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1 Template

```

1 // Racso programmed here
2 #include <bits/stdc++.h>
3 using namespace std;
4 typedef long long ll;
5 typedef long double ld;
6 typedef __int128 sll;
7 typedef pair<int,int> ii;
8 typedef pair<ll,ll> pll;
9 typedef vector<int> vi;
10 typedef vector<ll> vll;
11 typedef vector<ii> vii;
12 typedef vector<vi> vvi;
13 typedef vector<vii> vvii;
14 typedef vector<pll> vpll;
15 typedef unsigned int uint;
16 typedef unsigned long long ull;
17 #define fi first
18 #define se second
19 #define pb push_back
20 #define all(v) v.begin(),v.end()
21 #define rall(v) v.rbegin(),v.rend()
22 #define sz(a) (int)(a.size())
23 #define fori(i,a,n) for(int i = a; i < n; i++)
24 #define endl '\n'
25 const int MOD = 1e9+7;
26 const int INFTY = INT_MAX;

```

```

27 const long long LLINF = LLONG_MAX;
28 const double EPS = DBL_EPSILON;
29 void printVector( auto& v ){ fori(i,0,sz(v)) cout <<
    v[i] << " "; cout << endl; }
30 void fastIO() { ios_base::sync_with_stdio(0); cin.
    tie(0); cout.tie(0); }

```

Listing 1: Racso's template.

2 C++ Sintaxis

2.1 Compilation sentences

To compile and execute in C++:

```

g++-13 -Wall -o solucion.exe solucion.cpp
g++ -std=c++20 -Wall -o main a.cpp ./solucion.exe < input.txt > output.txt

```

To compile and execute in Java:

```

javac -Xlint Solucion.java
java Solucion < input.txt > output.txt

```

To execute in Python (two options):

```

python3 solucion.py < input.txt > output.txt
ppyy3 solucion.py < input.txt > output.txt

```

2.2 Custom comparators

```

1 // Using function
2 bool cmpFunction(const pair<int,int> &a, const pair<
    int,int> &b) {
3     return a.second < b.second;

```

```

4 }
5 sort(all(v), cmpFunction);
6 // Using functor
7 struct CmpFunctor {
8     bool operator()(const pair<int,int> &a, const pair<
9         <int,int> &b) const {
10         return a.second < b.second;
11     }
12 };
13 sort(all(v), CmpFunctor());
14 // Using lambda function
15 sort(all(v), [](const pair<int,int> &a, const pair<
16     int,int> &b) {
17     return a.second < b.second;
18 });

```

Listing 2: Template for custom sorting, using as example ordering a vii ascending by second element.

2.3 *STL DS Usage

2.4 *Strings methods

2.5 Pragas

```

1 #pragma GCC optimize("O3")
2 #pragma GCC target("avx2,bmi,bmi2,lzcnt,popcnt")
3 #pragma GCC optimize("unroll-loops")

```

Listing 3: Common pragmas.

2.6 Bit Manipulation Cheat Sheet

Bitwise operators:

- $\&$ (AND): Sets each bit to 1 if both bits are 1.
- $|$ (OR): Sets each bit to 1 if at least one bit is 1.
- \wedge (XOR): Sets each bit to 1 if bits are different.
- \sim (NOT): Inverts all bits.
- \ll (Left shift): Shifts bits left, fills with 0.
- \gg (Right shift): Shifts bits right.

Basic Bit Tasks:

- Get bit: $(n \& (1 \ll i)) \neq 0$
- Set bit: $n | (1 \ll i)$
- Clear bit: $n \& \sim(1 \ll i)$
- Toggle bit: $n \wedge (1 \ll i)$
- Clear LSB: $n \& (n - 1)$
- Get LSB: $n \& -n$

Set Operations:

- Subset check: $(A \& B) == B$
- Set union: $A | B$
- Set intersection: $A \& B$
- Set difference: $A \& \sim B$
- Toggle subset: $A \hat{=} B$

Equations:

Properties of bitwise:

- $a | b = a \oplus b + a \& b$

- $a \oplus (a \& b) = (a \mid b) \oplus b$
- $b \oplus (a \& b) = (a \mid b) \oplus a$
- $(a \& b) \oplus (a \mid b) = a \oplus b$

In addition and subtraction:

- $a + b = (a \mid b) + (a \& b)$
- $a + b = a \oplus b + 2(a \& b)$
- $a - b = (a \oplus (a \& b)) - ((a \mid b) \oplus a)$
- $a - b = ((a \mid b) \oplus b) - ((a \mid b) \oplus a)$
- $a - b = (a \oplus (a \& b)) - (b \oplus (a \& b))$
- $a - b = ((a \mid b) \oplus b) - (b \oplus (a \& b))$

Gray code: $G = B \oplus (B \gg 1)$

C++ built in functions:

- `__builtin_popcount(x)` - Count the number of set bits in x.
- `__builtin_clz(x)` - Count the number of leading zeros in x.
- `__builtin_ctz(x)` - Count the number of trailing zeros in x.

2.7 Comparing Floats

```
1 long double a, b, EPS = 1e-9;
2 if( abs(a - b) < EPS ) {
3     // 'a' equals 'b'
4 }
```

Listing 4: Check if two real numbers are equal using an epsilon scope.

2.8 Ceil

$$\left\lceil \frac{a}{b} \right\rceil = \frac{a+b-1}{b}$$

(Originally I thought $\lceil \frac{a}{b} \rceil = \frac{a-1}{b} + 1$, but this calculates the wrong way in the cases where $a = 0$)

```
1 int myCeil(long long a, long long b) {
2     return (a + b - 1)/b;
3 }
```

Listing 5: A way to do ceil operation between integers without making explicit conversions. `a` and `b` are `int`, but the operation `a+b-1` can cause an overflow, so they must be casted into `long long` to avoid this. The result must be `int` anyway.

3 Miscellaneous

3.1 Binary Search

```
1 int binary_search( vector<int>& list, int n, int
   target ) {
2     int x0 = 0, x1 = n-1, mid;
3     while( x0 <= x1 ) {
4         mid = (x0 + x1) / 2; // (x1 - x0) / 2 + x0;
5         if( list[mid] == target )
6             return mid;
7         list[mid] < target ? x0 = mid + 1 : x1 = mid
   - 1;
8     }
9     return -1;
10 }
```

Listing 6: Classic (Vanilla) implementation of Binary Search. Returns the index where **target** was found. Binary Search works on $O(\log_2(n))$, let n be the size of the container.

```

1 int binary_search( vector<int>& list, int n, int
   target ) {
2     int ans = 0;
3     function<bool(int)> check = [&](int idx)->bool {
4         return idx < n && list[idx] <= target;
5     };
6     for( int i = 31; i >= 0; i-- ) {
7         if( check( ans + (1 << i) ) )
8             ans += 1 << i;
9     }
10    return list[ans] == target ? ans : -1;
11 }
```

Listing 7: Logarithmic jumps implementation of Binary Search. Returns the index where **target** was found. Binary Search works on $O(\log_2(n))$, let n be the size of the container.

```

1 int binary_search( vector<int>& list, int n, int
   target ) {
2     int left = 1, right = n + 1, mid;
3     while(right - left >= 1) {
4         mid = left + (right - left) / 2;
5         if( list[mid] >= target && target > list[mid -
6             1] ) {
```

```

6         //----- TODO logic here -----//
7         break;
8     }
9     else
10        if( list[mid] < target )
11            left = mid + 1;
12        else
13            right = mid;
14    }
15 }
```

Listing 8: Binary Search implementation for searching an element in the interval $(numbers_{i-1}, numbers_i]$. Originally used on Codeforces problem 474 - B (Worms). Returns the index where **target** was found. Binary Search works on $O(\log_2(n))$, let n be the size of the container.

```

1 function<bool(ll)> check = [&](ll t) -> bool {
2     ll products = 0;
3     for(ll machine : v) {
4         products += t / machine;
5         if( products >= target )
6             return true;
7     }
8     return products >= target;
9 };
10 for(int i = 0; i < 70; i++) {
11     mid = (x0 + x1) / 2;
12     check(mid) ? x1 = mid : x0 = mid + 1;
13 }
```

Listing 9: Implementation of Binary Search in the Answer. Originally used on CSES problem *Factory Machines*. Binary Search works on $O(\log_2(n))$, let n be the size of the container.

3.1.1 *Parallel Binary Search

3.1.2 *Ternary Search

3.2 Kadane's Algorithm

```

1 ll arns = v[0], maxSum = 0;
2 for(i,0,n)
3 {
4     maxSum += v[i];
5     arns = max(arns, maxSum);
6     maxSum = max(0LL, maxSum);
7 }
```

Listing 10: Uses Kadane's Algorithm to find maximum subarray sum in $O(n)$.

4 Queries

4.1 Prefix Sum 2D

```

1 for(int i = 1; i <= n; i++)
2     for(int j = 1; j <= n; j++)
3     {
4         prefix[i][j] = prefix[i][j-1] + prefix[i-1][j] -
5         prefix[i-1][j-1];
6         prefix[i][j] += forest[i-1][j-1] == '*' ? 1 : 0;
```

```

6     }
7 for(int i = 0; i < q; i++)
8 {
9     pair<int,int> p1, p2;
10    cin >> p1.fi >> p1.se >> p2.fi >> p2.se;
11    int arns = prefix[p2.fi][p2.se];
12    arns -= prefix[p2.fi][p1.se-1] + prefix[p1.fi-1][
13        p2.se];
14    arns += prefix[p1.fi-1][p1.se-1];
15    cout << arns << endl;
```

Listing 11: Construction and query of how many 1's are there in a matrix. Originally used on *Forest Queries* from CSES.

4.2 *Sparse Table

4.3 *Sqrt Decomposition

4.4 *Fenwick Tree

4.5 *Fenwick Tree 2D

4.6 Segment Tree

```

1 typedef long long ll;
2 typedef vector<ll> vll;
3 typedef vector<int> vi;
4 const int INF = INT_MAX;
5 class Segment_tree {
6     public: vll t;
7     Segment_tree( int n = 1e5+10 ) {
```



```

8      t.assign(n*4,INF);
9  }
10 void update(int node, int index, int tl, int tr,
11 int val) {
12     if( tr < index || tl > index ) return;
13     if( tr == tl ) t[node] = val;
14     else {
15         int mid = tl + ((tr-tl)>>1);
16         int lft = node << 1;
17         int rght = lft + 1;
18         update(lft,index,tl,mid,val);
19         update(rght,index,mid+1,tr,val);
20         t[node] = min(t[lft],t[rght]);
21     }
22 ll query(int node, int l, int r, int tl, int tr)
23 {
24     if( tl > r || tr < l ) return INF;
25     if( tl >= l and tr <= r ) return t[node];
26     else {
27         int mid = tl + ((tr-tl)>>1);
28         int lft = node << 1;
29         int rght = lft + 1;
30         ll q1 = query(lft,l,r,tl,mid);
31         ll q2 = query(rght,l,r,mid+1,tr);
32         return min(q1,q2);
33     }
34 }

```

```

34 void build(vi &v, int node, int tl, int tr) {
35     if( tl == tr ) t[node] = v[tl];
36     else {
37         int mid = tl + ((tr-tl)>>1);
38         int lft = node << 1;
39         int rght = lft + 1;
40         build(v,lft,tl,mid);
41         build(v,rght,mid+1,tr);
42         t[node] = min(t[lft],t[rght]);
43     }
44 }
45 };
46 Segment_tree st(n);
47 st.build(v,1,0,n-1);
48 st.update(1,a-1,0,n-1,b);
49 st.query(1,a-1,b-1,0,n-1));

```

Listing 12: Segment Tree for Dynamic Range **Minimum** Queries. Racso's Implementation.

```

1 vector<long long> v, sex;
2 int n;
3 void build(int node, int l, int r){
4     if(l == r) sex[node] = v[l];
5     else{
6         int mid = (l+r)/2;
7         build(2*node, l, mid);
8         build(2*node + 1, mid+1, r);
9         sex[node] = sex[2*node] + sex[2*node +1];

```

```

10     }
11 }
12 void update(int node, int l, int r, int idx, int val)
13     ){
14     if(l == r){
15         v[idx] = val;
16         sex[node] = val;
17     }
18     else{
19         int mid = (l+r)/2;
20         if(l <= idx && idx <= mid) update(2*node, l,
21         mid, idx, val);
22         else update(2*node + 1, mid+1, r, idx, val);
23         sex[node] = sex[2*node] + sex[2*node + 1];
24     }
25 }
26 int query(int node, int tl, int tr, int l, int r){
27     if(r < tl || tr < l) return 0;
28     if(l <= tl && tr <= r) return sex[node];
29     int tm = (tl+tr)/2;
30     return query(2*node, tl, tm, l, r) + query(2*
31     node + 1, tm+1, tr, l, r);
32 }
33 v.resize(n);
34 sex.resize(4 * n);
35 build(1, 0, n - 1);
36 query(1, 0, n-1, l - 1, r - 1)

```

Listing 13: Segment Tree for Dynamic Range **Sum** Queries. Zum's Implementation.

