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1 Data Structures

1.1 BIT

```
#include <bits/stdc++.h>
using namespace std;
class Bit{
private:
    typedef long long t_bit;
    int nBit;
    int nLog;
    vector<t_bit> bit;
public:
    Bit(int n){
        nBit = n;
        nLog = 20;
        bit.resize(nBit + 1, 0);
    }
    //1-indexed
    t_bit get(int i){
        t_bit s = 0;
        for (; i > 0; i -= (i & -i))
            s += bit[i];
        return s;
    }
    //1-indexed [l, r]
    t_bit get(int l, int r){
        return get(r) - get(l - 1);
    }
    //1-indexed
    void add(int i, t_bit value){
        assert(i > 0);
        for (; i <= nBit; i += (i & -i))
            bit[i] += value;
    }
    t_bit lower_bound(t_bit value){
        t_bit sum = 0;
        int pos = 0;
        for (int i = nLog; i >= 0; i--){
            if ((pos + (1 << i) <= nBit) and (sum + bit[pos + (1 << i)] <
                value)){
                sum += bit[pos + (1 << i)];
                pos += (1 << i);
            }
        }
        return pos + 1;
    }
};
```

1.2 BIT 2D

```
#include <bits/stdc++.h>
using namespace std;
class Bit2d{
private:
    typedef long long t_bit;
    vector<vector<t_bit>> bit;
    int nBit, mBit;
public:
```

```
Bit2d(int n, int m){
    nBit = n;
    mBit = m;
    bit.resize(nBit + 1, vector<t_bit>(mBit + 1, 0));
}
//1-indexed
t_bit get(int i, int j){
    t_bit sum = 0;
    for (int a = i; a > 0; a -= (a & -a))
        for (int b = j; b > 0; b -= (b & -b))
            sum += bit[a][b];
    return sum;
}
//1-indexed
t_bit get(int a1, int b1, int a2, int b2){
    return get(a2, b2) - get(a2, b1 - 1) - get(a1 - 1, b2) + get(a1 -
        1, b1 - 1);
}
//1-indexed [i, j]
void add(int i, int j, t_bit value){
    for (int a = i; a <= nBit; a += (a & -a))
        for (int b = j; b <= mBit; b += (b & -b))
            bit[a][b] += value;
}
};
```

1.3 BIT In Range

```
#include <bits/stdc++.h>
using namespace std;
class BitRange{
private:
    typedef long long t_bit;
    vector<t_bit> bit1, bit2;
    t_bit get(vector<t_bit> &bit, int i){
        t_bit sum = 0;
        for (; i > 0; i -= (i & -i))
            sum += bit[i];
        return sum;
    }
    void add(vector<t_bit> &bit, int i, t_bit value){
        for (; i < (int)bit.size(); i += (i & -i))
            bit[i] += value;
    }
public:
    BitRange(int n){
        bit1.assign(n + 1, 0);
        bit2.assign(n + 1, 0);
    }
    //1-indexed [i, j]
    void add(int i, int j, t_bit v){
        add(bit1, i, v);
        add(bit1, j + 1, -v);
        add(bit2, i, v * (i - 1));
        add(bit2, j + 1, -v * j);
    }
    //1-indexed
    t_bit get(int i){
        return get(bit1, i) * i - get(bit2, i);
    }
};
```

```
//1-indexed [i,j]
t_bit get(int i, int j){
    return get(j) - get(i - 1);
}
};
```

1.4 Dynamic Median

```
#include <bits/stdc++.h>
using namespace std;
class DinamicMedian{
    typedef int t_median;
private:
    priority_queue<t_median> mn;
    priority_queue<t_median, vector<t_median>, greater<t_median>> mx;
public:
    double median(){
        if (mn.size() > mx.size())
            return mn.top();
        else
            return (mn.top() + mx.top()) / 2.0;
    }
    void push(t_median x){
        if (mn.size() <= mx.size())
            mn.push(x);
        else
            mx.push(x);
        if ((!mx.empty()) and (!mn.empty())){
            while (mn.top() > mx.top()){
                t_median a = mx.top();
                mx.pop();
                t_median b = mn.top();
                mn.pop();
                mx.push(b);
                mn.push(a);
            }
        }
    }
};
```

1.5 Implicit Treap

```
#include <bits/stdc++.h>
using namespace std;
namespace ITreap{
    const int N = 500010;
    typedef long long treap_t;
    treap_t X[N];
    int en = 1, Y[N], sz[N], L[N], R[N], root;

    const treap_t neutral = 0;
    treap_t op_val[N];
    bool rev[N];
    inline treap_t join(treap_t a, treap_t b, treap_t c){
        return a + b + c;
    }
    void calc(int u) { // update node given children info
        sz[u] = sz[L[u]] + 1 + sz[R[u]];
```

```
// code here, no recursion
    op_val[u] = join(op_val[L[u]], X[u], op_val[R[u]]);
}
void unlaze(int u) {
    if(!u) return;
    // code here, no recursion
    if (rev[u]){
        if(L[u])
            rev[L[u]] ^= rev[u];
        if(R[u])
            rev[R[u]] ^= rev[u];
        swap(L[u], R[u]);
        rev[u] = false;
    }
}
void split(int u, int s, int &l, int &r) { // l gets first s, r gets
    remaining
    unlaze(u);
    if(!u) return (void) (l = r = 0);
    if(sz[L[u]] < s) { split(R[u], s - sz[L[u]] - 1, l, r); R[u] = l;
        l = u; }
    else { split(L[u], s, l, r); L[u] = r; r = u; }
    calc(u);
}
int merge(int l, int r) { // els on l <= els on r
    unlaze(l); unlaze(r);
    if(!l || !r) return l + r;
    int u;
    if(Y[l] > Y[r]) { R[l] = merge(R[l], r); u = l; }
    else { L[r] = merge(l, L[r]); u = r; }
    calc(u);
    return u;
}
int new_node(treap_t x){
    X[en] = x;
    op_val[en] = x;
    rev[en] = false;
    return en++;
}
int nth(int u, int idx){
    if(!u)
        return 0;
    unlaze(u);
    if(idx <= sz[L[u]])
        return nth(L[u], idx);
    else if(idx == sz[L[u]] + 1)
        return u;
    else
        return nth(R[u], idx - sz[L[u]] - 1);
}
//Public
void init(int n=N-1) { // call before using other funcs
    //init position 0
    sz[0] = 0;
    op_val[0] = neutral;
    //init Treap
    root = 0;
    for(int i = en = 1; i <= n; i++) { Y[i] = i; sz[i] = 1; L[i] = R[i]
        ] = 0; }
    random_shuffle(Y + 1, Y + n + 1);
}
```

```

//0-indexed
void insert(int idx, int val){
    int a, b;
    split(root, idx, a, b);
    root = merge(merge(a, new_node(val)), b);
}
//0-indexed
void erase(int idx){
    int a, b, c, d;
    split(root, idx, a, b);
    split(b, 1, c, d);
    root = merge(a, d);
}
//0-indexed
treap_t nth(int idx){
    int u = nth(root, idx+1);
    return X[u];
}
//0-indexed [l, r]
treap_t query(int l, int r){
    if(l > r) swap(l, r);
    int a, b, c, d;
    split(root, l, a, d);
    split(d, r - l + 1, b, c);
    treap_t ans = op_val[b];
    root = merge(a, merge(b, c));
    return ans;
}
//0-indexed [l, r]
void reverse(int l, int r){
    if (l > r) swap(l, r);
    int a, b, c, d;
    split(root, l, a, d);
    split(d, r - l + 1, b, c);
    if(b)
        rev[b] ^= 1;
    root = merge(a, merge(b, c));
}
};

```

1.6 LiChao Tree

```

#include <bits/stdc++.h>
using namespace std;
const int INF = 0x3f3f3f3f;
class LiChaoTree{
private:
    typedef int t_line;
    struct Line{
        t_line k, b;
        Line() {}
        Line(t_line k, t_line b) : k(k), b(b) {}
    };
    int n_tree, min_x, max_x;
    vector<Line> li_tree;
    t_line f(Line l, int x){
        return l.k * x + l.b;
    }
    void add(Line nw, int v, int l, int r){
        int m = (l + r) / 2;

```

```

        bool lef = f(nw, l) > f(li_tree[v], l);
        bool mid = f(nw, m) > f(li_tree[v], m);
        if (mid)
            swap(li_tree[v], nw);
        if (r - l == 1)
            return;
        else if (lef != mid)
            add(nw, 2 * v, l, m);
        else
            add(nw, 2 * v + 1, m, r);
    }
    int get(int x, int v, int l, int r){
        int m = (l + r) / 2;
        if (r - l == 1)
            return f(li_tree[v], x);
        else if (x < m)
            return max(f(li_tree[v], x), get(x, 2 * v, l, m));
        else
            return max(f(li_tree[v], x), get(x, 2 * v + 1, m, r));
    }
public:
    LiChaoTree(int mn_x, int mx_x){
        min_x = mn_x;
        max_x = mx_x;
        n_tree = max_x - min_x + 5;
        li_tree.resize(4 * n_tree, Line(0, -INF));
    }
    void add(t_line k, t_line b){
        add(Line(k, b), 1, min_x, max_x);
    }
    t_line get(int x){
        return get(x, 1, min_x, max_x);
    }
};

