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1 Setup

1.1 header.h

```
1 #pragma once // Delete this when copying this
file
```

```
2 #include <bits/stdc++.h>
3 using namespace std;
4
5 #define ll long long
6 #define ull unsigned ll
7 #define ld long double
8 #define pl pair<ll, ll>
9 #define pi pair<int, int> // use pl where
```

```
possible/necessary
10 #define vl vector<ll>
11 #define vi vector<int> // change to vl where
possible/necessary
12 #define vb vector<bool>
13 #define vvi vector<vi>
14 #define vvl vector<vl>
15 #define vpl vector<pl>
```

```

16 #define vpi vector<pi>
17 #define vld vector<ld>
18 #define vvpi vector<vpi>
19 #define in_fast(el, cont) (cont.find(el) != cont.
    end())
20 #define in(el, cont) (find(cont.begin(), cont.end
    (), el) != cont.end())
21 #define all(x) x.begin(), x.end()
22 #define rall(x) x.rbegin(), x.rend()
23
24 constexpr int INF = 20000000010;
25 constexpr ll LLINF = 900000000000000000010LL;
26
27 // int main() {
28 //   ios::sync_with_stdio(false); // do not use
    cout + printf
29 //   cin.tie(NULL);
30 //   cout << fixed << setprecision(12);
31 //   return 0;
32 // }
```

1.2 Bash for c++ compile with header.h

```

1 #!/bin/bash
2 if [ $# -ne 1 ];then echo "Usage: $0 <input_file
    >"; exit 1;fi
3 f="$1";d=code;/o=a.out
4 [ -f $d/$f ] || { echo "Input file not found: $f
    "; exit 1; }
5 g++ -I$d $d/$f -o $o && echo "Compilation
    successful. Executable '$o' created." || echo
    "Compilation failed."
```

1.3 Bash for run tests c++

```

1 g++ $1/$1.cpp -o $1/$1.out
2 for file in $1/*.in; do diff <($1/$1.out < "$file
    ") "${file%.in}.ans"; done
```

1.4 Bash for run tests python

```

1 for file in $1/*.in; do diff <(python3 $1/$1.py <
    "$file") "${file%.in}.ans"; done
```

1.4.1 Aux. helper C++

```

1 #include "header.h"
2
3 int main() {
4     // Read in a line including white space
5     string line;
6     getline(cin, line);
7     // When doing the above read numbers as
    follows:
8     int n;
9     getline(cin, line);
10    stringstream ss(line);
11    ss >> n;
12
13    // Count the number of 1s in binary
    represnatation of a number
14    ull number;
15    __builtin_popcountll(number);
16 }
17
18 // __int128
19 using lll = __int128;
20 ostream& operator<< (ostream& o, __int128 n) {
21     auto t = n<0 ? -n : n; char b[128], *d = end(b)
    ;
22     do *--d = '0'+t%10, t /= 10; while (t);
23     if(n<0) *--d = '-';
24     o.rdbuf()->sputn(d,end(b)-d);
25     return o;
26 }
```

1.4.2 Aux. helper python

```

1 from functools import lru_cache
2
3 # Read until EOF
4 while True:
5     try:
6         pattern = input()
7     except EOFError:
8         break
9
10 @lru_cache(maxsize=None)
11 def smth_memoi(i, j, s):
12     # Example in-built cache
13     return "sol"
14
15 # Fast I
16 import io, os
17 def fast_io():
18     finput = io.BytesIO(os.read(0,
19         os.fstat(0).st_size)).readline
20     s = finput().decode()
21     return s
```

```

22
23 # Fast O
24 import sys
25 def fast_out():
26     n = 5
27     sys.stdout.write(str(n)+"\n")
```

2 Python

2.1 Graphs

2.1.1 BFS

```

1 from collections import deque
2 def bfs(g, roots, n):
3     q = deque(roots)
4     explored = set()
5     distances = [0 if v in roots else float('inf'
        ) for v in range(n)]
6
7     while len(q) != 0:
8         node = q.popleft()
9         if node in explored: continue
10        explored.add(node)
11        for neigh in g[node]:
12            if neigh not in explored:
13                q.append(neigh)
14                distances[neigh] = distances[node
                    ] + 1
15    return distances
```

2.1.2 Dijkstra

```

1 from heapq import *
2 def dijkstra(n, root, g): # g = {node: (cost,
    neigh)}
3     dist = [float("inf")]*n
4     dist[root] = 0
5     prev = [-1]*n
6
7     pq = [(0, root)]
8     heapify(pq)
9     visited = set([])
10
11    while len(pq) != 0:
12        _, node = heappop(pq)
13
14        if node in visited: continue
15        visited.add(node)
16
17    # In case of disconnected graphs
```

```

18 if node not in g:
19     continue
20
21 for cost, neigh in g[node]:
22     alt = dist[node] + cost
23     if alt < dist[neigh]:
24         dist[neigh] = alt
25         prev[neigh] = node
26         heappush(pq, (alt, neigh))
27 return dist

```

2.1.3 Topological Sort

```

1 #Python program to print topological sorting of a
  DAG
2 from collections import defaultdict
3
4 #Class to represent a graph
5 class Graph:
6     def __init__(self,vertices):
7         self.graph = defaultdict(list) #
          dictionary containing adjacency List
8         self.V = vertices #No. of vertices
9
10    # function to add an edge to graph
11    def addEdge(self,u,v):
12        self.graph[u].append(v)
13
14    # A recursive function used by
      topologicalSort
15    def topologicalSortUtil(self,v,visited,stack)
      :
16
17        # Mark the current node as visited.
18        visited[v] = True
19
20        # Recur for all the vertices adjacent to
          this vertex
21        for i in self.graph[v]:
22            if visited[i] == False:
23                self.topologicalSortUtil(i,
                    visited,stack)
24
25        # Push current vertex to stack which
          stores result
26        stack.insert(0,v)
27
28    # The function to do Topological Sort. It
      uses recursive
29    # topologicalSortUtil()
30    def topologicalSort(self):
31        # Mark all the vertices as not visited
32        visited = [False]*self.V
33        stack =[]

```

```

34
35    # Call the recursive helper function to
      store Topological
36    # Sort starting from all vertices one by
      one
37    for i in range(self.V):
38        if visited[i] == False:
39            self.topologicalSortUtil(i,
                visited,stack)
40
41    # Print contents of stack
42    return stack
43
44    def isCyclicUtil(self, v, visited, recStack):
45
46        # Mark current node as visited and
          # adds to recursion stack
47        visited[v] = True
48        recStack[v] = True
49
50
51        # Recur for all neighbours
52        # if any neighbour is visited and in
          # recStack then graph is cyclic
53        for neighbour in self.graph[v]:
54            if visited[neighbour] == False:
55                if self.isCyclicUtil(neighbour,
                    visited, recStack) == True:
56                    return True
57            elif recStack[neighbour] == True:
58                return True
59
60
61        # The node needs to be popped from
          # recursion stack before function ends
62        recStack[v] = False
63        return False
64
65    # Returns true if graph is cyclic else false
66    def isCyclic(self):
67        visited = [False] * (self.V + 1)
68        recStack = [False] * (self.V + 1)
69        for node in range(self.V):
70            if visited[node] == False:
71                if self.isCyclicUtil(node,
                    visited, recStack) == True:
72                    return True
73
74        return False

```

2.1.4 Kruskal (UnionFind)

```

1 class UnionFind:
2     def __init__(self, n):
3         self.parent = [-1]*n
4
5     def find(self, x):

```

```

6         if self.parent[x] < 0:
7             return x
8         self.parent[x] = self.find(self.parent[x]
          ])
9         return self.parent[x]
10
11    def connect(self, a, b):
12        ra = self.find(a)
13        rb = self.find(b)
14        if ra == rb:
15            return False
16        if self.parent[ra] > self.parent[rb]:
17            self.parent[rb] += self.parent[ra]
18            self.parent[ra] = rb
19        else:
20            self.parent[ra] += self.parent[rb]
21            self.parent[rb] = ra
22        return True
23
24    # Full MST is len(spanning)==n-1
25    def kruskal(n, edges):
26        uf = UnionFind(n)
27        spanning = []
28        edges.sort(key = lambda d: -d[2])
29        while edges and len(spanning) < n-1:
30            u, v, w = edges.pop()
31            if not uf.connect(u, v):
32                continue
33            spanning.append((u, v, w))
34        return spanning
35
36    # Example
37    edges = [(1, 2, 10), (2, 3, 20)]

```

2.2 Num. Th. / Comb.

2.2.1 nCk % prime

```

1 # Note: p must be prime and k < p
2 def fermat_binom(n, k, p):
3     if k > n:
4         return 0
5     # calculate numerator
6     num = 1
7     for i in range(n-k+1, n+1):
8         num *= i % p
9     num %= p
10    # calculate denominator
11    denom = 1
12    for i in range(1,k+1):
13        denom *= i % p
14    denom %= p
15    # numerator * denominator^(p-2) (mod p)
16    return (num * pow(denom, p-2, p)) % p

```

2.2.2 Sieve of E. $O(n)$ so actually faster than C++ version, but more memory

```

1 MAX_SIZE = 10**8+1
2 isprime = [True] * MAX_SIZE
3 prime = []
4 SPF = [None] * (MAX_SIZE)
5
6 def manipulated_seive(N): # Up to N (not
    included)
7     isprime[0] = isprime[1] = False
8     for i in range(2, N):
9         if isprime[i] == True:
10             prime.append(i)
11             SPF[i] = i
12             j = 0
13             while (j < len(prime) and
14                    i * prime[j] < N and
15                    prime[j] <= SPF[i]):
16                 isprime[i * prime[j]] = False
17                 SPF[i * prime[j]] = prime[j]
18                 j += 1

```

2.3 Strings

2.3.1 LCS

```

1 def longestCommonSubsequence(text1, text2): # 0(
    m*n) time, 0(m) space
2     n = len(text1)
3     m = len(text2)
4
5     # Initializing two lists of size m
6     prev = [0] * (m + 1)
7     cur = [0] * (m + 1)
8
9     for idx1 in range(1, n + 1):
10         for idx2 in range(1, m + 1):
11             # If characters are matching
12             if text1[idx1 - 1] == text2[idx2 -
13                 1]:
14                 cur[idx2] = 1 + prev[idx2 - 1]
15             else:
16                 # If characters are not matching
17                 cur[idx2] = max(cur[idx2 - 1],
18                                prev[idx2])
19
20     prev = cur.copy()
21
22     return cur[m]

```

2.3.2 KMP

```

1 class KMP:
2     def partial(self, pattern):
3         """ Calculate partial match table: String
4             -> [Int]"""
5         ret = [0]
6         for i in range(1, len(pattern)):
7             j = ret[i - 1]
8             while j > 0 and pattern[j] != pattern
9                 [i]: j = ret[j - 1]
10            ret.append(j + 1 if pattern[j] ==
11                pattern[i] else j)
12        return ret
13
14    def search(self, T, P):
15        """KMP search main algorithm: String ->
16            String -> [Int]
17        Return all the matching position of
18        pattern string P in T"""
19        partial, ret, j = self.partial(P), [], 0
20        for i in range(len(T)):
21            while j > 0 and T[i] != P[j]: j =
22                partial[j - 1]
23            if T[i] == P[j]: j += 1
24            if j == len(P):
25                ret.append(i - (j - 1))
26                j = partial[j - 1]
27        return ret

```

2.3.3 Edit distance

```

1 def editDistance(str1, str2):
2     # Get the lengths of the input strings
3     m = len(str1)
4     n = len(str2)
5
6     # Initialize a list to store the current row
7     curr = [0] * (n + 1)
8
9     # Initialize the first row with values from 0
10    to n
11    for j in range(n + 1):
12        curr[j] = j
13
14    # Initialize a variable to store the previous
15    value
16    previous = 0
17
18    # Loop through the rows of the dynamic
19    programming matrix
20    for i in range(1, m + 1):
21        # Store the current value at the beginning of
22        the row
23        previous = curr[0]
24        curr[0] = i

```

```

21
22 # Loop through the columns of the dynamic
23 programming matrix
24 for j in range(1, n + 1):
25     # Store the current value in a temporary
26     variable
27     temp = curr[j]
28
29     # Check if the characters at the current
30     positions in str1 and str2 are the same
31     if str1[i - 1] == str2[j - 1]:
32         curr[j] = previous
33     else:
34         # Update the current cell with the
35         minimum of the three adjacent cells
36         curr[j] = 1 + min(previous, curr[j - 1],
37                            curr[j])
38
39     # Update the previous variable with the
40     temporary value
41     previous = temp
42
43 # The value in the last cell represents the
44 minimum number of operations
45 return curr[n]

```

2.3.4 Bitstring Slower than a set for many elements, but hashable

```

1 def add_element(bit_string, index):
2     return bit_string | (1 << index)
3
4 def remove_element(bit_string, index):
5     return bit_string & ~(1 << index)
6
7 def contains_element(bit_string, index):
8     return (bit_string & (1 << index)) != 0

```

2.4 Other Algorithms

2.4.1 Rotate matrix

```

1 def rotate_matrix(m):
2     return [[m[j][i] for j in range(len(m))] for
3             i in range(len(m[0])-1,-1,-1)]

```

2.5 Geometry

2.5.1 Convex Hull

```

1 def vec(a,b):
2     return (b[0]-a[0],b[1]-a[1])
3 def det(a,b):
4     return a[0]*b[1] - b[0]*a[1]
5
6 def convexhull(P):
7     if (len(P) == 1):
8         return [(p[0][0], p[0][1])]
9
10    h = sorted(P)
11    lower = []
12    i = 0
13    while i < len(h):
14        if len(lower) > 1:
15            a = vec(lower[-2], lower[-1])
16            b = vec(lower[-1], h[i])
17            if det(a,b) <= 0 and len(lower) > 1:
18                lower.pop()
19                continue
20        lower.append(h[i])
21        i += 1
22
23    upper = []
24    i = 0
25    while i < len(h):
26        if len(upper) > 1:
27            a = vec(upper[-2], upper[-1])
28            b = vec(upper[-1], h[i])
29            if det(a,b) >= 0:
30                upper.pop()
31                continue
32        upper.append(h[i])
33        i += 1
34
35    reversedupper = list(reversed(upper[1:-1]))
36    reversedupper.extend(lower)
37    return reversedupper

