Can Tho University
CTU.NegativeZero

Contents

1 Contest

1.1 C++

```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());

const int MOD = (int) 1e9 + 7;
const int INF = 0x3f3f3f3f;

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

    return 0;
}
```

1.2 Debug

```cpp
#define debug(...) { string _s = #__VA_ARGS__; replace(begin(_s), end(_s),
    ',', ' '); stringstream _ss(_s); istream_iterator<string> _it(_ss);
    out_error(_it, __VA_ARGS__);}

void out_error(istream_iterator<string> it) { cerr << '\n'; }

template<typename T, typename ...Args>
void out_error(istream_iterator<string> it, T a, Args... args) {
    cerr << " [" << *it << " = " << a << "] ";
    out_error(++it, args...);
}

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

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

1.3 Java

```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

```
{
    "cmd": ["g++", "-std=c++17", "-fmax-errors=5", "-DLOCAL", "-Wall", "-
    Wextra", "-o", "${file_path}/${file_base_name}.out", "${file}"],
    "file_regex": "^(..[^:]*):([0-9]+):?([0-9]+)?:? (.*)$",
    "working_dir": "${file_path}",
    "selector": "source.cpp, source.c++"
}
```

1.5 .bashrc

```
alias cpp='g++ -std=c++17 -fmax-errors=5 -DLOCAL -Wall -Wextra'

#Stress-testing
function test {
  SOL=$1
  CHECKER=$2
  for i in {1..100};
    do
      ./gen.out > in && ./"$CHECKER.out" < in > ans && ./"$SOL.out" < in >
    out && diff -Z out ans && echo "Test $i passed!!" || break;
    done
}
```

2 Data structures

2.1 Sparse table

```cpp
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

```cpp
#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>;

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

```cpp
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   Segment tree

```cpp
/**
 * 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].
 */
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) {
```

```cpp
        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);
    }
};
```

2.5   Efficient segment tree

```cpp
template<typename T> struct SegmentTree {
    int n;
```

```cpp
    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;
    }
};
```

2.6 Persistent lazy segment tree

```cpp
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);
```

```cpp
        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;
    }
};
```

2.7 Disjoint sparse table

```cpp
/**
 * Description: range query on a static array.
```

```
3   * Time: O(1) per query.
4   * Tested: stress-test.
5   */
6  const int MOD = (int) 1e9 + 7;
7  struct DisjointSparseTable { // product queries.
8      int n, h;
9      vector<vector<int>> dst;
10     vector<int> lg;
11     DisjointSparseTable(int _n) : n(_n) {
12         h = 1; // in case n = 1: h = 0 !!.
13         int p = 1;
14         while (p < n) p *= 2, h++;
15         lg.resize(p); lg[1] = 0;
16         for (int i = 2; i < p; ++i) {
17             lg[i] = 1 + lg[i / 2];
18         }
19         dst.resize(h, vector<int>(n));
20     }
21     void build(const vector<int> &A) {
22         for (int lv = 0; lv < h; ++lv) {
23             int len = (1 << lv);
24             for (int k = 0; k < n; k += len * 2) {
25                 int mid = min(k + len, n);
26                 dst[lv][mid - 1] = A[mid - 1] % MOD;
27                 for (int i = mid - 2; i >= k; --i) {
28                     dst[lv][i] = 1LL * A[i] * dst[lv][i + 1] % MOD;
29                 }
30                 if (mid == n) break;
31                 dst[lv][mid] = A[mid] % MOD;
32                 for (int i = mid + 1; i < min(mid + len, n); ++i) {
33                     dst[lv][i] = 1LL * A[i] * dst[lv][i - 1] % MOD;
34                 }
35             }
36         }
37     }
38     int get(int l, int r) {
39         if (l == r) {
40             return dst[0][l];
41         }
42         int i = lg[l ^ r];
43         return 1LL * dst[i][l] * dst[i][r] % MOD;
44     }
45 };
```

2.8 Fenwick tree

```
1  using tree_type = long long;
2  struct FenwickTree {
3      int n;
4      vector<tree_type> fenw_coeff, fenw;
5      FenwickTree() {}
6      FenwickTree(int _n) : n(_n) {
7          fenw_coeff.assign(n, 0); // fenwick tree with coefficient (n - i).
```

