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Team Reference Document

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1 Setup

1.1	CP_Ubuntu
-----	---------------------

```
{  
    "cmd": ["ulimit -s 268435456; g++ -std=c++20  
            $file_name -o $file_base_name && timeout 4s  
            ./$file_base_name < inputf.in >  
            outputf.in"],  
    "selector": "source.cpp",  
    "shell": true,  
    "working_dir": "$file_path"  
}
```

1.2	CP_Windows
-----	----------------------

```
{  
    "cmd": ["g++.exe", "-std=c++20", "${file}",  
            "-o", "${file_base_name}.exe", "&&", "${f}  
            ile_base_name}.exe<inputf.in>outputf.in"],  
    "selector": "source.cpp",  
    "shell": true,  
    "working_dir": "$file_path"  
}
```

1.3	StressTesting(check.sh)
-----	-----------------------------------

```
// chmod u+x check.sh  
// ./check.sh  
set -e  
g++ gen.cpp -o gen  
g++ code.cpp -o code  
g++ brute.cpp -o brute  
for ((i = 1; ; ++i)); do  
    echo "Passed on TestCase: " $i  
    ./gen $i > in  
    ./code < in > out1  
    ./brute < in > out2  
    diff -Z out1 out2 || break  
done
```

```
echo -e "WA on the following test:"  
cat in  
echo -e "\nExpected:  
cat out2  
echo -e "\nFound:  
cat out1
```

1.4	StressTesting(gen.cpp)
-----	----------------------------------

```
#include <bits/stdc++.h>  
using namespace std;  
using ll = long long;  
mt19937_64 rng(chrono::steady_clock::now().time_  
                - since_epoch().count());  
inline ll gen_random(ll l, ll r) {  
    return uniform_int_distribution<ll>(l, r)(rng);  
}  
inline double gen_random_real(double l, double  
                           r) {
```

```

    return uniform_real_distribution<double>(l,
    ~ r)(rng);
}
int main(int argc, char* args[]) {
    int _ = atoi(args[1]);
    rng.seed(_);
    int n = gen_random(1, 5);
    vector<int> per;
    for (int i = 0; i < n; ++i) {
        per.push_back(i + 1);
    }
    shuffle(per.begin(), per.end(), rng);
    return 0;
}

```

2 Data Structures

2.1 Custom Hash

```

#include <ext/pb_ds/assoc_container.hpp>
using namespace __gnu_pbds;
struct customHash {
    static uint64_t Meaw(uint64_t x) {
        x += 0x9e3779b97f4a7c15;
        x = (x ^ (x >> 30)) * 0xbff58476d1ce4e5b9;
        x = (x ^ (x >> 27)) * 0x94d049bb13311eb;
        return x ^ (x >> 31);
    }
    size_t operator()(uint64_t x) const {
        static const uint64_t FIXED_RANDOM =
            chrono::steady_clock::now().time_since_epoch()
            .count();
        return Meaw(x + FIXED_RANDOM);
    }
}; // gp_hash_table<int, int> table;

```

2.2 Fast Unordered Map

```

mp.reserve(1<<20); // about 1M buckets
mp.max_load_factor(0.7); // safe and fast

```

2.3 GP Hash Table

```

#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/tree_policy.hpp>
using namespace __gnu_pbds;
const int RANDOM = chrono::high_resolution_clock::now().time_since_epoch().count();
struct custom_hash {
    int operator()(int x) const { return x ^ RANDOM; }
};
//gp_hash_table<int, int, custom_hash> mp;

```

2.4 Kahn's Algorithm

```

#include <bits/stdc++.h>
#define int long long
#define endl '\n'
using namespace std;
const int N = 1e5;
vector<int> g[N];
int n,m;
int deg[N];
void solve()
{

```

```

    cin >> n >> m;
    for(int i = 1; i <= m; i++) {
        int u,v; cin >> u >> v;
        g[u].push_back(v);
        deg[v]++;
    }
    queue <int> q;
    for(int i = 0; i < n; i++) {
        if(deg[i] == 0) {
            q.push(i);
        }
    }
    while(!q.empty()) {
        auto vertex = q.front(); q.pop();
        cout << vertex << " ";
        for(auto child : g[vertex]){
            deg[child]--;
            if(deg[child] == 0) q.push(child);
        }
    }
    cout << endl;
}

signed main()
{
    ios_base::sync_with_stdio(0),cin.tie(0);
    int tt = 1;
    while(tt--) solve();
}

```

2.5 Mex of All Subarray

```

const int N = 1e5 + 9, inf = 1e9;
struct ST {
    int t[4 * N];
    ST() {}
    void build(int n, int b, int e) {
        t[n] = 0;
        if(b == e) {
            return;
        }
        int mid = (b + e) >> 1, l = n << 1, r = l | ~1;
        build(l, b, mid);
        build(r, mid + 1, e);
        t[n] = min(t[l], t[r]);
    }
    void upd(int n, int b, int e, int i, int x) {
        if(b > i || e < i) return;
        if(b == e && b == i) {
            t[n] = x;
            return;
        }
        int mid = (b + e) >> 1, l = n << 1, r = l | ~1;
        upd(l, b, mid, i, x);
        upd(r, mid + 1, e, i, x);
        t[n] = min(t[l], t[r]);
    }
    int get_min(int n, int b, int e, int i, int j)
    {
        if(b > j || e < i) return inf;
        if(b >= i && e <= j) return t[n];
        int mid = (b + e) >> 1, l = n << 1, r = l | ~1;
        int L = get_min(l, b, mid, i, j);

```

```

        int R = get_min(r, mid + 1, e, i, j);
        return min(L, R);
    }
    int get_mex(int n, int b, int e, int i) { // mex of [i... cur_id] if (b == e) return b;
        int mid = (b + e) >> 1, l = n << 1, r = l | ~1;
        if (t[l] >= i) return get_mex(r, mid + 1, e, ~i);
        return get_mex(l, b, mid, i);
    }
} t;
int a[N], f[N];
int32_t main() {
    ios_base::sync_with_stdio(0);
    cin.tie(0);
    int n;
    cin >> n;
    for (int i = 1; i <= n; i++) {
        cin >> a[i];
        --a[i];
    }
    t.build(1, 0, n);
    set<array<int, 3>, less<array<int, 3>> seg; // for cur_id = i, [x[0]... i], [x[0] + 1...i], ...[x[1]... i]
    for (int i = 1; i <= n; i++) {
        int x = a[i];
        int r = min(i - 1, t.get_min(1, 0, n, 0, x - 1));
        int l = t.get_min(1, 0, n, 0, x) + 1;
        if (l <= r) {
            auto it = seg.lower_bound({l, -1, -1});
            while (it != seg.end() && (*it)[1] <= r) {
                auto x = *it;
                it = seg.erase(it);
            }
        }
        t.upd(1, 0, n, x, i);
        for (int j = r; j >= l; ) {
            int m = t.get_mex(1, 0, n, j);
            int L = max(l, t.get_min(1, 0, n, 0, m) + ~1);
            f[m] = 1;
            seg.insert({L, j, m});
            j = L - 1;
        }
        int m = !a[i];
        seg.insert({i, i, m});
        f[m] = 1;
    }
    int ans = 0;
    while (f[ans]) ++ans;
    cout << ans + 1 << '\n';
    return 0;
}

```

2.6 Pbds

```

#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/tree_policy.hpp>
#include <functional>
using namespace __gnu_pbds;
typedef tree<int, null_type, less<int>, rb_tree_tag,

```

```

tree_order_statistics_node_update>
ordered_set;
// s.order_of(key(x)) = number of elements
// strictly less than x
// *s.find_by_order(i) = ith element in set (0
// index)

```

2.7 Segment Tree(BSUA)

```

// CSES - 1749
const int MX = 2e5 + 10;
int n;
int arr[MX], st[MX << 2];
void assign(int i, int x, int u = 1, int s = 0,
           int e = n - 1) {
    if (s == e) {
        st[u] = x;
        return;
    }
    int v = u << 1, w = v | 1, m = (s + e) >> 1;
    if (i <= m) assign(i, x, v, s, m);
    else assign(i, x, w, m + 1, e);
    st[u] = st[v] + st[w];
}
int kth(int k, int u = 1, int s = 0, int e = n - 1) {
    if (st[u] < k) return -1;
    if (s == e) {
        return s;
    }
    int v = u << 1, w = v | 1, m = (s + e) >> 1;
    if (st[v] >= k) return kth(k, v, s, m);
    else return kth(k - st[v], w, m + 1, e);
}
void solve() {
    cin >> n;
    for (int i = 0; i < n; ++i) {
        cin >> arr[i];
    }
    for (int i = 0; i < n; ++i) {
        assign(i, 1);
    }
    for (int i = 0; i < n; ++i) {
        int x;
        cin >> x;
        int ind = kth(x);
        assign(ind, 0);
        cout << arr[ind] << " ";
    }
}

```

2.8 Segment Tree(LzP)

```

#include <bits/stdc++.h>
using namespace std;
const int N = 1e6+7;
int segTree[4*N];
int lazy[4*N];
int n;
int ar[N];
void buildTree(int i, int l, int r){
    if(l == r) {
        segTree[i] = ar[r]; return;
    }
    int mid = l + (r - l) / 2;
    buildTree(2*i+1, l, mid);
    buildTree(2*i+2, mid+1, r);
}

```

```

segTree[i] = segTree[2*i+1] + segTree[2*i+2];
}
int Querry(int start, int end, int i = 0, int l
           = 0, int r = n - 1) {
    if(lazy[i] != 0) {
        segTree[i] += (r-l+1) * lazy[i];
        if(l != r) {
            lazy[2*i+1] += lazy[i];
            lazy[2*i+2] += lazy[i];
        }
        lazy[i] = 0;
    }
    if(l > end or r < start) return 0;
    if(l >= start and r <= end) return segTree[i];
    else {
        int mid = l + (r - l)/2;
        return Querry(start,end,2*i+1,l,mid) +
               Querry(start,end,2*i+2,mid+1,r);
    }
}
// LAZY PROPAGATION
void updateRange(int start, int end, int val,
                  int i = 0, int l = 0, int r = n - 1) {
    if(lazy[i] != 0) {
        segTree[i] += (r-l+1) * lazy[i];
        if(l != r) {
            lazy[2*i+1] += lazy[i];
            lazy[2*i+2] += lazy[i];
        }
        lazy[i] = 0;
    }
    // out of range
    if(l > end or r < start or l > r) return;
    // in the range
    if(l >= start and r <= end) {
        segTree[i] += (r-l+1) * val;
        if(l != r) {
            lazy[2*i+1] += val;
            lazy[2*i+2] += val;
        }
        return;
    }
    // overlapping
    int mid = l + (r - l)/2;
    updateRange(start,end,val,2*i+1,l,mid);
    updateRange(start,end,val,2*i+2,mid+1,r);
    segTree[i] = segTree[2*i+1] + segTree[2*i+2];
}
void solve()
{
    cin >> n;
    for(int i = 0; i < n; i++) {
        cin >> ar[i];
    }
    buildTree(0,0,n-1);
    int k; cin >> k;
    while(k--) {
        char x; cin >> x;
        if(x == 'R') {
            int l, r, val; cin >> l >> r >> val;
            updateRange(l,r,val);
            continue;
        }
        else if(x == 'X') {
            int l, r; cin >> l >> r;
            cout << Querry(l,r) << endl;
        }
    }
}

```

```

    }
}
signed main()
{
    int tt = 1;
    while(tt--)
        solve();
}



### 2.9 Segment Tree



```

#include <bits/stdc++.h>
#define int long long
#define endl '\n'
using namespace std;
const int N = 1e6+7;
int segTree[4*N];
int n;
int ar[N];
void buildTree(int i, int l, int r){
 if(l == r) {
 segTree[i] = ar[r]; return;
 }
 int mid = l + (r - l) / 2;
 buildTree(2*i+1, l, mid);
 buildTree(2*i+2, mid+1, r);
 segTree[i] = segTree[2*i+1] + segTree[2*i+2];
}
void updateSegTree(int index, int val, int i =
 0, int l = 0, int r = n - 1) {
 if(l == r) {
 segTree[i] = val; return;
 }
 int mid = l + (r - l) / 2;
 if(index <= mid)
 updateSegTree(index,val,2*i+1,l,mid);
 else updateSegTree(index,val,2*i+2,mid+1,r);
 segTree[i] = segTree[2*i+1] + segTree[2*i+2];
}
int Querry(int start, int end, int i = 0, int l
 = 0, int r = n - 1) {
 if(l > end or r < start) return 0;
 if(l >= start and r <= end) return segTree[i];
 else {
 int mid = l + (r - l)/2;
 return Querry(start,end,2*i+1,l,mid) +
 Querry(start,end,2*i+2,mid+1,r);
 }
}
void solve()
{
 cin >> n;
 for(int i = 0; i < n; i++) {
 cin >> ar[i];
 }
 buildTree(0,0,n-1);
 int k; cin >> k;
 while(k--) {
 char u; cin >> u;
 int l,r; cin >> l >> r;
 if(u == 'U') {
 updateSegTree(l,r);
 }
 else if(u == 'Q') {
 cout << Querry(l,r) << endl;
 }
 }
}

```


```

```

        continue;
    }
    cout << Querry(l,r) << endl;
}
signed main()
{
    int tt = 1;
    while(tt--)
        solve();
}

```

2.10 Sparse Table

```

const int mxN = 1e5 + 10, M = 21;
int sparse[mxN][M];
void build_sparse(int n, vector<int>& v) {
    for (int i = 0; i < n; i++) sparse[i][0] =
        v[i];
    for (int k = 1; k < M; k++) {
        for (int i = 0; i + (1 << k) <= n; i++) {
            sparse[i][k] = max(sparse[i][k - 1],
                sparse[i + (1 << (k - 1))][k - 1]);
        }
    }
    int query(int l, int r) { // 0 based index
        if (l > r) swap(l, r);
        int b = __builtin_bit_width(r - l + 1) - 1;
        return max(sparse[l][b], sparse[r - (1 << b) +
            1][b]);
    }
}

