ab + bc + ca) / 2;
    return sqrt(p) * sqrt(p - ab) * sqrt(p - bc) * sqrt(p - ca);
}
double rInCircle(double ab, double bc, double ca) {
    double p = (ab + bc + ca) / 2;
    return areaTriangle(ab, bc, ca) / p;
}
double rInCircle(Point a, Point b, Point c) {
    return rInCircle(abs(a - b), abs(b - c), abs(c - a));
}
bool inCircle(Point p1, Point p2, Point p3, Point &ctr, double &r) {
    r = rInCircle(p1, p2, p3);
    if (fabs(r) < EPS) return false;
    Line l1, l2;
    double ratio = abs(p2 - p1) / abs(p3 - p1);
    Point p = p2 + (p3 - p2) * (ratio / (1 + ratio));
    PointsToLine(p1, p, l1);
```

```cpp
    ratio = abs(p1 - p2) / abs(p2 - p3);
    p = p1 + (p3 - p1) * ( ratio / (1 + ratio));
    PointsToLine(p2, p, l2);
    areIntersect(l1, l2, ctr);
    return true;
}
double rCircumCircle(double ab, double bc, double ca) {
    return ab * bc * ca / (4.0 * areaTriangle(ab, bc, ca));
}
double rCircumCircle(Point a, Point b, Point c) {
    return rCircumCircle(abs(b - a), abs(c - b), abs(a - c));
}
```

8.1.5 Convex hull

convex_hull.h, 17 lines

```cpp
#include "point.h"

vector<Point> CH_Andrew(vector<Point> &Pts) { // overall O(n log n)
    int n = Pts.size(), k = 0;
    vector<Point> H(2 * n);
    sort(Pts.begin(), Pts.end());
    for (int i = 0; i < n; ++i) {
        while ((k >= 2) && !ccw(H[k - 2], H[k - 1], Pts[i])) --k;
        H[k++] = Pts[i];
    }
    for (int i = n - 2, t = k + 1; i >= 0; --i) {
        while ((k >= t) && !ccw(H[k - 2], H[k - 1], Pts[i])) --k;
        H[k++] = Pts[i];
    }
    H.resize(k);
    return H;
}
```

8.1.6 Polygon

polygon.h, 40 lines

```cpp
#include "point.h"

double perimeter(const vector<Point> &P) {
    double ans = 0.0;
    for (int i = 0; i < (int)P.size() - 1; ++i)
        ans += abs(P[i] - P[i + 1]);
    return ans;
}
double area(const vector<Point> &P) {
    double ans = 0.0;
    for (int i = 0; i < (int)P.size() - 1; ++i)
        ans += (P[i].x * P[i + 1].y - P[i + 1].x * P[i].y);
    return fabs(ans) / 2.0;
}
bool isConvex(const vector<Point> &P) {
    int n = (int)P.size();
    if (n <= 3) return false;
    bool firstTurn = ccw(P[0], P[1], P[2]);
    for (int i = 1; i < n - 1; ++i)
        if (ccw(P[i], P[i + 1], P[(i + 2) == n ? 1 : i + 2]) != firstTurn)
            return false;
    return true;
}
int insidePolygon(Point pt, const vector<Point> &P) {
    int n = (int)P.size();
    if (n <= 3) return -1;
    bool on_polygon = false;
    for (int i = 0; i < n - 1; ++i)
        if (fabs(abs(P[i] - pt) + abs(pt - P[i + 1]) - abs(P[i] - P[i + 1])) < EPS)
            on_polygon = true;
    if (on_polygon) return 0;
    double sum = 0.0;
    for (int i = 0; i < n - 1; ++i) {
        if (ccw(pt, P[i], P[i + 1]))
            sum += angle(P[i] - pt, P[i + 1] - pt);
        else
            sum -= angle(P[i] - pt, P[i + 1] - pt);
    }
    return fabs(sum) > PI ? 1 : -1;
}
```

8.2 Minimum enclosing circle

Description: computes the minimum circle that encloses all the given points.

minimum_enclosing_circle.h, 34 lines

```cpp
#include "point.h"
// TODO: make it compatible with circle.h

Point center_from(double bx, double by, double cx, double cy) {
    double B = bx * bx + by * by, C = cx * cx + cy * cy, D = bx * cy - by * cx;
    return Point((cy * B - by * C) / (2 * D), (bx * C - cx * B) / (2 * D));
}