```

2.5.2 Geometry

```

1
2 def vec(a,b):
3     return (b[0]-a[0],b[1]-a[1])
4
5 def det(a,b):
6     return a[0]*b[1] - b[0]*a[1]
7
8     lower = []
9     i = 0
10    while i < len(h):
11        if len(lower) > 1:
12            a = vec(lower[-2], lower[-1])
13            b = vec(lower[-1], h[i])
14            if det(a,b) <= 0 and len(lower) > 1:

```

```

15        lower.pop()
16        continue
17        lower.append(h[i])
18        i += 1
19
20    # find upper hull
21    # det <= 0 -> replace
22    upper = []
23    i = 0
24    while i < len(h):
25        if len(upper) > 1:
26            a = vec(upper[-2], upper[-1])
27            b = vec(upper[-1], h[i])
28            if det(a,b) >= 0:
29                upper.pop()
30                continue
31        upper.append(h[i])
32        i += 1

```

2.6 Other Data Structures

2.6.1 Segment Tree

```

1 N = 100000 # limit for array size
2 tree = [0] * (2 * N) # Max size of tree
3
4 def build(arr, n): # function to build the tree
5     # insert leaf nodes in tree
6     for i in range(n):
7         tree[n + i] = arr[i]
8
9     # build the tree by calculating parents
10    for i in range(n - 1, 0, -1):
11        tree[i] = tree[i << 1] + tree[i << 1 | 1]
12
13 def updateTreeNode(p, value, n): # function to
14     update a tree node
15     # set value at position p
16     tree[p + n] = value
17     p = p + n
18
19     i = p # move upward and update parents
20     while i > 1:
21         tree[i >> 1] = tree[i] + tree[i >> 1]
22         i >>= 1
23
24 def query(l, r, n): # function to get sum on
25     interval [l, r]
26     res = 0
27     # loop to find the sum in the range
28     l += n
29     r += n
30     while l < r:
31         if l & 1:

```

```

30         res += tree[l]
31         l += 1
32     if r & 1:
33         r -= 1
34         res += tree[r]
35     l >>= 1
36     r >>= 1
37     return res

```

2.6.2 Trie

```

1 class TrieNode:
2     def __init__(self):
3         self.children = [None]*26
4         self.isEndOfWord = False
5
6 class Trie:
7     def __init__(self):
8         self.root = self.getNode()
9
10    def getNode(self):
11        return TrieNode()
12
13    def _charToIndex(self,ch):
14        return ord(ch)-ord('a')
15
16    def insert(self,key):
17        pCrawl = self.root
18        length = len(key)
19        for level in range(length):
20            index = self._charToIndex(key[level])
21            if not pCrawl.children[index]:
22                pCrawl.children[index] = self.
23                    getNode()
24            pCrawl = pCrawl.children[index]
25            pCrawl.isEndOfWord = True
26
27    def search(self, key):
28        pCrawl = self.root
29        length = len(key)
30        for level in range(length):
31            index = self._charToIndex(key[level])
32            if not pCrawl.children[index]:
33                return False
34            pCrawl = pCrawl.children[index]
35
36        return pCrawl.isEndOfWord

```

3.1 Graphs

3.1.1 BFS

```

1 #include "header.h"
2 #define graph unordered_map<ll, unordered_set<ll>>
3 vi bfs(int n, graph& g, vi& roots) {
4     vi parents(n+1, -1); // nodes are 1..n
5     unordered_set<int> visited;
6     queue<int> q;
7     for (auto x: roots) {
8         q.emplace(x);
9         visited.insert(x);
10    }
11    while (not q.empty()) {
12        int node = q.front();
13        q.pop();
14
15        for (auto neigh: g[node]) {
16            if (not in(neigh, visited)) {
17                parents[neigh] = node;
18                q.emplace(neigh);
19                visited.insert(neigh);
20            }
21        }
22    }
23    return parents;
24 }
25 vi reconstruct_path(vi parents, int start, int
    goal) {
26     vi path;
27     int curr = goal;
28     while (curr != start) {
29         path.push_back(curr);
30         if (parents[curr] == -1) return vi(); //
            No path, empty vi
31         curr = parents[curr];
32     }
33     path.push_back(start);
34     reverse(path.begin(), path.end());
35     return path;
36 }
```

3.1.2 DFS Cycle detection / removal

```

1 #include "header.h"
2 void removeCyc(ll node, unordered_map<ll, vector<
    pair<ll, ll>>& neighs, vector<bool>& visited
3 vector<bool>& recStack, vector<ll>& ans) {
4     if (!visited[node]) {
5         visited[node] = true;
6         recStack[node] = true;
```

```

7         auto it = neighs.find(node);
8         if (it != neighs.end()) {
9             for (auto util: it->second) {
10                 ll nnode = util.first;
11                 if (recStack[nnode]) {
12                     ans.push_back(util.second);
13                 } else if (!visited[nnode]) {
14                     removeCyc(nnode, neighs,
15                             visited, recStack, ans);
16                 }
17             }
18         }
19         recStack[node] = false;
20 }
```

3.1.3 Dijkstra

```

1 #include "header.h"
2 vector<int> dijkstra(int n, int root, map<int,
    vector<pair<int, int>>& g) {
3     unordered_set<int> visited;
4     vector<int> dist(n, INF);
5     priority_queue<pair<int, int>> pq;
6     dist[root] = 0;
7     pq.push({0, root});
8     while (!pq.empty()) {
9         int node = pq.top().second;
10        int d = -pq.top().first;
11        pq.pop();
12
13        if (in(node, visited)) continue;
14        visited.insert(node);
15
16        for (auto e : g[node]) {
17            int neigh = e.first;
18            int cost = e.second;
19            if (dist[neigh] > dist[node] + cost) {
20                dist[neigh] = dist[node] + cost;
21                pq.push({-dist[neigh], neigh});
22            }
23        }
24    }
25    return dist;
26 }
```

3.1.4 Floyd-Warshall

```

1 #include "header.h"
2 // g[i][j] = infity if not path from i to j
3 // if g[i][i] < 0, i is contained in a negative
    cycle
```

```

4 void warshall(vvl g) {
5     for (int i=0; i<g.size(); ++i) {
6         for (int j=0; j<g.size(); ++j) {
7             for (int k=0; k<g.size(); ++k) {
8                 if (g[i][k] < LLINF and g[k][j] <
                    LLINF and g[i][j] > g[i][k]
9                     + g[k][j]) {
10                    g[i][j] = g[i][k] + g[k][j];
11                }
12            }
13        }
14    }
```

3.1.5 Kruskal Minimum spanning tree of undirected weighted graph

```

1 #include "header.h"
2 #include "disjoint_set.h"
3 // O(E log E)
4 pair<set<pair<ll, ll>>, ll> kruskal(vector<tuple
    <ll, ll, ll>>& edges, ll n) {
5     set<pair<ll, ll>> ans;
6     ll cost = 0;
7
8     sort(edges.begin(), edges.end());
9     DisjointSet<ll> fs(n);
10
11     ll dist, i, j;
12     for (auto edge: edges) {
13         dist = get<0>(edge);
14         i = get<1>(edge);
15         j = get<2>(edge);
16
17         if (fs.find_set(i) != fs.find_set(j)) {
18             fs.union_sets(i, j);
19             ans.insert({i, j});
20             cost += dist;
21         }
22     }
23     return pair<set<pair<ll, ll>>, ll> {ans, cost
24 }
```

3.1.6 Hungarian algorithm

```

1 #include "header.h"
2
3 template <class T> bool ckmin(T &a, const T &b) {
4     return b < a ? a = b, 1 : 0; }
5
6 /**
7  * Given J jobs and W workers (J <= W), computes
8  * the minimum cost to assign each
9  * prefix of jobs to distinct workers.
10 * @tparam T a type large enough to represent
11 * integers on the order of J *
12 * max(|C|)
```

```

9  * @param C a matrix of dimensions JxW such that
    C[j][w] = cost to assign j-th
10 * job to w-th worker (possibly negative)
11 *
12 * @return a vector of length J, with the j-th
    entry equaling the minimum cost
13 * to assign the first (j+1) jobs to distinct
    workers
14 */
15 template <class T> vector<T> hungarian(const
    vector<vector<T>> &C) {
16     const int J = (int)size(C), W = (int)size(C
        [0]);
17     assert(J <= W);
18     // job[w] = job assigned to w-th worker, or
        -1 if no job assigned
19     // note: a W-th worker was added for
        convenience
20     vector<int> job(W + 1, -1);
21     vector<T> ys(J), yt(W + 1); // potentials
22     // -yt[W] will equal the sum of all deltas
23     vector<T> answers;
24     const T inf = numeric_limits<T>::max();
25     for (int j_cur = 0; j_cur < J; ++j_cur) { //
        assign j_cur-th job
26         int w_cur = W;
27         job[w_cur] = j_cur;
28         // min reduced cost over edges from Z to
            worker w
29         vector<T> min_to(W + 1, inf);
30         vector<int> prv(W + 1, -1); // previous
            worker on alternating path
31         vector<bool> in_Z(W + 1); // whether
            worker is in Z
32         while (job[w_cur] != -1) { // runs at
            most j_cur + 1 times
33             in_Z[w_cur] = true;
34             const int j = job[w_cur];
35             T delta = inf;
36             int w_next;
37             for (int w = 0; w < W; ++w) {
38                 if (!in_Z[w]) {
39                     if (ckmin(min_to[w], C[j][w]
                        - ys[j] - yt[w]))
                        prv[w] = w_cur;
40                     if (ckmin(delta, min_to[w]))
                        w_next = w;
41                 }
42             }
43             // delta will always be non-negative,
44             // except possibly during the first
                time this loop runs
45             // if any entries of C[j_cur] are
                negative
46             for (int w = 0; w <= W; ++w) {

```

```

48         if (in_Z[w]) ys[job[w]] += delta,
            yt[w] -= delta;
49         else min_to[w] -= delta;
50     }
51     w_cur = w_next;
52 }
53 // update assignments along alternating
    path
54 for (int w; w_cur != W; w_cur = w) job[
    w_cur] = job[w = prv[w_cur]];
55 answers.push_back(-yt[W]);
56 }
57 return answers;
58 }

```

3.1.7 Suc. shortest path Calculates max flow, min cost

```

1 #include "header.h"
2 // map<node, map<node, pair<cost, capacity>>>
3 #define graph unordered_map<int, unordered_map<
    int, pair<ld, int>>>
4 graph g;
5 const ld infity = 1e60l; // Change if necessary
6 ld fill(int n, vld& potential) { // Finds max
    flow, min cost
7     priority_queue<pair<ld, int>> pq;
8     vector<bool> visited(n+2, false);
9     vi parent(n+2, 0);
10    vld dist(n+2, infity);
11    dist[0] = 0.1;
12    pq.emplace(make_pair(0.1, 0));
13    while (not pq.empty()) {
14        int node = pq.top().second;
15        pq.pop();
16        if (visited[node]) continue;
17        visited[node] = true;
18        for (auto& x : g[node]) {
19            int neigh = x.first;
20            int capacity = x.second.second;
21            ld cost = x.second.first;
22            if (capacity and not visited[neigh]) {
23                ld d = dist[node] + cost + potential[node]
                    - potential[neigh];
24                if (d + 1e-10l < dist[neigh]) {
25                    dist[neigh] = d;
26                    pq.emplace(make_pair(-d, neigh));
27                    parent[neigh] = node;
28                }
29            }
30        }
31        for (int i = 0; i < n+2; i++) {
32            potential[i] = min(infity, potential[i] + dist
                [i]);
33        }

```

```

33     if (not parent[n+1]) return infity;
34     ld ans = 0.1;
35     for (int x = n+1; x; x=parent[x]) {
36         ans += g[parent[x]][x].first;
37         g[parent[x]][x].second--;
38         g[x][parent[x]].second++;
39     }
40     return ans;
41 }

```

3.1.8 Bipartite check

```

1 #include "header.h"
2 int main() {
3     int n;
4     vvi adj(n);
5
6     vi side(n, -1); // will have 0's for one
        side 1's for other side
7     bool is_bipartite = true; // becomes false
        if not bipartite
8     queue<int> q;
9     for (int st = 0; st < n; ++st) {
10        if (side[st] == -1) {
11            q.push(st);
12            side[st] = 0;
13            while (!q.empty()) {
14                int v = q.front();
15                q.pop();
16                for (int u : adj[v]) {
17                    if (side[u] == -1) {
18                        side[u] = side[v] ^ 1;
19                        q.push(u);
20                    } else {
21                        is_bipartite &= side[u]
                            != side[v];
22                    }
23                }

```

3.1.9 Find cycle directed

```

1 #include "header.h"
2 int n;
3 const int mxN = 2e5+5;
4 vvi adj(mxN);
5 vector<char> color;
6 vi parent;
7 int cycle_start, cycle_end;
8 bool dfs(int v) {
9     color[v] = 1;
10    for (int u : adj[v]) {
11        if (color[u] == 0) {
12            parent[u] = v;

```



```

13     if (dfs(u)) return true;
14 } else if (color[u] == 1) {
15     cycle_end = v;
16     cycle_start = u;
17     return true;
18 }
19 }
20 color[v] = 2;
21 return false;
22 }
23 void find_cycle() {
24     color.assign(n, 0);
25     parent.assign(n, -1);
26     cycle_start = -1;
27     for (int v = 0; v < n; v++) {
28         if (color[v] == 0 && dfs(v)) break;
29     }
30     if (cycle_start == -1) {
31         cout << "Acyclic" << endl;
32     } else {
33         vector<int> cycle;
34         cycle.push_back(cycle_start);
35         for (int v = cycle_end; v != cycle_start;
36             v = parent[v])
37             cycle.push_back(v);
38         cycle.push_back(cycle_start);
39         reverse(cycle.begin(), cycle.end());
40
41         cout << "Cycle Found: ";
42         for (int v : cycle) cout << v << " ";
43         cout << endl;
44     }

```

3.1.10 Find cycle undirected

```

1 #include "header.h"
2 int n;
3 const int mxN = 2e5 + 5;
4 vvi adj(mxN);
5 vector<bool> visited;
6 vi parent;
7 int cycle_start, cycle_end;
8 bool dfs(int v, int par) { // passing vertex and
9     its parent vertex
10     visited[v] = true;
11     for (int u : adj[v]) {
12         if (u == par) continue; // skipping edge
13         to parent vertex
14         if (visited[u]) {
15             cycle_end = v;
16             cycle_start = u;
17             return true;
18         }