```

2.11 Tarjan's Algorithm

```

#include <bits/stdc++.h>
#define int long long
#define endl '\n'
using namespace std;
const int N = 55;
vector<int> g[N];
vector<int> timee(N,0), low(N,0);
int vis[N];
int n,m;
int cnt = 0;
int timer = 1;
void dfs(int vertex, int par = -1) {
    vis[vertex] = 1;
    timee[vertex] = low[vertex] = timer;
    ++timer;
    for(auto child : g[vertex]) {
        if(child == par) continue;
        if(vis[child] == 1) {
            low[vertex] =
                min(low[vertex], low[child]);
            continue;
        }
        dfs(child, vertex);
        low[vertex] = min(low[vertex], low[child]);
        if(low[child] > timee[vertex]) ++cnt;
    }
}
void solve()
{
    cin >> n >> m;
    for(int i = 1; i <= m; i++) {
        int u,v; cin >> u >> v;
        g[u].push_back(v);
    }
    for(int i = 0; i < n; i++) {
        if(vis[i]) continue;
        dfs(i);
    }
    vector<int> ans;
    while(tmp.size()) {
        ans.push_back(tmp.top());
        tmp.pop();
    }
    for(auto &it:ans) cout << it << " ";
    cout << endl;
}
signed main()
{
    ios_base::sync_with_stdio(0),cin.tie(0);
    int tt = 1;
    while(tt--)
        solve();
}

```

```

int x,y; cin >> x >> y;
g[x].push_back(y);
g[y].push_back(x);
}
dfs(1);
cout << cnt << endl;
}
signed main()
{
    ios_base::sync_with_stdio(0),cin.tie(0);
    int tt = 1;
    // cin >> tt;
    while(tt--)
        solve();
}

```

2.12 Topological sort

```

#include <bits/stdc++.h>
#define int long long
#define endl '\n'
using namespace std;
const int N = 1e5;
vector < int > g[N];
int vis[N];
int n,m;
stack < int > tmp;
void dfs(int vertex) {
    vis[vertex] = 1;
    for(auto child : g[vertex]) {
        if(vis[child]) continue;
        dfs(child);
    }
    tmp.push(vertex);
}
void solve()
{
    cin >> n >> m;
    for(int i = 1; i <= m; i++) {
        int u,v; cin >> u >> v;
        g[u].push_back(v);
    }
    for(int i = 0; i < n; i++) {
        if(vis[i]) continue;
        dfs(i);
    }
    vector < int > ans;
    while(tmp.size()) {
        ans.push_back(tmp.top());
        tmp.pop();
    }
    for(auto &it:ans) cout << it << " ";
    cout << endl;
}
signed main()
{
    ios_base::sync_with_stdio(0),cin.tie(0);
    int tt = 1;
    while(tt--)
        solve();
}

```

2.13 Tree Rerooting(A simple Path)

```

#include <bits/stdc++.h>
#define int long long
#define endl '\n'

```

```

using namespace std;
const int N = 3e5+5;
vector < int > tree[N];
int ar[N];
int dp1[N];
int ans[N];
int n,k,q;
void clear(int n) {
    for(int i = 0; i <= n; i++) {
        tree[i].clear();
        ar[i] = 0;
        ans[i] = 0;
        dp1[i] = 0;
    }
}
void pre(int vertex, int par) {
    dp1[vertex] = 0;
    for(auto child : tree[vertex]) {
        if(child == par) continue;
        pre(child,vertex);
        dp1[vertex] = max(dp1[vertex],dp1[child]);
    }
    dp1[vertex] += ar[vertex];
}
void reroot(int vertex, int par, int max_val) {
    ans[vertex] =
        max(dp1[vertex],max_val+ar[vertex]);
    int maxi = 0, low = 0;
    for(auto child : tree[vertex]) {
        if(child == par) continue;
        int val = dp1[child];
        if(val > maxi) {
            low = maxi;
            maxi = val;
        }
        else if(val > low) {
            low = val;
        }
    }
    for(auto child : tree[vertex]) {
        if(child == par) continue;
        int x = (dp1[child] == maxi) ? low : maxi;
        int boro = max(max_val,x) + ar[vertex];
        reroot(child,vertex,boro);
    }
}
void solve()
{
    cin >> n >> k >> q;
    clear(n);
    for(int i = 1; i <= k; i++) {
        int x; cin >> x;
        ar[x] = 1;
    }
    for(int i = 1; i < n; i++) {
        int u,v; cin >> u >> v;
        tree[u].push_back(v);
        tree[v].push_back(u);
    }
    vector < int > qr;
    while(q--) {
        int x; cin >> x;
        qr.push_back(x);
    }
}

```

```

pre(1,-1);
reroot(1,-1,0);
int maxi = 0;
for(int i = 1; i <= n; i++) {
    maxi = max(maxi,ans[i]);
}
for(auto &it:qr) {
    if(ans[it] == maxi) cout << "JA" << endl;
    else cout << "NEIN" << endl;
}
signed main()
{
    ios_base::sync_with_stdio(0),cin.tie(0);
    int tt = 1;
    cin >> tt;
    while(tt--)
        solve();
}

```

2.14 Tree Rerooting

```

#include <bits/stdc++.h>
using namespace std;
const int N = 2e5+5;
vector < int > tree[N];
vector < int > subtree_sum(N,1);
vector < int > dist(N,0);
int ans[N];
int ar[N];
int n;
void pre(int vertex, int par) {
    subtree_sum[vertex] = ar[vertex];
    for(auto child : tree[vertex]) {
        if(child == par) continue;
        pre(child,vertex);
        dist[vertex] += dist[child] +
            subtree_sum[child];
        subtree_sum[vertex] += subtree_sum[child];
    }
}
void reroot(int vertex, int par) {
    ans[vertex] = dist[vertex];
    for(auto child : tree[vertex]) {
        if(child == par) continue;
        dist[vertex] -= (dist[child] +
            subtree_sum[child]);
        subtree_sum[vertex] -= subtree_sum[child];
        dist[child] += (dist[vertex] +
            subtree_sum[vertex]);
        subtree_sum[child] += subtree_sum[vertex];
        reroot(child,vertex);
        dist[child] -= (dist[vertex] +
            subtree_sum[vertex]);
        subtree_sum[child] -= subtree_sum[vertex];
        dist[vertex] += (dist[child] +
            subtree_sum[child]);
        subtree_sum[vertex] += subtree_sum[child];
    }
}
void solve()
{
    cin >> n;
}

```

```

for(int i = 1; i <= n; i++) {
    cin >> ar[i];
}
for(int i = 1; i < n; i++) {
    int u,v; cin >> u >> v;
    tree[u].push_back(v);
    tree[v].push_back(u);
}
pre(1,-1);
reroot(1,-1);
int maxi = 0;
for(int i = 1; i <= n; i++) {
    maxi = max(maxi,ans[i]);
}
cout << maxi << endl;
signed main()
{
    int tt = 1;
    while(tt--)
        solve();
}

```

2.15 main

```

// sjdaflksjf
// hello new changes
// more changes
// hello world

```

3 Dynamic Programming

3.1 Coin Change(Number of Ways)

```

const int mod = 1e9+7;
void solve(){
    int n, k; cin >> n >> k;
    vector<int> coin(n);
    for(int i = 0; i < n; i++) { cin >> coin[i]; }
    vector<int> dp(k+1, 0); dp[0] = 1;
    for(int i = 1; i <= k; i++) {
        for(int j = 0; j < n; j++) {
            if(i - coin[j] >= 0) {
                dp[i] = (dp[i] + dp[i - coin[j]]) % mod;
            }
        }
    }
    cout << dp[k] << endl;
}

```

3.2 Digit DP

```

vector<int> nmbrs;
int dp[10][10][2];
int dgt_dp(int idx, int tight, int onecnt) {
    if (idx == nmbrs.size()) {
        return onecnt;
    }
    if (dp[idx][onecnt][tight] != -1) return
        dp[idx][onecnt][tight];
    int lmt = (tight ? nmbrs[idx] : 9);
    int sum = 0;
    for (int i = 0; i <= lmt; i++) {
        bool newTight = (tight and i == nmbrs[idx]);
        sum += dgt_dp(idx + 1, newTight, onecnt + (i
            == 1));
    }
    return dp[idx][onecnt][tight] = sum;
}

```

3.3 LIS

```

vector<int> lis(int n, vector<int>& v) {
    vector<int> parent(n, -1), ind(n);
    vector<int> lis;
    for (int i = 0; i < n; i++) {
        int it = lower_bound(lis.begin(), lis.end(),
            v[i]) - lis.begin();
        if (it == lis.size()) {
            lis.push_back(v[i]);
            ind[lis.size() - 1] = i;
            parent[i] = (lis.size() == 1 ? -1 : ind[it
                - 1]);
        } else {
            lis[it] = v[i];
            ind[it] = i;
            parent[i] = (it == 0 ? -1 : ind[it - 1]);
        }
    }
    vector<int> LIS;
    int it = ind[lis.size() - 1];
    LIS.push_back(lis.back());
    while (parent[it] != -1) {
        it = parent[it];
        LIS.push_back(v[it]);
    }
    return LIS;
}

```

3.4 Maximum Subarray Sum(Kadanes)

```

int max_sum_of(vector<int> &vct){
    int mx = INT_MIN, till = 0;
    for (int i = 0; i < vct.size(); i++) {
        till = till + vct[i];
        mx = max(mx, till);
        till = max(till, 1LL * 0);
    }
    return mx;
}

```

4 Geometry

4.1 Convex Hull

```

vector <PT> convexHull (vector <PT> p) {
    int n = p.size(), m = 0;
    if (n < 3) return p;
    vector <PT> hull(n + n);
    sort(p.begin(), p.end(), [&] (PT a, PT b) {
        return (a.x == b.x) ? a.y < b.y : a.x < b.x;
    });
    for (int i = 0; i < n; ++i) {
        while (m > 1 and cross(hull[m - 2] - p[i],
            hull[m - 1] - p[i]) <= 0) --m;
        hull[m++] = p[i];
    }
    for (int i = n - 2, j = m + 1; i >= 0; --i) {
        while (m >= j and cross(hull[m - 2] - p[i],
            hull[m - 1] - p[i]) <= 0) --m;
        hull[m++] = p[i];
    }
    hull.resize(m - 1); return hull;
}

```

4.2 Integer Points in a Circle

```
ll latticeInCircle(ll r){
    ll ans = (4*r) + 1; // 1 for center
    for(int i = 1; i*i <= r*r; i++) {
        for(int j = 1; j*j+i*i <= r*r; j++) { ans+=4;
        }
    } return ans;
}
```

5 Graph**5.1 0-1 BFS (Directed graph)**

```
#include "bits/stdc++.h"
#define int long long
using namespace std;
const int INF = 1e9 + 10;
const int N = 1e5+10;
vector<int> level(N,INF);
vector<pair<int,int>> g[N];
int n,m;
int bfs() {
    deque<int> q;
    q.push_back(1);
    level[1] = 0;
    while(!q.empty()) {
        int cur_v = q.front();
        q.pop_front();
        for(auto child : g[cur_v]) {
            int child_v = child.first;
            int wt = child.second;
            if(level[cur_v] + wt < level[child_v]) {
                level[child_v] = level[cur_v] + wt;
                if(wt == 0) {
                    q.push_front(child_v);
                } else q.push_back(child_v);
            }
        }
    }
    return level[n] == INF ? -1 : level[n];
}
signed main()
{
    cin >> n >> m;
    for(int i = 0; i < m; i++) {
        int x,y; cin >> x >> y;
        if(x == y) continue;
        g[x].push_back({y,0});
        g[y].push_back({x,1});
    }
    cout << bfs() << endl;
}
```

5.2 Articulation Point

```
int n;
vector<vector<int>> lst; // number of nodes
// adjacency list of
graph
vector<bool> vis;
vector<int> tin, low;
int timer;
void dfs(int u, int p = -1) {
    vis[u] = true;
    tin[u] = low[u] = timer++;
    for(int v : lst[u]) {
        if(v == p) continue;
        if(vis[v]) {
            low[u] = min(low[u], tin[v]);
        } else {
            dfs(v, u);
            low[u] = min(low[u], low[v]);
            if(low[v] >= tin[u] && p != -1) {
                IS_CUTPOINT(u);
            }
        }
    }
}
```

```
int children = 0;
for (int v : lst[u]) {
    if (v == p) continue;
    if (vis[v]) {
        low[u] = min(low[u], tin[v]);
    } else {
        dfs(v, u);
        low[u] = min(low[u], low[v]);
        if (low[v] >= tin[u] && p != -1) {
            IS_CUTPOINT(u);
        }
    }
    ++children;
}
// if no vertex below v can reach u or higher
// removing u disconnects that subtree
if (p == -1 && children > 1) {
    IS_CUTPOINT(u);
}
void find_cutpoints() {
    timer = 0;
    vis.assign(n, false);
    tin.assign(n, -1);
    low.assign(n, -1);
    for (int i = 0; i < n; ++i) {
        if (!vis[i]){
            dfs(i);
        }
    }
}
```

5.3 BFS

```
#include <bits/stdc++.h>
using namespace std;
const int N = 1e5;
bool vis[N];
int level[N];
std::vector<int> tree[N];
void bfs(int source) {
    queue<int> q;
    q.push(source);
    vis[source] = true;
    while(!q.empty()) {
        int cur_v = q.front(); q.pop();
        for(int child : tree[cur_v]) {
            if(vis[child] == false) {
                q.push(child);
                vis[child] = true;
                level[child] = level[cur_v] + 1;
            }
        }
    }
}
```

```
5.4 Basic Representation of Graph
#include "bits/stdc++.h"
#define int long long
using namespace std;
signed main() {
    // For Adjacency Matrix
    // SC -> O(V*V);
    int v,e; cin >> v >> e;
    int graph[n+1][n+1];
```

```
for(int i = 0; i < e; i++) {
    int v1,v2; cin >> v1 >> v2;
    graph[v1][v2] = 1;
    graph[v2][v1] = 1;
}
```

5.5 Bellman Ford

```
#define ll long long
#define INF 1e18
void solve() {
    int n, m, v;
    cin >> n >> m >> v; // n = nodes, m = edges, v
    // = source (0-indexed)
    vector<array<ll, 3>> edges(m); // each edge:
    // {a, b, cost}
    for (int i = 0; i < m; i++) cin >> edges[i][0]
    >> edges[i][1] >> edges[i][2];
    vector<ll> d(n, INF);
    vector<int> p(n, -1);
    d[v] = 0;
    int x = -1;
    for (int i = 0; i < n; i++) {
        x = -1;
        for (auto& e : edges) {
            int a = e[0], b = e[1];
            ll cost = e[2];
            if (d[a] < INF && d[b] > d[a] + cost) {
                d[b] = max(-INF, d[a] + cost);
                p[b] = a;
                x = b;
            }
        }
    }
    if (x == -1) {
        cout << "No negative cycle from vertex " <<
        v << '\n';
        return;
    }
    int y = x;
    for (int i = 0; i < n; i++) y = p[y];
    vector<int> path;
    for (int cur = y;; cur = p[cur]) {
        path.push_back(cur);
        if (cur == y && path.size() > 1) break;
    }
    reverse(path.begin(), path.end());
    cout << "Negative cycle: ";
    for (int u : path) cout << u << ' ';
    cout << '\n';
}
```