Circle Circle_from(Point A, Point B, Point C) {
    Point I = center_from(B.x - A.x, B.y - A.y, C.x - A.x, C.y - A.y);
    return Circle(I + A, abs(I));
}

const int N = 100005;
int n, x[N], y[N];
Point a[N];

Circle emo_welzl(int n, vector<Point> T) {
    if (T.size() == 3 || n == 0) {
        if (T.size() == 0) return Circle(Point(0, 0), -1);
        if (T.size() == 1) return Circle(T[0], 0);
        if (T.size() == 2) return Circle((T[0] + T[1]) / 2, abs(T[0] - T[1]) / 2);
        return Circle_from(T[0], T[1], T[2]);
    }
    random_shuffle(a + 1, a + n + 1);
    Circle Result = emo_welzl(0, T);
    for (int i = 1; i <= n; i++)
        if (abs(Result.x - a[i]) > Result.y + 1e-9) {
            T.push_back(a[i]);
            Result = emo_welzl(i - 1, T);
            T.pop_back();
        }
    return Result;
}
```

9 Linear algebra

9.1 Gauss elimination

Time: $O(\min(n,m) \cdot nm)$ or $O(n^3)$ in case $n = m$.

gauss_elimination.h, 45 lines

```cpp
const double EPS = 1e-9;
const int INF = 2; // it doesn't actually have to be infinity or a big number
int gauss (vector < vector<double> > a, vector<double> & ans) {
    int n = (int) a.size();
    int m = (int) a[0].size() - 1;
    vector<int> where (m, -1);
```

```
    for (int col=0, row=0; col<m && row<n; ++col) {
        int sel = row;
        for (int i=row; i<n; ++i) {
            if (abs (a[i][col]) > abs (a[sel][col])) sel = i;
        }
        if (abs (a[sel][col]) < EPS) continue;
        for (int i=col; i<=m; ++i) {
            swap (a[sel][i], a[row][i]);
        }
        where[col] = row;

        for (int i=0; i<n; ++i) {
            if (i != row) {
                double c = a[i][col] / a[row][col];
                for (int j=col; j<=m; ++j) {
                    a[i][j] -= a[row][j] * c;
                }
            }
        }
        ++row;
    }
    ans.assign (m, 0);
    for (int i=0; i<m; ++i) {
        if (where[i] != -1) {
            ans[i] = a[where[i]][m] / a[where[i]][i];
        }
    }
    for (int i=0; i<n; ++i) {
        double sum = 0;
        for (int j=0; j<m; ++j) {
            sum += ans[j] * a[i][j];
        }
        if (abs (sum - a[i][m]) > EPS) return 0;
    }
    for (int i=0; i<m; ++i) {
        if (where[i] == -1) return INF;
    }
    return 1;
}
```

9.2 Gauss determinant

Description: computing determinant of a square matrix A by applying Gauss elimination to produces a row echolon matrix B, then the determinant of A is equal to product of the elements of the diagonal of B.
Time: $O(N^3)$.

gauss_determinant.h, 32 lines

```
const double EPS = 1e-9;
double determinant(vector<vector<double>> A) {
    int n = (int) A.size();
    double det = 1;
    for (int i = 0; i < n; ++i) {
        // find non-zero cell
        int k = i;
        for (int j = i + 1; j < n; ++j) {
            if (abs(A[j][i]) > abs(A[k][i])) k = j;
        }
        if (abs(A[k][i]) < EPS) {
            det = 0;
            break;
        }
        if (i != k) {
            swap(A[i], A[k]);
            det = -det;
        }
        det *= A[i][i];
        for (int j = i + 1; j < n; ++j) {
            A[i][j] /= A[i][i];
        }
        for (int j = 0; j < n; ++j) {
            if (j != i && abs(A[j][i]) > EPS) {
                for (int k = i + 1; k < n; ++k) {
                    A[j][k] -= A[i][k] * A[j][i];
                }
            }
        }
    }
    return det;
}
```

9.3 Bareiss determinant

Description: Bareiss algorithm for computing determinant of a square matrix A with integer entries using only integer arithmetic.
Usage:

- Kirchhoff's theorem: finding the number of spanning trees.

Time: $O(N^3)$.

bareiss_determinant.h, 28 lines