4.6.1 *2D Segment Tree

4.6.2 *Persistent Segment Tree

4.6.3 *Lazy Propagation

4.7 Ordered Set

```

1  //<-- Header.
2  #include <bits/stdc++.h>
3  #include <ext/pb_ds/assoc_container.hpp>
4  #include <ext/pb_ds/tree_policy.hpp>
5  using namespace std;
6  using namespace __gnu_pbds;
7  template<typename T, typename Cmp = less<T>>
8  using ordered_set = tree<T,null_type,Cmp,rb_tree_tag
9  ,tree_order_statistics_node_update>;
10 //<-- Declaration.
11 ordered_set<int> oset;
12 //<-- Methods usage.
13 // K-th element in a set (counting from zero).
14 ordered_set<int>::iterator it = oset.find_by_order(k
15 );
16 // Number of items strictly smaller than k.
17 ordered_set<int>::iterator it = oset.order_of_key(k
18 );
19 // Every other std::set method.

```

Listing 14: Ordered set necessary includes in header, declaration of the object, and usage of its new methods.

4.7.1 Multi-Ordered Set

```

1 //<-- Header.
2 #include <bits/stdc++.h>
3 #include <ext/pb_ds/assoc_container.hpp>
4 #include <ext/pb_ds/tree_policy.hpp>
5 using namespace std;
6 using namespace __gnu_pbds;
7 template<typename T, typename Cmp = less<T>>
8 using ordered_set = tree<T,null_type,Cmp,rb_tree_tag
    ,tree_order_statistics_node_update>;
9 //<-- Use in main.
10 ordered_set<pair<int,int>> multi_aset;
11 map<int,int> cuenta;
12 function<void(int)> insertar = [&](int val) -> void
    {
13     multi_aset.insert({val,++cuenta[val]});
14 };
15 function<void(int)> eliminar = [&](int val) -> void
    {
16     multi_aset.erase({val,cuenta[val]--});
17 };

```

Listing 15: Declaration of multi-aset structure.

4.8 *Treap

4.9 *Trie

5 Graph Theory

5.1 Breadth-First Search (BFS)

```

1 vector<vector<int>> graph;
2 vector<bool> visited;
3 graph.assign(n, vector<int>() ); // <--- main
4 visited.assign(n, false); // <--- main
5
6 void bfs( int s ) {
7     queue<int> q;
8     q.push( s );
9     visited[ s ] = true;
10    while( ! q.empty() ) {
11        int u = q.front();
12        q.pop();
13        for( auto v : graph[ u ] ) {
14            if( ! visited[ u ] ) {
15                visited[ u ] = true;
16                q.push( v );
17                // --- ToDo logic here ---
18            }
19        }
20    }
21    return;
22 }

```

Listing 16: Iterative implementation of BFS graph traversal over a graph represented as a AdjacencyList on vector of vectors. BFS runs in $O(|V| + |E|)$.

```

1  int n, m;
2  string arns = "";
3  cin >> n >> m;
4  vector<vector<bool>> visited(n, vector<bool>(m, false)
   );
5  vector<string> path(n, string(m, '0'));
6  vector<string> grid(n);
7  vii dirs = {{0,1},{0,-1},{1,0},{-1,0}};
8  string commands = "LRUD";
9  queue<ii> q;
10 ii start, end, curr;
11 function<bool(int,int)> valid = [&](int i, int j) ->
    bool {
12     return ( i >= 0 && i < n && j >= 0 && j < m &&
        grid[i][j] != '#' && ! visited[i][j] );
13 };
14 fori(i,0,n) cin >> grid[i];
15 fori(i,0,n) {
16     fori(j,0,m)
17         if( grid[i][j] == 'A' ) {
18             visited[i][j] = true;
19             q.push( {i,j} );
20         }
21 }

```

```

22 while( ! q.empty() ) {
23     curr = q.front();
24     q.pop();
25     int i = curr.fi;
26     int j = curr.se;
27     if( grid[i][j] == 'B' ) {
28         end.fi = i;
29         end.se = j;
30         break;
31     }
32     int newI, newJ;
33     fori(I,0,4) {
34         newI = i + dirs[I].fi;
35         newJ = j + dirs[I].se;
36         if( valid(newI,newJ) ) {
37             visited[newI][newJ] = true;
38             q.push( {newI,newJ} );
39             path[newI][newJ] = commands[I];
40         }
41     }
42 }
43 while( path[ end.fi ][ end.se ] != '0' ) {
44     fori(i,0,4) {
45         if( path[ end.fi ][ end.se ] == commands[i] )
46         {
47             arns += i & 1 ? commands[i-1] : commands[i

```

```

48         end.se -= dirs[i].se;
49     }
50 }
51 }
52 reverse(all(arns));
53 if( arns == "" ) cout << "NO" << endl;
54 else cout << "YES" << endl << arns.size() << endl <<
    arns << endl;

```

Listing 17: BFS on Grid to find shortest path from an starting point A to an end B . Once the path is found, it reconstruct it with movements $LRUD$. Works in $O(n \cdot m)$. Originally used on problem *Labyrinth* from CSES.

5.2 Deep-First Search (DFS)

```

1 vector<vector<int>> graph;
2 vector<bool> visited;
3 graph.assign(n, vector<int>()); // <--- main
4 visited.assign(n, false); // <--- main
5
6 void dfs( int s ) {
7     if( visited[s] == true ) return;
8     visited[s] = true;
9     vector<int>::iterator i;
10    for( i = graph[s].begin(); i < graph[s].end();
++i) {
11        if( ! visited[*i] ) {
12            // --- ToDo logic here ---
13            dfs(*i);

```

```

14    }
15 }
16 }

```

Listing 18: Recursive implementation of DFS graph traversal over a graph represented as a AdjacencyList on vector of vectors. DFS runs in $O(|V| + |E|)$.

```

1 vector<vector<int>> graph;
2 vector<bool> visited;
3 void dfs( int s ) {
4     stack<int> stk;
5     stk.push(s);
6     while (!stk.empty()) {
7         int u = stk.top();
8         stk.pop();
9         if ( visited[u] ) continue;
10        visited[u] = true;
11        // --- ToDo logic here ---
12        for(auto it = graph[u].rbegin(); it != graph
[u].rend(); ++it)
13            if (!visited[*it])
14                stk.push(*it);
15    }
16 }

```

Listing 19: Iterative implementation of DFS graph traversal over a graph represented as a AdjacencyList on vector of vectors. DFS runs in $O(|V| + |E|)$.

```

1 typedef long long ll;
2 vector<vector<ll>> adj;

```

```

3 vector<bool> visited;
4 function<void(ll)> dfs = [&](ll u) -> void {
5     if( visited[u] ) return;
6     visited[u] = true;
7     for( ll v : adj[u] )
8         dfs(v);
9 };
10 dfs(n);

```

Listing 20: DFS implementation with a lambda function (adjacency list and visited don't need to be passed thorough argument). DFS runs in $O(|V| + |E|)$.

```

1 typedef long long ll;
2 typedef vector<ll> vll;
3 map<ll,vll> adj;
4 set<ll> visited;
5 function<void(ll)> dfs = [&](ll u) -> void {
6     if( visited.count(u) ) return;
7     visited.insert(u);
8     for( ll v : adj[u] )
9         dfs(v);
10 };
11 dfs(n);

```

Listing 21: DFS implementation with a lambda function implemented with a map instead of vector of vectors, and a set to track visited nodes. DFS runs in $O(|V| + |E|)$.

5.3 Shortest Path

5.3.1 Dijkstra's Algorithm

```

1 typedef long long ll;
2 typedef pair<ll,ll> pll;
3
4 vector<vector<ll>> graph;
5 vector<ll> visited;
6 graph.assign(n, vector<ll>() ); // <--- main
7 visited.assign(n, false); // <--- main
8
9 vector<ll> dijkstra( int n, int source, vector<
    vector<pll>> &graph ) {
10     vector<ll> dist( n, INFTY );
11     priority_queue<pll, vector<pll>, greater<pll>> pq;
12     dist[ source ] = 0;
13     pq.push( {0, source} );
14     while( ! pq.empty() ) {
15         ll d = pq.top().first;
16         ll u = pq.top().second;
17         pq.pop();
18         if( d > dist[ u ] ) continue;
19         for( auto &edge : graph[ u ] ) {
20             ll v = edge.first;
21             ll weight = edge.second;
22             if( dist[ u ] + weight < dist[ v ] ) {
23                 dist[ v ] = dist[ u ] + weight;
24                 pq.push( {dist[ v ], v} );

```

```

25     }
26 }
27 }
28 return dist;
29 }

```

Listing 22: Iterative implementation of Dijkstra's Algorithm for shortest path over a graph represented as a AdjacencyList on vector of vectors. Returns a vector with the shortest path to every other vertex in the graph. $O(|E| \times \log_2(|V|))$. doesn't work with negative weights.

```

1  vvp11 graph(n+1,vp11());
2  vector<bool> visited(n+1,false);
3  function<v11(int)> dijkstra = [&](int source) -> v11
    {
4      v11 dist(n+1,INF);
5      priority_queue<p11,vp11,greater<p11>> pq;
6      dist[source] = 0;
7      pq.push({0,source});
8      while( ! pq.empty() ) {
9          11 d = pq.top().fi;
10         11 u = pq.top().se;
11         pq.pop();
12         if( d > dist[u] ) continue;
13         for(p11 edge : graph[u]) {
14             11 v = edge.fi;
15             11 w = edge.se;
16             if( dist[u] + w < dist[v] ) {
17                 dist[v] = dist[u] + w;

```

```

18         pq.push({dist[v],v});
19     }
20 }
21 }
22 return dist;
23 };

```

Listing 23: Iterative implementation of Dijkstra's Algorithm as a Lambda Function for shortest path over a graph represented as a AdjacencyList on vector of vectors. Returns a vector with the shortest path to every other vertex in the graph. $O(|E| \times \log_2(|V|))$. Doesn't work with negative weights.

5.3.2 *Floyd-Warshall's Algorithm

5.3.3 Bellman-Ford Algorithm

```

1  int V, E;
2  cin >> V >> E;
3  vvi edges(E,vi(3,0));
4
5  for(int i = 1; i <= E; i++)
6      cin >> edges[i][0] >> edges[i][1] >> edges[i][2];
7
8  function<vi(int)> bellman_ford = [&](int src) -> vi
9  {
10     vi dist(V,INF);
11     dist[src] = 0;
12     for(int i = 0; i < V; i++)
13     {
14         for( vi edge : edges )

```

```

15     {
16         int u = edge[0];
17         int v = edge[1];
18         int w = edge[2];
19         if( dist[u] != INF and dist[u] + w < dist[v]
20     )
21     {
22         if( i == V-1 )
23             return = {-1};
24         dist[v] = dist[u] + w;
25     }
26 }
27 return dist;
28 };

```

Listing 24: Finds the shortest route from a source vertex, to every other one in the graph. Works over a list of edges. Runs in $O(|V| \times |E|)$. Can be used to find negative cycles.