```

1.7 MergeSort Tree

```

#include <bits/stdc++.h>
#define all(x) x.begin(),x.end()
using namespace std;
class MergeSortTree{
private:
    typedef vector<int> Node;
    Node neutral;
    vector<Node> st;
    int n;
    inline void join(Node &a, Node &b, Node &ans){
        ans.resize(a.size() + b.size());
        merge(all(a), all(b), ans.begin());
    }
    inline int szEq(int node, int k){
        return upper_bound(all(st[node]), k) - lower_bound(all(st[node]), k);
    }
    inline int szLt(int node, int k){
        return lower_bound(all(st[node]), k) - st[node].begin();
    }
public:
    template <class MyIterator>
    MergeSortTree(MyIterator begin, MyIterator end){

```

```

    int sz = end - begin;
    for (n = 1; n < sz; n <= 1);
    st.assign(n < 1, neutral);
    for (int i = 0; i < sz; i++, begin++)
        st[i + n].assign(1, *begin);
    for (int i = n - 1; i; i--){
        int l = (i < 1);
        join(st[l], st[l+1], st[i]);
    }
}
// 0-indexed
// Counts the number of elements less than k in the range [L..R]
int lt(int l, int r, int k){
    int ans = 0;
    for (l += n, r += n + 1; l < r; l >= 1, r >= 1){
        if (l & 1)
            ans += szLt(l++, k);
        if (r & 1)
            ans += szLt(--r, k);
    }
    return ans;
}
// 0-indexed
// Counts the number of elements equal to k in the range [L..R]
int eq(int l, int r, int k){
    int ans = 0;
    for (l += n, r += n + 1; l < r; l >= 1, r >= 1){
        if (l & 1)
            ans += szEq(l++, k);
        if (r & 1)
            ans += szEq(--r, k);
    }
    return ans;
}
};

```

1.8 Policy Based Tree

```

#include <bits/stdc++.h>
#include <ext/pb_ds/tree_policy.hpp>
#include <ext/pb_ds/assoc_container.hpp>
using namespace __gnu_pbds;
using namespace std;
typedef tree<int, null_type, less<int>, rb_tree_tag,
    tree_order_statistics_node_update> OrderedSet;
typedef tree<int, int, less<int>, rb_tree_tag,
    tree_order_statistics_node_update> OrderedMap;
//order_of_key(k) : Number of items strictly smaller than k .
//find_by_order(k) : K-th element in a set (counting from zero).

```

1.9 Queue Query

```

#include <bits/stdc++.h>
using namespace std;
class QueueQuery{
private:
    typedef long long t_queue;
    stack<pair<t_queue, t_queue>> s1, s2;

```

```

    t_queue cmp(t_queue a, t_queue b){
        return min(a, b);
    }
    void move(){
        if (s2.empty()){
            while (!s1.empty()){
                t_queue element = s1.top().first;
                s1.pop();
                t_queue result = s2.empty() ? element : cmp(element, s2.top().second);
                s2.push({element, result});
            }
        }
    }
public:
    void push(t_queue x){
        t_queue result = s1.empty() ? x : cmp(x, s1.top().second);
        s1.push({x, result});
    }
    void pop(){
        move();
        s2.pop();
    }
    t_queue front(){
        move();
        return s2.top().first;
    }
    t_queue query(){
        if (s1.empty() || s2.empty())
            return s1.empty() ? s2.top().second : s1.top().second;
        else
            return cmp(s1.top().second, s2.top().second);
    }
    t_queue size(){
        return s1.size() + s2.size();
    }
};

```

1.10 Randomized Heap

```

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

typedef int f_type;
struct Node{
    f_type value;
    Node *l, *r;
    Node(f_type x = 0): value(x){
        l = r = nullptr;
    }
};

inline bool heapMin(f_type a, f_type b){
    return a > b;
}

inline bool heapMax(f_type a, f_type b){
    return a < b;
}

struct RandomizedHeap{
    Node *root;
    int sz;

```

```

RandomizedHeap() {
    srand(time(NULL));
    root = nullptr;
    sz = 0;
}
void rdFree(Node *n) {
    if(n == nullptr) return;
    rdFree(n->l); rdFree(n->r);
    delete n;
}
~RandomizedHeap() {
    rdFree(root);
}
Node* merge(Node *t1, Node *t2) {
    if(!t1 || !t2)
        return t1 ? t1 : t2;
    if(heapMin(t1->value, t2->value))
        swap(t1, t2);
    if(rand() & 1)
        swap(t1->l, t1->r);
    t1->l = merge(t1->l, t2);
    return t1;
}
//Can be performed in O(logn) on average.
void merge(RandomizedHeap &oth) {
    root = merge(root, oth.root);
    sz += oth.sz;
    oth.root = nullptr;
}
int top() {
    return (root != nullptr) ? root->value : 0;
}
void pop() {
    if(root == nullptr) return;
    Node *l = root->l;
    Node *r = root->r;
    delete root;
    root = merge(l, r);
    sz--;
}
void push(int x) {
    Node *nw = new Node(x);
    root = merge(root, nw);
    sz++;
}
int size() {
    return sz;
}
};

```

1.11 Range Color

```

#include <bits/stdc++.h>
using namespace std;
class RangeColor {
private:
    typedef long long ll;
    struct Node {
        ll l, r;
        int color;
    };

```

```

    Node() {}
    Node(ll l1, ll r1, int color1) : l(l1), r(r1), color(color1) {}
    bool operator<(const Node &oth) const {
        return r < oth.r;
    }
};
std::set<Node> st;
vector<ll> ans;
public:
    RangeColor(ll first, ll last, int maxColor) {
        ans.resize(maxColor + 1);
        ans[0] = last - first + 1LL;
        st.insert(Node(first, last, 0));
    }
    //get color in position x
    int get(ll x) {
        auto p = st.upper_bound(Node(0, x - 1LL, -1));
        return p->color;
    }
    //set newColor in [a, b]
    void set(ll a, ll b, int newColor) {
        auto p = st.upper_bound(Node(0, a - 1LL, -1));
        assert(p != st.end());
        ll l = p->l;
        ll r = p->r;
        int oldColor = p->color;
        ans[oldColor] -= (r - l + 1LL);
        p = st.erase(p);
        if (l < a) {
            ans[oldColor] += (a - l);
            st.insert(Node(l, a - 1LL, oldColor));
        }
        if (b < r) {
            ans[oldColor] += (r - b);
            st.insert(Node(b + 1LL, r, oldColor));
        }
        while ((p != st.end()) and (p->l <= b)) {
            l = p->l;
            r = p->r;
            oldColor = p->color;
            ans[oldColor] -= (r - l + 1LL);
            if (b < r) {
                ans[oldColor] += (r - b);
                st.erase(p);
                st.insert(Node(b + 1LL, r, oldColor));
                break;
            } else {
                p = st.erase(p);
            }
        }
        ans[newColor] += (b - a + 1LL);
        st.insert(Node(a, b, newColor));
    }
    ll countColor(int x) {
        return ans[x];
    }
};

```

1.12 Segment Tree

```

#include <bits/stdc++.h>
using namespace std;
class SegTree{
private:
    typedef long long Node;
    Node neutral = 0;
    vector<Node> st;
    vector<int> v;
    int n;
    Node join(Node a, Node b){
        return (a + b);
    }
    void build(int node, int i, int j){
        if (i == j){
            st[node] = v[i];
            return;
        }
        int m = (i + j) / 2;
        int l = (node << 1);
        int r = l + 1;
        build(l, i, m);
        build(r, m + 1, j);
        st[node] = join(st[l], st[r]);
    }
    Node query(int node, int i, int j, int a, int b){
        if ((i > b) or (j < a))
            return neutral;
        if ((a <= i) and (j <= b))
            return st[node];
        int m = (i + j) / 2;
        int l = (node << 1);
        int r = l + 1;
        return join(query(l, i, m, a, b), query(r, m + 1, j, a, b));
    }
    void update(int node, int i, int j, int idx, Node value){
        if (i == j){
            st[node] = value;
            return;
        }
        int m = (i + j) / 2;
        int l = (node << 1);
        int r = l + 1;
        if (idx <= m)
            update(l, i, m, idx, value);
        else
            update(r, m + 1, j, idx, value);
        st[node] = join(st[l], st[r]);
    }
public:
    template <class MyIterator>
    SegTree(MyIterator begin, MyIterator end){
        n = end - begin;
        v = vector<int>(begin, end);
        st.resize(4 * n + 5);
        build(1, 0, n - 1);
    }
    //0-indexed [a, b]
    Node query(int a, int b){
        return query(1, 0, n - 1, a, b);
    }
    //0-indexed

```

```

    void update(int idx, int value){
        update(1, 0, n - 1, idx, value);
    }
};