```

```

17     parent[u] = v;
18     if (dfs(u, parent[u]))
19         return true;
20     }
21     return false;
22 }
23 void find_cycle() {
24     visited.assign(n, false);
25     parent.assign(n, -1);
26     cycle_start = -1;
27     for (int v = 0; v < n; v++) {
28         if (!visited[v] && dfs(v, parent[v]))
29             break;
30     }
31     if (cycle_start == -1) {
32         cout << "Acyclic" << endl;
33     } else {
34         vector<int> cycle;
35         cycle.push_back(cycle_start);
36         for (int v = cycle_end; v != cycle_start;
37             v = parent[v])
38             cycle.push_back(v);
39         cycle.push_back(cycle_start);
40         cout << "Cycle Found: ";
41         for (int v : cycle) cout << v << " ";
42         cout << endl;
43     }

```

3.1.11 Tarjan's SCC

```

1 #include "header.h"
2
3 struct Tarjan {
4     vvi &edges;
5     int V, counter = 0, C = 0;
6     vi n, l;
7     vector<bool> vs;
8     stack<int> st;
9     Tarjan(vvi &e) : edges(e), V(e.size()), n(V,
10         -1), l(V, -1), vs(V, false) {}
11 void visit(int u, vi &com) {
12     l[u] = n[u] = counter++;
13     st.push(u);
14     vs[u] = true;
15     for (auto &v : edges[u]) {
16         if (n[v] == -1) visit(v, com);
17         if (vs[v]) l[u] = min(l[u], l[v]);
18     }
19     if (l[u] == n[u]) {
20         while (true) {
21             int v = st.top();
22             st.pop();
23             vs[v] = false;

```

```

23         com[v] = C; //<== ACT HERE
24         if (u == v) break;
25     }
26     C++;
27 }
28 }
29 int find_sccs(vi &com) { // component indices
30     will be stored in 'com'
31     com.assign(V, -1);
32     C = 0;
33     for (int u = 0; u < V; ++u)
34         if (n[u] == -1) visit(u, com);
35     return C;
36 }
37 // scc is a map of the original vertices of the
38 // graph to the vertices
39 // of the SCC graph, scc_graph is its adjacency
40 // list.
41 // SCC indices and edges are stored in 'scc'
42 // and 'scc_graph'.
43 void scc_collapse(vi &scc, vvi &scc_graph) {
44     find_sccs(scc);
45     scc_graph.assign(C, vi());
46     set<pi> rec; // recorded edges
47     for (int u = 0; u < V; ++u) {
48         assert(scc[u] != -1);
49         for (int v : edges[u]) {
50             if (scc[v] == scc[u] ||
51                 rec.find({scc[u], scc[v]}) != rec.end())
52                 continue;
53             scc_graph[scc[u]].push_back(scc[v]);
54             rec.insert({scc[u], scc[v]});
55         }
56     }
57 }
58 // Function to find sources and sinks in the
59 // SCC graph
60 // The number of edges needed to be added is
61 // max(sources.size(), sinks.size())
62 void findSourcesAndSinks(const vvi &scc_graph,
63     vi &sources, vi &sinks) {
64     vi in_degree(C, 0), out_degree(C, 0);
65     for (int u = 0; u < C; ++u) {
66         for (auto v : scc_graph[u]) {
67             in_degree[v]++;
68             out_degree[u]++;
69         }
70     }
71     for (int i = 0; i < C; ++i) {
72         if (in_degree[i] == 0) sources.push_back(i);
73         if (out_degree[i] == 0) sinks.push_back(i);
74     }
75 }

```


3.1.12 SCC edges Prints out the missing edges to make the input digraph strongly connected

```
1 #include "header.h"
2 const int N=1e5+10;
3 int n,a[N],cnt[N],vis[N];
4 vector<int> hd,tl;
5 int dfs(int x){
6     vis[x]=1;
7     if(!vis[a[x]])return vis[x]=dfs(a[x]);
8     return vis[x]=x;
9 }
10 int main(){
11     scanf("%d",&n);
12     for(int i=1;i<=n;i++){
13         scanf("%d",&a[i]);
14         cnt[a[i]]++;
15     }
16     int k=0;
17     for(int i=1;i<=n;i++){
18         if(!cnt[i]){
19             k++;
20             hd.push_back(i);
21             tl.push_back(dfs(i));
22         }
23     }
24     int tk=k;
25     for(int i=1;i<=n;i++){
26         if(!vis[i]){
27             k++;
28             hd.push_back(i);
29             tl.push_back(dfs(i));
30         }
31     }
32     if(k==1&&!tk)k=0;
33     printf("%d\n",k);
34     for(int i=0;i<k;i++)printf("%d_ %d\n",tl[i],hd
35         [(i+1)%k]);
36     return 0;
37 }
```

3.1.13 Find Bridges

```
1 #include "header.h"
2 int n; // number of nodes
3 vvi adj; // adjacency list of graph
4 vector<bool> visited;
5 vi tin, low;
6 int timer;
7 void dfs(int v, int p = -1) {
8     visited[v] = true;
9     tin[v] = low[v] = timer++;
10    for (int to : adj[v]) {
11        if (to == p) continue;
```

```
12        if (visited[to]) {
13            low[v] = min(low[v], tin[to]);
14        } else {
15            dfs(to, v);
16            low[v] = min(low[v], low[to]);
17            if (low[to] > tin[v])
18                IS_BRIDGE(v, to);
19        }
20    }
21 }
22 void find_bridges() {
23     timer = 0;
24     visited.assign(n, false);
25     tin.assign(n, -1);
26     low.assign(n, -1);
27     for (int i = 0; i < n; ++i) {
28         if (!visited[i]) dfs(i);
29     }
30 }
```

3.1.14 Articulation points (i.e. cut off points)

```
1 #include "header.h"
2 int n; // number of nodes
3 vvi adj; // adjacency list of graph
4 vector<bool> visited;
5 vi tin, low;
6 int timer;
7 void dfs(int v, int p = -1) {
8     visited[v] = true;
9     tin[v] = low[v] = timer++;
10    int children=0;
11    for (int to : adj[v]) {
12        if (to == p) continue;
13        if (visited[to]) {
14            low[v] = min(low[v], tin[to]);
15        } else {
16            dfs(to, v);
17            low[v] = min(low[v], low[to]);
18            if (low[to] >= tin[v] && p!=-1)
19                IS_CUTPOINT(v);
20            ++children;
21        }
22    }
23    if(p == -1 && children > 1)
24        IS_CUTPOINT(v);
25 }
26 void find_cutpoints() {
27     timer = 0;
28     visited.assign(n, false);
29     tin.assign(n, -1);
30     low.assign(n, -1);
31     for (int i = 0; i < n; ++i) {
32         if (!visited[i]) dfs(i);
```

```
32     }
33 }
```

3.1.15 Topological sort

```
1 #include "header.h"
2 int n; // number of vertices
3 vvi adj; // adjacency list of graph
4 vector<bool> visited;
5 vi ans;
6 void dfs(int v) {
7     visited[v] = true;
8     for (int u : adj[v]) {
9         if (!visited[u]) dfs(u);
10    }
11    ans.push_back(v);
12 }
13 void topological_sort() {
14     visited.assign(n, false);
15     ans.clear();
16     for (int i = 0; i < n; ++i) {
17         if (!visited[i]) dfs(i);
18     }
19     reverse(ans.begin(), ans.end());
20 }
```

3.1.16 Bellmann-Ford Same as Dijkstra but allows neg. edges

```
1 #include "header.h"
2 // Switch vi and vvpj to vl and vvpl if necessary
3 void bellmann_ford_extended(vvpi &e, int source,
4     vi &dist, vb &cyc) {
5     dist.assign(e.size(), INF);
6     cyc.assign(e.size(), false); // true when u is
7     // in a <0 cycle
8     dist[source] = 0;
9     for (int iter = 0; iter < e.size() - 1; ++iter)
10    {
11        bool relax = false;
12        for (int u = 0; u < e.size(); ++u)
13            if (dist[u] == INF) continue;
14            else for (auto &e : e[u])
15                if (dist[u]+e.second < dist[e.first])
16                    dist[e.first] = dist[u]+e.second, relax
17                        = true;
18        if(!relax) break;
19    }
20    bool ch = true;
21    while (ch) { // keep going untill no
22        // more changes
23        ch = false; // set dist to -INF when in
24        // cycle
```

```

19 for (int u = 0; u < e.size(); ++u)
20     if (dist[u] == INF) continue;
21     else for (auto &e : e[u])
22         if (dist[e.first] > dist[u] + e.second
23             && !cyc[e.first]) {
24             dist[e.first] = -INF;
25             ch = true; //return true for cycle
26             //detection only
27             cyc[e.first] = true;
28         }
29 }

```

3.1.17 Ford-Fulkerson Basic Max. flow

```

1 #include "header.h"
2 #define V 6 // Num. of vertices in given graph
3
4 /* Returns true if there is a path from source 's'
5  ' to sink
6  't' in residual graph. Also fills parent[] to
7  store the
8  path */
9 bool bfs(int rGraph[V][V], int s, int t, int
10 parent[]) {
11     bool visited[V];
12     memset(visited, 0, sizeof(visited));
13     queue<int> q;
14     q.push(s);
15     visited[s] = true;
16     parent[s] = -1;
17
18     // Standard BFS Loop
19     while (!q.empty()) {
20         int u = q.front();
21         q.pop();
22
23         for (int v = 0; v < V; v++) {
24             if (visited[v] == false && rGraph[u][v] >
25                 0) {
26                 if (v == t) {
27                     parent[v] = u;
28                     return true;
29                 }
30                 q.push(v);
31                 parent[v] = u;
32                 visited[v] = true;
33             }
34         }
35     }
36     return false;
37 }
38
39 // Returns the maximum flow from s to t in the
40 given graph

```

```

36 int fordFulkerson(int graph[V][V], int s, int t)
37 {
38     int u, v;
39     int rGraph[V][V];
40     for (u = 0; u < V; u++)
41         for (v = 0; v < V; v++)
42             rGraph[u][v] = graph[u][v];
43
44     int parent[V]; // This array is filled by BFS
45     // and to
46     // store path
47     int max_flow = 0; // There is no flow initially
48     while (bfs(rGraph, s, t, parent)) {
49         int path_flow = INT_MAX;
50         for (v = t; v != s; v = parent[v]) {
51             u = parent[v];
52             path_flow = min(path_flow, rGraph[u][v]);
53         }
54         for (v = t; v != s; v = parent[v]) {
55             u = parent[v];
56             rGraph[u][v] -= path_flow;
57             rGraph[v][u] += path_flow;
58         }
59         max_flow += path_flow;
60     }
61     return max_flow;
62 }

```

3.1.18 Dinic max flow $O(V^2E)$, $O(Ef)$

```

1 using F = ll; using W = ll; // types for flow and
2 weight/cost
3 struct S{
4     const int v; // neighbour
5     const int r; // index of the reverse edge
6     F f; // current flow
7     const F cap; // capacity
8     const W cost; // unit cost
9     S(int v, int ri, F c, W cost = 0) :
10         v(v), r(ri), f(0), cap(c), cost(cost) {}
11     inline F res() const { return cap - f; }
12 };
13 struct FlowGraph : vector<vector<S>> {
14     FlowGraph(size_t n) : vector<vector<S>>(n) {}
15     void add_edge(int u, int v, F c, W cost = 0){
16         auto &t = *this;
17         t[u].emplace_back(v, t[v].size(), c, cost);
18         t[v].emplace_back(u, t[u].size()-1, c, -cost);
19     }
20 }

```

```

19 void add_arc(int u, int v, F c, W cost = 0){
20     auto &t = *this;
21     t[u].emplace_back(v, t[v].size(), c, cost);
22     t[v].emplace_back(u, t[u].size()-1, 0, -cost);
23 }
24 void clear() { for (auto &E : *this) for (
25     auto &e : E) e.f = 0LL; }
26 struct Dinic{
27     FlowGraph &edges; int V,s,t;
28     vi l; vector<vector<S>::iterator> its; //
29     levels and iterators
30     Dinic(FlowGraph &edges, int s, int t) :
31         edges(edges), V(edges.size()), s(s), t(t),
32         l(V,-1), its(V) {}
33     ll augment(int u, F c) { // we reuse the same
34         iterators
35         if (u == t) return c; ll r = 0LL;
36         for(auto &i : its[u]; i != edges[u].end()
37             ; i++){
38             auto &e = *i;
39             if (e.res() && l[u] < l[e.v]) {
40                 auto d = augment(e.v, min(c, e.
41                     res()));
42                 if (d > 0) { e.f += d; edges[e.v]
43                     [e.r].f -= d; c -= d;
44                     r += d; if (!c) break; }
45             }
46         }
47         return r;
48     }
49     ll run() {
50         ll flow = 0, f;
51         while(true) {
52             fill(l.begin(), l.end(), -1); l[s]=0;
53             // recalculate the layers
54             queue<int> q; q.push(s);
55             while(!q.empty()){
56                 auto u = q.front(); q.pop(); its[
57                     u] = edges[u].begin();
58                 for(auto &e : edges[u]) if(e.res
59                     () && l[e.v]<0)
60                     l[e.v] = l[u]+1, q.push(e.v);
61             }
62             if (l[t] < 0) return flow;
63             while ((f = augment(s, INF)) > 0)
64                 flow += f;
65         }
66     }
67 };

```

3.1.19 Edmonds-Karp Max flow $O(VE^2)$

```
1 /**
```

```

2  * Description: Flow algorithm with guaranteed
   complexity  $O(VE^2)$ . To get edge flow
   values, compare
3  * capacities before and after, and take the
   positive values only.
4  */
5
6  template<class T> T edmondsKarp(vector<
   unordered_map<int, T>>&
7   graph, int source, int sink) {
8   assert(source != sink);
9   T flow = 0;
10  vi par(sz(graph)), q = par;
11
12  for (;;) {
13   fill(all(par), -1);
14   par[source] = 0;
15   int ptr = 1;
16   q[0] = source;
17
18   rep(i, 0, ptr) {
19    int x = q[i];
20    for (auto e : graph[x]) {
21     if (par[e.first] == -1 && e.second > 0) {
22      par[e.first] = x;
23      q[ptr++] = e.first;
24      if (e.first == sink) goto out;
25     }
26    }
27   }
28   return flow;
29 out:
30   T inc = numeric_limits<T>::max();
31   for (int y = sink; y != source; y = par[y])
32    inc = min(inc, graph[par[y]][y]);
33
34   flow += inc;
35   for (int y = sink; y != source; y = par[y]) {
36    int p = par[y];
37    if ((graph[p][y] -= inc) <= 0) graph[p].
      erase(y);
38    graph[y][p] += inc;
39   }
40  }
41 }