5.4 Minimum Spanning Tree (MST)

5.4.1 *Prim's Algorithm

5.4.2 *Kruskal's Algorithm

5.5 *Bipartite Checking

5.6 *Negative Cycles

5.7 Topological Sort

```

1 vi topo;

```

```

2 vvi graph(V+1,vi());
3 vector<bool> visited(V+1,false);
4 function<void(int)> dfs = [&](int u) -> void {
5     visited[u] = true;
6     for(int v : graph[u])
7         if( ! visited[v] )
8             dfs(v);
9     topo.pb(u);
10 };
11 function<void()> topological_sort = [&]() -> void {
12     for(int i = 1; i <= V; i++)
13         if( ! visited[i] )
14             dfs(i);
15     reverse(all(topo));
16 };
17 topological_sort();
18 for(int i = 0; i < V; i++) cout << topo[i] << " ";

```

Listing 25: Recursive toposort implementation for unweighted DAG through vvi with DFS with inverted postorder. Runs in $O(|V| \times |E|)$.

d

```

1 vi indegree(V+1,0);
2 vvi graph(V+1,vi());
3 vector<bool> visited(V+1,false);
4 fori(i,0,E) {
5     graph[u].pb(v);
6     indegree[v]++;
7 }

```



```

8 function<vi()> topological_sort = [&]() -> vi {
9     vi order, deg = indegree; // copy
10    queue<int> q;
11    for(int i = 1; i <= V; i++)
12        if( deg[i] == 0 )
13            q.push(i);
14    while( ! q.empty() ) {
15        int u = q.front(); q.pop();
16        order.pb(u);
17        for(int v : graph[u]) {
18            deg[v]--;
19            if(deg[v] == 0)
20                q.push(v);
21        }
22    }
23    return order;
24 };
25 vi topo = topological_sort();
26 if( (int)(topo.size()) != V ) cout << "IMPOSSIBLE"
    << endl;

```

Listing 26: Kahn's Algorithm for Topological Sorting using BFS and indegree vertex analysis (nodes in a cycle will never have indegree zero). Works over unweighted directed graphs containing cycles through vvi. Runs in $O(|V| \times |E|)$.

5.8 Disjoint Set Union (DSU)

```

1 class DisjointSets {
2 private:

```

```

3     vector<int> parents;
4 public:
5     vector<int> sizes;
6     DisjointSets(int size) : parents(size), sizes(size
7         , 1) {
8         for (int i = 0; i < size; i++) { parents[i] = i;
9         }
10    }
11    /** @return the "representative" node in x's
12        component */
13    int find( int x ) {
14        return parents[x] == x ? x : ( parents[x] =
15        find( parents[x] ) );
16    }
17    /** @return whether the merge changed connectivity
18        */
19    bool unite( int x, int y ) {
20        int x_root = find(x);
21        int y_root = find(y);
22        if (x_root == y_root) return false;
23        if ( sizes[x_root] < sizes[y_root] ) swap(x_root
24        , y_root);
25        sizes[x_root] += sizes[y_root];
26        parents[y_root] = x_root;
27        return true;
28    }
29    /** @return whether x and y are in the same
30        connected component */

```

```

24 bool connected( int x, int y ){
25     return find(x) == find(y);
26 }
27 void printLists() {
28     cout << "Printing parents..." << endl;
29     for(auto i : parents)
30         cout << i << " ";
31     cout << endl << "Printing sizes..." << endl;
32     for(auto i : sizes )
33         cout << i << " ";
34 }
35 };
36 DisjointSets dsu( V );
37 int number_of_components = V, largest_component = 1;
38 if( dsu.unite(x, y) ) {
39     largest_component = max( largest_component, dsu.
40         sizes[ dsu.find( x ) ] );
41     number_of_components--;
42 }

```

Listing 27: Template and usage of DSU with path compression. Complexity of $O(m \alpha(n))$ for a sequence of m operations over n elements. Where α denotes Ackerman function, where $\alpha(n) \leq 4, \forall n \leq 10^{18}$. Practically $O(1)$.

5.9 *Condensation Graph

5.10 *Strongly Connected Components (SCC)