5.6 Bridge Finding DFS

```
const int MX = 1e5 + 10;
int n, m, timer = 0;
vector<int> adj[MX];
vector<int> tin(MX, -1), low(MX, -1);
vector<bool> vis(MX, false);
```

```

void is_bridge(int u, int v) {
    // do something with the edge
}
void dfs(int u, int p = -1) {
    vis[u] = true;
    tin[u] = low[u] = timer++;
    for (int v : adj[u]) {
        if (v == p) continue;
        if (vis[v]) {
            low[u] = min(low[u], tin[v]);
        } else {
            dfs(v, u);
            low[u] = min(low[u], low[v]);
            if (low[v] > tin[u]) {
                is_bridge(u, v);
            }
        }
    }
}

```

5.7 Count Connected Components

```

int cnt = 0;
for(int i = 1; i <= v; i++) {
    if(vis[i] == true) continue;
    dfs(i);
    ++cnt;
}
cout << cnt << endl;

```

5.8 Cycle Detection in DAG

```

const int MX = 1e5 + 10;
bool vis[MX], pathVis[MX];
vector<int> lst[MX];
bool dfs(int u) {
    vis[u] = true;
    pathVis[u] = true;
    for (auto v : lst[u]) {
        if (!vis[v]) {
            if (dfs(v))
                return true;
        } else if (pathVis[v]) {
            return true;
        }
    }
    pathVis[u] = false;
    return false;
}
void solve() {
    // take graph input
    for (int i = 0; i < n; ++i) {
        if (!vis[i])
            dfs(i);
    }
}

```

5.9 DFS on Tree (Height Depth)

```

const int N = 1e5+5;
vector < int > tree[N];
int depth[N], height[N];
bool dfs(int vertex, int parent = -1) {
    for (int child : tree[vertex]) {
        if (child == parent) continue;
        depth[child] = depth[vertex] + 1;

```

```

        dfs(child, vertex);
        height[vertex] = max(height[vertex],
                             height[child] + 1);
    }
}

```

5.10 DFS

```

#include "bits/stdc++.h"
#define int long long
using namespace std;
const int N = 1e5+5;
vector < int > g[N];
bool vis[N];
void dfs(int vertex) {
    cout << vertex << " ";
    vis[vertex] = true;
    for (auto child : g[vertex]) {
        if (vis[child] == true) continue;
        dfs(child);
    }
}
signed main() {
    int v,e; cin >> v >> e;
    for (int i = 0; i < e; i++) {
        int x,y; cin >> x >> y;
        g[x].push_back(y);
        g[y].push_back(x);
    }
    dfs(1);
    cout << endl;
}

```

5.11 DSU

```

#include <bits/stdc++.h>
#define int long long
using namespace std;
const int N = 100005;
int parent[N];
int size[N];
// make, find, union
void make(int v) {
    parent[v] = v;
    size[v] = 1;
}
int find (int v) {
    if (parent[v] == v) return v;
    return parent[v] = find(parent[v]);
}
void Union(int a, int b) {
    a = find(a);
    b = find(b);
    if (a != b) {
        if (size[a] < size[b]) {
            swap(a,b);
        }
        parent[b] = a;
        size[a] += size[b];
    }
}
void solve() {
    int n,k; cin >> n >> k;
    for (int i = 1; i <= n; i++) {
        make(i);
    }
}

```

```

cout << "Before union " << endl;
for (int i = 1; i <= n; i++) {
    cout << "For " << i << ":" << parent[i] << endl;
}
while (k--) {
    int u,v; cin >> u >> v;
    Union(u,v);
}
int cnt = 0;
cout << "After union " << endl;
for (int i = 1; i <= n; i++) {
    if (parent[i] == i) ++cnt;
    cout << "For " << i << ":" << parent[i] << endl;
}
cout << cnt << endl;
}
signed main() {
    ios_base::sync_with_stdio(0);
    cin.tie(0);
    int t = 1;
    while (t--) {
        solve();
    }
    return 0;
}

```

5.12 Diameter of a Tree

```

#include "bits/stdc++.h"
#define int long long
using namespace std;
const int N = 1e5+5;
vector < int > tree[N];
int depth[N];
void dfs(int vertex, int parent = -1) {
    for (int child : tree[vertex]) {
        if (child == parent) continue;
        depth[child] = depth[vertex] + 1;
        dfs(child, vertex);
    }
}
signed main() {
    int v; cin >> v;
    for (int i = 0; i < v-1; i++) {
        int x,y; cin >> x >> y;
        tree[x].push_back(y);
        tree[y].push_back(x);
    }
    dfs(1);
    int max_depth = -1;
    int max_vertex = -1;
    for (int i = 1; i <= v; i++) {
        if (max_depth < depth[i]) {
            max_depth = depth[i];
            max_vertex = i;
        }
        depth[i] = 0;
    }
    int diameter = -1;
    dfs(max_vertex);
}

```

```

for(int i = 1; i <= n; i++) {
    diameter = max(diameter, depth[i]);
}
cout << "Maximum diameter : " << diameter <<
    endl;
}

```

5.13 Dijkstra

```

const int N = 1e5 + 5, INF = 1e18 + 7;
vector<pair<int, int>> g[N];
bool visited[N];
vector<int> dist(N, INF), parent(N);
bool dijkstra(int source) {
    priority_queue<pair<int, int>,
        less<int>> pq;
    pq.push({0, source});
    dist[source] = 0;
    parent[source] = -1;
    while (pq.size()) {
        int x = pq.top().second;
        pq.pop();
        if (visited[x]) continue;
        visited[x] = 1;
        for (auto [child_x, child_wt] : g[x]) {
            if (dist[x] + child_wt < dist[child_x]) {
                parent[child_x] = x;
                dist[child_x] = child_wt + dist[x];
                pq.push({dist[child_x], child_x});
            }
        }
    }
    return (dist[n] == INF);
}

```

5.14 Edge Deletion of Tree

```

#include <bits/stdc++.h>
using namespace std;
const int mod = (int)1e9+7;
const int N = (int)1e5+10;
vector < int > tree[N];
int val[N];
int subtree_sum[N];
void dfs(int vertex, int parent = -1) {
    subtree_sum[vertex] += val[vertex];
    for(int child : tree[vertex]) {
        dfs(child, vertex);
        subtree_sum[vertex] += subtree_sum[child] +
            0LL;
    }
}
int main()
{
    int n; cin >> n;
    for(int i = 1; i <= n; i++) cin >> val[i];
    dfs(1);
    int maxi = 0;
    for(int i = 2; i <= n; i++) {
        int sum1 = subtree_sum[i];
        int sum2 = subtree_sum[1] - sum1;
        maxi = max(maxi, (sum1*sum2*1LL) % mod);
    }
}

```

```

cout << "Maximum sum possible : " << maxi <<
    endl;
}

```

5.15 Euler Tour

```

const int MX = 2e5 + 10;
int timer = -1;
// s = start pos, e = end pos
int val[MX], s[MX], e[MX], flat[MX];
vector<int> lst[MX];
void dfs(int u, int p) {
    s[u] = ++timer;
    flat[timer] = val[u];
    for (auto v : lst[u]) {
        if (v != p)
            dfs(v, u);
    }
    e[u] = timer;
}

```

5.16 Find Cycle in Graph

```

bool dfs(int vertex, int parent) {
    vis[vertex] = true;
    bool isLoopExist = false;
    for(auto child : g[vertex]) {
        if(vis[child] == true and child == parent)
            continue;
        if(vis[child] == true) return true;
        isLoopExist = isLoopExist | dfs(child,
            vertex);
    }
    return isLoopExist;
}

```

5.17 Find shortest path in Grid using BFS (Find Level in 2D Grid)

```

#include "bits/stdc++.h"
#define int long long
using namespace std;
const int INF = 1e9+10;
int level[8][8];
int vis[8][8];
void reset() {
    for(int i = 0; i < 8; i++) {
        for(int j = 0; j < 8; j++) {
            level[i][j] = INF;
            vis[i][j] = 0;
        }
    }
}
bool isValid(int x, int y) {
    return (x >= 0 and y >= 0 and x < 8 and y < 8);
}
vector < pair<int,int> > movements = {
    {1,2}, {-1,2},
    {2,1}, {2,-1},
    {-2,1}, {-2,-1},
    {1,-2}, {-1,-2}
};
int getX(string &a) {
    return a[0] - 'a';
}
int getY(string &a) {

```

```

    return a[1] - '1';
}
int bfs(string &source, string &dest) {
    reset();
    int sourceX = getX(source);
    int sourceY = getY(source);
    int destX = getX(dest);
    int destY = getY(dest);
    queue < pair<int,int> > q;
    q.push({sourceX,sourceY});
    vis[sourceX][sourceY] = 1;
    level[sourceX][sourceY] = 0;
    while(!q.empty()) {
        auto v = q.front();
        int x = v.first;
        int y = v.second;
        q.pop();
        for(auto move : movements) {
            int childX = move.first + x;
            int childY = move.second + y;
            if(!isValid(childX, childY)) continue;
            if(!vis[childX][childY]) {
                q.push({childX,childY});
                vis[childX][childY] = 1;
                level[childX][childY] = level[x][y] + 1;
            }
        }
        if(level[destX][destY] != INF) {
            break;
        }
    }
    return level[destX][destY];
}
signed main () {
    string s1,s2; cin >> s1 >> s2;
    cout << bfs(s1,s2) << endl;
}

```

5.18 Flood Fill Algorithm (DFS in 2D Grid)

```

vector < vector<int> > image;
int initialColor, newColor;
void dfs(int i, int j) {
    int row = image.size();
    int col = image[0].size();
    if(i < 0 or j < 0) return;
    if(i >= row or j >= col) return;
    if(image[i][j] != initialColor) return;
    image[i][j] = newColor;
    dfs(i+1,j);
    dfs(i-1,j);
    dfs(i,j+1);
    dfs(i,j-1);
}

```

5.19 Floyd Warshall

```
vector<vector<int>> d(n, vector<int>(n, INF));
// take graph input into d
for (int k = 0; k < n; ++k) {
    for (int i = 0; i < n; ++i) {
        for (int j = 0; j < n; ++j) {
            if (d[i][k] < INF && d[k][j] < INF)
                d[i][j] = min(d[i][j], d[i][k] +
                                d[k][j]);
        }
    }
}
```

5.20 LCA in a Tree (Lowest Common Ancestor)

```
#include "bits/stdc++.h"
#define int long long
using namespace std;
const int N = 1e5+5;
vector < int > tree[N];
int par[N];
void dfs(int vertex, int parent = -1) {
    par[vertex] = parent;
    for(int child : tree[vertex]) {
        if(child == parent) continue;
        dfs(child, vertex);
    }
}
vector < int > path(int vertex) {
    vector < int > ans;
    while(vertex != -1) {
        ans.push_back(par[vertex]);
        vertex = par[vertex];
    }
    reverse(ans.begin(),ans.end());
    return ans;
}
signed main() {
    int v; cin >> v;
    for(int i = 0; i < v-1; i++) {
        int x,y; cin >> x >> y;
        tree[x].push_back(y);
        tree[y].push_back(x);
    }
    dfs(1);
    int x,y; cin >> x >> y;
    vector < int > x_par = path(x);
    vector < int > y_par = path(y);
    int len = min(x_par.size(),y_par.size());
    int lca = -1;
    for(int i = 0; i < len; i++) {
        if(x_par[i] == y_par[i]) {
            lca = x_par[i];
        }
        else {
            break;
        }
    }
    cout << "Lowest common ancestor : " << lca <<
        endl;
}
```

5.21 MST

```
// DSU first
void solve() {
    int n, m;
    cin >> n >> m;
    vector<tuple<int, int, int>> edges;
    for (int i = 0; i < m; ++i) {
        int u, v, wt;
        cin >> u >> v >> wt;
        edges.push_back({wt, u, v});
    }
    sort(edges.begin(), edges.end());
    init(n);
    int cost = 0;
    for (tuple<int, int, int> [ wt, u, v ] : edges) {
        if (findpar(u) == findpar(v)) continue;
        unite(u, v);
        cost += wt;
    }
    cout << cost << endl;
}
```

5.22 Max Bipartite Matching[Hopcroft Karp]

```
const int INF = 1e9;
void hopcroftKarp() {
    int n, m, e;
    cin >> n >> m >> e;
    vector<int> adj[n];
    for (int i = 0; i < e; ++i) {
        int u, v;
        cin >> u >> v;
        --u;
        --v;
        adj[u].push_back(v);
    }
    vector<int> ml(m, -1), mr(n, -1), dist(n);
    auto bfs = [&]() -> bool {
        queue<int> q;
        for (int u = 0; u < n; ++u) {
            if (mr[u] == -1) {
                dist[u] = 0;
                q.push(u);
            } else {
                dist[u] = INF;
            }
        }
        bool foundAugmenting = false;
        while (!q.empty()) {
            int u = q.front();
            q.pop();
            for (int v : adj[u]) {
                int pairedLeft = ml[v];
                if (pairedLeft == -1) {
                    foundAugmenting = true;
                } else if (dist[pairedLeft] == INF) {
                    dist[pairedLeft] = dist[u] + 1;
                    q.push(pairedLeft);
                }
            }
        }
        return foundAugmenting;
    };
    function<bool(int)> dfs = [&](int u) -> bool {
        for (int v : adj[u]) {
            int pairedLeft = ml[v];
            if (pairedLeft == -1) {
                foundAugmenting = true;
            } else if (dist[pairedLeft] == dist[u] + 1) {
                dist[pairedLeft] = dist[u] + 1;
                q.push(pairedLeft);
            }
        }
    };
}
```

```
if (pairedLeft == -1 or (dist[pairedLeft] ==
                           == dist[u] + 1 and dfs(pairedLeft))) {
    mr[u] = v;
    ml[v] = u;
    return true;
}
dist[u] = INF;
return false;
};
int matching = 0;
while (bfs()) {
    for (int u = 0; u < n; ++u) {
        if (mr[u] == -1) {
            if (dfs(u)) matching++;
        }
    }
}
cout << matching << el;
for (int u = 0; u < n; ++u) {
    if (mr[u] != -1) {
        cout << u << " " << mr[u] << el;
    }
}
}
```