```

1.13 Segment Tree 2D

```

#include <bits/stdc++.h>
using namespace std;
struct SegTree2D{
private:
    int n, m;
    typedef int Node;
    Node neutral = -0x3f3f3f3f;
    vector<vector<Node>> seg;
    Node join(Node a, Node b){
        return max(a, b);
    }
public:
    SegTree2D(int n1, int m1){
        n = n1, m = m1;
        seg.assign(2 * n, vector<Node>(2 * m, 0));
    }
    void update(int x, int y, int val){
        assert(0 <= x && x < n && 0 <= y && y < m);
        x += n, y += m;
        seg[x][y] = val;
        for (int j = y / 2; j > 0; j /= 2)
            seg[x][j] = join(seg[x][2 * j], seg[x][2 * j + 1]);
        for (x /= 2; x > 0; x /= 2){
            seg[x][y] = join(seg[2 * x][y], seg[2 * x + 1][y]);
            for (int j = y / 2; j > 0; j /= 2){
                seg[x][j] = join(seg[x][2 * j], seg[x][2 * j + 1]);
            }
        }
    }
    vector<int> getCover(int l, int r, int N){
        l = std::max(0, l);
        r = std::min(N, r);
        vector<int> ans;
        for (l += N, r += N; l < r; l /= 2, r /= 2){
            if (l & 1)
                ans.push_back(l++);
            if (r & 1)
                ans.push_back(--r);
        }
        return ans;
    }
    Node query(int x1, int y1, int x2, int y2){
        auto c1 = getCover(x1, x2 + 1, n);
        auto c2 = getCover(y1, y2 + 1, m);
        Node ans = neutral;
        for (auto i : c1){
            for (auto j : c2){
                ans = join(ans, seg[i][j]);
            }
        }
        return ans;
    }
};

```

1.14 Segment Tree Iterative

```
#include <bits/stdc++.h>
using namespace std;
class SegTreeIterative{
private:
    typedef long long Node;
    Node neutral = 0;
    vector<Node> st;
    int n;
    inline Node join(Node a, Node b){
        return a + b;
    }
public:
    template <class MyIterator>
    SegTreeIterative(MyIterator begin, MyIterator end){
        int sz = end - begin;
        for (n = 1; n < sz; n <= 1);
        st.assign(n << 1, neutral);
        for (int i = 0; i < sz; i++, begin++){
            st[i + n] = (*begin);
        }
        for (int i = n - 1; i; i--){
            st[i] = join(st[(i << 1)], st[(i << 1) + 1]);
        }
    }
    //0-indexed
    void update(int i, Node x){
        st[i += n] = x;
        for (i >= 1; i; i >>= 1)
            st[i] = join(st[i << 1], st[(i << 1) + 1]);
    }
    //0-indexed [l, r]
    Node query(int l, int r){
        Node ansL = neutral, ansR = neutral;
        for (l += n, r += n + 1; l < r; l >>= 1, r >>= 1){
            if (l & 1)
                ansL = join(ansL, st[l++]);
            if (r & 1)
                ansR = join(st[--r], ansR);
        }
        return join(ansL, ansR);
    }
    Node lower_bound(int k){
        int no=1, l=0, r=n-1;
        while(l<r){
            int mid = (l+r)>>1;
            int lo = no<<1;
            if(st[lo] >= k){
                no = lo;
                r = mid;
            }else{
                k -= st[lo];
                no = lo + 1;
                l = mid + 1;
            }
        }
        if(st[no] >= k)
            return l;
        else
            return -1;
    }
};
```

1.15 Segment Tree Lazy

```
#include <bits/stdc++.h>
using namespace std;
class SegTreeLazy{
private:
    typedef long long Node;
    vector<Node> st;
    vector<long long> lazy;
    vector<int> v;
    int n;
    Node neutral = 0;
    inline Node join(Node a, Node b){
        return a + b;
    }
    inline void upLazy(int &node, int &i, int &j){
        if (lazy[node] != 0){
            st[node] += lazy[node] * (j - i + 1);
            //st[node] += lazy[node];
            if (i != j){
                lazy[(node << 1)] += lazy[node];
                lazy[(node << 1) + 1] += lazy[node];
            }
            lazy[node] = 0;
        }
    }
    void build(int node, int i, int j){
        if (i == j){
            st[node] = v[i];
            return;
        }
        int m = (i + j) / 2;
        int l = (node << 1);
        int r = l + 1;
        build(l, i, m);
        build(r, m + 1, j);
        st[node] = join(st[l], st[r]);
    }
    Node query(int node, int i, int j, int a, int b){
        upLazy(node, i, j);
        if ((i > b) or (j < a))
            return neutral;
        if ((a <= i) and (j <= b)){
            return st[node];
        }
        int m = (i + j) / 2;
        int l = (node << 1);
        int r = l + 1;
        return join(query(l, i, m, a, b), query(r, m + 1, j, a, b));
    }
    void update(int node, int i, int j, int a, int b, int value){
        upLazy(node, i, j);
        if ((i > j) or (i > b) or (j < a))
            return;
        if ((a <= i) and (j <= b)){
            lazy[node] = value;
            upLazy(node, i, j);
        }
    }
};
```



```

    }else{
        int m = (i + j) / 2;
        int l = (node << 1);
        int r = l + 1;
        update(l, i, m, a, b, value);
        update(r, m + 1, j, a, b, value);
        st[node] = join(st[l], st[r]);
    }
}
public:
    template <class MyIterator>
    SegTreeLazy(MyIterator begin, MyIterator end){
        n = end - begin;
        v = vector<int>(begin, end);
        st.resize(4 * n + 5);
        lazy.assign(4 * n + 5, 0);
        build(1, 0, n - 1);
    }
    //0-indexed [a, b]
    Node query(int a, int b){
        return query(1, 0, n - 1, a, b);
    }
    //0-indexed [a, b]
    void update(int a, int b, int value){
        update(1, 0, n - 1, a, b, value);
    }
};

        return seg[p] = x;
    int m = (l + r) / 2;
    if (a <= m)
        return seg[p] = join(update(a, x, L[lp], L[p] = cnt++, l, m),
                               seg[R[p] = R[lp]]);
    return seg[p] = join(seg[L[p] = L[lp]], update(a, x, R[lp], R[p] =
        cnt++, m + 1, r));
}
//Public:
//O(n)
void build(int n2, int *v2){
    n = n2, v = v2;
    T[0] = cnt++;
    build(0, 0, n - 1);
}
//O(log(n))
pst_t query(int a, int b, int tt){
    return query(a, b, T[tt], 0, n - 1);
}
//O(log(n))
//update: v[idx] = x;
int update(int idx, int x, int tt = t){
    update(idx, x, T[tt], T[++t] = cnt++, 0, n - 1);
    return t;
}
}; // namespace perseg

```

1.16 Segment Tree Persistent

```

#include <bits/stdc++.h>
using namespace std;
const int MAX = 3e4 + 10, UPD = 2e5 + 10, LOG = 20;
const int MAXS = 4 * MAX + UPD * LOG;
namespace PerSegTree{
    typedef long long pst_t;
    pst_t seg[MAXS];
    int T[UPD], L[MAXS], R[MAXS], cnt, t;
    int n, *v;
    pst_t neutral = 0;
    pst_t join(pst_t a, pst_t b){
        return a + b;
    }
    pst_t build(int p, int l, int r){
        if (l == r)
            return seg[p] = v[l];
        L[p] = cnt++, R[p] = cnt++;
        int m = (l + r) / 2;
        return seg[p] = join(build(L[p], l, m), build(R[p], m + 1, r));
    }
    pst_t query(int a, int b, int p, int l, int r){
        if (b < l or r < a)
            return 0;
        if (a <= l and r <= b)
            return seg[p];
        int m = (l + r) / 2;
        return join(query(a, b, L[p], l, m), query(a, b, R[p], m + 1, r));
    }
    pst_t update(int a, int x, int lp, int p, int l, int r){
        if (l == r)

```

1.17 Sparse Table

```

#include <bits/stdc++.h>
using namespace std;
class SparseTable{
private:
    typedef int t_st;
    vector<vector<t_st>> st;
    vector<int> log2;
    t_st neutral = 0x3f3f3f3f;
    int nLog;
    t_st join(t_st a, t_st b){
        return min(a, b);
    }
public:
    template <class MyIterator>
    SparseTable(MyIterator begin, MyIterator end){
        int n = end - begin;
        nLog = 20;
        log2.resize(n + 1);
        log2[1] = 0;
        for (int i = 2; i <= n; i++)
            log2[i] = log2[i / 2] + 1;
        st.resize(n, vector<t_st>(nLog, neutral));
        for (int i = 0; i < n; i++, begin++)
            st[i][0] = (*begin);
        for (int j = 1; j < nLog; j++)
            for (int i = 0; (i + (1 << (j - 1))) < n; i++)
                st[i][j] = join(st[i][j - 1], st[i + (1 << (j - 1))][j - 1]);
    }
    //0-indexed [a, b]
    t_st query(int a, int b){
        int d = b - a + 1;

```

```

t_st ans = neutral;
for (int j = nLog - 1; j >= 0; j--){
    if (d & (1 << j)){
        ans = join(ans, st[a][j]);
        a = a + (1 << (j));
    }
}
return ans;
}
//0-indexed [a, b]
t_st queryRMQ(int a, int b){
    int j = log2[b - a + 1];
    return join(st[a][j], st[b - (1 << j) + 1][j]);
}
};