5.11 2-SAT

```

1 struct TwoSatSolver {
2     int n_vars;
3     int n_vertices;
4     vector<vector<int>> adj, adj_t;
5     vector<bool> used;
6     vector<int> order, comp;
7     vector<bool> assignment;
8
9     TwoSatSolver(int _n_vars) : n_vars(_n_vars),
10        n_vertices(2 * n_vars), adj(n_vertices), adj_t(
11        n_vertices), used(n_vertices), order(), comp(
12        n_vertices, -1), assignment(n_vars) {
13        order.reserve(n_vertices);
14    }
15
16    void dfs1(int v) {
17        used[v] = true;
18        for (int u : adj[v]) {
19            if (!used[u])
20                dfs1(u);
21        }
22        order.push_back(v);
23    }
24
25    void dfs2(int v, int cl) {
26        comp[v] = cl;
27        for (int u : adj_t[v]) {
28            if (comp[u] == -1)
29                dfs2(u, cl);
30        }
31    }
32
33    void solve() {
34        dfs1(0);
35        reverse(order.begin(), order.end());
36        for (int i = 0; i < order.size(); i++) {
37            int v = order[i];
38            if (comp[v] == -1) {
39                dfs2(v, 1);
40            }
41        }
42        for (int i = 0; i < n_vars; i++) {
43            assignment[i] = comp[2*i] == 1;
44        }
45    }
46
47    bool satisfiable() {
48        return true;
49    }
50
51    void printAssignment() {
52        for (int i = 0; i < n_vars; i++) {
53            cout << i << ": " << assignment[i] << " ";
54            if (i % 10 == 9) cout << endl;
55        }
56    }
57
58    void printComponents() {
59        for (int i = 0; i < comp.size(); i++) {
60            cout << i << ": " << comp[i] << " ";
61            if (i % 10 == 9) cout << endl;
62        }
63    }
64
65    void printAdjacencyList() {
66        for (int i = 0; i < adj.size(); i++) {
67            cout << i << ": " << adj[i] << " ";
68            if (i % 10 == 9) cout << endl;
69        }
70    }
71
72    void printAdjacencyMatrix() {
73        for (int i = 0; i < adj.size(); i++) {
74            for (int j = 0; j < adj[i].size(); j++) {
75                cout << adj[i][j] << " ";
76            }
77            cout << endl;
78        }
79    }
80
81    void printUsed() {
82        for (int i = 0; i < used.size(); i++) {
83            cout << i << ": " << used[i] << " ";
84            if (i % 10 == 9) cout << endl;
85        }
86    }
87
88    void printOrder() {
89        for (int i = 0; i < order.size(); i++) {
90            cout << i << ": " << order[i] << " ";
91            if (i % 10 == 9) cout << endl;
92        }
93    }
94
95    void printComp() {
96        for (int i = 0; i < comp.size(); i++) {
97            cout << i << ": " << comp[i] << " ";
98            if (i % 10 == 9) cout << endl;
99        }
100    }
101
102    void printAssignmentAndComp() {
103        for (int i = 0; i < n_vars; i++) {
104            cout << i << ": " << assignment[i] << " ";
105            if (i % 10 == 9) cout << endl;
106        }
107        for (int i = 0; i < comp.size(); i++) {
108            cout << i << ": " << comp[i] << " ";
109            if (i % 10 == 9) cout << endl;
110        }
111    }
112
113    void printAdjacencyListAndComp() {
114        for (int i = 0; i < adj.size(); i++) {
115            cout << i << ": " << adj[i] << " ";
116            if (i % 10 == 9) cout << endl;
117        }
118        for (int i = 0; i < comp.size(); i++) {
119            cout << i << ": " << comp[i] << " ";
120            if (i % 10 == 9) cout << endl;
121        }
122    }
123
124    void printUsedAndComp() {
125        for (int i = 0; i < used.size(); i++) {
126            cout << i << ": " << used[i] << " ";
127            if (i % 10 == 9) cout << endl;
128        }
129        for (int i = 0; i < comp.size(); i++) {
130            cout << i << ": " << comp[i] << " ";
131            if (i % 10 == 9) cout << endl;
132        }
133    }
134
135    void printOrderAndComp() {
136        for (int i = 0; i < order.size(); i++) {
137            cout << i << ": " << order[i] << " ";
138            if (i % 10 == 9) cout << endl;
139        }
140        for (int i = 0; i < comp.size(); i++) {
141            cout << i << ": " << comp[i] << " ";
142            if (i % 10 == 9) cout << endl;
143        }
144    }
145
146    void printAssignmentAndOrder() {
147        for (int i = 0; i < n_vars; i++) {
148            cout << i << ": " << assignment[i] << " ";
149            if (i % 10 == 9) cout << endl;
150        }
151        for (int i = 0; i < order.size(); i++) {
152            cout << i << ": " << order[i] << " ";
153            if (i % 10 == 9) cout << endl;
154        }
155    }
156
157    void printAdjacencyListAndOrder() {
158        for (int i = 0; i < adj.size(); i++) {
159            cout << i << ": " << adj[i] << " ";
160            if (i % 10 == 9) cout << endl;
161        }
162        for (int i = 0; i < order.size(); i++) {
163            cout << i << ": " << order[i] << " ";
164            if (i % 10 == 9) cout << endl;
165        }
166    }
167
168    void printUsedAndOrder() {
169        for (int i = 0; i < used.size(); i++) {
170            cout << i << ": " << used[i] << " ";
171            if (i % 10 == 9) cout << endl;
172        }
173        for (int i = 0; i < order.size(); i++) {
174            cout << i << ": " << order[i] << " ";
175            if (i % 10 == 9) cout << endl;
176        }
177    }
178
179    void printOrderAndOrder() {
180        for (int i = 0; i < order.size(); i++) {
181            cout << i << ": " << order[i] << " ";
182            if (i % 10 == 9) cout << endl;
183        }
184        for (int i = 0; i < order.size(); i++) {
185            cout << i << ": " << order[i] << " ";
186            if (i % 10 == 9) cout << endl;
187        }
188    }
189
190    void printAssignmentAndAssignment() {
191        for (int i = 0; i < n_vars; i++) {
192            cout << i << ": " << assignment[i] << " ";
193            if (i % 10 == 9) cout << endl;
194        }
195        for (int i = 0; i < n_vars; i++) {
196            cout << i << ": " << assignment[i] << " ";
197            if (i % 10 == 9) cout << endl;
198        }
199    }
200
201    void printAdjacencyListAndAdjacencyList() {
202        for (int i = 0; i < adj.size(); i++) {
203            cout << i << ": " << adj[i] << " ";
204            if (i % 10 == 9) cout << endl;
205        }
206        for (int i = 0; i < adj.size(); i++) {
207            cout << i << ": " << adj[i] << " ";
208            if (i % 10 == 9) cout << endl;
209        }
210    }
211
212    void printUsedAndUsed() {
213        for (int i = 0; i < used.size(); i++) {
214            cout << i << ": " << used[i] << " ";
215            if (i % 10 == 9) cout << endl;
216        }
217        for (int i = 0; i < used.size(); i++) {
218            cout << i << ": " << used[i] << " ";
219            if (i % 10 == 9) cout << endl;
220        }
221    }
222
223    void printOrderAndOrder() {
224        for (int i = 0; i < order.size(); i++) {
225            cout << i << ": " << order[i] << " ";
226            if (i % 10 == 9) cout << endl;
227        }
228        for (int i = 0; i < order.size(); i++) {
229            cout << i << ": " << order[i] << " ";
230            if (i % 10 == 9) cout << endl;
231        }
232    }
233
234    void printAssignmentAndCompAndOrder() {
235        for (int i = 0; i < n_vars; i++) {
236            cout << i << ": " << assignment[i] << " ";
237            if (i % 10 == 9) cout << endl;
238        }
239        for (int i = 0; i < comp.size(); i++) {
240            cout << i << ": " << comp[i] << " ";
241            if (i % 10 == 9) cout << endl;
242        }
243        for (int i = 0; i < order.size(); i++) {
244            cout << i << ": " << order[i] << " ";
245            if (i % 10 == 9) cout << endl;
246        }
247    }
248
249    void printAdjacencyListAndCompAndOrder() {
250        for (int i = 0; i < adj.size(); i++) {
251            cout << i << ": " << adj[i] << " ";
252            if (i % 10 == 9) cout << endl;
253        }
254        for (int i = 0; i < comp.size(); i++) {
255            cout << i << ": " << comp[i] << " ";
256            if (i % 10 == 9) cout << endl;
257        }
258        for (int i = 0; i < order.size(); i++) {
259            cout << i << ": " << order[i] << " ";
260            if (i % 10 == 9) cout << endl;
261        }
262    }
263
264    void printUsedAndCompAndOrder() {
265        for (int i = 0; i < used.size(); i++) {
266            cout << i << ": " << used[i] << " ";
267            if (i % 10 == 9) cout << endl;
268        }
269        for (int i = 0; i < comp.size(); i++) {
270            cout << i << ": " << comp[i] << " ";
271            if (i % 10 == 9) cout << endl;
272        }
273        for (int i = 0; i < order.size(); i++) {
274            cout << i << ": " << order[i] << " ";
275            if (i % 10 == 9) cout << endl;
276        }
277    }
278
279    void printOrderAndCompAndOrder() {
280        for (int i = 0; i < order.size(); i++) {
281            cout << i << ": " << order[i] << " ";
282            if (i % 10 == 9) cout << endl;
283        }
284        for (int i = 0; i < comp.size(); i++) {
285            cout << i << ": " << comp[i] << " ";
286            if (i % 10 == 9) cout << endl;
287        }
288        for (int i = 0; i < order.size(); i++) {
289            cout << i << ": " << order[i] << " ";
290            if (i % 10 == 9) cout << endl;
291        }
292    }
293
294    void printAssignmentAndCompAndComp() {
295        for (int i = 0; i < n_vars; i++) {
296            cout << i << ": " << assignment[i] << " ";
297            if (i % 10 == 9) cout << endl;
298        }
299        for (int i = 0; i < comp.size(); i++) {
300            cout << i << ": " << comp[i] << " ";
301            if (i % 10 == 9) cout << endl;
302        }
303        for (int i = 0; i < comp.size(); i++) {
304            cout << i << ": " << comp[i] << " ";
305            if (i % 10 == 9) cout << endl;
306        }
307    }
308
309    void printAdjacencyListAndCompAndComp() {
310        for (int i = 0; i < adj.size(); i++) {
311            cout << i << ": " << adj[i] << " ";
312            if (i % 10 == 9) cout << endl;
313        }
314        for (int i = 0; i < comp.size(); i++) {
315            cout << i << ": " << comp[i] << " ";
316            if (i % 10 == 9) cout << endl;
317        }
318        for (int i = 0; i < comp.size(); i++) {
319            cout << i << ": " << comp[i] << " ";
320            if (i % 10 == 9) cout << endl;
321        }
322    }
323
324    void printUsedAndCompAndComp() {
325        for (int i = 0; i < used.size(); i++) {
326            cout << i << ": " << used[i] << " ";
327            if (i % 10 == 9) cout << endl;
328        }
329        for (int i = 0; i < comp.size(); i++) {
330            cout << i << ": " << comp[i] << " ";
331            if (i % 10 == 9) cout << endl;
332        }
333        for (int i = 0; i < comp.size(); i++) {
334            cout << i << ": " << comp[i] << " ";
335            if (i % 10 == 9) cout << endl;
336        }
337    }
338
339    void printOrderAndCompAndComp() {
340        for (int i = 0; i < order.size(); i++) {
341            cout << i << ": " << order[i] << " ";
342            if (i % 10 == 9) cout << endl;
343        }
344        for (int i = 0; i < comp.size(); i++) {
345            cout << i << ": " << comp[i] << " ";
346            if (i % 10 == 9) cout << endl;
347        }
348        for (int i = 0; i < comp.size(); i++) {
349            cout << i << ": " << comp[i] << " ";
350            if (i % 10 == 9) cout << endl;
351        }
352    }
353
354    void printAssignmentAndCompAndAssignment() {
355        for (int i = 0; i < n_vars; i++) {
356            cout << i << ": " << assignment[i] << " ";
357            if (i % 10 == 9) cout << endl;
358        }
359        for (int i = 0; i < comp.size(); i++) {
360            cout << i << ": " << comp[i] << " ";
361            if (i % 10 == 9) cout << endl;
362        }
363        for (int i = 0; i < n_vars; i++) {
364            cout << i << ": " << assignment[i] << " ";
365            if (i % 10 == 9) cout << endl;
366        }
367    }
368
369    void printAdjacencyListAndCompAndAssignment() {
370        for (int i = 0; i < adj.size(); i++) {
371            cout << i << ": " << adj[i] << " ";
372            if (i % 10 == 9) cout << endl;
373        }
374        for (int i = 0; i < comp.size(); i++) {
375            cout << i << ": " << comp[i] << " ";
376            if (i % 10 == 9) cout << endl;
377        }
378        for (int i = 0; i < n_vars; i++) {
379            cout << i << ": " << assignment[i] << " ";
380            if (i % 10 == 9) cout << endl;
381        }
382    }
383
384    void printUsedAndCompAndAssignment() {
385        for (int i = 0; i < used.size(); i++) {
386            cout << i << ": " << used[i] << " ";
387            if (i % 10 == 9) cout << endl;
388        }
389        for (int i = 0; i < comp.size(); i++) {
390            cout << i << ": " << comp[i] << " ";
391            if (i % 10 == 9) cout << endl;
392        }
393        for (int i = 0; i < n_vars; i++) {
394            cout << i << ": " << assignment[i] << " ";
395            if (i % 10 == 9) cout << endl;
396        }
397    }
398
399    void printOrderAndCompAndAssignment() {
400        for (int i = 0; i < order.size(); i++) {
401            cout << i << ": " << order[i] << " ";
402            if (i % 10 == 9) cout << endl;
403        }
404        for (int i = 0; i < comp.size(); i++) {
405            cout << i << ": " << comp[i] << " ";
406            if (i % 10 == 9) cout << endl;
407        }
408        for (int i = 0; i < n_vars; i++) {
409            cout << i << ": " << assignment[i] << " ";
410            if (i % 10 == 9) cout << endl;
411        }
412    }
413
414    void printAssignmentAndCompAndCompAndAssignment() {
415        for (int i = 0; i < n_vars; i++) {
416            cout << i << ": " << assignment[i] << " ";
417            if (i % 10 == 9) cout << endl;
418        }
419        for (int i = 0; i < comp.size(); i++) {
420            cout << i << ": " << comp[i] << " ";
421            if (i % 10 == 9) cout << endl;
422        }
423        for (int i = 0; i < comp.size(); i++) {
424            cout << i << ": " << comp[i] << " ";
425            if (i % 10 == 9) cout << endl;
426        }
427        for (int i = 0; i < n_vars; i++) {
428            cout << i << ": " << assignment[i] << " ";
429            if (i % 10 == 9) cout << endl;
430        }
431    }
432
433    void printAdjacencyListAndCompAndCompAndAssignment() {
434        for (int i = 0; i < adj.size(); i++) {
435            cout << i << ": " << adj[i] << " ";
436            if (i % 10 == 9) cout << endl;
437        }
438        for (int i = 0; i < comp.size(); i++) {
439            cout << i << ": " << comp[i] << " ";
440            if (i % 10 == 9) cout << endl;
441        }
442        for (int i = 0; i < comp.size(); i++) {
443            cout << i << ": " << comp[i] << " ";
444            if (i % 10 == 9) cout << endl;
445        }
446        for (int i = 0; i < n_vars; i++) {
447            cout << i << ": " << assignment[i] << " ";
448            if (i % 10 == 9) cout << endl;
449        }
450    }
451
452    void printUsedAndCompAndCompAndAssignment() {
453        for (int i = 0; i < used.size(); i++) {
454            cout << i << ": " << used[i] << " ";
455            if (i % 10 == 9) cout << endl;
456        }
457        for (int i = 0; i < comp.size(); i++) {
458            cout << i << ": " << comp[i] << " ";
459            if (i % 10 == 9) cout << endl;
460        }
461        for (int i = 0; i < comp.size(); i++) {
462            cout << i << ": " << comp[i] << " ";
463            if (i % 10 == 9) cout << endl;
464        }
465        for (int i = 0; i < n_vars; i++) {
466            cout << i << ": " << assignment[i] << " ";
467            if (i % 10 == 9) cout << endl;
468        }
469    }
470
471    void printOrderAndCompAndCompAndAssignment() {
472        for (int i = 0; i < order.size(); i++) {
473            cout << i << ": " << order[i] << " ";
474            if (i % 10 == 9) cout << endl;
475        }
476        for (int i = 0; i < comp.size(); i++) {
477            cout << i << ": " << comp[i] << " ";
478            if (i % 10 == 9) cout << endl;
479        }
480        for (int i = 0; i < comp.size(); i++) {
481            cout << i << ": " << comp[i] << " ";
482            if (i % 10 == 9) cout << endl;
483        }
484        for (int i = 0; i < n_vars; i++) {
485            cout << i << ": " << assignment[i] << " ";
486            if (i % 10 == 9) cout << endl;
487        }
488    }
489
490    void printAssignmentAndCompAndCompAndCompAndAssignment() {
491        for (int i = 0; i < n_vars; i++) {
492            cout << i << ": " << assignment[i] << " ";
493            if (i % 10 == 9) cout << endl;
494        }
495        for (int i = 0; i < comp.size(); i++) {
496            cout << i << ": " << comp[i] << " ";
497            if (i % 10 == 9) cout << endl;
498        }
499        for (int i = 0; i < comp.size(); i++) {
500            cout << i << ": " << comp[i] << " ";
501            if (i % 10 == 9) cout << endl;
502        }
503        for (int i = 0; i < n_vars; i++) {
504            cout << i << ": " << assignment[i] << " ";
505            if (i % 10 == 9) cout << endl;
506        }
507    }
508
509    void printAdjacencyListAndCompAndCompAndCompAndAssignment() {
510        for (int i = 0; i < adj.size(); i++) {
511            cout << i << ": " << adj[i] << " ";
512            if (i % 10 == 9) cout << endl;
513        }
514        for (int i = 0; i < comp.size(); i++) {
515            cout << i << ": " << comp[i] << " ";
516            if (i % 10 == 9) cout << endl;
517        }
518        for (int i = 0; i < comp.size(); i++) {
519            cout << i << ": " << comp[i] << " ";
520            if (i % 10 == 9) cout << endl;
521        }
522        for (int i = 0; i < n_vars; i++) {
523            cout << i << ": " << assignment[i] << " ";
524            if (i % 10 == 9) cout << endl;
525        }
526    }
527
528    void printUsedAndCompAndCompAndCompAndAssignment() {
529        for (int i = 0; i < used.size(); i++) {
530            cout << i << ": " << used[i] << " ";
531            if (i % 10 == 9) cout << endl;
532        }
533        for (int i = 0; i < comp.size(); i++) {
534            cout << i << ": " << comp[i] << " ";
535            if (i % 10 == 9) cout << endl;
536        }
537        for (int i = 0; i < comp.size(); i++) {
538            cout << i << ": " << comp[i] << " ";
539            if (i % 10 == 9) cout << endl;
540        }
541        for (int i = 0; i < n_vars; i++) {
542            cout << i << ": " << assignment[i] << " ";
543            if (i % 10 == 9) cout << endl;
544        }
545    }
546
547    void printOrderAndCompAndCompAndCompAndAssignment() {
548        for (int i = 0; i < order.size(); i++) {
549            cout << i << ": " << order[i] << " ";
550            if (i % 10 == 9) cout << endl;
551        }
552        for (int i = 0; i < comp.size(); i++) {
553            cout << i << ": " << comp[i] << " ";
554            if (i % 10 == 9) cout << endl;
555        }
556        for (int i = 0; i < comp.size(); i++) {
557            cout << i << ": " << comp[i] << " ";
558            if (i % 10 == 9) cout << endl;
559        }
560        for (int i = 0; i < n_vars; i++) {
561            cout << i << ": " << assignment[i] << " ";
562            if (i % 10 == 9) cout << endl;
563        }
564    }
565
566    void printAssignmentAndCompAndCompAndCompAndCompAndAssignment() {
567        for (int i = 0; i < n_vars; i++) {
568            cout << i << ": " << assignment[i] << " ";
569            if (i % 10 == 9) cout << endl;
570        }
571        for (int i = 0; i < comp.size(); i++) {
572            cout << i << ": " << comp[i] << " ";
573            if (i % 10 == 9) cout << endl;
574        }
575        for (int i = 0; i < comp.size(); i++) {
576            cout << i << ": " << comp[i] << " ";
577            if (i % 10 == 9) cout << endl;
578        }
579        for (int i = 0; i < n_vars; i++) {
580            cout << i << ": " << assignment[i] << " ";
581            if (i % 10 == 9) cout << endl;
582        }
583    }
584
585    void printAdjacencyListAndCompAndCompAndCompAndCompAndAssignment() {
586        for (int i = 0; i < adj.size(); i++) {
587            cout << i << ": " << adj[i] << " ";
588            if (i % 10 == 9) cout << endl;
589        }
590        for (int i = 0; i < comp.size(); i++) {
591            cout << i << ": " << comp[i] << " ";
592            if (i % 10 == 9) cout << endl;
593        }
594        for (int i = 0; i < comp.size(); i++) {
595            cout << i << ": " << comp[i] << " ";
596            if (i % 10 == 9) cout << endl;
597        }
598        for (int i = 0; i < n_vars; i++) {
599            cout << i << ": " << assignment[i] << " ";
600            if (i % 10 == 9) cout << endl;
601        }
602    }
603
604    void printUsedAndCompAndCompAndCompAndCompAndAssignment() {
605        for (int i = 0; i < used.size(); i++) {
606            cout << i << ": " << used[i] << " ";
607            if (i % 10 == 9) cout << endl;
608        }
609        for (int i = 0; i < comp.size(); i++) {
610            cout << i << ": " << comp[i] << " ";
611            if (i % 10 == 9) cout << endl;
612        }
613        for (int i = 0; i < comp.size(); i++) {
614            cout << i << ": " << comp[i] << " ";
615            if (i % 10 == 9) cout << endl;
616        }
617        for (int i = 0; i < n_vars; i++) {
618            cout << i << ": " << assignment[i] << " ";
619            if (i % 10 == 9) cout << endl;
620        }
621    }
622
623    void printOrderAndCompAndCompAndCompAndCompAndAssignment() {
624        for (int i = 0; i < order.size(); i++) {
625            cout << i << ": " << order[i] << " ";
626            if (i % 10 == 9) cout << endl;
627        }
628        for (int i = 0; i < comp.size(); i++) {
629            cout << i << ": " << comp[i] << " ";
630            if (i % 10 == 9) cout << endl;
631        }
632        for (int i = 0; i < comp.size(); i++) {
633            cout << i << ": " << comp[i] << " ";
634            if (i % 10 == 9) cout << endl;
635        }
636        for (int i = 0; i < n_vars; i++) {
637            cout << i << ": " << assignment[i] << " ";
638            if (i % 10 == 9) cout << endl;
639        }
640    }
641
642    void printAssignmentAndCompAndCompAndCompAndCompAndCompAndAssignment() {
643        for (int i = 0; i < n_vars; i++) {
644            cout << i << ": " << assignment[i] << " ";
645            if (i % 10 == 9) cout << endl;
646        }
647        for (int i = 0; i < comp.size(); i++) {
648            cout << i << ": " << comp[i] << " ";
649            if (i % 10 == 9) cout << endl;
650        }