```
8          fenw.assign(n, 0); // normal fenwick tree.
9      }
10     void build(const vector<int> &A) {
11         assert((int) A.size() == n);
12         vector<int> diff(n);
13         diff[0] = A[0];
14         for (int i = 1; i < n; ++i) {
15             diff[i] = A[i] - A[i - 1];
16         }
17         fenw_coeff[0] = (long long) diff[0] * n;
18         fenw[0] = diff[0];
19         for (int i = 1; i < n; ++i) {
20             fenw_coeff[i] = fenw_coeff[i - 1] + (long long) diff[i] * (n -
i);
21             fenw[i] = fenw[i - 1] + diff[i];
22         }
23         for (int i = n - 1; i >= 0; --i) {
24             int j = (i & (i + 1)) - 1;
25             if (j >= 0) {
26                 fenw_coeff[i] -= fenw_coeff[j];
27                 fenw[i] -= fenw[j];
28             }
29         }
30     }
31     void add(vector<tree_type> &fenw, int i, tree_type val) {
32         while (i < n) {
33             fenw[i] += val;
34             i |= (i + 1);
35         }
36     }
37     tree_type __prefix_sum(vector<tree_type> &fenw, int i) {
38         tree_type res{};
39         while (i >= 0) {
40             res += fenw[i];
41             i = (i & (i + 1)) - 1;
42         }
43         return res;
44     }
45     tree_type prefix_sum(int i) {
46         return __prefix_sum(fenw_coeff, i) - __prefix_sum(fenw, i) * (n - i
 - 1);
47     }
48     void range_add(int l, int r, tree_type val) {
49         add(fenw_coeff, l, (n - l) * val);
50         add(fenw_coeff, r + 1, (n - r - 1) * (-val));
51         add(fenw, l, val);
52         add(fenw, r + 1, -val);
53     }
54     tree_type range_sum(int l, int r) {
55         return prefix_sum(r) - prefix_sum(l - 1);
56     }
57 };
```

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

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

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

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

3.2 Sums

$$n^a + n^{a+1} + \cdots + n^b = \frac{n^{b+1} - n^a}{n - 1}, \; n \neq 1$$
$$1 + 2 + 3 + \cdots + n = \frac{n(n+1)}{2}$$
$$1^2 + 2^2 + 3^2 + \cdots + n^2 = \frac{n(n+1)(2n+1)}{6}$$
$$1^3 + 2^3 + 3^3 + \cdots + n^3 = \left(\frac{n(n+1)}{2}\right)^2$$
$$1^4 + 2^4 + 3^4 + \cdots + n^4 = \frac{n(n+1)(2n+1)(3n^2+3n-1)}{30}$$
$$1^5 + 2^5 + 3^5 + \cdots + n^5 = \frac{n^2(n+1)^2(2n^2+2n-1)}{12}$$
$$1^6 + 2^6 + 3^6 + \cdots + n^6 = \frac{n(n+1)(2n+1)(3n^4+6n^3-3n+1)}{42}$$
$$1^7 + 2^7 + 3^7 + \cdots + n^7 = \frac{n^2(n+1)^2(3n^4+6n^3-n^2-4n+2)}{24}$$

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 substring
 *  s[0..i] which is also a suffix of this substring.
 * Time complexity: O(|S|).
 */
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 Counting occurrences of each prefix

```cpp
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
}
```

4.3 Knuth–Morris–Pratt algorithm

```cpp
/**
 * Searching for a substring in a string.
 * Time complexity: O(N + M).
 */
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;
}
```

4.4 Suffix array

```cpp
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());
        s.pop_back();
```

```cpp
    }
    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) {
            // counting sort.
            for (int i = 0; i < n; ++i) norder[i] = (sa[i] - k + n) % n;
            for (int i = 0; i < n; ++i) 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, nv = v + k;
                if (nu >= n) nu -= n;
                if (nv >= n) nv -= 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; i < n; ++i) rank[sa[i]] = i;
        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;
        }
        // Note: lcp[i] = longest common prefix(sa[i - 1], sa[i]).
    }
};
```

4.5 Manacher's algorithm

```cpp
/**
 * 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 complexity: O(N).
 * Tested: https://judge.yosupo.jp/problem/enumerate_palindromes, stress-
   tested.
 */
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);
```

```
13        int l = 0, r = 0;
14        for (int i = 0; i < n; ++i) {
15            int mirror = l + r - i + z;
16            d[z][i] = (i > r ? 0 : min(d[z][mirror], r - i));
17            int L = i - d[z][i] - z, R = i + d[z][i];
18            while (L >= 0 && R < n && s[L] == s[R]) {
19                d[z][i]++; L--; R++;
20            }
21            if (R > r) {
22                l = L; r = R;
23            }
24        }
25    }
26    return d;
27 }
```

4.6   Trie