```

3.2 Dynamic Programming

3.2.1 Longest Incr. Subseq.

```

1 #include "header.h"
2 template<class T>
3 vector<T> index_path_lis(vector<T>& nums) {
4   int n = nums.size();

```

```

5   vector<T> sub;
6   vector<int> subIndex;
7   vector<T> path(n, -1);
8   for (int i = 0; i < n; ++i) {
9    if (sub.empty() || sub[sub.size() - 1] <
        nums[i]) {
10     path[i] = sub.empty() ? -1 : subIndex[sub.
        size() - 1];
11     sub.push_back(nums[i]);
12     subIndex.push_back(i);
13    } else {
14     int idx = lower_bound(sub.begin(), sub.end(),
        nums[i]) - sub.begin();
15     path[i] = idx == 0 ? -1 : subIndex[idx - 1];
16     sub[idx] = nums[i];
17     subIndex[idx] = i;
18    }
19   }
20   vector<T> ans;
21   int t = subIndex[subIndex.size() - 1];
22   while (t != -1) {
23    ans.push_back(t);
24    t = path[t];
25   }
26   reverse(ans.begin(), ans.end());
27   return ans;
28 }
29 // Length only
30 template<class T>
31 int length_lis(vector<T> &a) {
32   set<T> st;
33   typename set<T>::iterator it;
34   for (int i = 0; i < a.size(); ++i) {
35    it = st.lower_bound(a[i]);
36    if (it != st.end()) st.erase(it);
37    st.insert(a[i]);
38   }
39   return st.size();
40 }

```

3.2.2 0-1 Knapsack

```

1 #include "header.h"
2 // given a number of coins, calculate all
   possible distinct sums
3 int main() {
4   int n;
5   vi coins(n); // all possible coins to use
6   int sum = 0; // sum of the coins
7   vi dp(sum + 1, 0); // dp[x] = 1 if sum
   x can be made
8   dp[0] = 1; // sum 0 can be
   made
9   for (int c = 0; c < n; ++c) // first
   iteration: sums with first

```

```

10   for (int x = sum; x >= 0; --x) // coin,
   next first 2 coins etc
11   if (dp[x]) dp[x + coins[c]] = 1; // if sum
   x valid, x+c valid
12 }

```

3.2.3 Coin change Number of coins required to achieve a given value

```

1 #include "header.h"
2 // Returns total distinct ways to make sum using
   n coins of
3 // different denominations
4 int count(vi& coins, int n, int sum) {
5   // 2d dp array where n is the number of coin
6   // denominations and sum is the target sum
7   vector<vector<int>> dp(n + 1, vector<int>(
   sum + 1, 0));
8   dp[0][0] = 1;
9   for (int i = 1; i <= n; i++) {
10    for (int j = 0; j <= sum; j++) {
11
12     // without using the current coin,
13     dp[i][j] += dp[i - 1][j];
14
15     // using the current coin
16     if ((j - coins[i - 1]) >= 0)
17     dp[i][j] += dp[i][j - coins[i -
   1]];
18    }
19   }
20   return dp[n][sum];
21 }

```

3.3 Trees

3.3.1 Tree diameter

```

1 #include "header.h"
2 const int mxN = 2e5 + 5;
3 int n, d[mxN]; // distance array
4 vi adj[mxN]; // tree adjacency list
5 void dfs(int s, int e) {
6   d[s] = 1 + d[e]; // recursively calculate
   the distance from the starting node to each
   node
7   for (auto u : adj[s]) { // for each adjacent
   node
8     if (u != e) dfs(u, s); // don't move
   backwards in the tree
9   }
10 }

```

```

11 int main() {
12     // read input, create adj list
13     dfs(0, -1); // first dfs call
14     // to find farthest node from arbitrary node
15     dfs(distance(d, max_element(d, d + n)), -1);
16     // second dfs call to find farthest node
17     // from that one
18     cout << *max_element(d, d + n) - 1 << '\n'; //
19     // distance from second node to farthest is
20     // the diameter
21 }

```

3.3.2 Tree Node Count

```

1 #include "header.h"
2 // calculate amount of nodes in each node's
3 // subtree
4 const int mxN = 2e5 + 5;
5 int n, cnt[mxN];
6 vi adj[mxN];
7 void dfs(int s = 0, int e = -1) {
8     cnt[s] = 1; // count leaves as one
9     for (int u : adj[s]) {
10         dfs(u, s);
11         cnt[s] += cnt[u]; // add up nodes of the
12         // subtrees
13     }
14 }

```

3.4 Numerical

3.4.1 Template (for this section)

```

1 #include <bits/stdc++.h>
2 using namespace std;
3 #define rep(i, a, b) for(int i = a; i < (b); ++i)
4 #define all(x) begin(x), end(x)
5 #define sz(x) (int)(x).size()
6 typedef long long ll;
7 typedef pair<int, int> pii;
8 typedef vector<int> vi;

```

3.4.2 Polynomial

```

1 #include "template.cpp"
2
3 struct Poly {
4     vector<double> a;
5     double operator()(double x) const {
6         double val = 0;
7         for (int i = sz(a); i--;) (val += x) += a[i];

```

```

8         return val;
9     }
10 void diff() {
11     rep(i, 1, sz(a)) a[i-1] = i*a[i];
12     a.pop_back();
13 }
14 void divroot(double x0) {
15     double b = a.back(), c; a.back() = 0;
16     for(int i=sz(a)-1; i--;) c = a[i], a[i] = a[i
17     +1]*x0+b, b=c;
18     a.pop_back();
19 }
20 };

```

3.4.3 Poly Roots

```

1 /**
2  * Description: Finds the real roots to a
3  * polynomial.
4  * Usage: polyRoots({{2,-3,1}},-1e9,1e9) // solve
5  * x^2-3x+2 = 0
6  * Time: O(n^2 \log(1/\epsilon))
7  */
8 #include "Polynomial.h"
9 #include "template.cpp"
10 vector<double> polyRoots(Poly p, double xmin,
11 double xmax) {
12     if (sz(p.a) == 2) { return {-p.a[0]/p.a[1]}; }
13     vector<double> ret;
14     Poly der = p;
15     der.diff();
16     auto dr = polyRoots(der, xmin, xmax);
17     dr.push_back(xmin-1);
18     dr.push_back(xmax+1);
19     sort(all(dr));
20     rep(i, 0, sz(dr)-1) {
21         double l = dr[i], h = dr[i+1];
22         bool sign = p(l) > 0;
23         if (sign ^ (p(h) > 0)) {
24             rep(it, 0, 60) { // while (h - l > 1e-8)
25                 double m = (l + h) / 2, f = p(m);
26                 if ((f <= 0) ^ sign) l = m;
27                 else h = m;
28             }
29             ret.push_back((l + h) / 2);
30         }
31     }
32     return ret;
33 }

```

3.4.4 Golden Section Search

```

1 /**
2  * Description: Finds the argument minimizing the
3  * function f(x) in the interval [a,b]
4  * assuming f(x) is unimodal on the interval, i.e.
5  * has only one local minimum and no local
6  * maximum. The maximum error in the result is
7  * $eps$. Works equally well for maximization
8  * with a small change in the code. See
9  * TernarySearch.h in the Various chapter for a
10  * discrete version.
11  * Usage:
12  * double func(double x) { return 4*x+.3*x*x; }
13  * double xmin = gss(-1000,1000,func);
14  * Time: O(\log((b-a) / \epsilon))
15  */
16 #include "template.cpp"
17
18 /// It is important for r to be precise,
19 /// otherwise we don't necessarily maintain the
20 /// inequality a < x1 < x2 < b.
21 double gss(double a, double b, double (*f)(double
22 )) {
23     double r = (sqrt(5)-1)/2, eps = 1e-7;
24     double x1 = b - r*(b-a), x2 = a + r*(b-a);
25     double f1 = f(x1), f2 = f(x2);
26     while (b-a > eps)
27         if (f1 < f2) { //change to > to find maximum
28             b = x2; x2 = x1; f2 = f1;
29             x1 = b - r*(b-a); f1 = f(x1);
30         } else {
31             a = x1; x1 = x2; f1 = f2;
32             x2 = a + r*(b-a); f2 = f(x2);
33         }
34     return a;
35 }

```

3.4.5 Hill Climbing

```

1 /**
2  * Description: Poor man's optimization for
3  * unimodal functions.
4  */
5 #include "template.cpp"
6
7 typedef array<double, 2> P;
8
9 template<class F> pair<double, P> hillClimb(P
10 start, F f) {
11     pair<double, P> cur(f(start), start);
12     for (double jmp = 1e9; jmp > 1e-20; jmp /= 2) {
13         rep(j, 0, 100) rep(dx, -1, 2) rep(dy, -1, 2) {
14             P p = cur.second;
15             p[0] += dx*jmp;
16             p[1] += dy*jmp;

```

```

15     cur = min(cur, make_pair(f(p), p));
16 }
17 }
18 return cur;
19 }

```

3.4.6 Integration

```

1 /**
2  * Description: Simple integration of a function
3  * over an interval using
4  * Simpson's rule. The error should be
5  * proportional to  $h^4$ , although in
6  * practice you will want to verify that the
7  * result is stable to desired
8  * precision when epsilon changes.
9  */
10 #include "template.cpp"
11
12 template<class F>
13 double quad(double a, double b, F f, const int n
14             = 1000) {
15     double h = (b - a) / 2 / n, v = f(a) + f(b);
16     rep(i,1,n*2)
17         v += f(a + i*h) * (i&1 ? 4 : 2);
18     return v * h / 3;
19 }

```

3.4.7 Integration Adaptive

```

1 /**
2  * Description: Fast integration using an
3  * adaptive Simpson's rule.
4  * Usage:
5  * double sphereVolume = quad(-1, 1, [](double x)
6  * {
7  *     return quad(-1, 1, [&](double y) {
8  *         return quad(-1, 1, [&](double z) {
9  *             return x*x + y*y + z*z < 1; });});});
10  */
11 #include "template.cpp"
12
13 typedef double d;
14 #define S(a,b) (f(a) + 4*f((a+b) / 2) + f(b)) * (
15             b-a) / 6
16
17 template <class F>
18 d rec(F& f, d a, d b, d eps, d S) {
19     d c = (a + b) / 2;
20     d S1 = S(a, c), S2 = S(c, b), T = S1 + S2;
21     if (abs(T - S) <= 15 * eps || b - a < 1e-10)
22         return T + (T - S) / 15;

```

```

21     return rec(f, a, c, eps / 2, S1) + rec(f, c, b,
22         eps / 2, S2);
23 }
24 template<class F>
25 d quad(d a, d b, F f, d eps = 1e-8) {
26     return rec(f, a, b, eps, S(a, b));
27 }

```

3.5 Num. Th. / Comb.

3.5.1 Basic stuff

```

1 #include "header.h"
2 ll gcd(ll a, ll b) { while (b) { a %= b; swap(a,
3     b); } return a; }
4 ll lcm(ll a, ll b) { return (a / gcd(a, b)) * b;
5 }
6 ll mod(ll a, ll b) { return ((a % b) + b) % b; }
7 // Finds x, y s.t. ax + by = d = gcd(a, b).
8 void extended_euclid(ll a, ll b, ll &x, ll &y, ll
9     &d) {
10     ll xx = y = 0;
11     ll yy = x = 1;
12     while (b) {
13         ll q = a / b;
14         ll t = b; b = a % b; a = t;
15         t = xx; xx = x - q * xx; x = t;
16         t = yy; yy = y - q * yy; y = t;
17     }
18     d = a;
19 }
20 // solves ab = 1 (mod n), -1 on failure
21 ll mod_inverse(ll a, ll n) {
22     ll x, y, d;
23     extended_euclid(a, n, x, y, d);
24     return (d > 1 ? -1 : mod(x, n));
25 }
26 // All modular inverses of [1..n] mod P in O(n)
27 time.
28 vi inverses(ll n, ll P) {
29     vi I(n+1, 1LL);
30     for (ll i = 2; i <= n; ++i)
31         I[i] = mod(-(P/i) * I[P%i], P);
32     return I;
33 }
34 // (a*b)%m
35 ll mulmod(ll a, ll b, ll m){
36     ll x = 0, y=a%m;
37     while(b>0){
38         if(b&1) x = (x+y)%m;
39         y = (2*y)%m, b /= 2;
40     }
41     return x % m;
42 }

```

```

39 // Finds  $b^e \pmod m$  in  $O(\lg n)$  time, ensure that  $b <
40 m$  to avoid overflow!
41 ll powmod(ll b, ll e, ll m) {
42     ll p = e<2 ? 1 : powmod((b*b)%m,e/2,m);
43     return e&1 ? p*b%m : p;
44 }
45 // Solve  $ax + by = c$ , returns false on failure.
46 bool linear_diophantine(ll a, ll b, ll c, ll &x,
47     ll &y) {
48     ll d = gcd(a, b);
49     if (c % d) {
50         return false;
51     } else {
52         x = c / d * mod_inverse(a / d, b / d);
53         y = (c - a * x) / b;
54         return true;
55     }
56 }
57 // Description: Tonelli-Shanks algorithm for
58 // modular square roots. Finds  $x$  s.t.  $x^2 = a
59 \pmod p$  ( $-x$  gives the other solution).  $O(
60 \log^2 p)$  worst case,  $O(\log p)$  for most  $p$ 
61 ll sqrtmod(ll a, ll p) {
62     a %= p; if (a < 0) a += p;
63     if (a == 0) return 0;
64     assert(powmod(a, (p-1)/2, p) == 1); // else no
65     solution
66     if (p % 4 == 3) return powmod(a, (p+1)/4, p);
67     //  $a^{(n+3)/8}$  or  $2^{(n+3)/8} * 2^{(n-1)/4}$  works if
68      $p \equiv 5 \pmod 8$ 
69     ll s = p - 1, n = 2;
70     int r = 0, m;
71     while (s % 2 == 0)
72         ++r, s /= 2;
73     /// find a non-square mod p
74     while (powmod(n, (p - 1) / 2, p) != p - 1) ++n;
75     ll x = powmod(a, (s + 1) / 2, p);
76     ll b = powmod(a, s, p), g = powmod(n, s, p);
77     for (; r = m) {
78         ll t = b;
79         for (m = 0; m < r && t != 1; ++m)
80             t = t * t % p;
81         if (m == 0) return x;
82         ll gs = powmod(g, 1LL << (r - m - 1), p);
83         g = gs * gs % p;
84         x = x * gs % p;
85         b = b * g % p;
86     }
87 }