```

```

26     }
27 }
28
29 bool solve_2SAT() {
30     order.clear();
31     used.assign(n_vertices, false);
32     for (int i = 0; i < n_vertices; ++i) {
33         if (!used[i])
34             dfs1(i);
35     }
36
37     comp.assign(n_vertices, -1);
38     for (int i = 0, j = 0; i < n_vertices; ++i)
39     {
40         int v = order[n_vertices - i - 1];
41         if (comp[v] == -1)
42             dfs2(v, j++);
43     }
44
45     assignment.assign(n_vars, false);
46     for (int i = 0; i < n_vertices; i += 2) {
47         if (comp[i] == comp[i + 1])
48             return false;
49         assignment[i / 2] = comp[i] > comp[i +
50 1];
51     }
52     return true;
53 }

```

```

52
53 void add_disjunction(int a, bool na, int b, bool
54 nb) {
55     // na and nb signify whether a and b are to
56     be negated
57     a = 2 * a ^ na;
58     b = 2 * b ^ nb;
59     int neg_a = a ^ 1;
60     int neg_b = b ^ 1;
61     adj[neg_a].push_back(b);
62     adj[neg_b].push_back(a);
63     adj_t[b].push_back(neg_a);
64     adj_t[a].push_back(neg_b);
65 }
66
67 static void example_usage() {
68     TwoSatSolver solver(3); // a, b, c
69     solver.add_disjunction(0, false, 1, true);
70     // a v not b
71     solver.add_disjunction(0, true, 1, true);
72     // not a v not b
73     solver.add_disjunction(1, false, 2, false);
74     // b v c
75     solver.add_disjunction(0, false, 0, false);
76     // a v a
77     assert(solver.solve_2SAT() == true);
78     auto expected = vector<bool>(True, False,
79 True);

```

```

73     assert(solver.assignment == expected);
74 }
75 };

```

Listing 28: 2-SAT implementation from `cp-algorithms.com`. Each component added is an expression of the form $a \vee b$, which is equivalent to $\neg a \Rightarrow b \wedge \neg b \Rightarrow a$ (if one of the variables is false, then the other one must be true). A directed graph is constructed based on these implications: For each x , there are two vertices v_x and $v_{\neg x}$. If there is an edge $a \Rightarrow b$, then there also is an edge $\neg b \Rightarrow \neg a$. For any x , if x is reachable from $\neg x$ and $\neg x$ is reachable from x , the problem has no solution. This means, each variable must be in a different SCC than their negative. This is verified by the method `solve_2SAT()`, which returns a boolean: `True` if it has a solution and `False` if it doesn't.

Giant Pizza How does a particular 2-SAT problem look like? Following is the statement for the problem CSES 1684 (Giant Pizza):

Uolevi's family is going to order a large pizza and eat it together. A total of n family members will join the order, and there are m possible toppings. The pizza may have any number of toppings. Each family member gives two wishes concerning the toppings of the pizza. The wishes are of the form "topping x is good/bad". Your task is to choose the toppings so that at least one wish from everybody becomes true (a good topping is included in the pizza or a bad topping is not included).

Input

The first input line has two integers n and m : the number of family members and toppings. The toppings are numbered $1, 2, \dots, m$. After this, there are n lines describing the wishes. Each line has two wishes of the form " $+$ x " (topping x is good) or " $-$ x " (topping x is bad).

Output

Print a line with m symbols: for each topping " $+$ " if it is included and " $-$ " if it is not included. You can print any valid solution. If there are no valid

solutions, print "IMPOSSIBLE".

```

1  int main(){
2      fastIO();
3      int n = nxt(), m = nxt();
4      TwoSatSolver TwoSat(m);
5
6      for(i, 0, n){
7          char type1, type2;
8          int top1, top2;
9          cin >> type1 >> top1 >> type2 >> top2;
10
11         top1--; top2--;
12         TwoSat.add_disjunction(top1, type1 == '-',
13                                top2, type2 == '-');
14     }
15
16     if(TwoSat.solve_2SAT()){
17         for(i, 0, m){
18             if(TwoSat.assignment[i])
19                 cout << "+ ";
20             else
21                 cout << "- ";
22         }
23     } else cout << "IMPOSSIBLE";
24     return 0;
25 }

```

Listing 29: Main method for solving CSES 1684 Giant Pizza using 2-SAT template.

5.12 *Bridges and point articulation

5.13 Flood Fill

```

1 vector<string> grid(n);
2 vii dirs = {{0,1},{0,-1},{1,0},{-1,0}};
3 ii start;
4 int arns = 0;
5 function<void(int,int)> traverse = [&](int i, int j)
    -> void {
6     if( grid[i][j] == '#' ) return;
7     int newI, newJ;
8     if( grid[i][j] != '.' ) arns += grid[i][j] - '0';
9     grid[i][j] = '#';
10    for( ii move : dirs ) {
11        newI = i + move.fi; newJ = j + move.se;
12        if( newI >= 0 && newI < n && newJ >= 0 && newJ <
            m && grid[newI][newJ] == 'T' )
13            return;
14    }
15    for( ii move : dirs ) {
16        newI = i + move.fi; newJ = j + move.se;
17        if( newI >= 0 && newI < n && newJ >= 0 && newJ <
            m )
18            traverse(newI, newJ);
19    }

```

```

20 };
21 fori(i,0,n)
22     cin >> grid[i];
23 fori(i,0,n) {
24     fori(j,0,m) {
25         if( grid[i][j] == 'S' ) {
26             grid[i][j] = '.';
27             start.fi = i;
28             start.se = j;
29         }
30     }
31 }
32 traverse(start.fi, start.se);
33 cout << arns << endl;

```

Listing 30: Traverse a matrix of 'n' x 'm' on grid representation. The matrix is composed of '.' for a valid space (empty), '#' for a wall, 'T' for a trap, and a number for a treasure. This implementation takes the sum of every treasure in the maze. The condition for moving to the next location is that there are no Traps nearby (up, down, left, right), so the player will never be killed while traversing. It also implements a way to read numerous test cases, but without knowing beforehand how many there are. Runs in $O(n \cdot m)$. Originally used on the problem *Treasures* from 2024-2025 ICPC Bolivia Pre-National Contest.