```
1 struct Trie {
2     const static int ALPHABET = 26;
3     const static char minChar = 'a';
4     struct Vertex {
5         int next[ALPHABET];
6         bool leaf;
7         Vertex() {
8             leaf = false;
9             fill(next, next + ALPHABET, -1);
10        }
11    };
12    vector<Vertex> trie;
13    Trie() { trie.emplace_back(); }
14
15    void insert(const string &s) {
16        int i = 0;
17        for (const char &ch : s) {
18            int j = ch - minChar;
19            if (trie[i].next[j] == -1) {
20                trie[i].next[j] = trie.size();
21                trie.emplace_back();
22            }
23            i = trie[i].next[j];
24        }
25        trie[i].leaf = true;
26    }
27    bool find(const string &s) {
28        int i = 0;
29        for (const char &ch : s) {
30            int j = ch - minChar;
31            if (trie[i].next[j] == -1) {
32                return false;
33            }
34            i = trie[i].next[j];
35        }
```

```
36        return (trie[i].leaf ? true : false);
37    }
38 };
```

4.7   Hashing

```
1 struct Hash61 {
2     static const uint64_t MOD = (1LL << 61) - 1;
3     static uint64_t BASE;
4     static vector<uint64_t> pw;
5     uint64_t addmod(uint64_t a, uint64_t b) const {
6         a += b;
7         if (a >= MOD) a -= MOD;
8         return a;
9     }
10    uint64_t submod(uint64_t a, uint64_t b) const {
11        a += MOD - b;
12        if (a >= MOD) a -= MOD;
13        return a;
14    }
15    uint64_t mulmod(uint64_t a, uint64_t b) const {
16        uint64_t low1 = (uint32_t) a, high1 = (a >> 32);
17        uint64_t low2 = (uint32_t) b, high2 = (b >> 32);
18
19        uint64_t low = low1 * low2;
20        uint64_t mid = low1 * high2 + low2 * high1;
21        uint64_t high = high1 * high2;
22
23        uint64_t ret = (low & MOD) + (low >> 61) + (high << 3) + (mid >>
   29) + (mid << 35 >> 3) + 1;
24        // ret %= MOD:
25        ret = (ret >> 61) + (ret & MOD);
26        ret = (ret >> 61) + (ret & MOD);
27        return ret - 1;
28    }
29    void ensure_pw(int m) {
30        int n = (int) pw.size();
31        if (n >= m) return;
32        pw.resize(m);
33        for (int i = n; i < m; ++i) {
34            pw[i] = mulmod(pw[i - 1], BASE);
35        }
36    }
37
38    vector<uint64_t> pref;
39    int n;
40    template<typename T> Hash61(const T &s) { // strings or arrays.
41        n = (int) s.size();
42        ensure_pw(n);
43        pref.resize(n + 1);
44        pref[0] = 0;
45        for (int i = 0; i < n; ++i) {
46            pref[i + 1] = addmod(mulmod(pref[i], BASE), s[i]);
```

```
47          }
48      }
49      inline uint64_t operator()(const int from, const int to) const {
50          assert(0 <= from && from <= to && to < n);
51          // pref[to + 1] - pref[from] * pw[to - from + 1]
52          return submod(pref[to + 1], mulmod(pref[from], pw[to - from + 1]));
53      }
54  };
55  mt19937 rng((unsigned int) chrono::steady_clock::now().time_since_epoch().
        count());
56  uint64_t Hash61::BASE = (MOD >> 2) + rng() % (MOD >> 1);
57  vector<uint64_t> Hash61::pw = vector<uint64_t>(1, 1);
```

5 Number Theory

5.1 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: $\sum\limits_{d|n} \phi(d) = n$.

  - $\phi(n)$ 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 $n = p_1^{k_1} \cdot p_2^{k_2} \cdots p_m^{k_m}$:

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

- 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 $n \geq \log_2 M$:

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

5.2 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:

  - $\sum\limits_{d|n} \mu(d) = [n = 1]$.

  - If a and b are **coprime**, then $\mu(ab) = \mu(a) \cdot \mu(b)$.

  - Mobius inversion: let f and g be arithmetic functions:

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

.

5.3 Primes

Approximating the number of primes up to n:

n	$\pi(n)$	$\dfrac{n}{\ln n - 1}$
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, $\dfrac{n}{\ln n - 1}$ is used to approximate $\pi(n)$).

5.4 Wilson's theorem

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

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

5.5 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:

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