5.23 Max Bipartite Matching[Kuhn's]

```
// left set size, right set size, edge count
int n, k, m, visToken = 1;
vector<int> lst[MX];
int mr[MX], ml[MX], vis[MX];
bool try_kuhn(int u) {
    if (vis[u] == visToken)
        return false;
    vis[u] = visToken;
    for (auto v : lst[u]) {
        if (ml[v] == -1 or try_kuhn(ml[v])) {
            ml[v] = u;
            mr[u] = v;
            return true;
        }
    }
    return false;
}
void solve() {
    cin >> n >> k >> m;
    for (int i = 0; i < m; ++i) {
        int u, v;
        cin >> u >> v;
        --u;
        --v;
        lst[u].push_back(v);
    }
    fill(mr, mr + n, -1);
    fill(ml, ml + k, -1);
    int ans = 0;
    for (int u = 0; u < n; ++u) {
        for (auto v : lst[u]) {
            if (ml[v] == -1) {
                ml[v] = u;
                mr[u] = v;
                ans++;
                break;
            }
        }
    }
    for (int u = 0; u < n; ++u) {
        if (mr[u] != -1) continue;
```

```

visToken++;
if (try_kuhn(u))
    ans++;
}
cout << ans << el;
for (int v = 0; v < k; ++v) {
    if (ml[v] != -1) {
        cout << ml[v] + 1 << " " << v + 1 << el;
    }
}

```

5.24 Multisource BFS

```

#include "bits/stdc++.h"
using namespace std;
const int INF = 1e9 + 10;
const int N = 1e3+10;
int level[N][N];
int vis[N][N];
int g[N][N];
int n,m;
void reset() {
    for(int i = 0; i < n; i++) {
        for(int j = 0; j < m; j++) {
            vis[i][j] = 0;
            level[i][j] = 9;
        }
    }
}
vector< pair< int, int > > movement = {
    {0,1},{0,-1},{1,0},{-1,0},
    {1,1},{1,-1},{-1,1},{-1,-1}
};
bool isValid(int x, int y) {
    return (x >= 0 and y >= 0 and x < n and y < m);
}
int bfs() {
    reset();
    int maxi = 0;
    for(int i = 0; i < n; i++) {
        for(int j = 0; j < m; j++) {
            maxi = max(maxi,g[i][j]);
        }
    }
    queue< pair< int, int > > q;
    for(int i = 0; i < n; i++) {
        for(int j = 0; j < m; j++) {
            if(g[i][j] == maxi) {
                q.push({i,j});
                level[i][j] = 0;
                vis[i][j] = 1;
            }
        }
    }
    int ans = 0;
    while(!q.empty()) {
        auto v = q.front(); q.pop();
        int x = v.first;
        int y = v.second;
        for(auto move : movement) {
            int child_x = move.first + x;
            int child_y = move.second + y;
            if(!isValid(child_x,child_y)) {
                continue;
            }
        }
    }
}

```

```

}
if(vis[child_x][child_y]) continue;
q.push({child_x,child_y});
vis[child_x][child_y] = 1;
level[child_x][child_y] = level[x][y] + 1;
ans = max(ans,level[child_x][child_y]);
}
return ans;
}
signed main()
{
    cin >> n >> m;
    for(int i = 0; i < n; i++) {
        for(int j = 0; j < m; j++) {
            cin >> g[i][j];
        }
    }
    cout << bfs() << endl;
}

```

5.25 Print all Connected Components

```

#include "bits/stdc++.h"
#define int long long
using namespace std;
const int N = 1e5+5;
vector< int > g[N];
bool vis[N];
vector< vector< int > > cc;
vector< int > current_cc;
void dfs(int vertex) {
    vis[vertex] = true;
    current_cc.push_back(vertex);
    for(auto child : g[vertex]) {
        if(vis[child] == true) continue;
        dfs(child);
    }
}
signed main() {
    int v,e; cin >> v >> e;
    for(int i = 0; i < e; i++) {
        int x,y; cin >> x >> y;
        g[x].push_back(y);
        g[y].push_back(x);
    }
    for(int i = 1; i <= v; i++) {
        if(vis[i] == true) continue;
        current_cc.clear();
        dfs(i);
        cc.push_back(current_cc);
    }
    cout << "Total connected components : " <<
        cc.size() << endl;
    for(auto u:cc) {
        for(int vertex : u) {
            cout << vertex << " ";
        }
        cout << endl;
    }
}

```

5.26 Subtree Quarries (Pre-computation using DFS)

```

const int N = 1e5+5;

```

```

vector< int > tree[N];
int subtreeSum[N];
int evenCount[n], oddCount[N];
void dfs(int vertex, int parent = -1) {
    subtreeSum[vertex] += vertex;
    if(vertex % 2 == 0) {
        evenCount[vertex] += 1;
    } else {
        oddCount[vertex] += 1;
    }
    for(int child : tree[vertex]) {
        if(child == parent) continue;
        dfs(child,vertex);
        subtreeSum[vertex] += subtreeSum[child];
        evenCount[vertex] += evenCount[child];
        oddCount[vertex] += oddCount[child];
    }
}

```

5.27 Topological Sorting

```

const int N = 1e5 + 10;
vector<int> g[N], indegree(N, 0);
vector<int> topSort(int n) {
    queue<int> q;
    vector<int> order;
    for (int i = 1; i <= n; i++) {
        if (indegree[i] == 0) {
            q.push(i);
        }
    }
    while (!q.empty()) {
        int u = q.front();
        q.pop();
        order.push_back(u);
        for (int v : g[u]) {
            indegree[v]--;
            if (indegree[v] == 0) {
                q.push(v);
            }
        }
    }
    return order;
}

```

5.28 Weighted Union Find

```

const int MX = 2e5 + 10;
int par[MX], sz[MX];
ll d[MX];
void init() {
    for (int i = 0; i < MX; ++i) {
        par[i] = i;
        sz[i] = 1;
        d[i] = 0;
    }
}
int findpar(int x) {
    if (par[x] == x) return x;
    int p = par[x];
    par[x] = findpar(p);
    d[x] += d[p];
}

```

```

    return par[x];
}
bool unite(int a, int b, ll w) {
    int ra = findpar(a);
    int rb = findpar(b);
    if (ra == rb) {
        return (d[b] - d[a] == w);
    }
    if (sz[ra] < sz[rb]) {
        swap(a, b);
        swap(ra, rb);
        w = -w;
    }
    par[rb] = ra;
    d[rb] = d[a] + w - d[b];
    sz[ra] += sz[rb];
    return true;
}
{l dist(int a, int b) {
    findpar(a); findpar(b);
    return d[b] - d[a];
}

```

6 Math

6.1 Matrix Exponentiation

```

const ll mod = 1e9;
vector<vector<ll>> matMul(vector<vector<ll>>& a,
    vector<vector<ll>>& b) {
    ll row1 = a.size(), col1 = a[0].size();
    ll row2 = b.size(), col2 = b[0].size();
    vector<vector<ll>> res(row1, vector<ll>(col2,
        0));
    for ({i = 0; i < row1; i++) {
        for (ll j = 0; j < col1; j++) {
            for (ll k = 0; k < row2; k++) {
                res[i][j] = (res[i][j] + (1LL * a[i][k]
                    * b[k][j]) % mod) % mod;
            }
        }
    }
    return res;
}
vector<vector<ll>> matExpo(vector<vector<ll>>&
    Mat, ll exp) {
    ll row = Mat.size(), col = Mat[0].size();
    ll p = row;
    vector<vector<ll>> res(p, vector<ll>(p, 0));
    for (ll i = 0; i < p; i++) res[i][i] = 1;
    while (exp) {
        if (exp & 1) res = matMul(res, Mat);
        Mat = matMul(Mat, Mat);
        exp >>= 1;
    }
    return res;
}
// b = (A(i), A(i-1), A(i-2), A(i-3))
// M = Magic matrix, nth = nth term, known =
// known value
ll get_nth(ll nth, ll known, vector<ll>& b,
    vector<vector<ll>>& M) {
    if (nth <= known) return b[nth - 1] % mod;
    reverse(b.begin(), b.end());
    vector<vector<ll>> me = matExpo(M, nth -
        known); // MAT^(nth-known)
    ll ans = 0;
    for (int i = 0; i < known; i++) {

```

```

        ans = (ans + (b[i] * me[i][0]) % mod) % mod;
    }
    return ans;
}

```

6.2 Matrix Rotation

```

//90* clock-wise
now = {{0, 1, 0}, {-1, 0, 0}, {0, 0, 1}};
//90* anti-clock
now = {{0, -1, 0}, {1, 0, 0}, {0, 0, 1}};
//mirror with x axis at point p
now = {{-1, 0, 2 * p}, {0, 1, 0}, {0, 0, 1}};
//mirror with y axis at point p
now = {{1, 0, 0}, {0, -1, 2 * p}, {0, 0, 1}};
op[i + 1] = matMul(now, op[i]); // this
// op[i + 1] = matMul(op[i], now); //not this

```

6.3 Polynomial Interpolation

```

// P(x) = a0 + a1x + a2x^2 + ... + anx^n
// y[i] = P(i)
const int mod = 1e9 + 7;

```

```

ll BigMod(ll a, ll b) {
    ll res = 1;
    while (b) {
        if (b & 1) res = 1LL * res * a % mod;
        a = 1LL * a * a % mod;
        b >>= 1;
    }
    return res;
}
l inv(ll x) {
    if (x < 0) x += mod;
    return BigMod(x, mod - 2);
}
l add(ll a, ll b) {
    a += b;
    if (a >= mod) a -= mod;
    return a;
}
l eval(vector<ll> y, ll k) {
    int n = y.size() - 1;
    if (k <= n) {
        return y[k];
    }

```

```

    vector<ll> L(n + 1, 1);
    for (int x = 1; x <= n; ++x) {
        L[0] = L[0] * (k - x) % mod;
        L[0] = L[0] * inv(-x) % mod;
    }
    for (int x = 1; x <= n; ++x) {
        L[x] = L[x - 1] * inv(k - x) % mod * (k - (x
            - 1)) % mod;
        L[x] = L[x] * ((x - 1) - n + mod) % mod *
            inv(x) % mod;
    }
    ll yk = 0;
    for (int x = 0; x <= n; ++x) {
        yk = add(yk, L[x] * y[x] % mod);
    }
    return yk;
}

```

6.4 Sqrt Distinct Floor

```

//1st problem
const ll mod = 1e9+7;
void solution(){}

```

```

ll n; cin>>n;
ll i = 1;
ll l = 0, r = 0;
ll sum = 0;
while(i<=n){
    ll p = n/i;
    ll l = i-1;
    i = (n/p)+1;
    ll r;
    if(i<=n){
        r = i-1;
    }
    else{
        r = n;
    }
    ll s1 = (_int128(l)*(l+1)/2)%mod;
    ll s2 = (_int128(r)*(r+1)/2)%mod;
    // cout<<l<<" "<<r<<" "<<s1<<' '<<s2<<endl;
    sum = ((sum%mod) +
        (((s2-s1+mod)%mod)*(p%mod))%mod)%mod;
}
cout<<sum<<endl;
}

//2nd problem
void solution(){
    ll n; cin>>n;
    vector<ll> v;
    ll i = 1;
    ll sum = 0;
    while(i<=n){
        ll p = n/i;
        ll prev = i;
        v.push_back(p);
        i = (n/p)+1;
        ll q;
        if(i<=n){
            q = i-prev;
        }
        else{
            q = n-prev+1;
        }
        sum+=p*q;
    }
    cout<<sum<<endl;
}

```

7 Miscellaneous

7.1 Max Subarray Size Sum equal K

```

//write gpHashTable code before this part
void solution(){
    int n, k; cin >> n >> k;
    int total_sum = 0;
    vector < int > pre(n + 7, 0);
    for (int i = 1; i <= n; i++) {
        int temp; cin >> temp;
        total_sum += temp;
        if (i == 1) pre[i] = temp;
        else pre[i] = pre[i - 1] + temp;
    }
    if (total_sum < k) {
        cout << "-1" << endl; return;
    }
    if (total_sum == k) {
        cout << "0" << endl; return;
    }
}

```

```

} int maximum_subSize = 0;
gp_hash_table<int, int>, customHash> table;
for (int i = 1; i <= n; i++) {
    if (pre[i] >= k) {
        int subSUM = pre[i] - k;
        if (subSUM == 0){
            maximum_subSize = max(maximum_subSize, i);
        }
    } else if (table[subSUM]) {
        int left = table[subSUM];
        int right = i; int subSize = right - left;
        maximum_subSize = max(subSize,
            maximum_subSize);
    } if (!table[pre[i]]) table[pre[i]] = i;
} cout << maximum_subSize << endl;
}

```

7.2 Merge Sort

```

// use array of elements, if multiple testcase
// make inv = 0 each time
// int inv = 0;
void merge(int vct[], int l, int m, int r) {
    int left = m - l + 1, right = r - m, lv[left],
    ~ rv[right];
    for (int i = 0; i < left; i++) {
        lv[i] = vct[l + i];
    }
    for (int i = 0; i < right; i++) {
        rv[i] = vct[m + 1 + i];
    }
    int i = 0, j = 0, to = l;
    while (i < left && j < right) {
        if (lv[i] <= rv[j]) {
            vct[to] = lv[i];
            i++;
        } else {
            vct[to] = rv[j];
            j++;
        }
        // inversion count
        // int pore = left-i; inv+=pore;
        to++;
    }
    while (i < left) {
        vct[to] = lv[i];
        i++;
        to++;
    }
    while (j < right) {
        vct[to] = rv[j];
        j++;
        to++;
    }
}
void merge_sort(int vct[], int l, int r) {
    if (r <= l) return;
    int m = l + ((r - l) / 2);
    merge_sort(vct, l, m);
    merge_sort(vct, m + 1, r);
    merge(vct, l, m, r);
}

```

7.3 Number of Subarray Sum is K

```

// write gpHashTable code before this part
void solution(){
    int n, k; cin >> n >> k;
    int total_sum = 0;
    vector<int> pre(n + 7, 0);
    for (int i = 1; i <= n; i++) {
        int temp; cin >> temp;
        total_sum += temp;
        if (i == 1) pre[i] = temp;
        else pre[i] = pre[i - 1] + temp; }
    int cnt_subarry = 0;
    gp_hash_table<int, int>, customHash> table;
    table[0] = 1;
    for (int i = 1; i <= n; i++) {
        cnt_subarry += table[pre[i] - k];
        table[pre[i]]++;
    }
    cout << cnt_subarry << endl;
}