```

1.18 Sqrt Decomposition

```

#include <bits/stdc++.h>
using namespace std;
struct SqrtDecomposition{
    typedef long long t_sqrt;
    int sqrtLen;
    vector<t_sqrt> block;
    vector<t_sqrt> v;
    template <class MyIterator>
    SqrtDecomposition(MyIterator begin, MyIterator end){
        int n = end - begin;
        sqrtLen = (int)sqrt(n + .0) + 1;
        v.resize(n);
        block.resize(sqrtLen + 5);
        for (int i = 0; i < n; i++, begin++){
            v[i] = (*begin);
            block[i / sqrtLen] += v[i];
        }
    }
    //0-indexed
    void update(int idx, t_sqrt new_value){
        t_sqrt d = new_value - v[idx];
        v[idx] += d;
        block[idx / sqrtLen] += d;
    }
    //0-indexed [l, r]
    t_sqrt query(int l, int r){
        t_sqrt sum = 0;
        int c_l = l / sqrtLen, c_r = r / sqrtLen;
        if (c_l == c_r){
            for (int i = l; i <= r; i++)
                sum += v[i];
        } else {
            for (int i = l, end = (c_l + 1) * sqrtLen - 1; i <= end; i++)
                sum += v[i];
            for (int i = c_l + 1; i <= c_r - 1; i++)
                sum += block[i];
            for (int i = c_r * sqrtLen; i <= r; i++)
                sum += v[i];
        }
        return sum;
    }
};

```

1.19 Sqrt Tree

```

#include <bits/stdc++.h>
using namespace std;
class SqrtTree{
private:
    typedef long long t_sqrt;
    t_sqrt op(const t_sqrt &a, const t_sqrt &b){
        return a | b;
    }
    inline int log2Up(int n){
        int res = 0;
        while ((1 << res) < n)
            res++;
        return res;
    }
    int n, lg, indexSz;
    vector<t_sqrt> v;
    vector<int> clz, layers, onLayer;
    vector<vector<t_sqrt>> pref, suf, between;
    inline void buildBlock(int layer, int l, int r){
        pref[layer][l] = v[l];
        for (int i = l + 1; i < r; i++)
            pref[layer][i] = op(pref[layer][i - 1], v[i]);
        suf[layer][r - 1] = v[r - 1];
        for (int i = r - 2; i >= l; i--)
            suf[layer][i] = op(v[i], suf[layer][i + 1]);
    }
    inline void buildBetween(int layer, int lBound, int rBound, int
        betweenOffs){
        int bSzLog = (layers[layer] + 1) >> 1;
        int bCntLog = layers[layer] >> 1;
        int bSz = 1 << bSzLog;
        int bCnt = (rBound - lBound + bSz - 1) >> bSzLog;
        for (int i = 0; i < bCnt; i++){
            t_sqrt ans;
            for (int j = i; j < bCnt; j++){
                t_sqrt add = suf[layer][lBound + (j << bSzLog)];
                ans = (i == j) ? add : op(ans, add);
                between[layer - 1][betweenOffs + lBound + (i << bCntLog) + j]
                    = ans;
            }
        }
    }
    inline void buildBetweenZero(){
        int bSzLog = (lg + 1) >> 1;
        for (int i = 0; i < indexSz; i++){
            v[n + i] = suf[0][i << bSzLog];
        }
        build(1, n, n + indexSz, (1 << lg) - n);
    }
    inline void updateBetweenZero(int bid){
        int bSzLog = (lg + 1) >> 1;
        v[n + bid] = suf[0][bid << bSzLog];
        update(1, n, n + indexSz, (1 << lg) - n, n + bid);
    }
    void build(int layer, int lBound, int rBound, int betweenOffs){
        if (layer >= (int)layers.size())
            return;
        int bSz = 1 << ((layers[layer] + 1) >> 1);
    }
};

```

```

for (int l = lBound; l < rBound; l += bSz){
    int r = min(l + bSz, rBound);
    buildBlock(layer, l, r);
    build(layer + 1, l, r, betweenOffs);
}
if (layer == 0)
    buildBetweenZero();
else
    buildBetween(layer, lBound, rBound, betweenOffs);
}
void update(int layer, int lBound, int rBound, int betweenOffs, int
x){
    if (layer >= (int)layers.size())
        return;
    int bSzLog = (layers[layer] + 1) >> 1;
    int bSz = 1 << bSzLog;
    int blockIdx = (x - lBound) >> bSzLog;
    int l = lBound + (blockIdx << bSzLog);
    int r = min(l + bSz, rBound);
    buildBlock(layer, l, r);
    if (layer == 0)
        updateBetweenZero(blockIdx);
    else
        buildBetween(layer, lBound, rBound, betweenOffs);
    update(layer + 1, l, r, betweenOffs, x);
}
inline t_sqrt query(int l, int r, int betweenOffs, int base){
    if (l == r)
        return v[l];
    if (l + 1 == r)
        return op(v[l], v[r]);
    int layer = onLayer[clz[(l - base) ^ (r - base)]];
    int bSzLog = (layers[layer] + 1) >> 1;
    int bCntLog = layers[layer] >> 1;
    int lBound = ((l - base) >> layers[layer]) << layers[layer] +
        base;
    int lBlock = ((l - lBound) >> bSzLog) + 1;
    int rBlock = ((r - lBound) >> bSzLog) - 1;
    t_sqrt ans = suf[layer][l];
    if (lBlock <= rBlock){
        t_sqrt add;
        if (layer == 0)
            add = query(n + lBlock, n + rBlock, (1 << lg) - n, n);
        else
            add = between[layer - 1][betweenOffs + lBound + (lBlock <<
                bCntLog) + rBlock];
        ans = op(ans, add);
    }
    ans = op(ans, pref[layer][r]);
    return ans;
}
public:
template <class MyIterator>
SqrtTree(MyIterator begin, MyIterator end){
    n = end - begin;
    v.resize(n);
    for (int i = 0; i < n; i++, begin++)
        v[i] = (*begin);
    lg = log2Up(n);
    clz.resize(1 << lg);
    onLayer.resize(lg + 1);

```

```

    clz[0] = 0;
    for (int i = 1; i < (int)clz.size(); i++)
        clz[i] = clz[i >> 1] + 1;
    int tlg = lg;
    while (tlg > 1){
        onLayer[tlg] = (int)layers.size();
        layers.push_back(tlg);
        tlg = (tlg + 1) >> 1;
    }
    for (int i = lg - 1; i >= 0; i--)
        onLayer[i] = max(onLayer[i], onLayer[i + 1]);
    int betweenLayers = max(0, (int)layers.size() - 1);
    int bSzLog = (lg + 1) >> 1;
    int bSz = 1 << bSzLog;
    indexSz = (n + bSz - 1) >> bSzLog;
    v.resize(n + indexSz);
    pref.assign(layers.size(), vector<t_sqrt>(n + indexSz));
    suf.assign(layers.size(), vector<t_sqrt>(n + indexSz));
    between.assign(betweenLayers, vector<t_sqrt>((1 << lg) + bSz));
    build(0, 0, n, 0);
}
//0-indexed
inline void update(int x, const t_sqrt &item){
    v[x] = item;
    update(0, 0, n, 0, x);
}
//0-indexed [l, r]
inline t_sqrt query(int l, int r){
    return query(l, r, 0, 0);
}
};

```

1.20 Stack Query

```

#include <bits/stdc++.h>
using namespace std;
struct StackQuery{
    typedef int t_stack;
    stack<pair<t_stack, t_stack>> st;
    t_stack cmp(t_stack a, t_stack b){
        return min(a, b);
    }
    void push(t_stack x){
        t_stack new_value = st.empty() ? x : cmp(x, st.top().second);
        st.push({x, new_value});
    }
    void pop(){
        st.pop();
    }
    t_stack top(){
        return st.top().first;
    }
    t_stack query(){
        return st.top().second;
    }
    t_stack size(){
        return st.size();
    }
};