```cpp
vector<int> zeckendoft_theorem(int n) {
    vector<int> fibs = {1, 1};
    int sz = 2;
    while (fibs.back() <= n) {
        fibs.push_back(fibs[sz - 1] + fibs[s - 2]);
        sz++;
    }
    fibs.pop_back();
    vector<int> nums;
    int p = sz - 1;
    while (n > 0) {
        if (n >= fibs[p]) {
            nums.push_back(fibs[p]);
            n -= fibs[p];
        }
        p--;
    }
    return nums;
}
```

5.6 Bitwise operation

- $a + b = (a \oplus b) + 2(a \mathbin{\&} b)$
- $a \mid b = (a \oplus b) + (a \mathbin{\&} b)$
- $a \mathbin{\&} (b \oplus c) = (a \mathbin{\&} b) \oplus (a \mathbin{\&} c)$
- $a \mid (b \mathbin{\&} c) = (a \mid b) \mathbin{\&} (a \mid c)$
- $a \mathbin{\&} (b \mid c) = (a \mathbin{\&} b) \mid (a \mathbin{\&} c)$

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

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

```cpp
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;
```
```cpp
    }
    // Time complexity: O(3^n).
}
```

5.7 Pollard's rho algorithm

```cpp
const int PRIME_MAX = (int) 4e4; // for handle numbers <= 1e9.
const int LIMIT = (int) 1e9;
vector<int> primes;

void linear_sieve(int n);
num_type mulmod(num_type a, num_type b, num_type mod);
num_type powmod(num_type a, num_type n, num_type mod);

bool miller_rabin(num_type a, num_type d, int s, num_type mod) {
    // mod - 1 = a ^ (d * 2^s).
    num_type x = powmod(a, d, mod);
    if (x == 1 || x == mod - 1) return true;
    for (int i = 1; i <= s - 1; ++i) {
        x = mulmod(x, x, mod);
        if (x == mod - 1) return true;
    }
    return false;
}
bool is_prime(num_type n, int ITERATION = 10) {
    if (n < 4) return (n == 2 || n == 3);
    if (n % 2 == 0 || n % 3 == 0) return false;
    num_type d = n - 1;
    int s = 0;
    while (d % 2 == 0) {
        d /= 2;
        s++;
    }
    for (int i = 0; i < ITERATION; ++i) {
        num_type a = (num_type) (rand() % (n - 2)) + 2;
        if (miller_rabin(a, d, s, n) == false) {
            return false;
        }
    }
    return true;
}
num_type f(num_type x, int c, num_type mod) { // f(x) = (x^2 + c) % mod.
    x = mulmod(x, x, mod);
    x += c;
    if (x >= mod) x -= mod;
    return x;
}
num_type pollard_rho(num_type n, int c) {
    // algorithm to find a random divisor of 'n'.
    // using random function: f(x) = (x^2 + c) % n.
    num_type x = 2, y = x, d;
    long long p = 1;
    int dist = 0;
```

```
48        while (true) {
49            y = f(y, c, n);
50            dist++;
51            d = __gcd(llabs(x - y), n);
52            if (d > 1) break;
53            if (dist == p) { dist = 0; p *= 2; x = y; }
54        }
55        return d;
56    }
57    void factorize(int n, vector<num_type> &factors);
58    void llfactorize(num_type n, vector<num_type> &factors) {
59        if (n < 2) return;
60        if (n < LIMIT) {
61            factorize(n, factors);
62            return;
63        }
64        if (is_prime(n)) {
65            factors.emplace_back(n);
66            return;
67        }
68        num_type d = n;
69        for (int c = 2; d == n; c++) {
70            d = pollard_rho(n, c);
71        }
72        llfactorize(d, factors);
73        llfactorize(n / d, factors);
74    }
75    vector<num_type> gen_divisors(vector<pair<num_type, int>> &factors) {
76        vector<num_type> divisors = {1};
77        for (auto &x : factors) {
78            int sz = (int) divisors.size();
79            for (int i = 0; i < sz; ++i) {
80                num_type cur = divisors[i];
81                for (int j = 0; j < x.second; ++j) {
82                    cur *= x.first;
83                    divisors.push_back(cur);
84                }
85            }
86        }
87        return divisors; // this array is NOT sorted yet.
88    }
```

5.8 Combinatorics

5.8.1 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 ($n = 0, 1, 2, \ldots, 12$):

$$C_n = 1, 1, 2, 5, 14, 42, 132, 429, 1430, 4862, 16796, 58786$$

- 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.

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

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

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

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

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

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

6 Linear algebra

6.1 Gauss elimination