```
long long determinant(vector<vector<long long>> A) {
    int n = (int) A.size();
    long long prev = 1;
    int sign = 1;
    for (int i = 0; i < n - 1; ++i) {
        // find non-zero cell
        if (A[i][i] == 0) {
            int k = -1;
            for (int j = i + 1; j < n; ++j) {
                if (A[j][i] != 0) {
                    k = i;
                    break;
                }
            }
            if (k == -1) return 0;
            swap(A[i], A[k]);
            sign = -sign;
        }
        for (int j = i + 1; j < n; ++j) {
            for (int k = i + 1; k < n; ++k) {
                assert((A[j][k] * A[i][i] - A[j][i] * A[i][k]) % prev == 0);
                A[j][k] = (A[j][k] * A[i][i] - A[j][i] * A[i][k]) / prev;
            }
        }
        prev = A[i][i];
    }
    return sign * A[n - 1][n - 1];
}
```

10 Graph

10.1 Bellman-Ford algorithm

Description: single source shortest path in a weighted (negative or positive) directed graph.
Time: $O(VE)$.

bellman_ford.h, 36 lines

```
const int64_t INF = (int64_t) 2e18;
struct Edge {
    int u, v; // u -> v
    int64_t w;
    Edge() {}
```

```cpp
    Edge(int _u, int _v, int64_t _w) : u(_u), v(_v), w(_w) {}
};
int n;
vector<Edge> edges;
vector<int64_t> bellmanFord(int s) {
    // dist[stating] = 0.
    // dist[u] = +INF, if u is unreachable.
    // dist[u] = -INF, if there is a negative cycle on the path from s to u.
    // -INF < dist[u] < +INF, otherwise.
    vector<int64_t> dist(n, INF);
    dist[s] = 0;
    for (int i = 0; i < n - 1; ++i) {
        bool any = false;
        for (auto [u, v, w] : edges) {
            if (dist[u] != INF && dist[v] > w + dist[u]) {
                dist[v] = w + dist[u];
                any = true;
            }
        }
        if (!any) break;
    }
    // handle negative cycles
    for (int i = 0; i < n - 1; ++i) {
        for (auto [u, v, w] : edges) {
            if (dist[u] != INF && dist[v] > w + dist[u]) {
                dist[v] = -INF;
            }
        }
    }
    return dist;
}
```

10.2 Articulation point and Bridge

Description: finding articulation points and bridges in a simple undirected graph.
Time: $O(V + E)$.

articulation_point_and_bridge.h, 39 lines

```cpp
const int N = (int) 1e5;
vector<int> g[N];
int num[N], low[N], dfs_timer;
bool joint[N];
vector<pair<int, int>> bridges;
void dfs(int u, int prev) {
    low[u] = num[u] = ++dfs_timer;
    int child = 0;
    for (int v : g[u]) {
        if (v == prev) continue;
        if (num[v]) low[u] = min(low[u], num[v]);
        else {
            dfs(v, u);
            low[u] = min(low[u], low[v]);
            child++;
            if (low[v] >= num[v]) {
                bridges.emplace_back(u, v);
            }
            if (u != prev && low[v] >= num[u]) joint[u] = true;
        }
    }
    if (u == prev && child > 1) joint[u] = true;
}

int solve() {
    int n, m;
    cin >> n >> m;
    for (int i = 0; i < m; ++i) {
        int u, v;
        cin >> u >> v;
        u--; v--;
        g[u].push_back(v);
        g[v].push_back(u);
    }
    for (int i = 0; i < n; ++i) {
        if (!num[i]) dfs(i, i);
    }
    return 0;
}
```

10.3 Topo sort

Description: a topological sort of a directed acyclic graph is a linear ordering of its vertices such that for every directed edge from vertex u to vertex v, u comes before v in the ordering.
Note: if there are cycles, the returned list will have size smaller than n.
Time: $O(V + E)$.

topo_sort.h, 20 lines

```cpp
vector<int> topo_sort(const vector<vector<int>> &g) {
    int n = (int) g.size();
    vector<int> indeg(n);
    for (int u = 0; u < n; ++u) {
        for (int v : g[u]) indeg[v]++;
    }
    queue<int> q; // Note: use min-heap to get the smallest lexicographical
     order.
    for (int u = 0; u < n; ++u) {
        if (indeg[u] == 0) q.emplace(u);
    }
    vector<int> topo;
    while (!q.empty()) {
        int u = q.front(); q.pop();
        topo.emplace_back(u);
        for (int v : g[u]) {
            if (--indeg[v] == 0) q.emplace(v);
        }
    }
    return topo;
}
```

10.4 Strongly connected components

10.4.1 Tarjan's Algorithm

Description: Tarjan's algorithm finds strongly connected components (SCC) in a directed graph. If two vertices u and v belong to the same component, then scc_id[u] == scc_id[v].
Time: $O(V + E)$.

tarjan.h, 25 lines