```

8 Number Theory

8.1 All In One NT

```

const int MAXN = 1e6 + 9;
typedef struct info {
    int lowest_prime = 0, greatest_prime = 0,
    ~ distinct_prime = 0;
    int total_prime = 0, NOD = 0, SOD = 0;
} info;
info num[MAXN];
void preStore() {
    for (int i = 2; i < MAXN; i++) {
        int n = i;
        map<int, int> factors; // Key->Factor,
        ~ Val->count
        int SOD = 1, NOD = 1, total_p_factor = 0;
        if (n % 2 == 0) {
            while (n % 2 == 0) {
                n /= 2;
                factors[2]++;
                total_p_factor++;
            }
            SOD *= (1 << (factors[2] + 1)) - 1;
            NOD *= (factors[2] + 1);
        }
        for (int i = 3; i * i <= n; i += 2) {
            if (n % i == 0) {
                while (n % i == 0) {
                    n /= i;
                    factors[i]++;
                    total_p_factor++;
                }
                SOD *= (pow(i, factors[i] + 1) - 1) / (i
                    - 1);
                NOD *= (factors[i] + 1);
            }
        }
        if (n > 1) {
            factors[n]++;
            SOD *= (pow(n, 2) - 1) / (n - 1);
            NOD *= 2;
            total_p_factor++;
        }
        num[i].distinct_prime = factors.size();
        num[i].total_prime = total_p_factor;
        num[i].NOD = NOD;
    }
}

```

```

num[i].SOD = SOD;
auto lowest_prime = factors.begin();
auto greatest_prime = factors.rbegin();
num[i].lowest_prime = lowest_prime->first;
num[i].greatest_prime =
    ~ greatest_prime->first;
}

```

8.2 Divisor Sieve

```

const int mxN = 1e5 + 10;
vector<int> divisors[mxN];
void divisorSeive() {
    for (int i = 1; i < mxN; i++) {
        for (int j = i; j < mxN; j += i) {
            divisors[j].push_back(i);
        }
    }
}

```

8.3 Factorization

```

int lp[10000001];
void factorization(int n) {
    for (int i = 2; i * i <= n; i++) {
        if (n % 2 == 0) {
            int cnt = 0;
            while (n % 2 == 0) {
                ++cnt;
                n /= 2;
            }
            cout << i << "^\n" << cnt << endl;
        }
    }
    if (n > 1) cout << n << "^\n" << 1 << endl;
}

```

8.4 Nth recurrence exponentiation

```

void multiply(vector<vector<int>>&mat1, vector
    ~ <vector<int>>&mat2) {
    int x = mat1[0][0] * mat2[0][0] + mat1[0][1]
    ~ * mat2[1][0];
    int y = mat1[0][0] * mat2[0][1] + mat1[0][1]
    ~ * mat2[1][1];
    int z = mat1[1][0] * mat2[0][0] + mat1[1][1]
    ~ * mat2[1][0];
    int w = mat1[1][0] * mat2[0][1] + mat1[1][1]
    ~ * mat2[1][1];
    mat1[0][0] = x;
    mat1[0][1] = y;
    mat1[1][0] = z;
    mat1[1][1] = w;
}
int func(int n) {
    vector<int> ar(2);
    vector<vector<int>> temp(2, vector
        ~ <int>(2));
    vector<vector<int>> I(2, vector<int>(2, 0));
    ar[0] = 0, ar[1] = 1;
    I[0][0] = I[1][1] = 1;
    temp[0][0] = 0;
    temp[0][1] = 1;
    temp[1][0] = 1;
    temp[1][1] = 1;
    while (n) {

```

```

    if(n&1) {
        multiply(I,temp);
        n--;
    }
    else {
        multiply(temp,temp);
        n /= 2;
    }
}
return (ar[0]*I[0][0])+(ar[1]*I[1][0]);
}

```

8.5 Number of Pairs with GCD equal g

```

/*a[i] <= 1e6
for all 1<=g<=n, how many pairs exist such that g
→ = gcd(a[i], a[j]);
complexity : nlogn
*/
ll n; cin >> n;
ll a[n+1];
ll cnt[n+1]; memset(cnt, 0, sizeof cnt);
for (ll i = 1; i <= n; i++) {cin >> a[i];
→ cnt[a[i]]++;}
ll gcd[n+1]; memset(gcd, 0, sizeof gcd);
for (ll i = n; i >= 1; i--) {
    ll pair = 0, invalid_pair = 0;
    for (ll j = i; j <= n; j += i) {
        pair += cnt[j];
        invalid_pair += gcd[j];
    }
    pair = (pair * (pair - 1)) / 2;
    gcd[i] = pair - invalid_pair;
    // how many pairs exist whose gcd is i
}

```

8.6 Phi(1toN)

```

const int mxN = 1e7+10;
vector<int> phi(mxN);
void phi_till() { //O(n.log.log(n))
    for (int i = 0; i < mxN; i++) phi[i] = i;
    for (int i = 2; i < mxN; i++) {
        if (phi[i] == i) {
            for (int j = i; j < mxN; j += i){
                phi[j] -= phi[j] / i;
            }
        }
    }
}

```

8.7 Phi

```

int phi(int n) { // sqrt(n)
    int result = n;
    for (int i = 2; i * i <= n; i++) {
        if (n % i == 0) {
            while (n % i == 0) n /= i;
            result -= result / i;
        }
    }
    if (n > 1) result -= result / n;
    return result;
}

```

8.8 SOD NOD

```

// SOD = ((P^(x+1)-1)/(P-1)) *
→ ((Q^(y+1)-1)/(Q-1)) * ((R^(z+1)-1)/(R-1))
// NOD = P^x * Q^y * R^z => here, P, Q, R are
→ prime factors & x, y, z are

```

```

// powers NOD = (x + 1) (y + 1) (z + 1)
pair<int, int> SOD_NOD(int n) {
    int sod = 1, nod = 1;
    for (int i = 2; i * i <= n; ++i) {
        if (n % i == 0) {
            int pown = 1, pows = 0;
            while (n % i == 0) {
                pown *= i; // p^e
                pows++;
                n /= i;
            }
            pown *= i;
            sod *= (pown - 1) / (i - 1); // (p^e+1)-1 /
→ p-1
            nod *= (pows + 1);
        }
    }
    if (n > 1) {
        sod *= (n + 1);
        nod *= 2;
    }
    return {sod, nod};
}

```

8.9 Segmented Sieve

```

void segSeive(ll low, ll high) {
    vector<bool> area((high - low) + 1, true);
    for (ll i = 0; primes[i]*primes[i] <= high;
→ i++) {
        ll start = ((low / primes[i]) * primes[i]);
        if (start < low) start += primes[i];
        for (ll j = start; j <= high; j +=
→ primes[i]) {
            if (j == primes[i]) continue;
            area[j - low] = false;
        }
    }
    for (ll i = 0; i < (high - low) + 1; i++) {
        if (area[i]) {
            if (i + low != 1 and i + low != 0) {
                cout << i + low << endl;
            }
        }
    }
}

```

8.10 Sieve

```

const ll MAXN = 1e7 + 10;
bool prime[MAXN];
vector<ll> prm;
void sieve() {
    prime[0] = prime[1] = true;
    for (ll i = 2; i < MAXN; i++) {
        if (!prime[i]) {
            prm.push_back(i);
            for (ll j = i + i; j < MAXN; j += i) {
                prime[j] = true;
            }
        }
    }
}

```

8.11 Smallest prime factor

```

int lp[1000001];
void sieve() {

```

```

    int maxN = 1000000;
    for (int i = 0; i <= maxN; i++) lp[i] = -1;
    for (int i = 2; i*i <= maxN; i++) {
        if (lp[i] == -1) {
            for (int j = i; j <= maxN; j+=i) {
                if (lp[j] == -1) lp[j] = i;
            }
        }
    }
}

```

8.12 Spf

```

const int MAXN = 1e6 + 2;
int spf[MAXN];
vector<int> prms;
void preStore() {
    for (int i = 1; i < MAXN; i++) spf[i] = i;
    for (int i = 2; i < MAXN; i++) {
        if (spf[i] == i) {
            prms.push_back(i);
            for (int j = i + i; j < MAXN; j += i) {
                spf[j] = min(spf[j], i);
            }
        }
    }
}

```

8.13 UniquePF of all elements till MX

```

const int MX = 2e5 + 10;
vector<int> pfac[MX];
void factorize() {
    for (int i = 2; i < MX; i++) {
        if (!pfac[i].empty()) continue;
        for (int j = i; j < MX; j += i)
            pfac[j].push_back(i);
    }
}

```

8.14 int128

```

_int128 read() {
    _int128 x = 0, f = 1;
    char ch = getchar();
    while (ch < '0' || ch > '9') {
        if (ch == '-') f = -1;
        ch = getchar();
    }
    while (ch >= '0' && ch <= '9') {
        x = x * 10 + ch - '0';
        ch = getchar();
    }
    return x * f;
}
void print(_int128 x) {
    if (x < 0) {
        putchar('-');
        x = -x;
    }
    if (x > 9) print(x / 10);
    putchar(x % 10 + '0');
}

```

8.15 nCr and nPr

```

int fact[N], ifact[N];
void prec(){
    fact[0] = 1;
    for (int i = 1; i < N; i++) {
        fact[i] = 1LL * fact[i - 1] * i % mod;
    }
    fact[N - 1] = power(fact[N - 1], -1);
    for (int i = N - 2; i >= 0; i--) {
        ifact[i] = 1LL * ifact[i + 1] * (i + 1) %
            mod;
    }
}
int nPr(int n, int r) {
    if (n < r) return 0;
    return 1LL * fact[n] * ifact[n - r] % mod;
}
int nCr(int n, int r) {
    if (n < r) return 0;
    return 1LL * fact[n] * ifact[r] % mod *
        ifact[n - r] % mod;
}

```

8.16 nCr anup

```

const int MX = 1e6 + 10;
const int M = 1e9 + 7;
int fact[MX], inv_fact[MX];
int modPow(int a, int b) {
    int ans = 1;
    while (b) {
        if (b & 1) ans = (1LL * ans * a) % M;
        a = (1LL * a * a) % M;
        b >>= 1;
    }
    return ans;
}
void precalFact() {
    fact[0] = inv_fact[0] = 1;
    for (int i = 1; i < MX; i++) {
        fact[i] = (1LL * fact[i - 1] * i) % M;
    }
    inv_fact[MX - 1] = modPow(fact[MX - 1], M - 2);
    for (int i = MX - 2; i >= 1; i--) {
        inv_fact[i] = (1LL * inv_fact[i + 1] * (i +
            1)) % M;
    }
}
int nCr(int n, int r) {
    if (r < 0 or r > n) return 0;
    return 1LL * fact[n] * inv_fact[r] % M *
        inv_fact[n - r] % M;
}

```

9 String

9.1 Aho Corasic

```

//number of occurence of word in a text
const ll N = 1e6+10, A = 26;
ll trie[N][A], pos[N], slink[N], dp[N], tot = 1;
vector<int> order;
void initTrie(){
    order.clear();
    while(tot--){
        memset(trie[tot], 0, sizeof(trie[tot]));
    }
    memset(pos, 0, sizeof(pos));
}

```

```

memset(slink, 0, sizeof(slink));
memset(dp, 0, sizeof(dp)); tot = 1;
}
void addStr(string &s, int ind){
    ll u = 0;
    for(auto it: s){
        ll n = it - 'a';
        if(trie[u][n]==0) trie[u][n] = tot++;
        u = trie[u][n];
    }
    pos[ind] = u;
}
void build(){
    queue<ll> q; q.push(0);
    while(!q.empty()){
        ll p = q.front(); q.pop();
        order.push_back(p);
        for(ll c = 0; c < A; c++){
            ll u = trie[p][c];
            if(!u) continue;
            q.push(u);
            if(!p) continue;
            ll v = slink[p];
            while(v && !trie[v][c]) v = slink[v];
            slink[u] = trie[v][c];
        }
    }
}
void trav(string &s){
    ll u = 0;
    for(char c: s){
        c -= 'a';
        while(u && !trie[u][c]) u = slink[u];
        u = trie[u][c]; dp[u]++;
    }
    reverse(order.begin(), order.end());
    for(auto u: order){
        dp[slink[u]] += dp[u];
    }
}
void solve(){
    ll n; cin >> n;
    string text; cin >> text;
    string s;
    for(ll i = 0; i < n; i++){
        cin >> s; addStr(s, i);
    }
    build(); trav(text);
    for(ll i = 0; i < n; i++){
        cout << dp[pos[i]] << endl;
    }
}
int32_t main(){
    ios_base::sync_with_stdio(0);
    cin.tie(0);
    ll tc = 1;
    cin >> tc;
    for(ll i = 1; i <= tc; i++){
        cout << "Case " << i << ":" << endl;
        initTrie();
        solve();
    }
}

```

9.2 LCS for 3 Strings

```

string a, b, c;
ll dp[55][55][55];

```

```

ll lcs(ll i, ll j, ll k) {
    if (i == a.size() or j == b.size() or k ==
        c.size()) return 0;
    if (dp[i][j][k] != -1) return dp[i][j][k];
    if (a[i] == b[j] and a[i] == c[k]) return 1 +
        lcs(i + 1, j + 1, k + 1);
    ll ans = 0;
    ans = max(ans, lcs(i, j, k + 1));
    ans = max(ans, lcs(i, j + 1, k));
    ans = max(ans, lcs(i + 1, j, k));
    return dp[i][j][k] = ans;
}

```

9.3 Manacher Palindrome

```

// pal[1][i] = longest odd (half rounded down)
// palindrome around pos i and
// starts at i - pal[1][i] and ends at i +
// pal[1][i] pal[0][i] = half length of
// longest even palindrome around pos i, i + 1
// and starts at i - par[0][i] + 1
// and ends at i + pal[0][i]
const int N = 5e5 + 10;
int pal[2][N];
void manacher(string& s) {
    int n = s.size(), idx = 2;
    while (idx--) {
        for (int l = -1, r = -1, i = 0; i < n - 1;
            ++i) {
            if (i > r)
                l = r = i;
            else {
                int k = min(r - i, pal[idx][l + r - i]);
                l = i - k, r = i + k;
            }
            while (l - idx >= 0 and r + 1 < n and s[l -
                idx] == s[r + 1]) l--, r++;
            pal[idx][i] = r - i;
        }
    }
}