5.14 Lava Flow (Multi-source BFS)

```

1 typedef array<int,3> iii;
2
3 vii dirs = {{1,0},{0,1},{-1,0},{0,-1}};

```

```

4 map<int,string> path = {{0,"D"},{1,"R"},{2,"U"},{3,"
    L"}}};
5 int n, m;
6 string arns = "";
7 bool escaped = false;
8 cin >> n >> m;
9 vector<string> grid(n);
10 vvi times(n,vi(m,INF)), prev(n,vi(m,-1));
11 vector<vector<bool>> visited(n,vector<bool>(m,false)
    );
12 queue<iii> q;
13 ii start, end;
14 for(int i = 0; i < n; i++) {
15     cin >> grid[i];
16     for(int j = 0; j < m; j++) {
17         if( grid[i][j] == 'M' ) {
18             q.push({i,j,0});
19             times[i][j] = 0;
20         }
21         else if( grid[i][j] == 'A' )
22             start = {i,j};
23     }
24 }
25 function<bool(int,int)> valid = [&](int I, int J) ->
    bool {
26     return (I >= 0) and (I < n) and (J >= 0) and (J <
        m) and (grid[I][J] != '#') and (times[I][J] ==
        INF);
27 };
28 function<bool(int,int)> valid_player = [&](int I,
    int J) -> bool {
29     return (I >= 0) and (I < n) and (J >= 0) and (J <
        m) and (!visited[I][J]) and (grid[I][J] != '#');
30 };
31 function<bool(int,int)> is_border = [&](int I, int J
    ) -> bool {
32     return I == 0 || I == n-1 || J == 0 || J == m-1;
33 };
34 // Corner cases
35 if( is_border(start.fi,start.se) ) {
36     cout << "YES" << endl << "0" << endl;
37     return 0;
38 }
39 // Multi-Source BFS
40 while( ! q.empty() ) {
41     iii u = q.front();
42     q.pop();
43     for(ii dir : dirs) {
44         int newI = u[0] + dir.fi;
45         int newJ = u[1] + dir.se;
46         int w = u[2] + 1;
47         if( valid(newI,newJ) ) {
48             times[newI][newJ] = w;
49             q.push({newI,newJ,w});
50         }
51     }

```

```

52 }
53 // Player BFS
54 q.push({start.fi,start.se,0});
55 visited[start.fi][start.se] = true;
56 while( ! q.empty() and !escaped ) {
57     iii u = q.front();
58     q.pop();
59     for(int i = 0; i < 4; i++) {
60         int newI = u[0] + dirs[i].fi;
61         int newJ = u[1] + dirs[i].se;
62         int w = u[2] + 1;
63         if( valid_player(newI,newJ) and w < times[newI][
newJ] ) {
64             visited[newI][newJ] = true;
65             prev[newI][newJ] = i;
66             q.push({newI,newJ,w});
67             if( is_border(newI,newJ) ) {
68                 end.fi = newI;
69                 end.se = newJ;
70                 escaped = true;
71                 break;
72             }
73         }
74     }
75 }
76 if( !escaped ) {
77     cout << "NO" << endl;
78     return 0;

```

```

79 }
80 // Path reconstruction
81 cout << "YES" << endl;
82 int i = end.fi;
83 int j = end.se;
84 while( prev[i][j] != -1 ) {
85     int oldI = i;
86     arns += path[ prev[i][j] ];
87     i -= dirs[prev[i][j]].fi;
88     j -= dirs[prev[oldI][j]].se;
89 }
90 reverse(all(arns));
91 cout << sz(arns) << endl << arns << endl;

```

Listing 31: Classic Lava Flow problem implementation, where the timer from the starting point A needs to be less than every other in the MS-BFS starting in M places. Once one edge is reached, the path is reconstructed from the output. Runs in BFS complexity $O(|V| + |E|)$. Originally used in the CSES problem *Monsters*.

5.15 MaxFlow

5.15.1 Dinic's Algorithm

```

1 const ll INF = 1e17;
2 /**
3  * @brief Represents a directed edge in a flow
4  *         network.
5  * @details Stores the edge's source, destination,
6  *         capacity, and current flow.

```

```

5  *          Used in max-flow algorithms like Dinic
   or Ford-Fulkerson. */
6  struct flowEdge {
7      int u; // Source node
8      int v; // Destination node
9      ll cap; // Maximum flow capacity of the edge
10     ll flow = 0; // Current flow through the edge (
        initially 0)
11     flowEdge( int u, int v, ll cap ) : u(u), v(v), cap
        (cap) {};
12 };
13 /**
14  * @brief Implementation of Dinic's max-flow
        algorithm.
15  * @details Manages a flow network with BFS (Level
        Graph) and DFS (Blocking Flow) optimizations. */
16 struct Dinic {
17     vector<flowEdge> edges; // All edges in the flow
        network (including reverse edges)
18     vector<vi> adj;
19     int n; // Total number of nodes in the graph
20     int s; // Source node
21     int t; // Sink node (destination of flow)
22     int id = 0; // Counter for edge indexing
23     vi level; // Stores the level (distance from 's')
        of each node during BFS
24     vi next; // Optimization for DFS: tracks the next
        edge to explore for each node

```

```

25     queue<int> q; // Queue for BFS traversal
26     /**
27     * @brief Constructs a Dinic solver for a flow
        network.
28     * @param n Number of nodes.
29     * @param s Source node.
30     * @param t Sink node. */
31     Dinic( int n, int s, int t ) : n(n), s(s), t(t) {
32         adj.resize(n); // Initialize adjacency list for
        'n' nodes.
33         level.resize(n); // Prepare level array for BFS.
34         next.resize(n); // Prepare next-edge array for
        DFS.
35         fill(all(level),-1); // Mark all levels as
        unvisited (-1).
36         level[s] = 0; // The source has level 0.
37         q.push(s); // Start BFS from the source.
38     }
39     /**
40     * @brief Adds a directed edge and its residual
        reverse edge to the flow network. */
41     void addEdge( int u, int v, ll cap ) {
42         edges.emplace_back(u,v,cap); // Original edge: u
        -> v
43         edges.emplace_back(v,u,0); // Residual edge: v
        -> u
44         adj[u].pb(id++);
45         adj[v].pb(id++);

```



```

46 }
47 /**
48  * @brief Performs BFS to construct the level
49  * graph (Layered Network) from source 's' to sink '
50  * t'.
51  * @details Assigns levels (minimum distances
52  * from 's') to all nodes and checks if 't' is
53  * reachable.
54  * Levels are used to guide the DFS
55  * phase in Dinic's algorithm.
56  * @return bool True if the sink 't' is reachable
57  * (i.e., there exists an augmenting path), false
58  * otherwise. */
59 bool bfs() {
60     while( ! q.empty() ) {
61         int curr = q.front();
62         q.pop();
63         for( auto e : adj[curr] ) {
64             if( edges[e].cap - edges[e].flow < 1 ) //
65             Skip saturated edges (no residual capacity).
66                 continue;
67             if( level[ edges[e].v ] != -1 ) // Skip
68             already visited nodes (level assigned).
69                 continue;
70             // Assign level to the neighbor node.
71             level[ edges[e].v ] = level[ edges[e].u ] +
72             1; // Next level = current + 1.
73
74             q.push( edges[e].v ); // Add neighbor to the
75             queue for further BFS.
76         }
77     }
78     return level[t] != -1; // Return whether the
79     sink 't' was reached (level[t] != -1).
80 }
81 /**
82  * @brief Finds a blocking flow using DFS in the
83  * level graph constructed by BFS.
84  * @param u Current node being processed.
85  * @param flow Maximum flow that can be sent from
86  * 'u' to the sink 't'.
87  * @return ll The amount of flow successfully
88  * sent to 't'. */
89 ll dfs( int u, ll flow ) {
90     if( flow == 0 ) // No remaining flow to send.
91         return 0;
92     if( u == t ) // Reached the sink; return
93         accumulated flow.
94         return flow;
95     // Explore edges from 'u' using 'next[u]' to
96     avoid revisiting processed edges.
97     for( int& cid = next[u]; cid < sz(adj[u]); cid++
98     ) {
99         int e = adj[u][cid]; // Index of the edge in '
100         edges'.

```

```

81     int v = edges[e].v; // Destination node of
the edge.
82     // Skip invalid edges:
83     // 1. Not in the level graph (level[u] + 1 !=
level[v]). Just edges in exactly one level ahead (
ensures shortest paths).
84     // 2. No residual capacity (cap - flow < 1).
85     if( level[edges[e].u] + 1 != level[v] || edges
[e].cap - edges[e].flow < 1 )
86         continue;
87     ll f = dfs( v, min(flow, edges[e].cap - edges[
e].flow ) ); // Recursively send flow to 'v'.
88     if( f == 0 ) // No flow could be sent via this
edge.
89         continue;
90     // Update residual capacities:
91     edges[e].flow += f; // Increase flow in
the original edge.
92     edges[ e ^ 1 ].flow -= f; // Decrease flow in
the reverse edge. (All reverse edges have
distinct parity)
93     return f; // Return the flow
sent.
94 }
95 return 0; // No augmenting path found from 'u'.
96 }
97 /**

```

```

98 * @brief Computes the maximum flow from source '
s' to sink 't' using Dinic's algorithm.
99 * @details Iterates through BFS and DFS phases
to find the maximum flow.
100     Accumulates flow while there exists
augmentation paths in the residual graph.
101     Restart auxiliary structures for every new
phase.
102 * @return ll The maximum flow value. */
103 ll maxFlow() {
104     ll flow = 0; // Tracks the total flow sent.
105     while( bfs() ) { // While there are augmenting
paths:
106         fill(all(next),0); // Reset 'next' for DFS.
107         for( ll f = dfs(s,INF); f != 0; f = dfs(s,
INF) ) // Send blocking flow in the level graph:
108             flow += f;
109         // Reset for next BFS phase:
110         fill(all(level),-1);
111         level[s] = 0;
112         q.push(s);
113     }
114     return flow;
115 }
116 /**
117 * @brief Finds edges belonging to the minimum
cut after maxFlow().

```

```

118     * @details First, it marks all the reachable
nodes from 's' with an augmentation path after
obtained the max flow
119     and all the saturated edges coming out from
any of the nodes who belong to the min-cut.
120     For 'minCut()' to work, 'maxFlow()' must be
first executed to get the min-cut.
121     If only is needed the value, is enough
returning the value of 'maxFlow()'.
122     * @return vii List of edges (u, v) in the min-
cut. Its size is the minimum number of 'roads' to
close. */
123 vii minCut() {
124     vii ans;
125     fill(all(level),-1); // Reset levels.
126     level[s] = 0;        // Mark source as reachable
.
127     q.push(s);
128     while( ! q.empty() ) { // BFS to mark nodes
reachable from 's' in the residual graph.
129         int curr = q.front();
130         q.pop();
131         for( int id = 0; id < sz(adj[curr]); id++ ) {
// For every edge going out from 'curr'.
132             int e = adj[curr][id];
133             // If 'v' is has not been visited yet, and
the edge have residual capacity.
134             if( level[edges[e].v] == -1 && edges[e].cap
- edges[e].flow > 0 ) {
135                 q.push(edges[e].v);
136                 level[edges[e].v] = level[edges[e].u] + 1;
137             }
138         }
139     }
140     for( int i = 0; i < sz(level); i++ ) {
141         if( level[i] != -1 ) {
142             for( int id = 0; id < sz(adj[i]); id++ ) {
143                 int e = adj[i][id];
144                 if( level[edges[e].v] == -1 && edges[e].
cap - edges[e].flow == 0 )
145                     ans.emplace_back(edges[e].u,edges[e].v);
146             }
147         }
148     }
149     return ans;
150 }
151 /**
152     * @brief Reconstructs the maximum bipartite
matching after running 'maxFlow()'.
153     * @details Every edge that belong to the
original graph and have flow greater than zero,
belongs to the matching.
154     For 'maximumMatching()' to work, 'maxFlow()'
'.

```

```

155     * @return vii List of matched pairs (boy, girl).
156     */
157     vii maximumMatching() {
158         vii ans;
159         fill(all(level), -1); // Reset levels.
160         level[s] = 0;        // Mark source as reachable
161         .
162         q.push(s);
163         while( ! q.empty() ) { // BFS to mark nodes
164             reachable via saturated edges with flow greater
165             than zero.
166             int curr = q.front();
167             q.pop();
168             for( int id = 0; id < sz(adj[curr]); id++ ) {
169                 int e = adj[curr][id];
170                 // If 'v' has not been visited yet, the edge
171                 is saturated and have flow greater than zero.
172                 if( level[edges[e].v] == -1 && edges[e].cap
173                 - edges[e].flow == 0 && edges[e].flow != 011 ) {
174                     q.push(edges[e].v);
175                     level[edges[e].v] = level[edges[e].u] + 1;
176                 }
177             }
178         }
179         for( int i = 0; i < sz(level); i++ ) { //
180             Collect original edges (boy -> girl) that are
181             saturated and have flow > 0.
182             if( level[i] != -1 ) {

```

```

175         for( int id = 0; id < sz(adj[i]); id++ ) {
176             int e = adj[i][id];
177             if( edges[e].u != s && edges[e].v != t
178             && edges[e].cap - edges[e].flow == 0 && edges[e].
179             flow != 011 )
180                 ans.emplace_back(edges[e].u, edges[e].v
181             );
182         }
183     }
184 };

```

Listing 32: Commented template for solving MaxFlow problems with Dinic's algorithm. Works in complexity $O(|V|^2 \times |E|)$. In bipartite graphs and graphs with unitary max capacity the complexity turns $O(|E| \times \sqrt{|V|})$.