```

1.21 Treap

```
#include <bits/stdc++.h>
using namespace std;
namespace Treap{
    const int N = 500010;
    typedef long long treap_t;
    treap_t X[N];
    int en = 1, Y[N], sz[N], L[N], R[N], root;

    const treap_t neutral = 0;
    treap_t op_val[N];
    inline treap_t join(treap_t a, treap_t b, treap_t c){
        return a + b + c;
    }
    void calc(int u) { // update node given children info
        sz[u] = sz[L[u]] + 1 + sz[R[u]];
        // code here, no recursion
        op_val[u] = join(op_val[L[u]], X[u], op_val[R[u]]);
    }
    void unlaze(int u) {
        if(!u) return;
        // code here, no recursion
    }
    void split(int u, treap_t x, int &l, int &r) { // l gets <= x, r
        gets > x
        unlaze(u);
        if(!u) return (void) (l = r = 0);
        if(X[u] <= x) { split(R[u], x, l, r); R[u] = l; l = u; }
        else { split(L[u], x, l, r); L[u] = r; r = u; }
        calc(u);
    }
    void split_sz(int u, int s, int &l, int &r) { // l gets first s, r
        gets remaining
        unlaze(u);
        if(!u) return (void) (l = r = 0);
        if(sz[L[u]] < s) { split_sz(R[u], s - sz[L[u]] - 1, l, r); R[u] =
            l; l = u; }
        else { split_sz(L[u], s, l, r); L[u] = r; r = u; }
        calc(u);
    }
    int merge(int l, int r) { // els on l <= els on r
        unlaze(l); unlaze(r);
        if(!l || !r) return l + r;
        int u;
        if(Y[l] > Y[r]) { R[l] = merge(R[l], r); u = l; }
        else { L[r] = merge(l, L[r]); u = r; }
        calc(u);
        return u;
    }
    int new_node(treap_t x){
        X[en] = x;
        op_val[en] = x;
        return en++;
    }
    int nth(int u, int idx){
        if(!u)
            return 0;
        unlaze(u);
        if(idx <= sz[L[u]])
```

```
        return nth(L[u], idx);
    } else if(idx == sz[L[u]] + 1)
        return u;
    } else
        return nth(R[u], idx - sz[L[u]] - 1);
}
//Public
void init(int n=N-1) { // call before using other funcs
    //init position 0
    sz[0] = 0;
    op_val[0] = neutral;
    //init Treap
    root = 0;
    for(int i = en = 1; i <= n; i++) { Y[i] = i; sz[i] = 1; L[i] = R[i]
        ] = 0; }
    random_shuffle(Y + 1, Y + n + 1);
}
void insert(treap_t x){
    int a, b;
    split(root, x, a, b);
    root = merge(merge(a, new_node(x)), b);
}
void erase(treap_t x){
    int a, b, c, d;
    split(root, x-1, a, b);
    split(b, x, c, d);
    split_sz(c, 1, b, c);
    root = merge(a, merge(c, d));
}
int count(treap_t x){
    int a, b, c, d;
    split(root, x-1, a, b);
    split(b, x, c, d);
    int ans = sz[c];
    root = merge(a, merge(c, d));
    return ans;
}
int size(){ return sz[root];}
//0-indexed
treap_t nth(int idx){
    int u = nth(root, idx + 1);
    return X[u];
}
//Query in k smallest elements
treap_t query(int k){
    int a, b;
    split_sz(root, k, a, b);
    treap_t ans = op_val[a];
    root = merge(a, b);
    return ans;
}
};
```

1.22 Union Find

```
#include <bits/stdc++.h>
using namespace std;
class UnionFind{
private:
    vector<int> p, w, sz;
```

```

public:
    UnionFind(int n){
        w.resize(n + 1, 1);
        sz.resize(n + 1, 1);
        p.resize(n + 1);
        for (int i = 0; i <= n; i++)
            p[i] = i;
    }
    int find(int x){
        if (p[x] == x)
            return x;
        return p[x] = find(p[x]);
    }
    bool join(int x, int y){
        x = find(x);
        y = find(y);
        if (x == y)
            return false;
        if (w[x] > w[y])
            swap(x, y);
        p[x] = y;
        sz[y] += sz[x];
        if (w[x] == w[y])
            w[y]++;
        return true;
    }
    bool isSame(int x, int y){
        return find(x) == find(y);
    }
    int size(int x){
        return sz[find(x)];
    }
};

```

1.23 Union Find With Rollback

```

#include <bits/stdc++.h>
using namespace std;
struct RollbackUF {
    vector<int> e;
    vector<tuple<int, int, int, int>> st;
    RollbackUF(int n) : e(n, -1) {}
    int size(int x) { return -e[find(x)]; }
    int find(int x) { return e[x] < 0 ? x : find(e[x]); }
    int time() { return st.size(); }
    void rollback(int t) {
        while (st.size() > t){
            auto [a1, v1, a2, v2] = st.back();
            e[a1] = v1; e[a2] = v2;
            st.pop_back();
        }
    }
    bool unite(int a, int b) {
        a = find(a), b = find(b);
        if (a == b) return false;
        if (e[a] > e[b]) swap(a, b);
        st.push_back({a, e[a], b, e[b]});
        e[a] += e[b]; e[b] = a;
        return true;
    }
}

```

```
};
```

1.24 Wavelet Tree

```

#include <bits/stdc++.h>
using namespace std;
namespace WaveletTree{
    const int MAXN = 100010, MAXW = MAXN*30; // MAXN * LOG(maxX-MinX)
    typedef int t_wavelet;
    int last;
    int v[MAXN], aux[MAXN];
    int lo[MAXW], hi[MAXW], l[MAXW], r[MAXW];
    vector<t_wavelet> a[MAXW];
    int stable_partition(int i, int j, t_wavelet mid){
        int pivot=0;
        for(int k=i; k<j; k++)
            aux[k] = v[k], pivot += (v[k]<=mid);
        int il=i, i2=i+pivot;
        for(int k=i; k<j; k++){
            if(aux[k]<=mid) v[il++] = aux[k];
            else v[i2++] = aux[k];
        }
        return il;
    }
    void build(int u, int i, int j, t_wavelet minX, t_wavelet maxX){
        lo[u] = minX, hi[u] = maxX;
        if (lo[u] == hi[u] or i >= j)
            return;
        t_wavelet mid = (minX + maxX - 1)/2;
        a[u].resize(j - i + 1);
        a[u][0] = 0;
        for(int k=i; k<j; k++)
            a[u][k-i+1] = a[u][k-i] + (v[k] <= mid);
        int pivot = stable_partition(i, j, mid);
        l[u] = last++, r[u] = last++;
        build(l[u], i, pivot, minX, mid);
        build(r[u], pivot, j, mid + 1, maxX);
    }
    inline int b(int u, int i){
        return i - a[u][i];
    }
}
//Public
template <class MyIterator>
void init(MyIterator begin, MyIterator end, t_wavelet minX,
        t_wavelet maxX){
    last = 1;
    int n = end-begin;
    for(int i=0; i<n; i++, begin++)
        v[i] = *begin;
    build(last++, 0, n, minX, maxX);
}
//kth smallest element in range [i, j]
//1-indexed
int kth(int i, int j, int k, int u=1){
    if (i > j)
        return 0;
    if (lo[u] == hi[u])
        return lo[u];
    int inLeft = a[u][j] - a[u][i - 1];
    int il = a[u][i - 1] + 1, jl = a[u][j];

```

```

    int i2 = b(u, i - 1) + 1, j2 = b(u, j);
    if (k <= inLeft)
        return kth(i1, j1, k, l[u]);
    return kth(i2, j2, k - inLeft, r[u]);
}
//Amount of numbers in the range [i, j] Less than or equal to k
//1-indexed
int lte(int i, int j, int k, int u=1){
    if (i > j or k < lo[u])
        return 0;
    if (hi[u] <= k)
        return j - i + 1;
    int i1 = a[u][i - 1] + 1, j1 = a[u][j];
    int i2 = b(u, i - 1) + 1, j2 = b(u, j);
    return lte(i1, j1, k, l[u]) + lte(i2, j2, k, r[u]);
}
//Amount of numbers in the range [i, j] equal to k
//1-indexed
int count(int i, int j, int k, int u=1){
    if (i > j or k < lo[u] or k > hi[u])
        return 0;
    if (lo[u] == hi[u])
        return j - i + 1;
    t_wavelet mid = (lo[u] + hi[u] - 1) / 2;
    int i1 = a[u][i - 1] + 1, j1 = a[u][j];
    int i2 = b(u, i - 1) + 1, j2 = b(u, j);
    if (k <= mid)
        return count(i1, j1, k, l[u]);
    return count(i2, j2, k, r[u]);
}
//swap v[i] with v[i+1]
//1-indexed
void swp(int i, int u=1){
    if (lo[u] == hi[u] or a[u].size() <= 2)
        return;
    if (a[u][i - 1] + 1 == a[u][i] and a[u][i] + 1 == a[u][i + 1])
        swp(a[u][i], l[u]);
    else if (b(u, i - 1) + 1 == b(u, i) and b(u, i) + 1 == b(u, i + 1))
        swp(b(u, i), r[u]);
    else if (a[u][i - 1] + 1 == a[u][i])
        a[u][i]--;
    else
        a[u][i]++;
}
};

```

2 Graph Algorithms

2.1 2-SAT

```

#include "strongly_connected_component.h"
using namespace std;
struct SAT{
    typedef pair<int, int> pii;
    vector<pii> edges;
    int n;
    SAT(int size){

```

```

        n = 2 * size;
    }
    vector<bool> solve2SAT(){
        vector<bool> vAns(n / 2, false);
        vector<int> comp = SCC::scc(n, edges);
        for (int i = 0; i < n; i += 2){
            if (comp[i] == comp[i + 1])
                return vector<bool>();
            vAns[i / 2] = (comp[i] > comp[i + 1]);
        }
        return vAns;
    }
    int v(int x){
        if (x >= 0)
            return (x << 1);
        x = ~x;
        return (x << 1) ^ 1;
    }
    void add(int a, int b){
        edges.push_back(pii(a, b));
    }
    void addOr(int a, int b){
        add(v(~a), v(b));
        add(v(~b), v(a));
    }
    void addImp(int a, int b){
        addOr(~a, b);
    }
    void addEqual(int a, int b){
        addOr(a, ~b);
        addOr(~a, b);
    }
    void addDiff(int a, int b){
        addEqual(a, ~b);
    }
};