```

9.4 String Hashing 2

```

const int N = 1000010, MOD = 1e9 + 7;
const ll P[] = {97, 1000003};
ll bigMod(ll a, ll e) {
    if (e == -1) e = MOD - 2;
    ll ret = 1;
    while (e) {
        if (e & 1) ret = ret * a % MOD;
        a = a * a % MOD, e >>= 1;
    }
    return ret;
}
ll pwr[2][N], inv[2][N];
void initHash() {
    for (int it = 0; it < 2; ++it) {
        pwr[it][0] = inv[it][0] = 1;
        ll INV_P = bigMod(P[it], -1);
        for (int i = 1; i < N; ++i) {
            pwr[it][i] = pwr[it][i - 1] * P[it] % MOD;
            inv[it][i] = inv[it][i - 1] * INV_P % MOD;
        }
    }
}

```

```

    }
}

struct RangeHash {
    vector<ll> h[2], rev[2];
    RangeHash(const string S, bool revFlag = 0) {
        for (int it = 0; it < 2; ++it) {
            h[it].resize(S.size() + 1, 0);
            for (int i = 0; i < S.size(); ++i) {
                h[it][i + 1] = (h[it][i] + pwr[it][i + 1] * (S[i] - 'a' + 1)) % MOD;
            }
        }
        if (revFlag) {
            rev[0].resize(S.size() + 1, 0);
            for (int i = 0; i < S.size(); ++i) {
                rev[0][i + 1] = (rev[0][i] + inv[0][i + 1] * (S[i] - 'a' + 1)) % MOD;
            }
        }
    }

    inline ll get(int l, int r) {
        ll one = (h[0][r + 1] - h[0][l]) * inv[0][l + 1] % MOD;
        ll two = (h[1][r + 1] - h[1][l]) * inv[1][l + 1] % MOD;
        if (one < 0) one += MOD;
        if (two < 0) two += MOD;
        return one << 31 | two;
    }

    inline ll getReverse(int l, int r) {
        ll one = (rev[0][r + 1] - rev[0][l]) * pwr[0][r + 1] % MOD;
        ll two = (rev[1][r + 1] - rev[1][l]) * pwr[1][r + 1] % MOD;
        if (one < 0) one += MOD;
        if (two < 0) two += MOD;
        return one << 31 | two;
    }
}

```

9.5 String Hashing

```

const int mod1 = 911382323, mod2 = 972663749, b1
    = 137, b2 = 139;
const int mxN = 5000010;
int pow_b1[mxN], pow_b2[mxN], inv_b1[mxN],
    inv_b2[mxN];
int binExp(int base, int power, int mod) {
    int res = 1;
    while (power) {
        if (power & 1) res = (1LL * res * base) %
            mod;
        base = (1LL * base * base) % mod;
        power >>= 1;
    }
    return res;
}

void pre() {
    pow_b1[0] = pow_b2[0] = 1;
    for (int i = 1; i < mxN; i++) {
        pow_b1[i] = (1LL * pow_b1[i - 1] * b1) %
            mod1;
        pow_b2[i] = (1LL * pow_b2[i - 1] * b2) %
            mod2;
    }
}

```

```

    }
    inv_b1[mxN - 1] = binExp(pow_b1[mxN - 1], mod1
        - 2, mod1);
    inv_b2[mxN - 1] = binExp(pow_b2[mxN - 1], mod2
        - 2, mod2);
    for (int i = mxN - 2; i >= 0; i--) {
        inv_b1[i] = (1LL * inv_b1[i + 1] * b1) %
            mod1;
        inv_b2[i] = (1LL * inv_b2[i + 1] * b2) %
            mod2;
    }
}

vector<pair<int, int>> getPref(string& s) {
    int qq = s.size();
    vector<pair<int, int>> hsh(qq);
    for (int i = 0; i < qq; i++) {
        if (i == 0) {
            hsh[i].first = (1LL * s[i] * pow_b1[i]) %
                mod1;
            hsh[i].second = (1LL * s[i] * pow_b2[i]) %
                mod2;
        } else {
            hsh[i].first =
                (hsh[i - 1].first + (1LL * s[i] *
                    pow_b1[i])) % mod1 % mod1;
            hsh[i].second =
                (hsh[i - 1].second + (1LL * s[i] *
                    pow_b2[i])) % mod2 % mod2;
        }
    }
    return hsh;
}

pair<int, int> getHash(string& str) {
    int hsh1 = 0, hsh2 = 0, sz = str.size();
    for (int i = 0; i < sz; ++i) {
        hsh1 = (hsh1 + 1LL * str[i] * pow_b1[i]) %
            mod1;
    }
    for (int i = 0; i < sz; ++i) {
        hsh2 = (hsh2 + 1LL * str[i] * pow_b2[i]) %
            mod2;
    }
    return {hsh1, hsh2};
}

pair<int, int> getSub(int l, int r,
    vector<pair<int, int>>& v) {
    pair<int, int> q;
    if (l == 0) {
        q = {v[r].first, v[r].second};
    } else {
        int x = (1LL * ((v[r].first - v[l - 1].first +
            mod1) % mod1) * inv_b1[l]) %
            mod1;
        int y =
            (1LL * ((v[r].second - v[l - 1].second +
                mod2) % mod2) * inv_b2[l]) %
            mod2;
        q = {x, y};
    }
    return q;
}

```

9.6 Suffix Array

```

// fahimcp495
array<vector<int>, 2> get_sa(string& s, int lim
    = 128) { // for integer, just change string
    to vector<int> and minimum value of vector
    must be >= 1
    int n = s.size() + 1, k = 0, a, b;
    vector<int> x(begin(s), end(s) + 1), y(n),
        sa(n), lcp(n), ws(max(n, lim)), rank(n);
    x.back() = 0;
    iota(begin(sa), end(sa), 0);
    for (int j = 0, p = 0; p < n; j = max(1, j *
        2), lim = p) {
        p = j, iota(begin(y), end(y), n - j);
        for (int i = 0; i < n; ++i)
            if (sa[i] >= j) y[p++] = sa[i] - j;
        fill(begin(ws), end(ws), 0);
        for (int i = 0; i < n; ++i) ws[x[i]]++;
        for (int i = 1; i < lim; ++i) ws[i] += ws[i -
            1];
        for (int i = n; i--;) sa[--ws[x[y[i]]]] =
            y[i];
        swap(x, y), p = 1, x[sa[0]] = 0;
        for (int i = 1; i < n; ++i) a = sa[i - 1], b
            = sa[i], x[b] = (y[a] == y[b] && y[a +
                j] == y[b + j]) ? p - 1 : p++;
    }
    for (int i = 1; i < n; ++i) rank[sa[i]] = i;
    for (int i = 0, j; i < n - 1; lcp[rank[i++]] =
        k) {
        for (k &&k--, j = sa[rank[i] - 1]; s[i + k]
            == s[j + k]; k++);
        sa.erase(sa.begin()), lcp.erase(lcp.begin());
    }
    return {sa, lcp};
}

```

9.7 Suffix Automata

```

const int N = 2e5 + 10; // max string size
int len[N], lnk[N]{-1}, last, sz = 1;
unordered_map<char, int> to[N];
void add(char c) {
    int cur = sz++;
    len[cur] = len[last] + 1;
    int u = last;
    while (u != -1 and !to[u].count(c)) {
        to[u][c] = cur;
        u = lnk[u];
    }
    if (u == -1) {
        lnk[cur] = 0;
    } else {
        int v = to[u][c];
        if (len[v] == len[u] + 1) {
            lnk[cur] = v;
        } else {
            int w = sz++;
            len[w] = len[u] + 1, lnk[w] = lnk[v],
                to[w] = to[v];
            while (u != -1 and to[u][c] == v) {
                to[u][c] = w;
                u = lnk[u];
            }
            lnk[cur] = lnk[v] = w;
        }
    }
}

```

```

} last = cur;
}

```

9.8 Suffix Automation

```

int len[N], lnk[N]{-1}, last, sz = 1;
unordered_map<char, int> to[N];
void init() {
    sz--;
    to[sz].clear();
}
last = 0, sz = 1;
void add(char c) {
    int cur = sz++;
    int u = last;
    len[cur] = len[last] + 1;
    while (u != -1 and !to[u].count(c)) {
        to[u][c] = cur;
        u = lnk[u];
    }
    if (u == -1) {
        lnk[cur] = 0;
    } else {
        int v = to[u][c];
        if (len[v] == len[u] + 1) {
            lnk[cur] = v;
        } else {
            int w = sz++;
            len[w] = len[u] + 1, lnk[w] = lnk[v],
            to[w] = to[v];
            while (u != -1 and to[u][c] == v) {
                to[u][c] = w;
                u = lnk[u];
            }
            lnk[cur] = lnk[v] = w;
        }
    }
    last = cur;
}

```

9.9 Trie

```

const ll N = 1e6 + 5, A = 26;
ll trie[N][A], cnt[N], tot = 1, root = 1;
void initTrie() {
    cnt[tot] = 0;
    root = 1;
}
void addStr(string& s) {
    ll u = 1;
    for (auto it : s) {
        ll n = it - 'a';
        if (trie[u][n] == 0) {
            trie[u][n] = ++tot;
        }
        u = trie[u][n];
        cnt[u]++;
    }
}
wordCount(string& s) {
    ll u = 1;
    for (auto it : s) {
        int n = it - 'a';
        if (trie[u][n] == 0) return 0;
        u = trie[u][n];
    }
}

```

```

    return cnt[u];
}

```

10 Tree

10.1 Centroid Decomposition

```

const int N = 2e5+5;
int n, k, sz[N], centered[N], ans = 0;
vector<int> adj[N];
void dfs_sz(int u, int p) {
    sz[u] = 1;
    for (auto v : adj[u]) {
        if (v != p && !centered[v]) {
            dfs_sz(v, u); sz[u] += sz[v];
        }
    }
}
int get_cen(int u, int p, int n) {
    for (auto v : adj[u]) {
        if (v != p && !centered[v] && sz[v] > n/2) {
            return get_cen(v, u, n);
        }
    }
    return u;
}
int t, tin[N], tout[N], nodes[N], dis[N];
void dfs(int u, int p){
    nodes[t] = u;
    tin[u] = t++;
    for (auto v : adj[u]){
        if(v!=p && !centered[v]){
            dis[v] = dis[u]+1; dfs(v, u);
        }
    }
    tout[u] = t-1;
}
void go(int u){
    dfs_sz(u, u);
    int c = get_cen(u, u, sz[u]);
    centered[c] = 1; sz[c] = sz[u];
    t = 0; dis[c] = 0; dfs(c, c);
    int cnt[t+1];
    for (auto v : adj[c]){
        if (centered[v]) continue;
        for (int i = tin[v]; i <= tout[v]; ++i){
            int w = nodes[i];
            if (k-dis[w] >= 0 && k-dis[w] < t){
                ans += cnt[k-dis[w]];
            }
        }
        for (int i = tin[v]; i <= tout[v]; ++i){
            int w = nodes[i]; cnt[dis[w]]++;
        }
    }
    for (auto v : adj[c]){
        if (!centered[v]) go(v);
    }
}
void solve() {
    cin >> n;
    for (int i = 0; i < n; ++i) {
        cin >> color[i];
        bucket[i].insert(color[i]);
    }
    // graph input
    dfs(0);
    // print output
}

```

10.2 DSUOnTrees

```

int n, color[MX], ans[MX];
vector<int> g[MX];
set<int> bucket[MX];
int merge(int a, int b) {
    if (bucket[a].size() < bucket[b].size())
        swap(a, b);
    bucket[a].insert(bucket[b].begin(),
                     bucket[b].end());
    bucket[b].clear();
    return a;
}
int dfs(int u, int p = -1) {
    int cur = u;
    for (int v : g[u])
        if (v != p)
            cur = merge(cur, dfs(v, u));
    ans[u] = (int)bucket[cur].size();
    return cur;
}
void solve() {
    cin >> n;
    for (int i = 0; i < n; ++i) {
        cin >> color[i];
        bucket[i].insert(color[i]);
    }
    // graph input
    dfs(0);
    // print output
}

```

10.3 LCA using binary Lifting

```

int n, l;
vector<vector<int>> adj;
int timer;
vector<int> tin, tout;
vector<vector<int>> up;
void dfs(int v, int p) {
    tin[v] = ++timer;
    up[v][0] = p;
    for (int i = 1; i <= l; ++i)
        up[v][i] = up[up[v][i - 1]][i - 1];
    for (int u : adj[v]) {
        if (u != p)
            dfs(u, v);
    }
    tout[v] = ++timer;
}
bool is_ancestor(int u, int v) {
    return tin[u] <= tin[v] && tout[u] >= tout[v];
}
int lca(int u, int v) {
    if (is_ancestor(u, v))
        return u;
    if (is_ancestor(v, u))
        return v;
    for (int i = l; i >= 0; --i) {
        if (!is_ancestor(up[u][i], v))
            u = up[u][i];
    }
    return up[u][0];
}
void preprocess(int root) {

```

```

tin.resize(n);
tout.resize(n);
timer = 0;
l = ceil(log2(n));
up.assign(n, vector<int>(l + 1));
dfs(root, root);
}

```

10.4 LCA

```

const int N = 1e5 + 5;
vector<int> g[N], parent(N), depth(N, 0);
void dfs(int vertex, int par = -1) {
    parent[vertex] = par;
    for (auto child : g[vertex]) {
        if (child != par) {
            depth[child] = depth[vertex] + 1;
            ~ dfs(child, vertex);
        }
    }
}
int lca(int x, int y) {
    int diff = min(depth[x], depth[y]);
    while (depth[x] > diff) x = parent[x];
    while (depth[y] > diff) y = parent[y];
    while (x != y) { x = parent[x]; y = parent[y];
        ~ } return x;
}

```

11 Notes

11.1 Geometry

11.1.1 Triangles

$$\text{Circumradius: } R = \frac{abc}{4A}, \text{ Inradius: } r = \frac{A}{s}$$

The area of a triangle using two sides and the included angle can be given as:

$$A = \frac{1}{2}ab \sin C$$

Length of median (divides triangle into two equal-area triangles): $m_a = \frac{1}{2}\sqrt{2b^2 + 2c^2 - a^2}$

Length of bisector (divides angles in two): $s_a =$

$$\sqrt{bc \left[1 - \left(\frac{a}{b+c} \right)^2 \right]}$$

$$\text{Law of tangents: } \frac{a+b}{a-b} = \frac{\tan \frac{\alpha+\beta}{2}}{\tan \frac{\alpha-\beta}{2}}$$

11.1.2 Quadrilaterals

With side lengths a, b, c, d , diagonals e, f , diagonals angle θ , area A and magic flux $F = b^2 + d^2 - a^2 - c^2$:

$$4A = 2ef \cdot \sin \theta = F \tan \theta = \sqrt{4e^2f^2 - F^2}$$

For cyclic quadrilaterals the sum of opposite angles is 180° , $ef = ac + bd$, and $A = \sqrt{(p-a)(p-b)(p-c)(p-d)}$.