```
1    const double EPS = 1e-9;
2    const int INF = 2; // it doesn't actually have to be infinity or a big
         number
3    int gauss (vector < vector<double> > a, vector<double> & ans) {
4        int n = (int) a.size();
5        int m = (int) a[0].size() - 1;
6        vector<int> where (m, -1);
7        for (int col=0, row=0; col<m && row<n; ++col) {
8            int sel = row;
9            for (int i=row; i<n; ++i)
10               if (abs (a[i][col]) > abs (a[sel][col]))
11                   sel = i;
12           if (abs (a[sel][col]) < EPS)
```

```
13          continue;
14      for (int i=col; i<=m; ++i)
15          swap (a[sel][i], a[row][i]);
16      where[col] = row;
17
18      for (int i=0; i<n; ++i)
19          if (i != row) {
20              double c = a[i][col] / a[row][col];
21              for (int j=col; j<=m; ++j)
22                  a[i][j] -= a[row][j] * c;
23          }
24      ++row;
25  }
26  ans.assign (m, 0);
27  for (int i=0; i<m; ++i)
28      if (where[i] != -1)
29          ans[i] = a[where[i]][m] / a[where[i]][i];
30  for (int i=0; i<n; ++i) {
31      double sum = 0;
32      for (int j=0; j<m; ++j)
33          sum += ans[j] * a[i][j];
34      if (abs (sum - a[i][m]) > EPS)
35          return 0;
36  }
37  for (int i=0; i<m; ++i)
38      if (where[i] == -1)
39          return INF;
40  return 1;
41 }
```

7   Geometry

7.1   Fundamentals

7.1.1   Point

```
1  const double PI = acos(-1);
2  const double EPS = 1e-9;
3  typedef double ftype;
4  struct point {
5      ftype x, y;
6      point(ftype _x = 0, ftype _y = 0): x(_x), y(_y) {}
7      point& operator+=(const point& other) {
8          x += other.x; y += other.y; return *this;
9      }
10     point& operator-=(const point& other) {
11         x -= other.x; y -= other.y; return *this;
12     }
13     point& operator*=(ftype t) {
14         x *= t; y *= t; return *this;
15     }
16     point& operator/=(ftype t) {
17         x /= t; y /= t; return *this;
```

```
18     }
19     point operator+(const point& other) const {
20         return point(*this) += other;
21     }
22     point operator-(const point& other) const {
23         return point(*this) -= other;
24     }
25     point operator*(ftype t) const {
26         return point(*this) *= t;
27     }
28     point operator/(ftype t) const {
29         return point(*this) /= t;
30     }
31     point rotate(double angle) const {
32         return point(x * cos(angle) - y * sin(angle), x * sin(angle) + y *
       cos(angle));
33     }
34     friend istream& operator>>(istream &in, point &t);
35     friend ostream& operator<<(ostream &out, const point& t);
36     bool operator<(const point& other) const {
37         if (fabs(x - other.x) < EPS)
38             return y < other.y;
39         return x < other.x;
40     }
41 };
42
43 istream& operator>>(istream &in, point &t) {
44     in >> t.x >> t.y;
45     return in;
46 }
47 ostream& operator<<(ostream &out, const point& t) {
48     out << t.x << ' ' << t.y;
49     return out;
50 }
51
52 ftype dot(point a, point b) {return a.x * b.x + a.y * b.y;}
53 ftype norm(point a) {return dot(a, a);}
54 ftype abs(point a) {return sqrt(norm(a));}
55 ftype angle(point a, point b) {return acos(dot(a, b) / (abs(a) * abs(b)));}
56 ftype proj(point a, point b) {return dot(a, b) / abs(b);}
57 ftype cross(point a, point b) {return a.x * b.y - a.y * b.x;}
58 bool ccw(point a, point b, point c) {return cross(b - a, c - a) > EPS;}
59 bool collinear(point a, point b, point c) {return fabs(cross(b - a, c - a))
        < EPS;}
60 point intersect(point a1, point d1, point a2, point d2) {
61     double t = cross(a2 - a1, d2) / cross(d1, d2);
62     return a1 + d1 * t;
63 }
```

7.1.2   Line

```
1  struct line {
2      double a, b, c;
```

```cpp
    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;
    }
}
```

7.1.3   Circle

```cpp
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;
}
```

7.1.4   Triangle