Download Speed How does a particular flow problem looks like? Following is the statement for the problem CSES 1694 (Download Speed):

Consider a network consisting of n computers and m connections. Each connection specifies how fast a computer can send data to another computer.

Kotivalo wants to download some data from a server. What is the maximum speed he can do this, using the connections in the network?

Input

The first input line has two integers n and m : the number of computers and connections. The computers are numbered $1, 2, \dots, n$. Computer 1 is the server and computer n is Kotivalo's computer.

After this, there are m lines describing the connections. Each line has three

integers a , b , and c : computer a can send data to computer b at speed c .

Output

Print one integer: the maximum speed Kotivalo can download data.

```

1  int main()
2  {
3      fastIO();
4
5      int n, m, u, v, w;
6
7      cin >> n >> m;
8
9      Dinic flow(n+1,1,n); // size n+1 to fix 0-
indexed indexes, 1 is the source (server), 'n' is
the sink (Kotivalo)
10
11     fori(i,0,m)
12     {
13         cin >> u >> v >> w;
14         flow.addEdge(u,v,w);
15     }
16
17     cout << flow.maxFlow() << endl;
18
19     return 0;
20 }
```

Listing 33: Main method for solving CSES 1697 Download Speed using MaxFlow template.

Police Chase Max Flow-Min Cut Theorem: $\text{MaxFlow} = \text{MinCut}$.

Following is the statement for the problem CSES 1695 (Police Chase):

Kaaleppi has just robbed a bank and is now heading to the harbor. However, the police wants to stop him by closing some streets of the city.

What is the minimum number of streets that should be closed so that there is no route between the bank and the harbor?

Input

The first input line has two integers n and m : the number of crossings and streets. The crossings are numbered $1, 2, \dots, n$. The bank is located at crossing 1, and the harbor is located at crossing n .

After this, there are m lines that describing the streets. Each line has two integers a and b : there is a street between crossings a and b . All streets are two-way streets, and there is at most one street between two crossings.

Output

First print an integer k : the minimum number of streets that should be closed. After this, print k lines describing the streets. You can print any valid solution.

```

1  int main()
2  {
3      fastIO();
4
5      int n, m, u, v;
6      vii minCut;
7
8      cin >> n >> m;
9
10     Dinic flow(n+1,1,n); // size n+1 to fix 0-
indexed indexes, 1 is the source (bank), 'n' is
the sink (harbor)
11 }
```

```

12     fori(i,0,m)
13     {
14         cin >> u >> v;
15         flow.addEdge(u,v,1);
16         flow.addEdge(v,u,1);
17     }
18
19     flow.maxFlow();
20     minCut = flow.minCut();
21
22     cout << (sz(minCut)/2) << endl;
23     for(int i = 0; i < sz(minCut); i += 2)
24         cout << minCut[i].fi << " " << minCut[i].se
25         << endl;
26
27     return 0;
28 }

```

Listing 34: Main method for solving CSES 1695 Police Chase using MaxFlow template.

School Dance MaxFlow = MinCut = MaxMatching.

Following is the statement for the problem CSES 1696 (School Dance):

There are n boys and m girls in a school. Next week a school dance will be organized. A dance pair consists of a boy and a girl, and there are k potential pairs.

Your task is to find out the maximum number of dance pairs and show how this number can be achieved.

Input

The first input line has three integers n , m and k : the number of boys, girls, and potential pairs. The boys are numbered $1, 2, \dots, n$, and the girls are numbered $1, 2, \dots, m$.

After this, there are k lines describing the potential pairs. Each line has two integers a and b : boy a and girl b are willing to dance together.

Output

First print one integer r : the maximum number of dance pairs. After this, print r lines describing the pairs. You can print any valid solution.

```

1  int main()
2  {
3      fastIO();
4
5      int n, m, k, a, b;
6      ll maxPairs;
7      vii pairs;
8
9      cin >> n >> m >> k;
10
11     Dinic flow(n+m+2,0,n+m+1);
12
13     fori(boy,0,n+1)
14         flow.addEdge(0,boy,1);
15
16     fori(girl,n+1,n+m+1)
17         flow.addEdge(girl,n+m+1,1);
18
19     fori(i,0,k)
20     {

```

```

21     cin >> a >> b;
22     flow.addEdge(a,n+b,1);
23 }
24
25 maxPairs = flow.maxFlow();
26 pairs = flow.maximumMatching();
27
28 cout << maxPairs << endl;
29 for(i,0,sz(pairs))
30     cout << pairs[i].fi << " " << (pairs[i].se -
31     n) << endl;;
32
33 return 0;
34 }

```

Listing 35: Main method for solving CSES 1696 School Dancing using MaxFlow template.

5.15.2 *Ford-Fulkerson Algorithm

5.15.3 *Goldber-Tarjan Algorithm

6 Trees

6.1 Counting Childrens

```

1 vi childrens(n+1,0);
2 vvi graph(n+1);
3 vector<bool> visited(n+1, false);
4 for(i,2,n+1) {
5     cin >> tmp;

```

```

6     graph[tmp].pb(i);
7     graph[i].pb(tmp);
8 }
9 function<int(int)> dfs = [&](int u) -> int {
10     visited[u] = true;
11     for(int v : graph[u]) {
12         if( !visited[v] )
13             childrens[u] += dfs(v);
14     }
15     return childrens[u] + 1;
16 };
17 dfs(1);

```

Listing 36: Algorithm that counts how many childrens does every node have, from 2..n in a rooted tree (root = 1).

6.2 *Tree Diameter

6.3 *Centroid Decomposition

6.4 *Euler Tour

6.5 *Lowest Common Ancestor (LCA)

6.6 *Heavy-Light Decomposition (HLD)

7 Strings

7.1 Knuth-Morris-Pratt Algorithm (KMP)

```

1 // Longest Prefix-Suffix
2 vi compute_LPS(string s) {
3     size_t len = 0, i = 1, sz = s.size();

```

```

4   vi lps(sz,0);
5   while( i < sz ) {
6       if( s[i] == s[len] )
7           lps[i++] = ++len;
8       else
9           if( len != 0 )
10              len = lps[len-1];
11          else
12              lps[i++] = 0;
13   }
14   return lps;
15 }
16 // Get number of occurrences of a pattern p in a
    string s
17 int kmp(string s, string p) {
18     vi lps = compute_LPS(p);
19     size_t n = s.size(), m = p.size(), i = 0, j = 0;
20     int cnt = 0;
21     while( i < n ) {
22         if( p[j] == s[i] ) {
23             j++; i++;
24         }
25         if( j == m ) { // Full match
26             cnt++;
27             j = lps[ j - 1 ];
28         }
29         else if( i < n and p[j] != s[i] ) { // Mismatch
            after j matches

```

```

30         if( j != 0 )
31             j = lps[ j - 1 ];
32         else
33             i++;
34     }
35 }
36 return cnt;
37 }

```

Listing 37: KMP algorithm for counting how many times a pattern appear into a string. Runs in $O(n + m)$.

7.2 *Suffix Array

7.3 *Rolling Hashing

7.4 *Z Function

7.5 *Aho-Corasick Algorithm

8 Dynamic Programming

8.1 *Coins

8.2 *Longest Increasing Subsequence (LIS)

8.3 *Edit Distance

8.4 *Knapsack

8.5 *SOS DP

8.6 *Digit DP

8.7 *Bitmask DP

9 Mathematics

9.1 Number Theory

9.1.1 Greatest Common Divisor (GCD)

```

1 int gcd(int a, int b) {
2     if (a == 0) return b;
3     if (b == 0) return a;
4     if (a == b) return a;
5     if (a > b)
6         return gcd(a - b, b);
7     return gcd(a, b - a);
8 }
```

Listing 38: Implementation of handmade GCD, because using `gcd()` runs slow with long long, also `__gcd()`.

9.1.2 Gauss Sum

The sum of the first n natural numbers in $O(1)$.

$$S = \frac{n(n+1)}{2} \quad (1)$$

$$n = \sqrt{2S + \frac{1}{4}} - \frac{1}{2} \quad (2)$$

```

1 int S = (1LL * n * (1LL * n + 1LL))/2;
2 int n = (int)( sqrt( 2 * S + 0.25 ) - 0.5 )
```

Listing 39: Implementation of the Gauss Sum.

9.1.3 *Modular Theory

9.1.4 *Modulo Inverse

9.1.5 *Fermat's Little Theorem

9.1.6 *Chinese Remainder Theorem

9.1.7 Binpow

```

1 const int MOD = 1e9+7;
2 int binpow( long long a, long long b ) { // a^b
3     long long sol = 1;
4     a %= MOD;
5     while( b > 0 ) {
6         if( b & 1 )
```

```

7         sol = ( 1LL * sol * a ) % MOD;
8         a = ( 1LL * a * a ) % MOD;
9         b >= 1;
10    }
11    return sol % MOD;
12 }

```

Listing 40: Applying binary exponentiation to a problem requiring $a^b \bmod (10^9 + 7)$ in $O(\log_2(b))$.

9.1.8 Matrix Exponentiation (Linear Recurrency)

```

1 template <typename T> void matmul(vector<vector<T>>
   &a, const vector<vector<T>>& b) {
2     size_t n = a.size(), m = a[0].size(), p = b[0].
       size();
3     assert(m == b.size());
4     vector<vector<T>> c(n, vector<T>(p));
5     for(size_t i = 0; i < n; i++)
6         for(size_t j = 0; j < p; j++)
7             for(size_t k = 0; k < m; k++)
8                 c[i][j] = (c[i][j] + a[i][k] * b[k][j])
               % MOD;
9     a = c;
10 }
11 template <typename T> struct Matrix {
12     vector<vector<T>> mat;
13     Matrix() {}
14     Matrix(vector<vector<T>> a) { mat = a; }

```

```

15 Matrix(int n, int m) {
16     mat.resize(n);
17     for(int i = 0; i < n; i++) {mat[i].resize(m);
18     }
19     int rows() const { return mat.size(); }
20     int cols() const { return mat[0].size(); }
21     void makeIden() {
22         for(int i = 0; i < rows(); i++)
23             for(int j = 0; j < cols(); j++)
24                 mat[i][j] = (i == j ? 1 : 0);
25     }
26     Matrix operator*=(const Matrix &b) {
27         matmul(mat, b.mat);
28         return *this;
29     }
30     void print() {
31         for(int i = 0; i < rows(); i++) {
32             for(int j = 0; j < cols(); j++)
33                 cout << mat[i][j] << " ";
34             cout << endl;
35         }
36     }
37     Matrix operator*(const Matrix &b) { return Matrix
       (*this) *= b; }
38 };
39 int main() {
40     Matrix<ll> A( {{1,1},{1,0}} );

```

```

41 Matrix<ll> ini(2,1);
42 ini.mat[0][0] = 0;
43 ini.mat[1][0] = 1;
44 Matrix<ll> iden(2,2);
45 iden.makeIden();
46 ll n;
47 cin >> n;
48 while(n > 0) {
49     if( n & 1 ) iden *= A;
50     A *= A;
51     n >>= 1;
52 }
53 Matrix<ll> res = iden * ini;
54 cout << res.mat[0][0] << endl;
55 return 0;
56 }

```

Listing 41: Template to pow a matrix of size n to a certain exponent with logarithmic time (using binpow), and multiply it to another matrix, with modulo operation, as well as how to use it. Full implementation for calculating n -th Fibonacci term with linear recurrency.