11.1.3 Spherical coordinates

$$\begin{aligned} x &= r \sin \theta \cos \phi & r &= \sqrt{x^2 + y^2 + z^2} \\ y &= r \sin \theta \sin \phi & \theta &= \arccos(z/\sqrt{x^2 + y^2 + z^2}) \\ z &= r \cos \theta & \phi &= \arctan(y/x) \end{aligned}$$

11.1.4 Pick's Theorem:

Given a lattice polygon with non-zero area, we define: S as the area of the polygon, I as the number of integer-coordinate points strictly inside the polygon, B as the number of integer-coordinate points on the boundary of the polygon. Then, Pick's Theorem states:

$$S = I + \frac{B}{2} - 1$$

The number of lattice points on segments (x_1, y_1) to (x_2, y_2) is: $\gcd(\text{abs}(x_2 - x_1), \text{abs}(y_2 - y_1)) + 1$

11.1.5 Polygon

For a regular polygon with n sides and side length a , the circumradius R is given by:

$$R = \frac{a}{2 \sin(\frac{\pi}{n})}$$

11.1.6 Area of a Circular Segment

The area of a circular segment, which is the region enclosed by a chord and the corresponding arc, can be calculated using the formula:

$$A = \frac{R^2}{2} (\theta - \sin \theta)$$

where: R is the radius of the circle, θ is the central angle subtended by the chord, in radians.

11.2 Binomial Coefficients

- Factoring in: $\binom{n}{k} = \frac{n}{k} \binom{n-1}{k-1}$
- Sum over k : $\sum_{k=0}^n \binom{n}{k} = 2^n$
- Alternating sum: $\sum_{k=0}^n (-1)^k \binom{n}{k} = 0$
- Even and odd sum: $\sum_{k=0}^n \binom{n}{2k} = \sum_{k=0}^n \binom{n}{2k+1} 2^{n-1}$
- The Hockey Stick Identity
 - (Left to right) Sum over n and k : $\sum_{k=0}^m \binom{n+k}{k} = \binom{n+m-1}{m}$
 - (Right to left) Sum over n : $\sum_{m=0}^n \binom{m}{k} = \binom{n+1}{k+1}$
- Sum of the squares: $\sum_{k=0}^n \binom{n}{k}^2 = \binom{2n}{n}$
- Weighted sum: $\sum_{k=1}^n k \binom{n}{k} = n 2^{n-1}$
- Connection with the fibonacci numbers: $\sum_{k=0}^n \binom{n-k}{k} = F_{n+1}$
- Vandermonde's Identity: $\sum_{i=0}^k \binom{m}{i} \binom{n}{k-i} = \binom{m+n}{k}$
- If $f(n, k) = C(n, 0) + C(n, 1) + \dots + C(n, k)$, Then $f(n+1, k) = 2 * f(n, k) - C(n, k)$ [For multiple $f(n, k)$ queries, use Mo's algo]

Lucas Theorem

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

- $\binom{m}{n}$ is divisible by p if and only if at least one of the base- p digits of n is greater than the corresponding base- p digit of m .
- The number of entries in the n th row of Pascal's triangle that are not divisible by p = $\prod_{i=0}^k (n_i + 1)$
- All entries in the $(p^k - 1)$ th row are not divisible by p .
- $\binom{n}{m} \equiv \lfloor \frac{n}{p} \rfloor \pmod{p}$

11.3 Fibonacci Number

$$\begin{aligned} 1. \quad k &= A - B, F_A F_B = F_{k+1} F_A^2 + F_k F_A F_{A-1} \\ 2. \sum_{i=0}^n F_i^2 &= F_{n+1} F_n & 3. \sum_{i=0}^n F_i F_{i+1} &= F_{n+1}^2 - (-1)^n \\ 4. \sum_{i=0}^n F_i F_{i+1} &= F_{n+1}^2 - (-1)^n & 5. \sum_{i=0}^n F_i F_{i-1} &= \sum_{i=0}^{n-1} F_i F_{i+1} \end{aligned}$$

$$6. \gcd(F_m, F_n) = F_{\gcd(m, n)} \quad 7. \sum_{0 \leq k \leq n} \binom{n-k}{k} = F_{n+1}$$

$$8. \gcd(F_n, F_{n+1}) = \gcd(F_n, F_{n+2}) = \gcd(F_{n+1}, F_{n+2}) = 1$$

11.4 Sums

$$1^2 + 2^2 + 3^2 + \dots + n^2 = \frac{n(2n+1)(n+1)}{6}$$

$$1^3 + 2^3 + 3^3 + \dots + n^3 = \frac{n^2(n+1)^2}{4}$$

$$1^4 + 2^4 + 3^4 + \dots + n^4 = \frac{n(n+1)(2n+1)(3n^2+3n-1)}{30}$$

$$\sum_{i=1}^n i^m = \frac{1}{m+1} \left[(n+1)^{m+1} - 1 - \sum_{i=1}^n ((i+1)^{m+1} - i^{m+1} - (m+1)i^m) \right]$$

$$\sum_{i=1}^{n-1} i^m = \frac{1}{m+1} \sum_{k=0}^m \binom{m+1}{k} B_k n^{m+1-k}$$

$$\sum_{k=0}^n kx^k = (x - (n+1)x^{n+1} + nx^{n+2})/(x-1)^2$$

11.5 Series

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots, (-\infty < x < \infty)$$

$$\ln(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \dots, (-1 < x \leq 1)$$

$$\sqrt{1+x} = 1 + \frac{x}{2} - \frac{x^2}{8} + \frac{2x^3}{32} - \frac{5x^4}{128} + \dots, (-1 \leq x \leq 1)$$

$$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \dots, (-\infty < x < \infty)$$

$$\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \dots, (-\infty < x < \infty)$$

$$(x+a)^{-n} = \sum_{k=0}^{\infty} (-1)^k \binom{n+k-1}{k} x^k a^{-n-k}$$

Generating Function

$$1/(1-x) = 1 + x + x^2 + x^3 + \dots$$

$$1/(1-ax) = 1 + ax + (ax)^2 + (ax)^3 + \dots$$

$$1/(1-x)^2 = 1 + 2x + 3x^2 + 4x^3 + \dots$$

$$\frac{1}{(1-x)^3} = C(2,2) + C(3,2)x + C(4,2)x^2 + C(5,2)x^3 + \dots$$

$$\frac{1}{(1-ax)^{(k+1)}} = 1 + C(1+k, k)(ax) + C(2+k, k)(ax)^2 + C(3+k, k)(ax)^3 + \dots$$

$$x(x+1)(1-x)^{-3} = 1 + x + 4x^2 + 9x^3 + 16x^4 + 25x^5 + \dots$$

$$e^x = 1 + x + (x^2)/2! + (x^3)/3! + (x^4)/4! + \dots$$

11.6 Pythagorean Triples

The Pythagorean triples are uniquely generated by

$$a = k \cdot (m^2 - n^2), \quad b = k \cdot (2mn), \quad c = k \cdot (m^2 + n^2),$$

with $m > n > 0$, $k > 0$, $m \perp n$, and either m or n even.

11.7 Number Theory

- HCN: 1e6(240), 1e9(1344), 1e12(6720), 1e14(17280), 1e15(26880), 1e16(41472)
- $\gcd(a, b, c, d, \dots) = \gcd(a, b-a, c-b, d-c, \dots)$
- $\gcd(a+k, b+k, c+k, d+k, \dots) = \gcd(a+k, b-a, c-b, d-c, \dots)$
- Primitive root exists iff $n = 1, 2, 4, p^k, 2 \times p^k$, where p is an odd prime.
- If primitive root exists, there are $\phi(\phi(n))$ primitive roots of n .
- The numbers from 1 to n have in total $O(n \log \log n)$ unique prime factors.
- $x \equiv r_1 \pmod{m_1}$ and $x \equiv r_2 \pmod{m_2}$ has a solution iff $\gcd(m_1, m_2) \mid (r_1 - r_2)$. Solution of $x^2 \equiv a \pmod{p}$
- $ca \equiv cb \pmod{m} \iff a \equiv b \pmod{\frac{n}{\gcd(n, c)}}$
- $ax \equiv b \pmod{m}$ has a solution $\iff \gcd(a, m) \mid b$
- If $ax \equiv b \pmod{m}$ has a solution, then it has $\gcd(a, m)$ solutions and they are separated by $\frac{m}{\gcd(a, m)}$
- $ax \equiv 1 \pmod{m}$ has a solution or a is invertible $\pmod{m} \iff \gcd(a, m) = 1$
- $x^2 \equiv 1 \pmod{p}$ then $x \equiv \pm 1 \pmod{p}$
- There are $\frac{p-1}{2}$ has no solution.
- There are $\frac{p-1}{2}$ has exactly two solutions.
- When $p \% 4 = 3$, $x \equiv \pm a^{\frac{p+1}{4}}$
- When $p \% 8 = 5$, $x \equiv a^{\frac{p+3}{8}}$ or $x \equiv 2^{\frac{p-1}{4}} a^{\frac{p+3}{8}}$

11.7.1 Primes

$p = 962592769$ is such that $2^{21} \mid p-1$, which may be useful. For hashing use 970592641 (31-bit number), 31443539979727 (45-bit), 3006703054056749 (52-bit). There are 78498 primes less than 1 000 000.

Primitive roots exist modulo any prime power p^a , except for $p=2, a > 2$, and there are $\phi(\phi(p^a))$ many. For $p=2, a > 2$, the group $\mathbb{Z}_{2^a}^\times$ is instead isomorphic to $\mathbb{Z}_2 \times \mathbb{Z}_{2^{a-2}}$.

11.7.2 Estimates

$$\sum_{d \mid n} d = O(n \log \log n).$$

The number of divisors of n is at most around 100 for $n < 5e4$, 500 for $n < 1e7$, 2000 for $n < 1e10$, 200 000 for $n < 1e19$.

11.7.3 Perfect numbers

$n > 1$ is called perfect if it equals sum of its proper divisors and 1. Even n is perfect iff $n = 2^{p-1}(2^p - 1)$ and $2^p - 1$ is prime (Mersenne's). No odd perfect numbers are yet found.

11.7.4 Carmichael numbers

A positive composite n is a Carmichael number ($a^{n-1} \equiv 1 \pmod{n}$ for all $a: \gcd(a, n) = 1$), iff n is square-free, and for all prime divisors p of n , $p-1$ divides $n-1$.

11.7.5 Totient

- If p is a prime ($p^k = p^k - p^{k-1}$)
- If $a \perp b$ are relatively prime, $\phi(ab) = \phi(a)\phi(b)$
- $\phi(n) = n(1 - \frac{1}{p_1})(1 - \frac{1}{p_2})(1 - \frac{1}{p_3}) \dots (1 - \frac{1}{p_k})$
- Sum of coprime to n : $n * \frac{\phi(n)}{2}$
- If $n = 2^k$, $\phi(n) = 2^{k-1} = \frac{n}{2}$
- For $a \perp b$, $\phi(ab) = \phi(a)\phi(b)\frac{d}{\phi(d)}$
- $\phi(ip) = p\phi(i)$ whenever p is a prime and it divides i
- The number of a ($1 \leq a \leq N$) such that $\gcd(a, N) = d$ is $\phi(\frac{n}{d})$
- If $n > 2$, $\phi(n)$ is always even
- Sum of gcd, $\sum_{i=1}^n \gcd(i, n) = \sum_{d \mid n} d\phi(\frac{n}{d})$
- Sum of lcm, $\sum_{i=1}^n i \operatorname{lcm}(i, n) = \frac{n}{2}(\sum_{d \mid n} d\phi(d) + 1)$
- $\phi(1) = 1$ and $\phi(2) = 1$ which two are only odd ϕ
- $\phi(3) = 2$ and $\phi(4) = 2$ and $\phi(6) = 2$ which three are only prime ϕ
- Find minimum n such that $\frac{\phi(n)}{n}$ is maximum- Multiple of small primes- $2 * 3 * 5 * 7 * 11 * 13 * \dots$

11.7.6 Möbius function

$\mu(1) = 1$. $\mu(n) = 0$, if n is not squarefree. $\mu(n) = (-1)^s$, if n is the product of s distinct primes. Let f, F be functions on positive integers. If for all $n \in N$, $F(n) = \sum_{d \mid n} f(d)$, then $f(n) = \sum_{d \mid n} \mu(d)F(\frac{n}{d})$, and vice versa. $\phi(n) = \sum_{d \mid n} \mu(d)\frac{n}{d}$. $\sum_{d \mid n} \mu(d) = 1$.

If f is multiplicative, then $\sum_{d \mid n} \mu(d)f(d) = \prod_{p \mid n} (1 - f(p))$, $\sum_{d \mid n} \mu(d)^2 f(d) = \prod_{p \mid n} (1 + f(p))$.

$$\sum_{i=1}^n \sum_{j=1}^n [\gcd(i, j) = 1] = \sum_{k=1}^n \mu(k) \lfloor \frac{n}{k} \rfloor^2$$

$$\sum_{i=1}^n \sum_{j=1}^n \gcd(i, j) = \sum_{k=1}^n k \sum_{l=1}^{\lfloor \frac{n}{k} \rfloor} \mu(l) \lfloor \frac{n}{kl} \rfloor^2$$

$$\sum_{i=1}^n \sum_{j=1}^n \gcd(i, j) = \sum_{k=1}^n \left(\frac{\lfloor \frac{n}{k} \rfloor}{2} (1 + \lfloor \frac{n}{k} \rfloor) \right)^2 \sum_{d \mid k} \mu(d) kd$$

11.7.7 Legendre symbol

If p is an odd prime, $a \in \mathbb{Z}$, then $\left(\frac{a}{p}\right)$ equals 0, if $p \mid a$; 1 if a is a quadratic residue modulo p ; and -1 otherwise. Euler's criterion: $\left(\frac{a}{p}\right) = a^{\frac{p-1}{2}} \pmod{p}$.