```

2.2 Arborescence

```

#include <bits/stdc++.h>
#include "../data_structures/union_find_with_rollback.h"
using ll = long long;
struct Edge { int a, b; ll w; };
struct Node { /// lazy skew heap node
    Edge key;
    Node *l, *r;
    ll delta;
    void prop() {
        key.w += delta;
        if (l) l->delta += delta;
        if (r) r->delta += delta;
        delta = 0;
    }
    Edge top() { prop(); return key; }
};
Node *merge(Node *a, Node *b) {
    if (!a || !b) return a ? b;
    a->prop(), b->prop();
    if (a->key.w > b->key.w) swap(a, b);
    swap(a->l, (a->r = merge(b, a->r)));
}

```

```

    return a;
}
void pop(Node& a) { a->prop(); a = merge(a->l, a->r); }
void free(vector<Node*> &v){
    for(auto &x: v)
        delete x;
}
// O(M * log(N))
pair<ll, vector<int>> dmst(int n, int r, vector<Edge>& g) {
    RollbackUF uf(n);
    vector<Node*> heap(n);
    vector<Node*> vf;
    for (Edge e : g){
        Node* node = new Node{e};
        vf.push_back(node);
        heap[e.b] = merge(heap[e.b], node);
    }
    ll res = 0;
    vector<int> seen(n, -1), path(n), par(n);
    seen[r] = r;
    vector<Edge> Q(n), in(n, {-1, -1}), comp;
    deque<tuple<int, int, vector<Edge>>> cycs;
    for(int s = 0; s < n; ++s) {
        int u = s, qi = 0, w;
        while (seen[u] < 0) {
            if (!heap[u]){
                free(vf);
                return {-1, {}};
            }
            Edge e = heap[u]->top();
            heap[u]->delta -= e.w, pop(heap[u]);
            Q[qi] = e, path[qi++] = u, seen[u] = s;
            res += e.w, u = uf.find(e.a);
            if (seen[u] == s) { /// found cycle, contract
                Node* cyc = 0;
                int end = qi, time = uf.time();
                do cyc = merge(cyc, heap[w = path[--qi]]);
                while (uf.unite(u, w));
                u = uf.find(u), heap[u] = cyc, seen[u] = -1;
                cycs.push_front({u, time, {&Q[qi], &Q[end]}});
            }
        }
        for(int i = 0; i < qi; ++i) in[uf.find(Q[i].b)] = Q[i];
    }
    for (auto& [u, t, c] : cycs) { /// restore sol (optional)
        uf.rollback(t);
        Edge inEdge = in[u];
        for (auto& e : c) in[uf.find(e.b)] = e;
        in[uf.find(inEdge.b)] = inEdge;
    }
    for(int i = 0; i < n; ++i) par[i] = in[i].a;
    free(vf);
    return {res, par};
}
///Careful with overflow
pair<ll, vector<int>> dmstAnyRoot(int n, vector<Edge> v) {
    ll maxEdge = 1000000010;
    ll INF = n*maxEdge;
    for(int i=0; i<n; i++)
        v.push_back(Edge({n, i, INF}));
    auto [ans, dad] = dmst(n+1, n, v);

```

```

    if(ans >= 0 and ans < 2*INF){
        for(int i=0; i<n; i++){
            if(dad[i] == n)
                dad[i] = -1;
            dad.pop_back();
            return {ans - INF, dad};
        }
    }
    return {-1, {}};
}

```

2.3 Articulation Point

```

#include <bits/stdc++.h>

using namespace std;

const int MAXN = 500010;
typedef pair<int, int> pii;
///Articulation Point
namespace AP{
    vector<int> adj[MAXN];
    vector<bool> visited, isAP;
    vector<int> tin, low;
    int timer, n;
    vector<pii> bridges;
    void init(int n1){
        n = n1;
        for(int i=0; i<n; i++) adj[i].clear();
    }
    void addEdge(int a, int b){
        adj[a].push_back(b);
        adj[b].push_back(a);
    }
    void dfs(int u, int p = -1) {
        visited[u] = true;
        tin[u] = low[u] = timer++;
        int children=0;
        for (int to : adj[u]) {
            if (to == p) continue;
            if (visited[to]) {
                low[u] = min(low[u], tin[to]);
            } else {
                dfs(to, u);
                low[u] = min(low[u], low[to]);
                if (low[to] >= tin[u] && p!=-1)
                    isAP[u] = true;
                ++children;
            }
        }
        if(p == -1 && children > 1)
            isAP[u] = true;
    }
    vector<bool> findArticulationPoint() {
        timer = 0;
        visited.assign(n, false);
        tin.assign(n, -1);
        low.assign(n, -1);
        isAP.assign(n, false);
        for (int i = 0; i < n; i++) {

```

```

        if (!visited[i])
            dfs(i);
    }
    return isAP;
}
};

```

2.4 BFS 0-1

```

#include <bits/stdc++.h>
using namespace std;
typedef pair<int, int> pii;
const int N = 500010;
const int INF = 0x3f3f3f3f;
namespace BFS01{
    vector<pii> adj[N];
    int n;
    void init(int n1){
        n = n1;
        for(int i=0; i<n; i++) adj[i].clear();
    }
    //0-indexed
    void addEdge(int u, int to, int w){
        adj[u].emplace_back(to, w);
    }
    vector<int> solve(int s){
        vector<int> d(n, INF);
        d[s] = 0;
        deque<int> q;
        q.push_front(s);
        while (!q.empty()) {
            int u = q.front();
            q.pop_front();
            for (auto edge : adj[u]) {
                int to = edge.first;
                int w = edge.second;
                if (d[u] + w < d[to]) {
                    d[to] = d[u] + w;
                    if (w == 1)
                        q.push_back(to);
                    else
                        q.push_front(to);
                }
            }
        }
        return d;
    }
};

```

2.5 Bridge

```

#include <bits/stdc++.h>
using namespace std;
const int MAXN = 500010;
typedef pair<int, int> pii;
namespace Bridge{
    vector<int> adj[MAXN];
    vector<bool> visited;

```

```

    vector<int> tin, low;
    int timer, n;
    vector<pii> bridges;
    void init(int n1){
        n = n1;
        for(int i=0; i<n; i++) adj[i].clear();
    }
    void addEdge(int a, int b){
        adj[a].push_back(b);
        adj[b].push_back(a);
    }
    void dfs(int u, int p = -1) {
        visited[u] = true;
        tin[u] = low[u] = timer++;
        for (int to : adj[u]) {
            if (to == p) continue;
            if (visited[to]) {
                low[u] = min(low[u], tin[to]);
            } else {
                dfs(to, u);
                low[u] = min(low[u], low[to]);
                if (low[to] > tin[u])
                    bridges.push_back({u, to});
            }
        }
    }
    vector<pii> findBridges() {
        timer = 0;
        visited.assign(n, false);
        tin.assign(n, -1);
        low.assign(n, -1);
        bridges.clear();
        for (int i = 0; i < n; i++) {
            if (!visited[i])
                dfs(i);
        }
        return bridges;
    }
};

```

2.6 Centroid

```

#include <bits/stdc++.h>
using namespace std;
const int MAXN = 500010;
typedef pair<int, int> pii;
namespace Centroid{
    vector<int> adj[MAXN];
    int sub[MAXN];
    int n;
    void init(int n1){
        n = n1;
        for(int i=0; i<n; i++) adj[i].clear();
    }
    void addEdge(int a, int b){
        adj[a].push_back(b);
        adj[b].push_back(a);
    }
    int dfsS(int u, int p){
        sub[u] = 1;

```



```

    for(int to: adj[u]){
        if(to != p)
            sub[u] += dfsS(to, u);
    }
    return sub[u];
}
pii dfsC(int u, int p){
    for(int to : adj[u]){
        if(to != p and sub[to] > n/2)
            return dfsC(to, u);
    }
    for(int to : adj[u]){
        if(to != p and (sub[to]*2) == n)
            return pii(u, to);
    }
    return pii(u, u);
}
pii findCentroid(){
    dfsS(0, -1);
    return dfsC(0, -1);
}
}

```

2.7 Centroid Decomposition

```

#include <bits/stdc++.h>
using namespace std;
// O(N*log(N))
struct CentroidDecomposition{
    vector<vector<int>> adj;
    vector<int> dad, sub;
    vector<bool> rem;
    int centroidRoot, n;
    void init(int _n){
        n = _n;
        adj.resize(n);
        dad.resize(n);
        sub.resize(n);
        rem.assign(n, false);
    }
    // Return Centroid Decomposition Tree
    vector<vector<int>> build(){
        assert(n > 0);
        centroidRoot = decomp(0, -1);
        vector<vector<int>> ret(n);
        for (int u = 0; u < n; u++){
            if (dad[u] != u)
                ret[dad[u]].push_back(u);
        }
        return ret;
    }
    void addEdge(int a, int b){
        adj[a].push_back(b);
        adj[b].push_back(a);
    }
    int decomp(int u, int p){
        int sz = dfs(u, p);
        int c = centroid(u, p, sz);
        if (p == -1)
            p = c;
    }
}