```

3.5.2 Mod. exponentiation Or use pow() in python

```

1 #include "header.h"

```

```

2 ll mod_pow(ll base, ll exp, ll mod) {
3     if (mod == 1) return 0;
4     if (exp == 0) return 1;
5     if (exp == 1) return base;
6
7     ll res = 1;
8     base %= mod;
9     while (exp) {
10        if (exp % 2 == 1) res = (res * base) % mod;
11        exp >>= 1;
12        base = (base * base) % mod;
13    }
14
15    return res % mod;
16 }

```

3.5.3 GCD Or math.gcd in python, std::gcd in C++

```

1 #include "header.h"
2 ll gcd(ll a, ll b) {
3     if (a == 0) return b;
4     return gcd(b % a, a);
5 }

```

3.5.4 Sieve of Eratosthenes

```

1 #include "header.h"
2 vl primes;
3 void getprimes(ll n) { // Up to n (not included)
4     vector<bool> p(n, true);
5     p[0] = false;
6     p[1] = false;
7     for(ll i = 0; i < n; i++) {
8         if(p[i]) {
9             primes.push_back(i);
10            for(ll j = i*2; j < n; j+=i) p[j] =
11                false;
12        }
13    }
14 }

```

3.5.5 Fibonacci % prime

```

1 #include "header.h"
2 const ll MOD = 1000000007;
3 unordered_map<ll, ll> Fib;
4 ll fib(ll n) {
5     if (n < 2) return 1;
6     if (Fib.find(n) != Fib.end()) return Fib[n];
7     Fib[n] = (fib((n + 1) / 2) * fib(n / 2) + fib
8         ((n - 1) / 2) * fib((n - 2) / 2)) % MOD;
9     return Fib[n];
10 }

```

3.5.6 nCk % prime

```

1 #include "header.h"
2 ll binom(ll n, ll k) {
3     ll ans = 1;
4     for(ll i = 1; i <= min(k, n-k); ++i) ans = ans
5         *(n+1-i)/i;
6     return ans;
7 }
8 ll mod_nCk(ll n, ll k, ll p) {
9     ll ans = 1;
10    while(n){
11        ll np = n%p, kp = k%p;
12        if(kp > np) return 0;
13        ans *= binom(np, kp);
14        n /= p; k /= p;
15    }
16    return ans;
17 }

```

3.5.7 Chin. rem. th.

```

1 #include "header.h"
2 #include "elementary.cpp"
3 // Solves x = a1 mod m1, x = a2 mod m2, x is
4 // unique modulo lcm(m1, m2).
5 // Returns {0, -1} on failure, {x, lcm(m1, m2)}
6 // otherwise.
7 pair<ll, ll> crt(ll a1, ll m1, ll a2, ll m2) {
8     ll s, t, d;
9     extended_euclid(m1, m2, s, t, d);
10    if (a1 % d != a2 % d) return {0, -1};
11    return {mod(s*a2 % m2 * m1 + t*a1 % m1 * m2, m1 *
12        m2) / d, m1 / d * m2};
13 }
14 // Solves x = ai mod mi. x is unique modulo lcm
15 // mi.
16 // Returns {0, -1} on failure, {x, lcm mi}
17 // otherwise.
18 pair<ll, ll> crt(vector<ll> &a, vector<ll> &m) {
19     pair<ll, ll> res = {a[0], m[0]};
20     for (ull i = 1; i < a.size(); ++i) {
21         res = crt(res.first, res.second, mod(a[i], m[
22             i]), m[i]);
23         if (res.second == -1) break;
24     }
25     return res;
26 }

```

3.5.8 Derangements Permutations of a set such that none of the elements appear in their original position:

$$!n = (n-1)(!(n-1) + !(n-2)) = \left[\frac{n!}{e} \right] \quad (1)$$

$$!n = 1 - e^{-1}, n \rightarrow \infty \quad (2)$$

3.6 Strings

3.6.1 Z alg. KMP alternative

```

1 #include "../header.h"
2 void Z_algorithm(const string &s, vi &Z) {
3     Z.assign(s.length(), -1);
4     int L = 0, R = 0, n = s.length();
5     for (int i = 1; i < n; ++i) {
6         if (i > R) {
7             L = R = i;
8             while (R < n && s[R - L] == s[R]) R++;
9             Z[i] = R - L; R--;
10        } else if (Z[i - L] >= R - i + 1) {
11            L = i;
12            while (R < n && s[R - L] == s[R]) R++;
13            Z[i] = R - L; R--;
14        } else Z[i] = Z[i - L];
15    }
16 }

```

3.6.2 KMP

```

1 #include "header.h"
2 void compute_prefix_function(string &w, vi &
3     prefix) {
4     prefix.assign(w.length(), 0);
5     int k = prefix[0] = -1;
6
7     for(int i = 1; i < w.length(); ++i) {
8         while(k >= 0 && w[k + 1] != w[i]) k = prefix[
9             k];
10        if(w[k + 1] == w[i]) k++;
11        prefix[i] = k;
12    }
13 }
14 void knuth_morris_pratt(string &s, string &w) {
15     int q = -1;
16     vi prefix;
17     compute_prefix_function(w, prefix);
18     for(int i = 0; i < s.length(); ++i) {
19         while(q >= 0 && w[q + 1] != s[i]) q = prefix[
20             q];
21         if(w[q + 1] == s[i]) q++;
22         if(q + 1 == w.length()) {

```



```

20 // Match at position (i - w.length() + 1)
21 q = prefix[q];
22 }
23 }
24 }

```

3.6.3 Aho-Corasick Also can be used as Knuth-Morris-Pratt algorithm

```

1 #include "header.h"
2
3 map<char, int> cti;
4 int cti_size;
5 template <int ALPHABET_SIZE, int (*mp)(char)>
6 struct AC_FSM {
7     struct Node {
8         int child[ALPHABET_SIZE], failure = 0,
9         match_par = -1;
10         vi match;
11     };
12     Node() { for (int i = 0; i < ALPHABET_SIZE;
13         ++i) child[i] = -1; };
14     vector<Node> a;
15     vector<string> &words;
16     AC_FSM(vector<string> &words) : words(words) {
17         a.push_back(Node());
18         construct_automaton();
19     }
20     void construct_automaton() {
21         for (int w = 0, n = 0; w < words.size(); ++w,
22             n = 0) {
23             for (int i = 0; i < words[w].size(); ++i) {
24                 if (a[n].child[mp(words[w][i])] == -1) {
25                     a[n].child[mp(words[w][i])] = a.size();
26                     a.push_back(Node());
27                 }
28                 n = a[n].child[mp(words[w][i])];
29             }
30             a[n].match.push_back(w);
31         }
32         queue<int> q;
33         for (int k = 0; k < ALPHABET_SIZE; ++k) {
34             if (a[0].child[k] == -1) a[0].child[k] = 0;
35             else if (a[0].child[k] > 0) {
36                 a[a[0].child[k]].failure = 0;
37                 q.push(a[0].child[k]);
38             }
39         }
40         while (!q.empty()) {
41             int r = q.front(); q.pop();
42             for (int k = 0, arck; k < ALPHABET_SIZE; ++
43                 k) {
44                 if ((arck = a[r].child[k]) != -1) {
45                     q.push(arck);
46                 }
47             }
48         }
49     }
50 }
51
52 void aho_corasick(string &sentence, vvi &
53     matches){
54     matches.assign(words.size(), vi());
55     int state = 0, ss = 0;
56     for (int i = 0; i < sentence.length(); ++i,
57         ss = state) {
58         while (a[ss].child[mp(sentence[i])] == -1)
59             ss = a[ss].failure;
60         state = a[ss].child[mp(sentence[i])];
61         for (ss = state; ss != -1; ss = a[ss].
62             match_par)
63             matches[w].push_back(i + 1 - words[w].
64                 length());
65     }
66 }
67 int char_to_int(char c) {
68     return cti[c];
69 }
70 int main() {
71     ll n;
72     string line;
73     while(getline(cin, line)) {
74         stringstream ss(line);
75         ss >> n;
76
77         vector<string> patterns(n);
78         for (auto& p: patterns) getline(cin, p);
79
80         string text;
81         getline(cin, text);
82
83         cti = {}, cti_size = 0;
84         for (auto c: text) {
85             if (not in(c, cti)) {
86                 cti[c] = cti_size++;
87             }
88         }
89         for (auto& p: patterns) {

```

```

90         for (auto c: p) {
91             if (not in(c, cti)) {
92                 cti[c] = cti_size++;
93             }
94         }
95     }
96     vvi matches;
97     AC_FSM <128+1, char_to_int> ac_fms(patterns);
98     ac_fms.aho_corasick(text, matches);
99     for (auto& x: matches) cout << x << endl;
100 }
101 }
102 }
103 }

```

```

90         for (auto c: p) {
91             if (not in(c, cti)) {
92                 cti[c] = cti_size++;
93             }
94         }
95     }
96     vvi matches;
97     AC_FSM <128+1, char_to_int> ac_fms(patterns);
98     ac_fms.aho_corasick(text, matches);
99     for (auto& x: matches) cout << x << endl;
100 }
101 }
102 }
103 }

```

3.6.4 Long. palin. subs Manacher - $O(n)$

```

1 #include "header.h"
2 void manacher(string &s, vi &pal) {
3     int n = s.length(), i = 1, l, r;
4     pal.assign(2 * n + 1, 0);
5     while (i < 2 * n + 1) {
6         if ((i&1) && pal[i] == 0) pal[i] = 1;
7         l = i / 2 - pal[i] / 2; r = (i-1) / 2 + pal[i]
8             / 2;
9         while (l - 1 >= 0 && r + 1 < n && s[l - 1] ==
10             s[r + 1])
11             --l, ++r, pal[i] += 2;
12         for (l = i - 1, r = i + 1; l >= 0 && r < 2 *
13             n + 1; --l, ++r) {
14             if (l <= i - pal[i]) break;
15             if (l / 2 - pal[l] / 2 > i / 2 - pal[i] /
16                 2)
17                 pal[r] = pal[l];
18             else { if (l >= 0)
19                 pal[r] = min(pal[l], i + pal[i] - r);
20                 break;
21             }
22         }
23         i = r;
24     }
25 }

```

3.6.5 Bitstring Slower than an unordered set for many elements, but hashable

```

1 #include "../header.h"
2
3 template<size_t len>
4 struct pair_hash { // To make it hashable (pair<
5     int, bitset<len>>)

```



```

5  std::size_t operator()(const std::pair<int,
    std::bitset<len>>& p) const {
6      std::size_t h1 = std::hash<int>{}(p.first
    );
7      std::size_t h2 = std::hash<std::bitset<
    len>>{}(p.second);
8      return h1 ^ (h2 << 1);
9  }
10 };
11 #define MAXN 1000
12 std::bitset<MAXN> bs;
13 // bs.set(idx) <- set idx-th bit (1)
14 // bs.reset(idx) <- reset idx-th bit (0)
15 // bs.flip(idx) <- flip idx-th bit
16 // bs.test(idx) <- idx-th bit == 1
17 // bs.count() <- number of 1s
18 // bs.any() <- any bit == 1

```

3.7 Geometry

3.7.1 essentials.cpp

```

1 #include "../header.h"
2 using C = ld; // could be long long or long
    double
3 constexpr C EPS = 1e-10; // change to 0 for C=ll
4 struct P { // may also be used as a 2D vector
5     C x, y;
6     P(C x = 0, C y = 0) : x(x), y(y) {}
7     P operator+ (const P &p) const { return {x + p.
    x, y + p.y}; }
8     P operator- (const P &p) const { return {x - p.
    x, y - p.y}; }
9     P operator* (C c) const { return {x * c, y * c
    }; }
10    P operator/ (C c) const { return {x / c, y / c
    }; }
11    C operator* (const P &p) const { return x*p.x +
    y*p.y; }
12    C operator^ (const P &p) const { return x*p.y -
    p.x*y; }
13    P perp() const { return P{y, -x}; }
14    C lensq() const { return x*x + y*y; }
15    ld len() const { return sqrt((ld)lensq()); }
16    static ld dist(const P &p1, const P &p2) {
17        return (p1-p2).len(); }
18    bool operator==(const P &r) const {
19        return ((*this)-r).lensq() <= EPS*EPS; }
20 };
21 C det(P p1, P p2) { return p1^p2; }
22 C det(P p1, P p2, P o) { return det(p1-o, p2-o);
    }
23 C det(const vector<P> &ps) {
24     C sum = 0; P prev = ps.back();

```

```

25     for(auto &p : ps) sum += det(p, prev), prev = p
    ;
26     return sum;
27 }
28 // Careful with division by two and C=ll
29 C area(P p1, P p2, P p3) { return abs(det(p1, p2,
    p3))/C(2); }
30 C area(const vector<P> &poly) { return abs(det(
    poly))/C(2); }
31 int sign(C c){ return (c > C(0)) - (c < C(0)); }
32 int ccw(P p1, P p2, P o) { return sign(det(p1, p2
    , o)); }
33
34 // Only well defined for C = ld.
35 P unit(const P &p) { return p / p.len(); }
36 P rotate(P p, ld a) { return P{p.x*cos(a)-p.y*sin
    (a), p.x*sin(a)+p.y*cos(a)}; }

```

3.7.2 Two segs. itersec.

```

1 #include "header.h"
2 #include "essentials.cpp"
3 bool intersect(P a1, P a2, P b1, P b2) {
4     if (max(a1.x, a2.x) < min(b1.x, b2.x)) return
    false;
5     if (max(b1.x, b2.x) < min(a1.x, a2.x)) return
    false;
6     if (max(a1.y, a2.y) < min(b1.y, b2.y)) return
    false;
7     if (max(b1.y, b2.y) < min(a1.y, a2.y)) return
    false;
8     bool l1 = ccw(a2, b1, a1) * ccw(a2, b2, a1) <=
    0;
9     bool l2 = ccw(b2, a1, b1) * ccw(b2, a2, b1) <=
    0;
10    return l1 && l2;
11 }