```cpp
const int N = (int) 5e5;
vector<int> g[N], st;
int low[N], num[N], dfs_timer, scc_id[N], scc;
bool used[N];
void Tarjan(int u) {
    low[u] = num[u] = ++dfs_timer;
    st.push_back(u);
    for (int v : g[u]) {
        if (used[v]) continue;
        if (num[v] == 0) {
            Tarjan(v);
            low[u] = min(low[u], low[v]);
        }
        else low[u] = min(low[u], num[v]);
    }
    if (low[u] == num[u]) {
```

```
        int v;
        do {
            v = st.back(); st.pop_back();
            used[v] = true;
            scc_id[v] = scc;
        } while (v != u);
        scc++;
    }
}
```

10.4.2 Kosaraju's algorithm

Description: Kosaraju's algorithm finds strongly connected components (SCC) in a directed graph in a straightforward way. Two vertices u and v belong to the same component iff scc_id[u] == scc_id[v]. This algorithm generates connected components numbered in topological order in corresponding condensation graph.
Time: $O(V + E)$.

kosaraju.h, 42 lines

```
const int N = (int) 1e5;
vector<int> g[N], rev_g[N], vers;
int scc_id[N];
bool vis[N];
int n, m;

void dfs1(int u) {
    vis[u] = true;
    for (int v : g[u]) {
        if (!vis[v]) {
            dfs1(v);
        }
    }
    vers.push_back(u);
}
void dfs2(int u, int id) {
    scc_id[u] = id;
    vis[u] = true;
    for (int v : rev_g[u]) {
        if (!vis[v]) {
            dfs2(v, id);
        }
    }
}
void Kosaraju() {
    for (int i = 0; i < n; ++i) {
        if (!vis[i]) dfs1(i);
    }
    memset(vis, 0, sizeof vis);
    int scc_cnt = 0;
    // iterating in reverse order
    for (int i = n - 1; i >= 0; --i) {
        int u = vers[i];
        if (!vis[u]) {
            dfs2(u, ++scc_cnt);
        }
    }
    cout << scc_cnt << '\n';
    for (int i = 0; i < n; ++i) {
        cout << scc_id[i] << " \n"[i == n - 1];
    }
}
```

10.5 K-th smallest shortest path

Description: finding the k-th smallest shortest path from vertex s to vertex t, each vertex can be visited more than once.

k_smallest_shortest_path.h, 24 lines

```
using adj_list = vector<vector<pair<int, int>>>;
vector<long long> k_smallest(const adj_list &g, int k, int s, int t) {
    int n = (int) g.size();
    vector<long long> ans;
    vector<int> cnt(n);
    using pli = pair<long long, int>;
    priority_queue<pli, vector<pli>, greater<pli>> pq;
    pq.emplace(0, s);
    while (!pq.empty() && cnt[t] < k) {
        int u = pq.top().second;
        long long d = pq.top().first;
        pq.pop();
        if (cnt[u] == k) continue;
        cnt[u]++;
        if (u == t) {
            ans.push_back(d);
        }
        for (auto [v, cost] : g[u]) {
            pq.emplace(d + cost, v);
        }
    }
    assert(k == (int) ans.size());
    return ans;
}
```

10.6 Eulerian path

10.6.1 Directed graph

Description: Hierholzer's algorithm. An Eulerian path in a directed graph is a path that visits all edges exactly once. An Eulerian cycle is a Eulerian path that is a cycle.
Time: $O(E)$.

eulerian_path_directed.h, 16 lines

```
vector<int> find_path_directed(const vector<vector<int>> &g, int s) {
    int n = (int) g.size();
    vector<int> stack, cur_edge(n), vertices;
    stack.push_back(s);
    while (!stack.empty()) {
        int u = stack.back();
        stack.pop_back();
        while (cur_edge[u] < (int) g[u].size()) {
            stack.push_back(u);
            u = g[u][cur_edge[u]++];
        }
        vertices.push_back(u);
    }
    reverse(vertices.begin(), vertices.end());
    return vertices;
}
```

10.6.2 Undirected graph

Description: Hierholzer's algorithm. An Eulerian path in a undirected graph is a path that visits all edges exactly once. An Eulerian cycle is a Eulerian path that is a cycle.
Time: $O(E)$.

eulerian_path_undirected.h, 21 lines