```cpp
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);
```

```
14      if (fabs(r) < EPS) return false;
15      line l1, l2;
16      double ratio = abs(p2 - p1) / abs(p3 - p1);
17      point p = p2 + (p3 - p2) * (ratio / (1 + ratio));
18      pointsToLine(p1, p, l1);
19      ratio = abs(p1 - p2) / abs(p2 - p3);
20      p = p1 + (p3 - p1) * ( ratio / (1 + ratio));
21      pointsToLine(p2, p, l2);
22      areIntersect(l1, l2, ctr);
23      return true;
24  }
25  double rCircumCircle(double ab, double bc, double ca) {
26      return ab * bc * ca / (4.0 * areaTriangle(ab, bc, ca));
27  }
28  double rCircumCircle(point a, point b, point c) {
29      return rCircumCircle(abs(b - a), abs(c - b), abs(a - c));
30  }
```

7.1.5 Convex hull

```
1  vector<point> CH_Andrew(vector<point> &Pts) { // overall O(n log n)
2      int n = Pts.size(), k = 0;
3      vector<point> H(2 * n);
4      sort(Pts.begin(), Pts.end());
5      for (int i = 0; i < n; ++i) {
6          while ((k >= 2) && !ccw(H[k - 2], H[k - 1], Pts[i])) --k;
7          H[k++] = Pts[i];
8      }
9      for (int i = n - 2, t = k + 1; i >= 0; --i) {
10          while ((k >= t) && !ccw(H[k - 2], H[k - 1], Pts[i])) --k;
11          H[k++] = Pts[i];
12      }
13      H.resize(k);
14      return H;
15  }
```

7.1.6 Polygon

```
1  double perimeter(const vector<point> &P) {
2      double ans = 0.0;
3      for (int i = 0; i < (int)P.size() - 1; ++i)
4          ans += abs(P[i] - P[i + 1]);
5      return ans;
6  }
7  double area(const vector<point> &P) {
8      double ans = 0.0;
9      for (int i = 0; i < (int)P.size() - 1; ++i)
10          ans += (P[i].x * P[i + 1].y - P[i + 1].x * P[i].y);
11      return fabs(ans) / 2.0;
12  }
13  bool isConvex(const vector<point> &P) {
14      int n = (int)P.size();
15      if (n <= 3) return false;
16      bool firstTurn = ccw(P[0], P[1], P[2]);
17      for (int i = 1; i < n - 1; ++i)
18          if (ccw(P[i], P[i + 1], P[(i + 2) == n ? 1 : i + 2]) != firstTurn)
19              return false;
20      return true;
21  }
22  int insidePolygon(point pt, const vector<point> &P) {
23      int n = (int)P.size();
24      if (n <= 3) return -1;
25      bool on_polygon = false;
26      for (int i = 0; i < n - 1; ++i)
27          if (fabs(abs(P[i] - pt) + abs(pt - P[i + 1]) - abs(P[i] - P[i + 1])
    ) < EPS)
28              on_polygon = true;
29      if (on_polygon) return 0;
30      double sum = 0.0;
31      for (int i = 0; i < n - 1; ++i) {
32          if (ccw(pt, P[i], P[i + 1]))
33              sum += angle(P[i] - pt, P[i + 1] - pt);
34          else
35              sum -= angle(P[i] - pt, P[i + 1] - pt);
36      }
37      return fabs(sum) > PI ? 1 : -1;
38  }
```

7.2 Minimum enclosing circle

```
1  /**
2   * Description: computes the minimum circle that encloses all the given
       points.
3   */
4  double abs(point a) { return sqrt(a.X * a.X + a.Y * a.Y); }
5
6  point center_from(double bx, double by, double cx, double cy) {
7      double B = bx * bx + by * by, C = cx * cx + cy * cy, D = bx * cy - by *
       cx;
8      return point((cy * B - by * C) / (2 * D), (bx * C - cx * B) / (2 * D));
9  }
10
11  circle circle_from(point A, point B, point C) {
12      point I = center_from(B.X - A.X, B.Y - A.Y, C.X - A.X, C.Y - A.Y);
13      return circle(I + A, abs(I));
14  }
15
16  const int N = 100005;
17  int n, x[N], y[N];
18  point a[N];
19
20  circle emo_welzl(int n, vector<point> T) {
21      if (T.size() == 3 || n == 0) {
22          if (T.size() == 0) return circle(point(0, 0), -1);
23          if (T.size() == 1) return circle(T[0], 0);
24          if (T.size() == 2) return circle((T[0] + T[1]) / 2, abs(T[0] - T
       [1]) / 2);
```