```

3.7.3 Convex Hull

```

1 #include "header.h"
2 #include "essentials.cpp"
3 struct ConvexHull { // O(n lg n) monotone chain.
4     size_t n;
5     vector<size_t> h, c; // Indices of the hull
    are in 'h', ccw.
6     const vector<P> &p;
7     ConvexHull(const vector<P> &p) : n(_p.size()),
    c(n), p(_p) {
8         std::iota(c.begin(), c.end(), 0);
9         std::sort(c.begin(), c.end(), [this](size_t l
    , size_t r) -> bool { return p[l].x != p[
    r].x ? p[l].x < p[r].x : p[l].y < p[r].y;
    });

```

```

10     c.erase(std::unique(c.begin(), c.end(), [this
    ](size_t l, size_t r) { return p[l] == p[
    r]; }), c.end());
11     for (size_t s = 1, r = 0; r < 2; ++r, s = h.
    size()) {
12         for (size_t i : c) {
13             while (h.size() > s && ccw(p[h.end()
    ][-2], p[h.end()[-1]], p[i]) <= 0)
14                 h.pop_back();
15             h.push_back(i);
16         }
17         reverse(c.begin(), c.end());
18     }
19     if (h.size() > 1) h.pop_back();
20 }
21 size_t size() const { return h.size(); }
22 template <class T, void U(const P &, const P &,
    const P &, T &)>
23 void rotating_calipers(T &ans) {
24     if (size() <= 2)
25         U(p[h[0]], p[h.back()], p[h.back()], ans);
26     else
27         for (size_t i = 0, j = 1, s = size(); i < 2
    * s; ++i) {
28             while (det(p[h[(i + 1) % s]] - p[h[i % s
    ]], p[h[(j + 1) % s]] - p[h[j]]) >=
    0)
29                 j = (j + 1) % s;
30             U(p[h[i % s]], p[h[(i + 1) % s]], p[h[j
    % s]], ans);
31         }
32     }
33 };
34 // Example: furthest pair of points. Now set ans
    = 0LL and call
35 // ConvexHull(pts).rotating_calipers<ll, update>(
    ans);
36 void update(const P &p1, const P &p2, const P &o,
    ll &ans) {
37     ans = max(ans, (ll)max((p1 - o).lensq(), (p2 -
    o).lensq()));
38 }
39 int main() {
40     ios::sync_with_stdio(false); // do not use
    cout + printf
41     cin.tie(NULL);
42
43     int n;
44     cin >> n;
45     while (n) {
46         vector<P> ps;
47         int x, y;
48         for (int i = 0; i < n; i++) {
49             cin >> x >> y;
50             ps.push_back({x, y});

```

```

51     }
52
53     ConvexHull ch(ps);
54     cout << ch.h.size() << endl;
55     for(auto& p: ch.h) {
56         cout << ps[p].x << " " << ps[p].y <<
            endl;
57     }
58     cin >> n;
59 }
60
61 return 0;
62 }

```

3.8 Other Algorithms

3.8.1 2-sat

```

1 #include "../header.h"
2 #include "../Graphs/tarjan.cpp"
3 struct TwoSAT {
4     int n;
5     vvi imp; // implication graph
6     Tarjan tj;
7
8     TwoSAT(int _n) : n(_n), imp(2 * _n, vi()), tj(
        imp) { }
9
10    // Only copy the needed functions:
11    void add_implies(int c1, bool v1, int c2, bool
        v2) {
12        int u = 2 * c1 + (v1 ? 1 : 0),
13            v = 2 * c2 + (v2 ? 1 : 0);
14        imp[u].push_back(v); // u => v
15        imp[v^1].push_back(u^1); // -v => -u
16    }
17    void add_equivalence(int c1, bool v1, int c2,
        bool v2) {
18        add_implies(c1, v1, c2, v2);
19        add_implies(c2, v2, c1, v1);
20    }
21    void add_or(int c1, bool v1, int c2, bool v2) {
22        add_implies(c1, !v1, c2, v2);
23    }
24    void add_and(int c1, bool v1, int c2, bool v2)
        {
25        add_true(c1, v1); add_true(c2, v2);
26    }
27    void add_xor(int c1, bool v1, int c2, bool v2)
        {
28        add_or(c1, v1, c2, v2);
29        add_or(c1, !v1, c2, !v2);
30    }
31    void add_true(int c1, bool v1) {

```

```

32    add_implies(c1, !v1, c1, v1);
33    }
34
35    // on true: a contains an assignment.
36    // on false: no assignment exists.
37    bool solve(vb &a) {
38        vi com;
39        tj.find_sccs(com);
40        for (int i = 0; i < n; ++i)
41            if (com[2 * i] == com[2 * i + 1])
42                return false;
43
44        vvi bycom(com.size());
45        for (int i = 0; i < 2 * n; ++i)
46            bycom[com[i]].push_back(i);
47
48        a.assign(n, false);
49        vb vis(n, false);
50        for(auto &&component : bycom){
51            for (int u : component) {
52                if (vis[u / 2]) continue;
53                vis[u / 2] = true;
54                a[u / 2] = (u % 2 == 1);
55            }
56        }
57        return true;
58    }
59 };

```

3.8.2 Matrix Solve

```

1 #include "header.h"
2 #define REP(i, n) for(auto i = decltype(n)(0); i
    < (n); i++)
3 using T = double;
4 constexpr T EPS = 1e-8;
5 template<int R, int C>
6 using M = array<array<T,C>,R>; // matrix
7 template<int R, int C>
8 T ReducedRowEchelonForm(M<R,C> &m, int rows) {
    // return the determinant
9     int r = 0; T det = 1; // MODIFIES
        the input
10    for(int c = 0; c < rows && r < rows; c++) {
11        int p = r;
12        for(int i=r+1; i<rows; i++) if(abs(m[i][c]) >
            abs(m[p][c])) p=i;
13        if(abs(m[p][c]) < EPS){ det = 0; continue; }
14        swap(m[p], m[r]); det = -det;
15        T s = 1.0 / m[r][c], t; det *= m[r][c];
16        REP(j,C) m[r][j] *= s; // make leading
            term in row 1
17        REP(i,rows) if (i!=r){ t = m[i][c]; REP(j,C)
            m[i][j] -= t*m[r][j]; }

```

```

18        ++r;
19    }
20    return det;
21 }
22 bool error, inconst; // error => multiple or
    inconsistent
23 template<int R,int C> // Mx = a; M:R*R, v:R*C =>
    x:R*C
24 M<R,C> solve(const M<R,R> &m, const M<R,C> &a,
    int rows){
25     M<R,R+C> q;
26     REP(r,rows){
27         REP(c,rows) q[r][c] = m[r][c];
28         REP(c,C) q[r][R+c] = a[r][c];
29     }
30     ReducedRowEchelonForm<R,R+C>(q,rows);
31     M<R,C> sol; error = false, inconst = false;
32     REP(c,C) for(auto j = rows-1; j >= 0; --j){
33         T t=0; bool allzero=true;
34         for(auto k = j+1; k < rows; ++k)
35             t += q[j][k]*sol[k][c], allzero &= abs(q[j]
                [k]) < EPS;
36         if(abs(q[j][j]) < EPS)
37             error = true, inconst |= allzero && abs(q[j]
                [R+c]) > EPS;
38         else sol[j][c] = (q[j][R+c] - t) / q[j][j];
                // usually q[j][j]=1
39     }
40    return sol;
41 }

```

3.8.3 Matrix Exp.

```

1 #include "header.h"
2 #define ITERATE_MATRIX(w) for (int r = 0; r < (w)
    ; ++r) \
3
4     for (int c = 0; c < (w); ++c)
5
6 template <class T, int N>
7 struct M {
8     array<array<T,N>,N> m;
9     M() { ITERATE_MATRIX(N) m[r][c] = 0; }
10    static M id() {
11        M I; for (int i = 0; i < N; ++i) I.m[i][i] =
            1; return I;
12    }
13    M operator*(const M &rhs) const {
14        M out;
15        ITERATE_MATRIX(N) for (int i = 0; i < N; ++i)
16            out.m[r][c] += m[r][i] * rhs.m[i][c];
17        return out;
18    }
19    M raise(ll n) const {
20        if(n == 0) return id();
21        if(n == 1) return *this;

```

```

20 auto r = (*this**this).raise(n / 2);
21 return (n%2 ? *this*r : r);
22 }
23 };

```

3.8.4 Finite field For FFT

```

1 #include "header.h"
2 #include "../Number_Theory/elementary.cpp"
3 template<ll p, ll w> // prime, primitive root
4 struct Field { using T = Field; ll x; Field(ll x
=0) : x{x} {}
5 T operator+(T r) const { return {(x+r.x)%p}; }
6 T operator-(T r) const { return {(x-r.x+p)%p};
}
7 T operator*(T r) const { return {(x*r.x)%p}; }
8 T operator/(T r) const { return (*this)*r.inv()
; }
9 T inv() const { return {mod_inverse(x,p)}; }
10 static T root(ll k) { assert( (p-1)%k==0 );
// (p-1)%k == 0?
11 auto r = powmod(w, (p-1)/abs(k), p); // k-
th root of unity
12 return k>0 ? T{r} : T{r}.inv();
13 }
14 bool zero() const { return x == 0LL; }
15 };
16 using F1 = Field<1004535809, 3>;
17 using F2 = Field<1107296257, 10>; // 1<<30 + 1<<25
+ 1
18 using F3 = Field<2281701377, 3>; // 1<<31 + 1<<27
+ 1

```

3.8.5 Complex field For FFR

```

1 #include "header.h"
2 const double m_pi = M_PI/64x;
3 struct Complex { using T = Complex; double u,v;
4 Complex(double u=0, double v=0) : u{u}, v{v} {}
5 T operator+(T r) const { return {u+r.u, v+r.v};
}
6 T operator-(T r) const { return {u-r.u, v-r.v};
}
7 T operator*(T r) const { return {u*r.u - v*r.v,
u*r.v + v*r.u}; }
8 T operator/(T r) const {
9 auto norm = r.u*r.u+r.v*r.v;
10 return {(u*r.u + v*r.v)/norm, (v*r.u - u*r.v)
/norm};
11 }
12 T operator*(double r) const { return T{u*r, v*r
}; }

```

```

13 T operator/(double r) const { return T{u/r, v/r
}; }
14 T inv() const { return T{1,0}/ *this; }
15 T conj() const { return T{u, -v}; }
16 static T root(ll k){ return {cos(2*m_pi/k), sin
(2*m_pi/k)}; }
17 bool zero() const { return max(abs(u), abs(v))
< 1e-6; }
18 };

```

3.8.6 FFT

```

1 #include "header.h"
2 #include "complex_field.cpp"
3 #include "fin_field.cpp"
4 void brinc(int &x, int k) {
5 int i = k - 1, s = 1 << i;
6 x ^= s;
7 if ((x & s) != s) {
8 --i; s >>= 1;
9 while (i >= 0 && ((x & s) == s))
10 x = x &~ s, --i, s >>= 1;
11 if (i >= 0) x |= s;
12 }
13 }
14 using T = Complex; // using T=F1,F2,F3
15 vector<T> roots;
16 void root_cache(int N) {
17 if (N == (int)roots.size()) return;
18 roots.assign(N, T{0});
19 for (int i = 0; i < N; ++i)
20 roots[i] = ((i&-i) == i)
21 ? T{cos(2.0*m_pi*i/N), sin(2.0*m_pi*i/N)}
22 : roots[i&-i] * roots[i-(i&-i)];
23 }
24 void fft(vector<T> &A, int p, bool inv = false) {
25 int N = 1<<p;
26 for(int i = 0, r = 0; i < N; ++i, brinc(r, p))
27 if (i < r) swap(A[i], A[r]);
28 // Uncomment to precompute roots (for T=Complex)
. Slower but more precise.
29 // root_cache(N);
30 // , sh=p-1 , --sh
31 for (int m = 2; m <= N; m <= 1) {
32 T w, w_m = T::root(inv ? -m : m);
33 for (int k = 0; k < N; k += m) {
34 w = T{1};
35 for (int j = 0; j < m/2; ++j) {
36 // T w = (!inv ? roots[j<<sh] : roots[j<<
sh].conj());
37 T t = w * A[k + j + m/2];
38 A[k + j + m/2] = A[k + j] - t;
39 A[k + j] = A[k + j] + t;
40 w = w * w_m;

```

```

41 }
42 }
43 }
44 if(inv){ T inverse = T(N).inv(); for(auto &x :
A) x = x*inverse; }
45 }
46 // convolution leaves A and B in frequency domain
state
47 // C may be equal to A or B for in-place
convolution
48 void convolution(vector<T> &A, vector<T> &B,
vector<T> &C){
49 int s = A.size() + B.size() - 1;
50 int q = 32 - __builtin_clz(s-1), N=1<<q; //
fails if s=1
51 A.resize(N,{}); B.resize(N,{}); C.resize(N,{});
52 fft(A, q, false); fft(B, q, false);
53 for (int i = 0; i < N; ++i) C[i] = A[i] * B[i];
54 fft(C, q, true); C.resize(s);
55 }
56 void square_inplace(vector<T> &A) {
57 int s = 2*A.size()-1, q = 32 - __builtin_clz(s
-1), N=1<<q;
58 A.resize(N,{}); fft(A, q, false);
59 for(auto &x : A) x = x*x;
60 fft(A, q, true); A.resize(s);
61 }

```

3.8.7 Polyn. inv. div.

```

1 #include "header.h"
2 #include "fft.cpp"
3 vector<T> &rev(vector<T> &A) { reverse(A.begin(),
A.end()); return A; }
4 void copy_into(const vector<T> &A, vector<T> &B,
size_t n) {
5 std::copy(A.begin(), A.begin()+min({n, A.size()
, B.size()}), B.begin());
6 }
7
8 // Multiplicative inverse of A modulo x^n.
Requires A[0] != 0!!
9 vector<T> inverse(const vector<T> &A, int n) {
10 vector<T> Ai{A[0].inv()};
11 for (int k = 0; (1<<k) < n; ++k) {
12 vector<T> As(4<<k, T{0}), Ais(4<<k, T{0});
13 copy_into(A, As, 2<<k); copy_into(Ai, Ais, Ai
.size());
14 fft(As, k+2, false); fft(Ais, k+2, false);
15 for (int i = 0; i < (4<<k); ++i) As[i] = As[i
]*Ais[i]*Ais[i];
16 fft(As, k+2, true); Ai.resize(2<<k, {});
17 for (int i = 0; i < (2<<k); ++i) Ai[i] = T(2)
* Ai[i] - As[i];