```
struct Edge {
    int to;
    list<Edge>::iterator reverse_edge;
    Edge(int _to) : to(_to) {}
};
vector<int> vertices;
void find_path(vector<list<Edge>> &g, int u) {
```

```
    while (!g[u].empty()) {
        int v = g[u].front().to;
        g[v].erase(g[u].front().reverse_edge);
        g[u].pop_front();
        find_path(g, v);
    }
    vertices.emplace_back(u); // reversion list.
}
void add_edge(vector<list<Edge>> &g, int u, int v) {
    g[u].emplace_front(v);
    g[v].emplace_front(u);
    g[u].front().reverse_edge = g[v].begin();
    g[v].front().reverse_edge = g[u].begin();
}
```

10.7 HLD

HLD.h, 70 lines

```
const int INF = 0x3f3f3f3f;
template<class SegmentTree>
struct HLD { // vertex update and max query on path u -> v
    int n;
    vector<vector<int>> g;
    SegmentTree seg_tree;
    vector<int> par, top, depth, sz, id;
    int timer = 0;
    bool VAL_IN_EDGE = false;
    HLD() {}
    HLD(int _n): n(_n), g(n), seg_tree(n), par(n), top(n), depth(n), sz(n),
     id(n) {}
    void build() {
        dfs_sz(0);
        dfs_hld(0);
    }
    void add_edge(int u, int v) {
        g[u].push_back(v);
        g[v].push_back(u);
    }
    void dfs_sz(int u) {
        sz[u] = 1;
        for (int &v : g[u]) { // MUST BE ref for the swap below
            par[v] = u;
            depth[v] = depth[u] + 1;
            g[v].erase(find(g[v].begin(), g[v].end(), u));
            dfs_sz(v);
            sz[u] += sz[v];
            if (sz[v] > sz[g[u][0]]) swap(v, g[u][0]);
        }
    }
    void dfs_hld(int u) {
        id[u] = timer++;
        for (int v : g[u]) {
            top[v] = (v == g[u][0] ? top[u] : v);
            dfs_hld(v);
        }
    }
    int lca(int u, int v) {
        while (top[u] != top[v]) {
            if (depth[top[u]] > depth[top[v]]) swap(u, v);
            v = par[top[v]];
        }
        // now u, v is in the same heavy-chain
        return (depth[u] < depth[v] ? u : v);
    }
    void set_vertex(int v, int x) {
        seg_tree.set(id[v], x);
    }
    void set_edge(int u, int v, int x) {
        if (u != par[v]) swap(u, v);
        seg_tree.set(id[v], x);
    }
    void set_subtree(int v, int x) {
        // modify segment_tree so that it supports range update
        seg_tree.set_range(id[v] + VAL_IN_EDGE, id[v] + sz[v] - 1, x);
    }
    int query_path(int u, int v) {
        int res = -INF;
        while (top[u] != top[v]) {
            if (depth[top[u]] > depth[top[v]]) swap(u, v);
            int cur = seg_tree.query(id[top[v]], id[v]);
            res = max(res, cur);
            v = par[top[v]];
        }
        if (depth[u] > depth[v]) swap(u, v);
        int cur = seg_tree.query(id[u] + VAL_IN_EDGE, id[v]);
        res = max(res, cur);
        return res;
    }
};
```

10.8 DSU on tree

dsu_on_tree.h, 32 lines

```
const int nmax = (int)2e5 + 1;
vector<int> adj[nmax];
int sz[nmax]; // sz[u] is the size of the subtree rooted at u
bool big[nmax];

void add(int u, int p, int del) {
    // do something...
    for(int v : adj[u]) {
        if(big[v] == false) {
            add(v, u, del);
        }
    }
}

void dsuOnTree(int u, int p, int keep) {
    int bigC = -1;
    for(int v : adj[u]) {
        if(v != p && (bigC == -1 || sz[bigC] < sz[v])) {
            bigC = v;
        }
    }
    for(int v : adj[u]) {
        if(v != p && v != bigC) dsuOnTree(v, u, 0);
    }
    if(bigC != -1) {
        big[bigC] = true;
        dsuOnTree(bigC, u, 1);
    }
    add(u, p, 1);
    if(bigC != -1) big[bigC] = false;
    if(keep == 0) add(u, p, -1);
}
```

10.9 2-SAT

Description: finds a way to assign values to boolean variables a, b, c,.. of a 2-SAT problem (each clause has at most two variables) so that the following formula becomes true: $(a \mid b) \,\&\, (\sim a \mid c) \,\&\, (b \mid \sim c) \ldots$
Usage:

- TwoSat twosat(number of boolean variables);
- twosat.either(a, ~b); // a is true or b is false
- twosat.solve(); // return true iff the above formula is satisfiable

Time: $O(V + E)$ where V is the number of boolean variables and E is the number of clauses.

two_sat.h, 49 lines