```
25          return circle_from(T[0], T[1], T[2]);
26      }
27      random_shuffle(a + 1, a + n + 1);
28      circle Result = emo_welzl(0, T);
29      for (int i = 1; i <= n; i++)
30          if (abs(Result.X - a[i]) > Result.Y + 1e-9) {
31              T.push_back(a[i]);
32              Result = emo_welzl(i - 1, T);
33              T.pop_back();
34          }
35      return Result;
36  }
```

8   Graph

8.1   Strongly connected components

```
1  /**
2   * Description: Tarjan's algorithm finds strongly connected components
3   *  in a directed graph. If vertices u and v belong to the same component,
4   *  then scc_id[u] == scc_id[v].
5   * Tested: https://judge.yosupo.jp/problem/scc
6   */
7  const int N = (int) 5e5;
8  vector<int> g[N], st;
9  int low[N], num[N], dfs_timer, scc_id[N], scc;
10 bool used[N];
11 void Tarjan(int u) {
12     low[u] = num[u] = ++dfs_timer;
13     st.push_back(u);
14     for (int v : g[u]) {
15         if (used[v]) continue;
16         if (num[v] == 0) {
17             Tarjan(v);
18             low[u] = min(low[u], low[v]);
19         }
20         else {
21             low[u] = min(low[u], num[v]);
22         }
23     }
24     if (low[u] == num[u]) {
25         int v;
26         do {
27             v = st.back(); st.pop_back();
28             debug(u, v)
29             used[v] = true;
30             scc_id[v] = scc;
31         } while (v != u);
32         scc++;
33     }
34 }
```

8.2   Topo sort

```
1  /**
2   * Description: A topological sort of a directed acyclic graph
3   *  is a linear ordering of its vertices such that for every directed edge
4   *  from vertex u to vertex v, u comes before v in the ordering.
5   * Note: If there are cycles, the returned list will have size smaller than
6          n (i.e, topo.size() < n).
6   * Tested: https://judge.yosupo.jp/problem/scc
7   */
8  vector<int> topo_sort(const vector<vector<int>> &g) {
9      int n = (int) g.size();
10     vector<int> indeg(n);
11     for (int u = 0; u < n; ++u) {
12         for (int v : g[u]) indeg[v]++;
13     }
14     queue<int> q; // Note: use min-heap to get the smallest lexicographical
        order.
15     for (int u = 0; u < n; ++u) {
16         if (indeg[u] == 0) q.emplace(u);
17     }
18     vector<int> topo;
19     while (!q.empty()) {
20         int u = q.front(); q.pop();
21         topo.emplace_back(u);
22         for (int v : g[u]) {
23             if (--indeg[v] == 0) q.emplace(v);
24         }
25     }
26     return topo;
27 }
```

8.3   K-th smallest shortest path

```
1  /** Finding the k-th smallest shortest path from vertex s to vertex t,
2   *  each vertex can be visited more than once.
3   */
4  using adj_list = vector<vector<pair<int, int>>>;
5  vector<int> k_smallest(const adj_list &g, int k, int s, int t) {
6      int n = (int) g.size();
7      vector<long long> ans;
8      vector<int> cnt(n);
9      using pli = pair<long long, int>;
10     priority_queue<pli, vector<pli>, greater<pli>> pq;
11     pq.emplace(0, s);
12     while (!pq.empty() && cnt[t] < k) {
13         int u = pq.top().second;
14         long long d = pq.top().first;
15         pq.pop();
16         if (cnt[u] == k) continue;
17         cnt[u]++;
18         if (u == t) {
19             ans.push_back(d);
```

```
20        }
21        for (auto [v, cost] : g[u]) {
22            pq.emplace(d + cost, v);
23        }
24    }
25    assert(ans.size() == k);
26    return ans;
27 }
```

8.4 Eulerian path

8.4.1 Directed graph

```
1  /**
2   * Hierholzer's algorithm.
3   * Description: An Eulerian path in a directed graph is a path that visits
        all edges exactly once.
4   *  An Eulerian cycle is a Eulerian path that is a cycle.
5   * Time complexity: O(|E|).
6   */
7  vector<int> find_path_directed(const vector<vector<int>> &g, int s) {
8      int n = (int) g.size();
9      vector<int> stack, cur_edge(n), vertices;
10     stack.push_back(s);
11     while (!stack.empty()) {
12         int u = stack.back();
13         stack.pop_back();
14         while (cur_edge[u] < (int) g[u].size()) {
15             stack.push_back(u);
16             u = g[u][cur_edge[u]++];
17         }
18         vertices.push_back(u);
19     }
20     reverse(vertices.begin(), vertices.end());
21     return vertices;
22 }
```

8.4.2 Undirected graph