```

```

    dad[c] = p;
    rem[c] = true;
    for (auto to : adj[c]){
        if (!rem[to])
            decomp(to, c);
    }
    return c;
}
int dfs(int u, int p){
    sub[u] = 1;
    for (int to : adj[u]){
        if (!rem[to] and to != p)
            sub[u] += dfs(to, u);
    }
    return sub[u];
}
int centroid(int u, int p, int sz){
    for (auto to : adj[u])
        if (!rem[to] and to != p and sub[to] > sz / 2)
            return centroid(to, u, sz);
    return u;
}
int operator[] (int i){
    return dad[i];
}
};

```

2.8 Checking Bipartiteness Online

```

#include <bits/stdc++.h>
using namespace std;
typedef pair<int, int> pii;
const int N = 500010;
pii parent[N];
int rk[N];
int bipartite[N];
void make_set(int v) {
    parent[v] = pii(v, 0);
    rk[v] = 0;
    bipartite[v] = true;
}
pii find_set(int v) {
    if (v != parent[v].first) {
        int parity = parent[v].second;
        parent[v] = find_set(parent[v].first);
        parent[v].second ^= parity;
    }
    return parent[v];
}
void add_edge(int a, int b) {
    pii pa = find_set(a);
    a = pa.first;
    int x = pa.second;
    pii pb = find_set(b);
    b = pb.first;
    int y = pb.second;
    if (a == b) {
        if (x == y)
            bipartite[a] = false;
    }else{
    }
}

```

```

    if (rk[a] < rk[b])
        swap (a, b);
    parent[b] = pii(a, x^y^1);
    bipartite[a] ^= bipartite[b];
    if (rk[a] == rk[b])
        ++rk[a];
}
}
bool is_bipartite(int v) {
    return bipartite[find_set(v).first];
}

```

2.9 Dinic

```

#include <bits/stdc++.h>
using namespace std;
//O((V^2)*E): for generic graph.
//O(sqrt(V)*E): on unit networks. A unit network is a network in which
//all the edges have unit capacity, and for any vertex except s and
//t either incoming or outgoing edge is unique. That's exactly the
//case with the network we build to solve the maximum matching
//problem with flows.
template <typename flow_t>
struct Dinic{
    struct FlowEdge{
        int from, to, id;
        flow_t cap, flow = 0;
        FlowEdge(int f, int t, flow_t c, int id1) : from(f), to(t), cap(c)
        {
            id = id1;
        }
    };
    const flow_t flow_inf = numeric_limits<flow_t>::max();
    vector<FlowEdge> edges;
    vector<vector<int>> adj;
    int n, m = 0;
    int s, t;
    vector<int> level, ptr;
    queue<int> q;
    bool bfs(){
        while (!q.empty()){
            int u = q.front();
            q.pop();
            for (int id : adj[u]){
                if (edges[id].cap - edges[id].flow < 1)
                    continue;
                if (level[edges[id].to] != -1)
                    continue;
                level[edges[id].to] = level[u] + 1;
                q.push(edges[id].to);
            }
        }
        return level[t] != -1;
    }
    flow_t dfs(int u, flow_t pushed){
        if (pushed == 0)
            return 0;
        if (u == t)
            return pushed;
        for (int &cid = ptr[u]; cid < (int)adj[u].size(); cid++){

```

```

            int id = adj[u][cid];
            int to = edges[id].to;
            if (level[u] + 1 != level[to] || edges[id].cap - edges[id].flow
                < 1)
                continue;
            flow_t tr = dfs(to, min(pushed, edges[id].cap - edges[id].flow));
            edges[id].flow += tr;
            edges[id ^ 1].flow -= tr;
            return tr;
        }
        return 0;
    }
}
//Public:
Dinic(){}
void init(int _n){
    n = _n;
    adj.resize(n);
    level.resize(n);
    ptr.resize(n);
}
void addEdge(int from, int to, flow_t cap, int id=0){
    assert(n>0);
    edges.emplace_back(from, to, cap, id);
    edges.emplace_back(to, from, 0, -id);
    adj[from].push_back(m);
    adj[to].push_back(m + 1);
    m += 2;
}
flow_t maxFlow(int s1, int t1){
    s = s1, t = t1;
    flow_t f = 0;
    //Reset Flow
    for(int i=0; i<m; i++)
        edges[i].flow = 0;
    while (true){
        level.assign(n, -1);
        level[s] = 0;
        q.push(s);
        if (!bfs())
            break;
        ptr.assign(n, 0);
        while (flow_t pushed = dfs(s, flow_inf))
            f += pushed;
    }
    return f;
}
};
// Returns the minimum cut edge IDs
vector<int> recoverCut(Dinic<int> &d){
    vector<bool> seen(d.n, false);
    queue<int> q;
    q.push(d.s);
    seen[d.s] = true;
    while (!q.empty()){
        int u = q.front();
        q.pop();
        for (int idx : d.adj[u]){
            auto e = d.edges[idx];

```

```

    if (e.cap == e.flow)
        continue;
    if (!seen[e.to]){
        q.push(e.to);
        seen[e.to] = true;
    }
}
vector<int> ans;
for(auto e: d.edges){
    if(e.cap > 0 and (e.cap == e.flow) and (seen[e.from] != seen[e.to])){
        if(e.id >= 0) ans.push_back(e.id);
    }
}
return ans;
}

```

2.10 Edmond's Blossoms

```

#include <bits/stdc++.h>
using namespace std;
const int MAXN = 510;
// Adaptado de: https://github.com/brunomaletta/Biblioteca/blob/master
//              /Codigo/Grafos/blossom.cpp
// Edmond's Blossoms algorithm give a maximum matching in general
// graphs (non-bipartite)
// O(N^3)
namespace EdmondBlossoms{
vector<int> adj[MAXN];
int match[MAXN];
int n, pai[MAXN], base[MAXN], vis[MAXN];
queue<int> q;
void init(int n1){
    n = n1;
    for(int i=0; i<n; i++){
        adj[i].clear();
    }
void addEdge(int a, int b){
    adj[a].push_back(b);
    adj[b].push_back(a);
}
void contract(int u, int v, bool first = 1) {
    static vector<bool> blossom;
    static int l;
    if (first) {
        blossom = vector<bool>(n, 0);
        vector<bool> teve(n, 0);
        int k = u; l = v;
        while (1) {
            teve[k = base[k]] = 1;
            if (match[k] == -1) break;
            k = pai[match[k]];
        }
        while (!teve[l = base[l]]) l = pai[match[l]];
    }
    while (base[u] != l) {
        blossom[base[u]] = blossom[base[match[u]]] = 1;
        pai[u] = v;
        v = match[u];
    }
}
}

```

```

    u = pai[match[u]];
}
if (!first) return;
contract(v, u, 0);
for (int i = 0; i < n; i++) if (bloss[base[i]]) {
    base[i] = l;
    if (!vis[i]) q.push(i);
    vis[i] = 1;
}
}
int getpath(int s) {
    for (int i = 0; i < n; i++)
        base[i] = i, pai[i] = -1, vis[i] = 0;
    vis[s] = 1; q = queue<int>(); q.push(s);
    while (q.size()) {
        int u = q.front(); q.pop();
        for (int i : adj[u]) {
            if (base[i] == base[u] or match[u] == i) continue;
            if (i == s or (match[i] != -1 and pai[match[i]] != -1))
                contract(u, i);
            else if (pai[i] == -1) {
                pai[i] = u;
                if (match[i] == -1) return i;
                i = match[i];
                vis[i] = 1; q.push(i);
            }
        }
    }
    return -1;
}
typedef pair<int, int> pii;
vector<pii> maximumMatching(){
    vector<pii> ans;
    memset(match, -1, sizeof(match));
    for (int i = 0; i < n; i++) if (match[i] == -1)
        for (int j : adj[i]) if (match[j] == -1) {
            match[i] = j;
            match[j] = i;
            break;
        }
    for (int i = 0; i < n; i++) if (match[i] == -1) {
        int j = getpath(i);
        if (j == -1) continue;
        while (j != -1) {
            int p = pai[j], pp = match[p];
            match[p] = j;
            match[j] = p;
            j = pp;
        }
    }
    for(int i=0; i < n; i++){
        if(i < match[i])
            ans.emplace_back(i, match[i]);
    }
    return ans;
}
};

```

2.11 Flow With Demand

```
#include "dinic.h"
```

```

using namespace std;
template <typename flow_t>
struct MaxFlowEdgeDemands{
    Dinic<flow_t> mf;
    vector<flow_t> ind, outd;
    flow_t D;
    int n;
    MaxFlowEdgeDemands(int n) : n(n){
        D = 0;
        mf.init(n + 2);
        ind.assign(n, 0);
        outd.assign(n, 0);
    }
    void addEdge(int a, int b, flow_t cap, flow_t demands){
        mf.addEdge(a, b, cap - demands);
        D += demands;
        ind[b] += demands;
        outd[a] += demands;
    }
    bool solve(int s, int t){
        mf.addEdge(t, s, numeric_limits<flow_t>::max());
        for (int i = 0; i < n; i++){
            if (ind[i]) mf.addEdge(n, i, ind[i]);
            if (outd[i]) mf.addEdge(i, n + 1, outd[i]);
        }
        return mf.maxFlow(n, n + 1) == D;
    }
};