```

```

18 }
19 Ai.resize(n);
20 return Ai;
21 }
22 // Polynomial division. Returns {Q, R} such that
23 // A = QB+R, deg R < deg B.
24 // Requires that the leading term of B is nonzero
25 .
26 pair<vector<T>, vector<T>> divmod(const vector<T>
    &A, const vector<T> &B) {
27     size_t n = A.size()-1, m = B.size()-1;
28     if (n < m) return {vector<T>(1, T(0)), A};
29     vector<T> X(A), Y(B), Q, R;
30     convolution(rev(X), Y = inverse(rev(Y), n-m+1),
        Q);
31     Q.resize(n-m+1); rev(Q);
32     X.resize(Q.size()), copy_into(Q, X, Q.size());
33     Y.resize(B.size()), copy_into(B, Y, B.size());
34     convolution(X, Y, X);
35     R.resize(m), copy_into(A, R, m);
36     for (size_t i = 0; i < m; ++i) R[i] = R[i] - X[
        i];
37     while (R.size() > 1 && R.back().zero()) R.
        pop_back();
38     return {Q, R};
39 }
40 }
41 vector<T> mod(const vector<T> &A, const vector<T>
    &B) {
42     return divmod(A, B).second;
43 }

```

3.8.8 Linear recurs. Given a linear recurrence of the form

$$a_n = \sum_{i=0}^{k-1} c_i a_{n-i-1}$$

this code computes a_n in $O(k \log k \log n)$ time.

```

1 #include "header.h"
2 #include "poly.cpp"
3 // x^k mod f
4 vector<T> xmod(const vector<T> f, ll k) {
5     vector<T> r{T(1)};
6     for (int b = 62; b >= 0; --b) {
7         if (r.size() > 1)
8             square_inplace(r), r = mod(r, f);
9         if ((k>>b)&1) {
10             r.insert(r.begin(), T(0));
11             if (r.size() == f.size()) {
12                 T c = r.back() / f.back();

```

```

13         for (size_t i = 0; i < f.size(); ++i)
14             r[i] = r[i] - c * f[i];
15         r.pop_back();
16     }
17 }
18 }
19 return r;
20 }
21 // Given A[0,k) and C[0, k), computes the n-th
22 // term of:
23 // A[n] = \sum_i C[i] * A[n-i-1]
24 T nth_term(const vector<T> &A, const vector<T> &C
    , ll n) {
25     int k = (int)A.size();
26     if (n < k) return A[n];
27     vector<T> f(k+1, T{1});
28     for (int i = 0; i < k; ++i)
29         f[i] = T{-1} * C[k-i-1];
30     f = xmod(f, n);
31     T r = T{0};
32     for (int i = 0; i < k; ++i)
33         r = r + f[i] * A[i];
34     return r;
35 }
36 }

```

3.8.9 Convolution Precise up to 9e15

```

1 #include "header.h"
2 #include "fft.cpp"
3 void convolution_mod(const vi &A, const vi &B, ll
    MOD, vi &C) {
4     int s = A.size() + B.size() - 1; ll m15 = (1LL
        <<15)-1LL;
5     int q = 32 - __builtin_clz(s-1), N=1<<q; //
        fails if s=1
6     vector<T> Ac(N), Bc(N), R1(N), R2(N);
7     for (size_t i = 0; i < A.size(); ++i) Ac[i] = T
        {A[i]&m15, A[i]>>15};
8     for (size_t i = 0; i < B.size(); ++i) Bc[i] = T
        {B[i]&m15, B[i]>>15};
9     fft(Ac, q, false); fft(Bc, q, false);
10    for (int i = 0, j = 0; i < N; ++i, j = (N-1)&(N
        -i)) {
11        T as = (Ac[i] + Ac[j].conj()) / 2;
12        T al = (Ac[i] - Ac[j].conj()) / T{0, 2};
13        T bs = (Bc[i] + Bc[j].conj()) / 2;
14        T bl = (Bc[i] - Bc[j].conj()) / T{0, 2};
15        R1[i] = as*bs + al*bl*T{0,1}, R2[i] = as*bl +
            al*bs;
16    }
17    fft(R1, q, true); fft(R2, q, true);
18    ll p15 = (1LL<<15)%MOD, p30 = (1LL<<30)%MOD; C.
        resize(s);

```

```

19     for (int i = 0; i < s; ++i) {
20         ll l = llround(R1[i].u), m = llround(R2[i].u)
            , h = llround(R1[i].v);
21         C[i] = (l + m*p15 + h*p30) % MOD;
22     }
23 }

```

3.8.10 Partitions of n Finds all possible partitions of a number

```

1 #include "header.h"
2 void printArray(int p[], int n) {
3     for (int i = 0; i < n; i++)
4         cout << p[i] << " ";
5     cout << endl;
6 }
7
8 void printAllUniqueParts(int n) {
9     int p[n]; // An array to store a partition
10    int k = 0; // Index of last element in a
        partition
11    p[k] = n; // Initialize first partition as
        number itself
12
13    // This loop first prints current partition
14    // then generates next
15    // partition. The loop stops when the current
16    // partition has all 1s
17    while (true) {
18        printArray(p, k + 1);
19
20        // Find the rightmost non-one value in p[].
21        // Also, update the
22        // rem_val so that we know how much value can
23        // be accommodated
24        int rem_val = 0;
25        while (k >= 0 && p[k] == 1) {
26            rem_val += p[k];
27            k--;
28        }
29
30        // if k < 0, all the values are 1 so there
31        // are no more partitions
32        if (k < 0) return;
33
34        // Decrease the p[k] found above and adjust
35        // the rem_val
36        p[k]--;
37        rem_val++;
38
39        // If rem_val is more, then the sorted order
40        // is violated. Divide
41        // rem_val in different values of size p[k]
42        // and copy these values at

```

```

35 // different positions after p[k]
36 while (rem_val > p[k]) {
37     p[k + 1] = p[k];
38     rem_val = rem_val - p[k];
39     k++;
40 }
41
42 // Copy rem_val to next position and
43 // increment position
44 p[k + 1] = rem_val;
45 k++;
46 }

```

3.8.11 Ternary search

```

1 /**
2  * Description:
3  * Find the smallest i in [a,b] that maximizes
4  * f(i), assuming that f(a) < ... < f(b).
5  * To reverse which of the sides allows non-
6  * strict inequalities, change the < marked
7  * with (A) to <=, and reverse the loop at (B).
8  * To minimize f, change it to >, also at (B).
9  * Usage:
10 int ind = ternSearch(0,n-1,[&](int i){return a
11 [i];});
12 * Time: O(log(b-a))
13 */
14 #include "../Numerical/template.cpp"
15
16 template<class F>
17 int ternSearch(int a, int b, F f) {
18     assert(a <= b);
19     while (b - a >= 5) {
20         int mid = (a + b) / 2;
21         if (f(mid) < f(mid+1)) a = mid; // (A)
22         else b = mid+1;
23     }
24     rep(i,a+1,b+1) if (f(a) < f(i)) a = i; // (B)
25     return a;
26 }

```

3.9 Other Data Structures

3.9.1 Disjoint set (i.e. union-find)

```

1 template <typename T>
2 class DisjointSet {
3     typedef T * iterator;
4     T *parent, n, *rank;
5     public:

```

```

6 // O(n), assumes nodes are [0, n)
7 DisjointSet(T n) {
8     this->parent = new T[n];
9     this->n = n;
10    this->rank = new T[n];
11
12    for (T i = 0; i < n; i++) {
13        parent[i] = i;
14        rank[i] = 0;
15    }
16 }
17
18 // O(log n)
19 T find_set(T x) {
20     if (x == parent[x]) return x;
21     return parent[x] = find_set(parent[x]);
22 }
23
24 // O(log n)
25 void union_sets(T x, T y) {
26     x = this->find_set(x);
27     y = this->find_set(y);
28
29     if (x == y) return;
30
31     if (rank[x] < rank[y]) {
32         T z = x;
33         x = y;
34         y = z;
35     }
36
37     parent[y] = x;
38     if (rank[x] == rank[y]) rank[x]++;
39 }
40 };

```

3.9.2 Fenwick tree (i.e. BIT) eff. update + prefix sum calc. Can be generalized to arbitrary dimensions by duplicating loops.

```

1 // #include "header.h"
2 template < class T >
3 struct FenwickTree { // use 1 based indices !!!
4     int n ; vector <T > tree ;
5     FenwickTree ( int n ) : n ( n ) { tree .
6         assign ( n + 1 , 0 ) ; }
7     T query ( int l , int r ) { return query ( r
8         ) - query ( l - 1 ) ; }
9     T query ( int r ) {
10         T s = 0;
11         for (; r > 0; r -= ( r & ( - r ) ) ) s +=
12             tree [ r ];
13         return s ;
14     }
15 };

```

```

11 }
12 void update ( int i , T v ) {
13     for (; i <= n ; i += ( i & ( - i ) ) )
14         tree [ i ] += v ;
15 }

```

3.9.3 Trie

```

1 #include "header.h"
2 const int ALPHABET_SIZE = 26;
3 inline int mp(char c) { return c - 'a'; }
4
5 struct Node {
6     Node* ch[ALPHABET_SIZE];
7     bool isleaf = false;
8     Node() {
9         for(int i = 0; i < ALPHABET_SIZE; ++i) ch[i]
10             = nullptr;
11     }
12     void insert(string &s, int i = 0) {
13         if (i == s.length()) isleaf = true;
14         else {
15             int v = mp(s[i]);
16             if (ch[v] == nullptr)
17                 ch[v] = new Node();
18             ch[v]->insert(s, i + 1);
19         }
20     }
21
22     bool contains(string &s, int i = 0) {
23         if (i == s.length()) return isleaf;
24         else {
25             int v = mp(s[i]);
26             if (ch[v] == nullptr) return false;
27             else return ch[v]->contains(s, i + 1);
28         }
29     }
30
31     void cleanup() {
32         for (int i = 0; i < ALPHABET_SIZE; ++i)
33             if (ch[i] != nullptr) {
34                 ch[i]->cleanup();
35                 delete ch[i];
36             }
37     }
38 };

```

3.9.4 Treap A binary tree whose nodes contain two values, a key and a priority, such that the key keeps the BST property

3.9.5 Segment tree

```

1 #include "header.h"
2 struct Node {
3     ll v;
4     int sz, pr;
5     Node *l = nullptr, *r = nullptr;
6     Node(ll val) : v(val), sz(1) { pr = rand(); }
7 };
8 int size(Node *p) { return p ? p->sz : 0; }
9 void update(Node* p) {
10     if (!p) return;
11     p->sz = 1 + size(p->l) + size(p->r);
12     // Pull data from children here
13 }
14 void propagate(Node *p) {
15     if (!p) return;
16     // Push data to children here
17 }
18 void merge(Node *&t, Node *l, Node *r) {
19     propagate(l), propagate(r);
20     if (!l) t = r;
21     else if (!r) t = l;
22     else if (l->pr > r->pr)
23         merge(l->r, l->r, r), t = l;
24     else merge(r->l, l, r->l), t = r;
25     update(t);
26 }
27 void spliti(Node *t, Node *&l, Node *&r, int
    index) {
28     propagate(t);
29     if (!t) { l = r = nullptr; return; }
30     int id = size(t->l);
31     if (index <= id) // id \in [index, \infty), so
        move it right
32         spliti(t->l, l, t->l, index), r = t;
33     else
34         spliti(t->r, t->r, r, index - id), l = t;
35     update(t);
36 }
37 void splitv(Node *t, Node *&l, Node *&r, ll val)
    {
38     propagate(t);
39     if (!t) { l = r = nullptr; return; }
40     if (val <= t->v) // t->v \in [val, \infty), so
        move it right
41         splitv(t->l, l, t->l, val), r = t;
42     else
43         splitv(t->r, t->r, r, val), l = t;
44     update(t);
45 }
46 void clean(Node *p) {
47     if (p) { clean(p->l), clean(p->r); delete p; }
48 }

```

```

1 #include "../header.h"
2 template <class T, const T&(*op)(const T&, const
    T&)>
3 struct SegmentTree {
4     int n; vector<T> tree; T id;
5     SegmentTree(int _n, T _id) : n(_n), tree(2 * n,
        _id), id(_id) { }
6     void update(int i, T val) {
7         for (tree[i+n] = val, i = (i+n)/2; i > 0; i
            /= 2)
8             tree[i] = op(tree[2*i], tree[2*i+1]);
9     }
10    T query(int l, int r) {
11        T lhs = T(id), rhs = T(id);
12        for (l += n, r += n; l < r; l >>= 1, r >>= 1)
13            {
14                if (l&1) lhs = op(lhs, tree[l++]);
15                if (!(r&1)) rhs = op(tree[r--], rhs);
16            }
17        return op(l == r ? op(lhs, tree[l]) : lhs,
            rhs);
18    };

```

3.9.6 Lazy segment tree Optimizes range updates

```

1 #include "../header.h"
2 using T=int; using U=int; using I=int; //
    exclusive right bounds
3 T t_id; U u_id;
4 T op(T a, T b){ return a+b; }
5 void join(U &a, U b){ a+=b; }
6 void apply(T &t, U u, int x){ t+=x*u; }
7 T convert(const I &i){ return i; }
8 struct LazySegmentTree {
9     struct Node { int l, r, lc, rc; T t; U u;
10         Node(int l, int r, T t=t_id, I l(l), r(r), lc(-1)
            ,rc(-1), t(t), u(u_id)){
11         };
12         int N; vector<Node> tree; vector<I> &init;
13         LazySegmentTree(vector<I> &init) : N(init.size()
            ), init(init){
14             tree.reserve(2*N-1); tree.push_back({0,N});
15             build(0, 0, N);
16         }
17         void build(int i, int l, int r) { auto &n =
            tree[i];
18             if (r > l+1) { int m = (l+r)/2;
19                 n.lc = tree.size(); n.rc = n.lc+1;
20                 tree.push_back({l,m}); tree.push_back({m
                    ,r});
21                 build(n.lc,l,m); build(n.rc,m,r);
22                 n.t = op(tree[n.lc].t, tree[n.rc].t);