```
struct TwoSat {
    int n;
    vector<vector<int>> g, tg; // g and transpose of g
    vector<int> comp, order;
    vector<bool> vis, vals;
    TwoSat(int _n): n(_n), g(2 * n), tg(2 * n),
        comp(2 * n), vis(2 * n), vals(n) {}
    void either(int u, int v) {
        u = max(2 * u, -2 * u - 1);
        v = max(2 * v, -2 * v - 1);
        g[u ^ 1].push_back(v);
        g[v ^ 1].push_back(u);
        tg[v].push_back(u ^ 1);
        tg[u].push_back(v ^ 1);
    }
    void set(int u) { either(u, u); }
    void dfs1(int u) {
        vis[u] = true;
        for (int v : g[u]) {
            if (!vis[v]) dfs1(v);
        }
        order.push_back(u);
    }
    void dfs2(int u, int scc_id) {
        comp[u] = scc_id;
        for (int v : tg[u]) {
            if (comp[v] == -1) dfs2(v, scc_id);
        }
    }
    bool solve() {
        for (int i = 0; i < 2 * n; ++i) {
            if (!vis[i]) dfs1(i);
        }
        fill(comp.begin(), comp.end(), -1);
        for (int i = 2 * n - 1, scc_id = 0; i >= 0; --i) {
            int u = order[i];
            if (comp[u] == -1) dfs2(u, scc_id++);
        }
        for (int i = 0; i < n; ++i) {
            int u = i * 2, nu = i * 2 + 1;
            if (comp[u] == comp[nu]) {
                return false;
            }
            vals[i] = comp[u] > comp[nu];
        }
        return true;
    }
    vector<bool> get_vals() { return vals; }
};
```

11 Misc.

11.1 Ternary search

Description: given an unimodal function $f(x)$, find the maximum/minimum of $f(x)$. Unimodal means the function strictly increases/decreases first, reaches a maximum/minimum (at a single point or over an interval), and then strictly decreases/increases.

ternary_search.h, 22 lines

```
const double eps = 1e-9;
template<typename T>
inline T func(T x) { return x * x; }

// these two functions below find min, for find max: change '<' below to '>'.
double ternary_search(double l, double r) { // min
    while (r - l > eps) {
        double mid1 = l + (r - l) / 3;
        double mid2 = r - (r - l) / 3;
        if (func(mid1) < func(mid2)) r = mid2;
        else l = mid1;
    }
    return l;
}
int ternary_search(int l, int r) { // min
    while (l < r) {
        int mid = l + (r - l) / 2;
        if (func(mid) < func(mid + 1)) r = mid;
        else l = mid + 1;
    }
    return l;
}
```

11.2 Matrix

matrix.h, 38 lines

```
using matrix_type = int;
const int MOD = (int) 1e9 + 7;
struct Matrix {
    static const matrix_type INF = numeric_limits<matrix_type>::max();
    int N, M;
    vector<vector<matrix_type>> mat;

    Matrix(int _N, int _M, matrix_type v = 0) : N(_N), M(_M) {
        mat.assign(N, vector<matrix_type>(M, v));
    }
    static Matrix identity(int n) { // return identity matrix.
        Matrix I(n, n);
        for (int i = 0; i < n; ++i) {
            I[i][i] = 1;
        }
        return I;
    }

    vector<matrix_type>& operator[](int r) { return mat[r]; }
    const vector<matrix_type>& operator[](int r) const { return mat[r]; }

    Matrix& operator*=(const Matrix &other) {
        assert(M == other.N); // [N x M] [other.N x other.M]
        Matrix res(N, other.M);
        for (int r = 0; r < N; ++r) {
            for (int c = 0; c < other.M; ++c) {
                long long square_mod = (long long) MOD * MOD;
                long long sum = 0;
                for (int g = 0; g < M; ++g) {
                    sum += (long long) mat[r][g] * other[g][c];
                    if (sum >= square_mod) sum -= square_mod;
                }
                res[r][c] = sum % MOD;
            }
        }
        mat.swap(res.mat); return *this;
    }
};
```