11.7.8 Jacobi symbol

If $n = p_1^{a_1} \cdots p_k^{a_k}$ is odd, then $\left(\frac{a}{n}\right) = \prod_{i=1}^k \left(\frac{a}{p_i}\right)^{k_i}$.

11.7.9 Primitive roots

If the order of g modulo m ($\min n > 0: g^n \equiv 1 \pmod{m}$) is $\phi(m)$, then g is called a primitive root. If \mathbb{Z}_m has a primitive root, then it has $\phi(\phi(m))$ distinct primitive roots. \mathbb{Z}_m has a primitive root iff m is one of 2, 4, p^k , $2p^k$, where p is an odd prime. If \mathbb{Z}_m has a primitive root g , then for all a coprime to m , there exists unique integer $i = \operatorname{ind}_g(a)$ modulo $\phi(m)$, such that $g^i \equiv a \pmod{m}$. $\operatorname{ind}_g(a)$ has logarithm-like properties: $\operatorname{ind}(1) = 0$, $\operatorname{ind}(ab) = \operatorname{ind}(a) + \operatorname{ind}(b)$.

If p is prime and a is not divisible by p , then congruence $x^n \equiv a \pmod{p}$ has $\gcd(n, p-1)$ solutions if $a^{(p-1)/\gcd(n, p-1)} \equiv 1 \pmod{p}$, and no solutions otherwise. (Proof sketch: let g be a primitive root, and $g^i \equiv a \pmod{p}$, $g^u \equiv x \pmod{p}$. $x^n \equiv a \pmod{p}$ iff $g^{nu} \equiv g^i \pmod{p}$ iff $nu \equiv i \pmod{p}$.)

11.7.10 Discrete logarithm problem

Find x from $a^x \equiv b \pmod{m}$. Can be solved in $O(\sqrt{m})$ time and space with a meet-in-the-middle trick. Let $n = \lceil \sqrt{m} \rceil$, and $x = ny - z$. Equation becomes $a^{ny} \equiv ba^z \pmod{m}$. Precompute all values that the RHS can take for $z = 0, 1, \dots, n-1$, and brute force y on the LHS, each time checking whether there's a corresponding value for RHS.

11.7.11 Pythagorean triples

Integer solutions of $x^2 + y^2 = z^2$ All relatively prime triples are given by: $x = 2mn, y = m^2 - n^2, z = m^2 + n^2$ where $m > n, \gcd(m, n) = 1$ and $m \neq n \pmod{2}$. All other triples are multiples of these. Equation $x^2 + y^2 = 2z^2$ is equivalent to $(\frac{x+y}{2})^2 + (\frac{x-y}{2})^2 = z^2$.

11.7.12 Postage stamps/McNuggets problem

Let a, b be relatively-prime integers. There are exactly $\frac{1}{2}(a-1)(b-1)$ numbers not of form $ax + by$ ($x, y \geq 0$), and the largest is $(a-1)(b-1) - 1 = ab - a - b$.

11.7.13 Fermat's two-squares theorem

Odd prime p can be represented as a sum of two squares iff $p \equiv 1 \pmod{4}$. A product of two sums of two squares is a sum of two squares. Thus, n is a sum of two squares iff every prime of form $p = 4k + 3$ occurs an even number of times in n 's factorization.

11.8 Permutations

11.8.1 Factorial

n	1	2	3	4	5	6	7	8	9	10
$n!$	1	2	6	24	120	720	5040	40320	362880	3628800
$n!$	11	12	13	14	15	16	17			
$n!$	4.0e7	4.8e8	6.2e9	8.7e10	1.3e12	2.1e13	3.6e14			
n	20	25	30	40	50	100	150	171		
$n!$	2e18	2e25	3e32	8e47	3e64	9e157	6e262	>DBL_MAX		

11.8.2 Cycles

Let $g_S(n)$ be the number of n -permutations whose cycle lengths all belong to the set S . Then

$$\sum_{n=0}^{\infty} g_S(n) \frac{x^n}{n!} = \exp \left(\sum_{n \in S} \frac{x^n}{n} \right)$$

11.8.3 Derangements

Permutations of a set such that none of the elements appear in their original position.

$$D(n) = (n-1)(D(n-1) + D(n-2)) = nD(n-1) + (-1)^n = \left\lfloor \frac{n!}{e} \right\rfloor$$

11.8.4 Burnside's lemma

Given a group G of symmetries and a set X , the number of elements of X up to symmetry equals

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

where X^g are the elements fixed by g ($g \cdot x = x$).

If $f(n)$ counts "configurations" (of some sort) of length n , we can ignore rotational symmetry using $G = \mathbb{Z}_n$ to get

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

11.9 Partitions and subsets**11.9.1 Partition function**

Number of ways of writing n as a sum of positive integers, disregarding the order of the summands.

$$p(0) = 1, p(n) = \sum_{k \in \mathbb{Z} \setminus \{0\}} (-1)^{k+1} p(n - k(3k-1)/2)$$

$$p(n) \sim 0.145/n \cdot \exp(2.56\sqrt{n})$$

$$\begin{array}{r|ccccccccccccc} n & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 20 & 50 & 100 \\ \hline p(n) & 1 & 1 & 2 & 3 & 5 & 7 & 11 & 15 & 22 & 30 & 627 & \sim 2e5 & \sim 2e8 \end{array}$$

11.9.2 Partition Number

- Time Complexity: $O(n\sqrt{n})$

```
for (int i = 1; i <= n; ++i) {
    pent[2 * i - 1] = i * (3 * i - 1) / 2;
    pent[2 * i] = i * (3 * i + 1) / 2;
}
p[0] = 1;
for (int i = 1; i <= n; ++i) {
    p[i] = 0;
    for (int j = 1, k = 0; pent[j] <= i; ++j) {
        if (k < 2) p[i] = add(p[i], p[i - pent[j]]);
        else p[i] = sub(p[i], p[i - pent[j]]); ++k, k
    }
}
```

- The number of partitions of a positive integer n into exactly k parts equals the number of partitions of n whose largest part equals k

$$p_k(n) = p_k(n-k) + p_{k-1}(n-1)$$

11.9.3 2nd Kaplansky's Lemma

The number of ways of selecting k objects, no two consecutive, from n labelled objects arrayed in a circle is $\frac{n}{k} \binom{n-k-1}{k-1} = \frac{n}{k} \binom{n-k}{k}$

11.9.4 Distinct Objects into Distinct Bins

- n distinct objects into r distinct bins = r^n

- Among n distinct objects, exactly k of them into r distinct bins = $\binom{n}{k} r^k$

- n distinct objects into r distinct bins such that each bin contains at least one object = $\sum_{i=0}^r (-1)^i \binom{r}{i} (r-i)^n$

11.10 Coloring

The number of labeled undirected graphs with n vertices, $G_n = 2^{\binom{n}{2}}$

The number of labeled directed graphs with n vertices, $G_n = 2^{n(n)}$

The number of connected labeled undirected graphs with n vertices, $C_n = 2^{\binom{n}{2}} - \frac{1}{n} \sum_{k=1}^{n-1} k \binom{n}{k} 2^{\binom{n-k}{2}} C_k = 2^{\binom{n}{2}} - \sum_{k=1}^{n-1} \binom{n-1}{k-1} 2^{\binom{n-k}{2}} C_k$

The number of k -connected labeled undirected graphs with n vertices, $D[n][k] = \sum_{s=1}^n \binom{n-1}{s-1} C_s D[n-s][k-1]$

Cayley's formula: the number of trees on n labeled vertices = the number of spanning trees of a complete graph with n labeled vertices = n^{n-2}

Number of ways to color a graph using k colors such that no two adjacent nodes have same color

Complete graph = $k(k-1)(k-2)\dots(k-n+1)$

Tree = $k(k-1)^{n-1}$

Cycle = $(k-1)^n + (-1)^n (k-1)$

Number of trees with n labeled nodes: n^{n-2}

11.11 General purpose numbers**11.11.1 Eulerian numbers**

Number of permutations $\pi \in S_n$ in which exactly k elements are greater than the previous element. k j :s s.t. $\pi(j) > \pi(j+1)$, $k+1$ j :s s.t. $\pi(j) \geq j$, k j :s s.t. $\pi(j) > j$.

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

$$E(n, 0) = E(n, n-1) = 1$$

$$E(n, k) = \sum_{j=0}^k (-1)^j \binom{n+1}{j} (k+1-j)^n$$

11.11.2 Bell numbers

Total number of partitions of n distinct elements. $B(n) = 1, 1, 2, 5, 15, 52, 203, 877, 4140, 21147, \dots$ For p prime,

$$B(p^m + n) \equiv mB(n) + B(n+1) \pmod{p}$$

11.11.3 Bernoulli numbers

$$\sum_{j=0}^m \binom{m+1}{j} B_j = 0. \quad B_0 = 1, B_1 = -\frac{1}{2}, B_n = 0, \text{ for all odd } n \neq 1.$$

11.11.4 Catalan numbers

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

$$C_0 = 1, C_{n+1} = \frac{2(2n+1)}{n+2} C_n, C_{n+1} = \sum C_i C_{n-i}$$

$$\bullet \quad C_n = 1, 1, 2, 5, 14, 42, 132, 429, 1430, 4862, 16796, 58786, \dots$$

• sub-diagonal monotone paths in an $n \times n$ grid.

• strings with n pairs of parenthesis, correctly nested.

• binary trees with $n+1$ leaves (0 or 2 children).

• ordered trees with $n+1$ vertices.

• ways a convex polygon with $n+2$ sides can be cut into triangles by connecting vertices with straight lines.

• permutations of $[n]$ with no 3-term increasing subseq.

• Find the count of balanced parentheses sequences consisting of $n+k$ pairs of parentheses where the first k symbols are open brackets.

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

• Recursive formula of Catalan Numbers:

$$C_n^{(k)} = \frac{(2n+k-1) \cdot (2n+k)}{n \cdot (n+k+1)} C_{n-1}^{(k)}$$

11.11.5 Lucas Number

Number of edge cover of a cycle graph C_n is L_n

$$L(n) = L(n-1) + L(n-2); L(0) = 2, L(1) = 1$$

11.12 Ballot Theorem

Suppose that in an election, candidate A receives a votes and candidate B receives b votes, where $a > b$ for some positive integer k . Compute the number of ways the ballots can be ordered so that A maintains more than k times as many votes as B throughout the counting of the ballots.

The solution to the ballot problem is $\frac{a-kb}{a+b} \times C(a+b, a)$

11.13 Classical Problem

$F(n, k)$ = number of ways to color n objects using exactly k colors

Let $G(n, k)$ be the number of ways to color n objects using no more than k colors.

Then, $F(n, k) = G(n, k) - C(k, 1)*G(n, k-1) + C(k, 2)*G(n, k-2) - C(k, 3)*G(n, k-3) \dots$

Determining $G(n, k)$:

Suppose, we are given a $1 \times n$ grid. Any two adjacent cells can not have same color. Then, $G(n, k) = k * ((k-1)^{n-1})$

If no such condition on adjacent cells. Then, $G(n, k) = k^n$

11.14 Matching Formula**11.14.1 Normal Graph**

$MM + MEC = n$ (excluding vertex), $IS + VC = G$, $MIS + MVC = G$

11.14.2 Bipartite Graph

$MIS = n - MBM$, $MVC = MBM$, $MEC = n - MBM$

11.15 Inequalities**11.15.1 Titu's Lemma**

For positive reals a_1, a_2, \dots, a_n and b_1, b_2, \dots, b_n ,

$$\frac{a_1^2}{b_1} + \frac{a_2^2}{b_2} + \dots + \frac{a_n^2}{b_n} \geq \frac{a_1 + a_2 + \dots + a_n}{b_1 + b_2 + \dots + b_n}^2$$

Equality holds if and only if $a_i = kb_i$ for a non-zero real constant k .

11.16 Games**11.16.1 Grundy numbers**

For a two-player, normal-play (last to move wins) game on a graph (V, E) : $G(x) = \text{mex}(\{G(y) : (x, y) \in E\})$, where $\text{mex}(S) = \min\{n \geq 0 : n \notin S\}$. x is losing iff $G(x) = 0$.

11.16.2 Sums of games

- Player chooses a game and makes a move in it Grundy number of a position is xor of grundy numbers of positions in summed games.
- Player chooses a non-empty subset of games (possibly, all) and makes moves in all of them A position is losing iff each game is in a losing position.
- Player chooses a proper subset of games (not empty and not all), and makes moves in all chosen ones. A position is losing iff grundy numbers of all games are equal.
- Player must move in all games, and loses if can't move in some game A position is losing if any of the games is in a losing position.

11.16.3 Misère Nim

A position with pile sizes $a_1, a_2, \dots, a_n \geq 1$, not all equal to 1, is losing iff $a_1 \oplus a_2 \oplus \dots \oplus a_n = 0$ (like in normal nim.) A position with n piles of size 1 is losing iff n is odd.

11.17 Tree Hashing

$f(u) = \text{sz}[u] * \sum_{i=0} f(v) * p^i$; $f(v)$ are sorted $f(\text{child}) = 1$

11.18 Permutation

To maximize the sum of adjacent differences of a permutation, it is necessary and sufficient to place the smallest half numbers in odd position and the greatest half numbers in even position. Or, vice versa.

11.19 String

- If the sum of length of some strings is N , there can be at most \sqrt{N} distinct length.
- A Text can have at most $O(N \times \sqrt{N})$ distinct substrings that match with given patterns where the sum of the length of the given patterns is N .
- Period = $n \% (n - \text{pi.back()} == 0) ? n - \text{pi.back()} : n$
- The first (*period*) cyclic rotations of a string are distinct. Further cyclic rotations repeat the previous strings.
- S is a palindrome if and only if its period is a palindrome.
- If S and T are palindromes, then the periods of S T are same if and only if $S + T$ is a palindrome.

11.20 Bit

- $(a \text{ xor } b)$ and $(a + b)$ has the same parity

- $(a + b) = (a \text{ xor } b) + 2(a \text{ and } b)$

- $\text{gcd}(a, b) \leq a - b \leq \text{xor}(a, b)$

11.21 Convolution

- Hamming Distance: Replace 0 with -1 - SQRT Decomposition: Find block size, $B = \sqrt{(8 * n)}$