```

```

22     } else n.t = convert(init[l]);
23 }
24 void push(Node &n, U u){ apply(n.t, u, n.r-n.l)
    ; join(n.u,u); }
25 void push(Node &n){push(tree[n.lc],n.u);push(
    tree[n.rc],n.u);n.u=u_id;}
26 T query(int l, int r, int i = 0) { auto &n =
    tree[i];
27     if(r <= n.l || n.r <= l) return t_id;
28     if(l <= n.l && n.r <= r) return n.t;
29     return push(n, op(query(l,r,n.lc),query(l,r,
        n.rc));
30 }
31 void update(int l, int r, U u, int i = 0) {
32     auto &n = tree[i];
33     if(r <= n.l || n.r <= l) return;
34     if(l <= n.l && n.r <= r) return push(n,u);
35     push(n); update(l,r,u,n.lc); update(l,r,u,n.
        rc);
36     n.t = op(tree[n.lc].t, tree[n.rc].t);
37 };

```

3.9.7 Suffix tree

```

1 #include "../header.h"
2 using T = char;
3 using M = map<T,int>; // or array<T,
    ALPHABET_SIZE>
4 using V = string; // could be vector<T> as
    well
5 using It = V::const_iterator;
6 struct Node{
7     It b, e; M edges; int link; // end is
    exclusive
8     Node(It b, It e) : b(b), e(e), link(-1) {}
9     int size() const { return e-b; }
10 };
11 struct SuffixTree{
12     const V &s; vector<Node> t;
13     int root,n,len,remainder,llink; It edge;
14     SuffixTree(const V &s) : s(s) { build(); }
15     int add_node(It b, It e){ return t.push_back({b
        ,e}), t.size()-1; }
16     int add_node(It b){ return add_node(b,s.end());
        }
17     void link(int node){ if(!llink) t[llink].link =
        node; llink = node; }
18     void build(){
19         len = remainder = 0; edge = s.begin();
20         n = root = add_node(s.begin(), s.begin());
21         for(auto i = s.begin(); i != s.end(); ++i){
22             ++remainder; llink = 0;
23             while(remainder){

```



```

24 if(len == 0) edge = i;
25 if(t[n].edges[*edge] == 0){ // add
    new leaf
26 t[n].edges[*edge] = add_node(i); link(n
    );
27 } else {
28 auto x = t[n].edges[*edge]; // next
    node [with edge]
29 if(len >= t[x].size()){ // walk to
    next node
30 len -= t[x].size(); edge += t[x].size
    (); n = x;
31 continue;
32 }
33 if(*(t[x].b + len) == *i){ // walk
    along edge
34 ++len; link(n); break;
35 } // split edge
36 auto split = add_node(t[x].b, t[x].b+
    len);
37 t[n].edges[*edge] = split;
38 t[x].b += len;
39 t[split].edges[*i] = add_node(i);
40 t[split].edges[*t[x].b] = x;
41 link(split);
42 }
43 --remainder;
44 if(n == root && len > 0)
45 --len, edge = i - remainder + 1;
46 else n = t[n].link > 0 ? t[n].link : root
    ;
47 }
48 }
49 }
50 };

```

3.9.8 UnionFind

```

1 #include "header.h"
2 struct UnionFind {
3     std::vector<int> par, rank, size;
4     int c;
5     UnionFind(int n) : par(n), rank(n, 0), size(n,
        1), c(n) {
6         for(int i = 0; i < n; ++i) par[i] = i;
7     }
8     int find(int i) { return (par[i] == i ? i : (
        par[i] = find(par[i]))); }
9     bool same(int i, int j) { return find(i) ==
        find(j); }
10    int get_size(int i) { return size[find(i)]; }
11    int count() { return c; }
12    int merge(int i, int j) {
13        if((i = find(i)) == (j = find(j))) return -1;

```

```

14    --c;
15    if(rank[i] > rank[j]) swap(i, j);
16    par[i] = j;
17    size[j] += size[i];
18    if(rank[i] == rank[j]) rank[j]++;
19    return j;
20 }
21 };

```

4 Other Mathematics

4.1 Helpful functions

4.1.1 Euler's Totient Function $n = p_1^{k_1-1} \cdot (p_1 - 1) \cdot \dots \cdot p_r^{k_r-1} \cdot (p_r - 1)$, where $p_1^{k_1} \cdot \dots \cdot p_r^{k_r}$ is the prime factorization of n .

```

1 # include "header.h"
2 ll phi(ll n) { // \Phi(n)
3     ll ans = 1;
4     for (ll i = 2; i*i <= n; i++) {
5         if (n % i == 0) {
6             ans *= i-1;
7             n /= i;
8             while (n % i == 0) {
9                 ans *= i;
10                n /= i;
11            }
12        }
13    }
14    if (n > 1) ans *= n-1;
15    return ans;
16 }
17 vi phis(int n) { // All \Phi(i) up to n
18     vi phi(n + 1, 0LL);
19     iota(phi.begin(), phi.end(), 0LL);
20     for (ll i = 2LL; i <= n; ++i)
21         if (phi[i] == i)
22             for (ll j = i; j <= n; j += i)
23                 phi[j] -= phi[j] / i;
24     return phi;
25 }

```

Formulas $\Phi(n)$ counts all numbers in $1, \dots, n-1$ co-prime to n .

$a^{\varphi(n)} \equiv 1 \pmod n$, a and n are coprimes.

$\forall e > \log_2 m : n^e \pmod m = n^{\Phi(m)+e \pmod{\Phi(m)}} \pmod m$.

$\gcd(m, n) = 1 \Rightarrow \Phi(m \cdot n) = \Phi(m) \cdot \Phi(n)$.

4.1.2 Pascal's trinagle $\binom{n}{k}$ is k -th element in the n -th row, indexing both from 0

```

1 #include "header.h"
2 void printPascal(int n) {
3     for (int line = 1; line <= n; line++) {
4         int C = 1; // used to represent C(line, i)
5         for (int i = 1; i <= line; i++) {
6
7             // The first value in a line is
8             // always 1
9             cout << C << " ";
10            C = C * (line - i) / i;
11        }
12        cout << "\n";
13    }

```


4.2 Theorems and definitions

Fermat's little theorem

$$a^p \equiv a \pmod{p}$$

Subfactorial

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

$$!(0) = 1, !n = n!(n-1) + (-1)^n$$

Binomials and other partitionings

$$\binom{n}{k} = \binom{n-1}{k} + \binom{n-1}{k-1} = \prod_{i=1}^k \frac{n-i+1}{i}$$

This last product may be computed incrementally since any product of k' consecutive values is divisible by $k'!$.

Basic identities: The hockeystick identity:

$$\sum_{k=r}^n \binom{k}{r} = \binom{n+1}{r+1}$$

or

$$\sum_{k \leq n} \binom{r+k}{k} = \binom{r+n+1}{n}$$

Also

$$\sum_{k=0}^n \binom{k}{m} = \binom{n+1}{m+1}$$

$$\sum_{i=0}^n \binom{n}{i} = 2^n$$

For $n, m \geq 0$ and p prime: write n, m in base p , i.e. $n = n_k p^k + \dots + n_1 p + n_0$ and $m = m_k p^k + \dots + m_1 p + m_0$. Then by Lucas theorem we have $\binom{n}{m} \equiv \prod_{i=0}^k \binom{n_i}{m_i} \pmod{p}$, with the convention that $n_i < m_i \implies \binom{n_i}{m_i} = 0$.

Fibonacci (See also number theory section)

$$\sum_{0 \leq k \leq n} \binom{n-k}{k} = F_{n+1}$$

$$F_n = \frac{1}{\sqrt{5}} \left(\frac{1+\sqrt{5}}{2} \right)^n - \frac{1}{\sqrt{5}} \left(\frac{1-\sqrt{5}}{2} \right)^n$$

$$\sum_{i=1}^n F_i = F_{n+2} - 1, \sum_{i=1}^n F_i^2 = F_n F_{n+1}$$

$$\gcd(F_m, F_n) = F_{\gcd(m, n)}$$

$$\gcd(F_n, F_{n+1}) = \gcd(F_n, F_{n+2}) = 1$$

Bit stuff $a + b = a \oplus b + 2(a \& b) = a|b + a \& b$.

k th bit is set in x iff $x \bmod 2^{k-1} \geq 2^k$, or iff $x \bmod 2^{k-1} - x \bmod 2^k \neq 0$ (i.e. $= 2^k$) It comes handy when you need to look at the bits of the numbers which are pair sums or subset sums etc.

$n \bmod 2^i = n \& (2^i - 1)$.

$$\forall k: 1 \oplus 2 \oplus \dots \oplus (4k-1) = 0$$

Stirling's numbers First kind: $S_1(n, k)$ count permutations on n items with k cycles. $S_1(n, k) = S_1(n-1, k-1) + (n-1)S_1(n-1, k)$ with $S_1(0, 0) = 1$. Note:

$$\sum_{k=0}^n S_1(n, k) x^k = x(x+1) \dots (x+n-1)$$

$$\sum_{k=0}^n S_1(n, k) = n!$$

Second kind: $S_2(n, k)$ count partitions of n distinct elements into exactly k non-empty groups.

$$S_2(n, k) = S_2(n-1, k-1) + k S_2(n-1, k)$$

$$S_2(n, 1) = S_2(n, n) = 1$$

$$S_2(n, k) = \frac{1}{k!} \sum_{i=0}^k (-1)^{k-i} \binom{k}{i} i^n$$

4.3 Geometry Formulas

$$\begin{aligned} [ABC] &= rs = \frac{1}{2} ab \sin \gamma \\ &= \frac{abc}{4R} = \sqrt{s(s-a)(s-b)(s-c)} = \frac{1}{2} |(B-A, C-A)^T| \end{aligned}$$

$$s = \frac{a+b+c}{2}$$

$$2R = \frac{a}{\sin \alpha}$$

cosine rule:

$$c^2 = a^2 + b^2 - 2ab \cos \gamma$$

Euler:

$$1 + CC = V - E + F$$

Pick:

$$\text{Area} = \text{itr pts} + \frac{\text{bdry pts}}{2} - 1$$

$$p \cdot q = |p||q| \cos(\theta) \quad |p \times q| = |p||q| \sin(\theta)$$

Given a non-self-intersecting closed polygon on n vertices, given as (x_i, y_i) , its centroid (C_x, C_y) is given as:

$$C_x = \frac{1}{6A} \sum_{i=0}^{n-1} (x_i + x_{i+1})(x_i y_{i+1} - x_{i+1} y_i),$$

$$C_y = \frac{1}{6A} \sum_{i=0}^{n-1} (y_i + y_{i+1})(x_i y_{i+1} - x_{i+1} y_i)$$

$$A = \frac{1}{2} \sum_{i=0}^{n-1} (x_i y_{i+1} - x_{i+1} y_i) = \text{polygon area}$$

Inclusion-Exclusion For appropriate f compute $\sum_{S \subseteq T} (-1)^{|T \setminus S|} f(S)$, or if only the size of S matters, $\sum_{s=0}^n (-1)^{n-s} \binom{n}{s} f(s)$. In some contexts we might use Stirling numbers, not binomial coefficients!

Some useful applications:

Graph coloring Let $I(S)$ count the number of independent sets contained in $S \subseteq V$ ($I(\emptyset) = 1$, $I(S) = I(S \setminus v) + I(S \setminus N(v))$). Let $c_k = \sum_{S \subseteq V} (-1)^{|V \setminus S|} I(S)$. Then V is k -colorable iff $v > 0$. Thus we can compute the chromatic number of a graph in $O^*(2^n)$ time.

Burnside's lemma Given a group G acting on a set X , the number of elements in X up to symmetry is

$$\frac{1}{|G|} \sum_{g \in G} |X^g|$$

with X^g the elements of X invariant under g . For example, if $f(n)$ counts “configurations” of some sort of length n , and we want to count them up to rotational symmetry using $G = \mathbb{Z}/n\mathbb{Z}$, then

$$g(n) = \frac{1}{n} \sum_{k=0}^{n-1} f(\gcd(n, k)) = \frac{1}{n} \sum_{k \parallel n} f(k) \phi(n/k)$$

I.e. for coloring with c colors we have $f(k) = k^c$.

Relatedly, in Pólya's enumeration theorem we imagine X as a set of n beads with G permuting the beads (e.g. a necklace, with G all rotations and reflections of the n -cycle, i.e. the dihedral group D_n). Suppose further that we had Y colors, then the number of G -invariant colorings Y^X/G is counted by

$$\frac{1}{|G|} \sum_{g \in G} |Y|^{c(g)}$$

with $c(g)$ counting the number of cycles of g when viewed as a permutation of X . We can generalize this to a weighted version: if the color i can occur exactly r_i times, then this is counted by the coefficient of $t_1^{r_1} \dots t_n^{r_n}$ in the polynomial

$$Z(t_1, \dots, t_n) = \frac{1}{|G|} \sum_{g \in G} \prod_{m \geq 1} (t_1^m + \dots + t_n^m)^{c_m(g)}$$

where $c_m(g)$ counts the number of length m cycles in g acting as a permutation on X . Note we get the original formula by setting all $t_i = 1$. Here Z is the cycle index. Note: you can cleverly deal with even/odd sizes by setting some t_i to -1 .

Lucas Theorem If p is prime, then:

$$\frac{p^a}{k} \equiv 0 \pmod{p}$$

Thus for non-negative integers $m = m_k p^k + \dots + m_1 p + m_0$ and $n = n_k p^k + \dots + n_1 p + n_0$:

$$\frac{m}{n} = \prod_{i=0}^k \frac{m_i}{n_i} \pmod{p}$$

Note: The fraction's mean integer division.

Catalan Numbers - Number of correct bracket sequence consisting of n opening and n closing brackets.

The number of ways to completely parenthesize $n+1$ factors.

The number of triangulations of a convex polygon with $n+2$ sides (i.e. the number of partitions of polygon into disjoint triangles by using the diagonals).

The number of ways to connect the $2n$ points on a circle to form n disjoint i.e. non-intersecting chords.

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

$$C_0 = 1, C_1 = 1, C_n = \sum_{k=0}^{n-1} C_k C_{n-1-k}$$

Narayana numbers The number of expressions containing n pairs of parentheses, which are correctly matched and which contain k distinct nestings.

$$N(n, k) = \frac{1}{n} \frac{n}{k} \frac{n}{k-1}$$