9.1.9 Prime checking

```

1 bool prime( int n ){
2     if( n == 2 )
3         return true;
4     if( n % 2 == 0 || n <= 1 )
5         return false;

```

```

6     for( int i = 3; i * i <= n; i += 2 )
7         if( ( n % i ) == 0 )
8             return false;
9     return true;
10 }

```

Listing 42: Returns if n is a prime number in $O(\sqrt{n})$. Avoids overflow $\forall n \leq 10^6$ ($\approx INT_MAX$).

9.1.10 Prime factorization

```

1 void prime_factorization(vll& factorization, ll n) {
2     for(long long d = 2; d*d <= n; d++) {
3         while(n % d == 0) {
4             factorization.push_back(d);
5             n /= d;
6         }
7     }
8     if( n > 1 )
9         factorization.push_back(n);
10 }

```

Listing 43: Returns prime factorization of the number n using *trial division*, simplest way. Runs in $O(\sqrt{n})$. e.g. for 12 the result is 2x2x3.

9.1.11 Sieve of Eratosthenes

```

1 void sieve_of_eratosthenes(vector<bool>& is_prime,
2     int n) {
3     is_prime.assign(n+1, true);

```

```

3   is_prime[0] = is_prime[1] = false;
4   for(int i = 2; i <= n; i++) {
5       if( is_prime[i] && (long long)i * i <= n ) {
6           for(int j = i*i; j <= n; j += i)
7               is_prime[j] = false;
8       }
9   }
10 }
```

Listing 44: Calculates every prime number up to n with sieve of eratosthenes in a boolean 1-indexed vector. Runs in $O(n \log \log n)$.

9.1.12 Sum of Divisors

```

1 ll sum_of_divisors(ll n) {
2     ll sum = 1;
3     for (long long i = 2; i * i <= n; i++) {
4         if(n % i == 0) {
5             int e = 0;
6             do {
7                 e++;
8                 n /= i;
9             } while (n % i == 0);
10            ll s = 0, pow = 1;
11            do {
12                s += pow;
13                pow *= i;
14            } while (e-- > 0);
15            sum *= s;

```

```

16     }
17 }
18 if(n > 1)
19     sum *= (1 + n);
20 return sum;
21 }
```

Listing 45: Calculates the sum of all divisors of number n . e.g. $sum_of_divisors(12) = 18$. Runs in $O(\sqrt{n})$.

```

1 void sum_of_divisors_sieve( vll& sigma, int n ) {
2     sigma.assign(n+1,0);
3     for(int i = 1; i <= n; i++)
4         for(int j = i; j <= n; j+=i)
5             sigma[j] += i;
6 }
```

Listing 46: Calculates the sum of all divisors of all numbers from 1 to n . Runs in $O(n \log(n))$.

9.2 Combinatorics

9.2.1 Binomial Coefficients

```

1 const int MAXN = 1e6+1;
2 vll fact(MAXN+1), inv(MAXN+1);
3 int binpow( ll a, ll b ) { // a^b
4     ll sol = 1;
5     a %= MOD;
6     while( b > 0 ) {

```

```

7         if( b & 1 )
8             sol = ( 1LL * sol * a ) % MOD;
9         a = ( 1LL * a * a ) % MOD;
10        b >>= 1;
11    }
12    return sol % MOD;
13 }
14 void combi() {
15     fact[0] = inv[0] = 1;
16     fori(i,1,MAXN+1) {
17         fact[i] = fact[i-1] * i % MOD;
18         inv[i] = binpow( fact[i], MOD - 2 );
19     }
20 }
21 ll nCr( ll n, ll r ) {
22     return fact[n] * inv[r] % MOD * inv[n-r] % MOD;
23 }
24 combi();
25 nCr(a,b);

```

Listing 47: Template for calculating binomial coefficients $\binom{n}{k} = \frac{n!}{k!(n-k)!}$. Precalculate *fact* and *inv* runs in $O(MAXN \cdot \log_2(MOD))$ ($\log_2(MOD) \approx 30$). So, in general case when $NMAX = 10^6$ and $MOD = 10^9 + 7$ can be generalized to $O(n \cdot \log(n))$, $n \leq 10^6$.

9.2.2 Common combinatorics formulas

$$\binom{n}{2} = \frac{n(n-1)}{2} \quad (3)$$

$$\sum_{k=0}^n \binom{n}{k} = 2^n \quad (4)$$

$$\sum_{k=0}^n \binom{n}{k} \binom{n}{n-k} = \binom{2n}{n} \quad (5)$$

$$\sum_{k=0}^n k \binom{n}{k} = n2^{n-1} \quad (6)$$

$$\sum_{k=0}^{\infty} \binom{2k}{k} \binom{2n-2k}{n-k} = 4^n \quad (7)$$

$$(8)$$

9.3 *Stars and Bars

9.4 Probability

9.5 Computational Geometry

9.5.1 *Cross Product

9.5.2 *Convex Hull

9.6 *Fast Fourier Transform (FFT)

10 Appendix

10.1 What to do against WA?

1. Have you done the correct complexity analysis?
2. Have you understood well the statement?
3. Have you corroborated yet the trivial test cases?
4. Have you checked all the corner cases?
5. Have you proposed a lot of non-trivial test cases?

6. Isn't there any possibility of overflow? (Multiplying two `int` needs to be fitted into a `long long`)
7. Have you done a desktop test?
8. Have you read all the variables? (`tc` variable on `main`)
9. Every part of your code works as it's meant to?

10.2 Primitive sizes

Data type	[B]	Minimum value it takes	Maximum value it takes
bool	1	0	1
signed char	1	0	255
unsigned char	1	-128	127
signed int	4	$-2,147,483,648 \approx -2 \times 10^9$	$2,147,483,647 \approx 2 \times 10^9$
unsigned int	4	0	$4,294,967,295 \approx 4 \times 10^9$
signed short	2	-32,768	32,767
unsigned short	2	0	65,535
signed long long int	8	$-9,223,372,036,854,775,808 \approx -9 \times 10^{18}$	$9,223,372,036,854,775,807 \approx 9 \times 10^{18}$
unsigned long long int	8	0	$18,446,744,073,709,551,615 \approx 18 \times 10^{18}$
float	4	1.1×10^{-38}	3.4×10^{38}
double	8	2.2×10^{-308}	1.7×10^{308}
long double	12	3.3×10^{-4932}	1.1×10^{4932}

Table 1: Capacity of primitive data types in C++.

10.3 Printable ASCII characters

32	whitespace	58	:	65	A	97	a
33	!	59	;	66	B	98	b
34	"	60	,	67	C	99	c
35	#	61	=	68	D	100	d
36	\$	62	?	69	E	101	e
37	%	63	@	70	F	102	f
38	&	64	^	71	G	103	g
39	'	91	[	72	H	104	h
40	(	92	\	73	I	105	i
41	)	93	]	74	J	106	j
42	*	94	^	75	K	107	k
43	+	95	_	76	L	108	l
44	,	96	`	77	M	109	m
45	-	126	~	78	N	110	n
46	.			79	O	111	o
47	/			80	P	112	p
48	0			81	Q	113	q
49	1			82	R	114	r
50	2			83	S	115	s
51	3			84	T	116	t
52	4			85	U	117	u
53	5			86	V	118	v
54	6			87	W	119	w
55	7			88	X	120	x
56	8			89	Y	121	y
57	9			90	Z	122	z

Table 2: Code and symbol of printable ASCII characters.

10.4 Numbers bit representation

1	00000001	31	00011111	61	00111101	91	01011011	121	01111001
2	00000010	32	00100000	62	00111110	92	01011100	122	01111010
3	00000011	33	00100001	63	00111111	93	01011101	123	01111011
4	00000100	34	00100010	64	01000000	94	01011110	124	01111100
5	00000101	35	00100011	65	01000001	95	01011111	125	01111101
6	00000110	36	00100100	66	01000010	96	01100000	126	01111110
7	00000111	37	00100101	67	01000011	97	01100001	127	01111111
8	00001000	38	00100110	68	01000100	98	01100010	128	10000000
9	00001001	39	00100111	69	01000101	99	01100011	129	10000001
10	00001010	40	00101000	70	01000110	100	01100100	130	10000010
11	00001011	41	00101001	71	01000111	101	01100101	131	10000011
12	00001100	42	00101010	72	01001000	102	01100110	132	10000100
13	00001101	43	00101011	73	01001001	103	01100111	133	10000101
14	00001110	44	00101100	74	01001010	104	01101000	134	10000110
15	00001111	45	00101101	75	01001011	105	01101001	135	10000111
16	00010000	46	00101110	76	01001100	106	01101010	136	10001000
17	00010001	47	00101111	77	01001101	107	01101011	137	10001001
18	00010010	48	00110000	78	01001110	108	01101100	138	10001010
19	00010011	49	00110001	79	01001111	109	01101101	139	10001011
20	00010100	50	00110010	80	01010000	110	01101110	140	10001100
21	00010101	51	00110011	81	01010001	111	01101111	141	10001101
22	00010110	52	00110100	82	01010010	112	01110000	142	10001110
23	00010111	53	00110101	83	01010011	113	01110001	143	10001111
24	00011000	54	00110110	84	01010100	114	01110010	144	10010000
25	00011001	55	00110111	85	01010101	115	01110011	145	10010001
26	00011010	56	00111000	86	01010110	116	01110100	146	10010010
27	00011011	57	00111001	87	01010111	117	01110101	147	10010011
28	00011100	58	00111010	88	01011000	118	01110110	148	10010100
29	00011101	59	00111011	89	01011001	119	01110111	149	10010101
30	00011110	60	00111100	90	01011010	120	01111000	150	10010110

10.5 How a vector<vector<pair<int,int>>> looks like

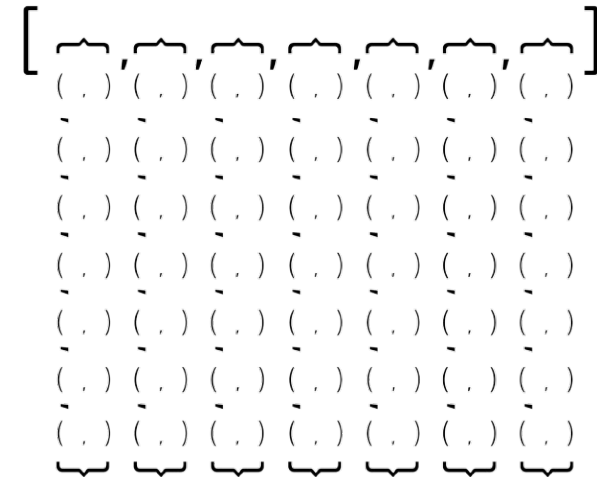


Figure 1: Visual representation of a vector of vector of pairs.

10.6 How all neighbours of a grid looks like

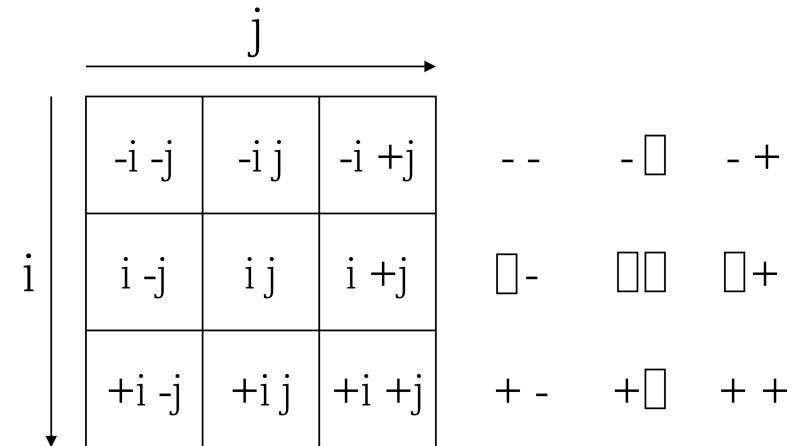


Figure 2: Visual representation of how all adjacent cells in a grid looks like.