```
1  /**
2   * Hierholzer's algorithm.
3   * Description: An Eulerian path in a undirected graph is a path that
        visits all edges exactly once.
4   *  An Eulerian cycle is a Eulerian path that is a cycle.
5   * Time complexity: O(|E|).
6   */
7  struct Edge {
8      int to;
9      list<Edge>::iterator reverse_edge;
10     Edge(int _to) : to(_to) {}
11 };
12 vector<int> vertices;
13 void find_path(vector<list<Edge>> &g, int u) {
14     while (!g[u].empty()) {
```

```
15            int v = g[u].front().to;
16            g[v].erase(g[u].front().reverse_edge);
17            g[u].pop_front();
18            find_path(g, v);
19        }
20        vertices.emplace_back(u); // reversion list.
21 }
22 void add_edge(int u, int v) {
23     g[u].emplace_front(v);
24     g[v].emplace_front(u);
25     g[u].front().reverse_edge = g[v].begin();
26     g[v].front().reverse_edge = g[u].begin();
27 }
```

9 Misc.

9.1 Ternary search

```
1  const double eps = 1e-9;
2  double ternary_search_max(double l, double r) {
3      // find x0 such that: f(x0) > f(x), \all x: l <= x <= r.
4      while (r - l > eps) {
5          double mid1 = l + (r - l) / 3;
6          double mid2 = r - (r - l) / 3;
7          if (f(mid1) < f(mid2)) l = mid1;
8          else r = mid2;
9      }
10     return l;
11 }
12 double ternary_search_min(double l, double r) {
13     // find x0 such that: f(x0) < f(x), \all x: l <= x <= r.
14     while (r - l > eps) {
15         double mid1 = l + (r - l) / 3;
16         double mid2 = r - (r - l) / 3;
17         if (f(mid1) > f(mid2)) l = mid1;
18         else r = mid2;
19     }
20     return l;
21 }
```

9.2 Dutch flag national problem

```
1  void dutch_flag_national(vector<int> &arr) {
2      // All elements that are LESS than pivot are moved to the LEFT.
3      // All elements that are GREATER than pivot are moved to the RIGHT.
4      // E.g. [1, 2, 0, 0, 2, 2, 1], pivot = 1 -> [0, 0, 1, 1, 2, 2, 2].
5      int n = (int) arr.size();
6      int i = 0, j = 0, k = n - 1;
7      int pivot = 1;
8      // 0....i....j....k....n
9      while (j <= k) {
10         if (arr[j] < pivot) {
11             swap(arr[i], arr[j]);
```

```
12            i++;
13            j++;
14        }
15        else if (arr[j] > pivot) {
16            swap(arr[j], arr[k]);
17            k--;
18        }
19        else {
20            j++;
21        }
22    }
23    // 0 <= index <= i - 1: arr[index] < mid.
24    // i <= index <= k: arr[index] = mid.
25    // k + 1 <= index < sz: arr[index] > mid.
26 }
```

9.3 Matrix

```
1  struct Matrix {
2      static const matrix_type INF = numeric_limits<matrix_type>::max();
3      int N, M;
4      vector<vector<matrix_type>> mat;
5
6      Matrix(int _N, int _M, matrix_type v = 0) : N(_N), M(_M) {
7          mat.assign(N, vector<matrix_type>(M, v));
8      }
9      static Matrix identity(int n) { // return identity matrix.
10         Matrix I(n, n);
11         for (int i = 0; i < n; ++i) {
12             I[i][i] = 1;
13         }
14         return I;
15     }
16
17     vector<matrix_type>& operator[](int r) { return mat[r]; }
18     const vector<matrix_type>& operator[](int r) const { return mat[r]; }
19
20     Matrix& operator*=(const Matrix &other) {
21         assert(M == other.N); // [N x M] [other.N x other.M]
22         Matrix res(N, other.M);
23         for (int r = 0; r < N; ++r) {
24             for (int c = 0; c < other.M; ++c) {
25                 long long square_mod = (long long) MOD * MOD;
26                 long long sum = 0;
27                 for (int g = 0; g < M; ++g) {
28                     sum += (long long) mat[r][g] * other[g][c];
29                     if (sum >= square_mod) sum -= square_mod;
30                 }
31                 res[r][c] = sum % MOD;
32             }
33         }
34         mat.swap(res.mat); return *this;
35     }
36 };
```