```

2.12 Floyd Warshall

```

#include <bits/stdc++.h>
using namespace std;
typedef long long ll;
const ll INFLL = 0x3f3f3f3f3f3f3f3f;
namespace FloydWarshall{
    vector<vector<ll>> dist;
    int n;
    void init(int n1){
        n = n1;
        dist.assign(n, vector<ll>(n, INFLL));
        for(int i=0; i<n; i++)
            dist[i][i] = 0LL;
    }
    void addEdge(int a, int b, ll w){
        dist[a][b] = min(dist[a][b], w);
    }
    vector<vector<ll>> solve(){
        for(int k=0; k<n; k++){
            for(int i=0; i<n; i++){
                for(int j=0; j<n; j++){
                    dist[i][j] = min(dist[i][j], dist[i][k] + dist[k][j]);
                }
            }
        }
        return dist;
    }
};

```

2.13 Hungarian

```

#include <bits/stdc++.h>
using namespace std;
//input: matrix n x m, n <= m
//return vector p of size n, where p[i] is the match for i
// and minimum cost
// time complexity: O(n^2 * m)
const int ms = 310, INF = 0x3f3f3f3f;
int u[ms], v[ms], p[ms], way[ms], minv[ms];
bool used[ms];
pair<vector<int>, int> solve(const vector<vector<int>> &matrix){
    int n = matrix.size();
    if (n == 0)
        return {vector<int>(), 0};
    int m = matrix[0].size();
    assert(n <= m);
    memset(u, 0, (n + 1) * sizeof(int));
    memset(v, 0, (m + 1) * sizeof(int));
    memset(p, 0, (m + 1) * sizeof(int));
    for (int i = 1; i <= n; i++){
        memset(minv, 0x3f, (m + 1) * sizeof(int));
        memset(way, 0, (m + 1) * sizeof(int));
        for (int j = 0; j <= m; j++){
            used[j] = 0;
            p[0] = i;
            int k0 = 0;
            do{
                used[k0] = 1;
                int i0 = p[k0], delta = INF, k1;
                for (int j = 1; j <= m; j++){
                    if (!used[j]){
                        int cur = matrix[i0 - 1][j - 1] - u[i0] - v[j];
                        if (cur < minv[j]){
                            minv[j] = cur;
                            way[j] = k0;
                        }
                        if (minv[j] < delta){
                            delta = minv[j];
                            k1 = j;
                        }
                    }
                }
            } while (p[k0]);
            do{
                int k1 = way[k0];
                p[k0] = p[k1];
                k0 = k1;
            } while (k0);
        }
    }
    vector<int> ans(n, -1);

```

```

for (int j = 1; j <= m; j++){
    if (!p[j]) continue;
    ans[p[j] - 1] = j - 1;
}
return {ans, -v[0]};
}

```

2.14 Prim

```

#include <bits/stdc++.h>
using namespace std;
typedef long long ll;
typedef pair<int, int> pii;
const int MAXN = 500010;
namespace Prim{
    vector<pii> adj[MAXN];
    int weight[MAXN];
    bool seen[MAXN];
    int n;
    void init(int n1){
        n = n1;
        for(int i=0; i<n; i++) adj[i].clear();
    }
    void addEdge(int a, int b, int w){
        adj[a].emplace_back(w, b);
        adj[b].emplace_back(w, a);
    }
    ll solve(){
        for(int i=0; i<n; i++){
            weight[i] = 0x3f3f3f3f;
            seen[i] = 0;
        }
        weight[0] = 0;
        priority_queue<pii, vector<pii>, greater<pii> > st;
        st.push(pii(weight[0], 0));
        ll ans = 0;
        while(!st.empty()){
            int u = st.top().second;
            st.pop();
            if(seen[u])
                continue;
            seen[u] = true;
            ans += weight[u];
            for(auto [edge, to]: adj[u]){
                if(!seen[to] and (edge < weight[to])){
                    weight[to] = edge;
                    st.emplace(weight[to], to);
                }
            }
        }
        return ans;
    }
};

```

2.15 HLD

```

#include <bits/stdc++.h>
#include "../data_structures/bit_range.h"

```

```

using namespace std;
#define F first
#define S second
using hld_t = long long;
using pii = pair<int, hld_t>;
struct HLD{
    vector<vector<pii>> adj;
    vector<int> sz, h, dad, pos;
    vector<hld_t> val, v;
    int t;
    bool edge;
    //Begin Internal Data Structure
    BitRange *bit;
    hld_t neutral = 0;
    inline hld_t join(hld_t a, hld_t b){
        return a+b;
    }
    inline void update(int a, int b, hld_t x){
        bit->add(a+1, b+1, x);
    }
    inline hld_t query(int a, int b){
        return bit->get(a+1, b+1);
    }
    //End Internal Data Structure
    void init(int n){
        dad.resize(n); pos.resize(n); val.resize(n); v.resize(n);
        adj.resize(n); sz.resize(n); h.resize(n);
        bit = new BitRange(n);
    }
    void dfs(int u, int p = -1){
        sz[u] = 1;
        for(pii &to: adj[u]) if(to.F != p){
            if(edge) val[to.F] = to.S;
            dfs(to.F, u);
            sz[u] += sz[to.F];
            if(sz[to.F] > sz[adj[u][0].F] or adj[u][0].F == p)
                swap(to, adj[u][0]);
        }
    }
    void build_hld(int u, int p=-1){
        dad[u] = p;
        pos[u] = t++;
        v[pos[u]] = val[u];
        for(pii to: adj[u]) if(to.F != p){
            h[to.F] = (to == adj[u][0]) ? h[u] : to.F;
            build_hld(to.F, u);
        }
    }
    void addEdge(int a, int b, hld_t w = 0){
        adj[a].emplace_back(b, w);
        adj[b].emplace_back(a, w);
    }
    void build(int root, bool is_edge){
        assert(!adj.empty());
        edge = is_edge;
        t = 0;
        h[root] = 0;
        dfs(root);
        build_hld(root);
        //Init Internal Data Structure
        for(int i=0; i<t; i++)

```

```

    update(i, i, v[i]);
}
hld_t query_path(int a, int b) {
    if (edge and a == b) return neutral;
    if (pos[a] < pos[b]) swap(a, b);
    if (h[a] == h[b]) return query(pos[b]+edge, pos[a]);
    return join(query(pos[h[a]], pos[a]), query_path(dad[h[a]], b));
}
void update_path(int a, int b, hld_t x) {
    if (edge and a == b) return;
    if (pos[a] < pos[b]) swap(a, b);
    if (h[a] == h[b]) return (void)update(pos[b]+edge, pos[a], x);
    update(pos[h[a]], pos[a], x); update_path(dad[h[a]], b, x);
}
hld_t query_subtree(int a) {
    if (edge and sz[a] == 1) return neutral;
    return query(pos[a]+edge, pos[a]+sz[a]-1);
}
void update_subtree(int a, hld_t x) {
    if (edge and sz[a] == 1) return;
    update(pos[a] + edge, pos[a]+sz[a]-1, x);
}
int lca(int a, int b) {
    if (pos[a] < pos[b]) swap(a, b);
    return h[a] == h[b] ? b : lca(dad[h[a]], b);
}
};

```

2.16 Kuhn

```

#include <bits/stdc++.h>
using namespace std;
mt19937 rng((int)chrono::steady_clock::now().time_since_epoch().count
());
namespace Kuhn{
    int na, nb;
    vector<vector<int>> adj;
    vector<int> vis, ma, mb;
    void init(int nal, int nbl){
        na = nal, nb = nbl;
        adj.assign(na, vector<int>());
        vis.assign(na + nb, 0);
        ma.assign(na, -1);
        mb.assign(nb, -1);
    }
    void addEdge(int a, int b) {
        adj[a].push_back(b);
    }
    bool dfs(int u) {
        vis[u] = 1;
        for (int to : adj[u]){
            if(vis[na+to])
                continue;
            vis[na+to] = 1;
            if (mb[to] == -1 or dfs(mb[to])) {
                ma[u] = to, mb[to] = u;
                return true;
            }
        }
        return false;
    }
}

```

```

}
int matching() {
    int ans = 0, c = 1;
    for (auto& v: adj)
        shuffle(v.begin(), v.end(), rng);
    while (c) {
        for (int j = 0; j < nb; j++)
            vis[na+j] = 0;
        c = 0;
        for (int i = 0; i < na; i++)
            if (ma[i] == -1 and dfs(i))
                ans++, c = 1;
    }
    return ans;
}
pair<vector<int>, vector<int>> minimumVertexCover() {
    matching();
    for (int i = 0; i < na+nb; i++)
        vis[i] = 0;
    for (int i = 0; i < na; i++)
        if (ma[i] == -1)
            dfs(i);
    vector<int> va, vb;
    for (int i = 0; i < na; i++)
        if (!vis[i])
            va.push_back(i);
    for (int i = 0; i < nb; i++)
        if (vis[na+i])
            vb.push_back(i);
    return {va, vb};
}
vector<int> maximumAntichain(){
    auto [l, r] = minimumVertexCover();
    set<int> L(l.begin(), l.end());
    set<int> R(r.begin(), r.end());
    vector<int> ans;
    for (int i = 0; i < na; i++)
        if (!L.count(i) and !R.count(i))
            ans.push_back(i);
    return ans;
}
};

```

2.17 Kruskal

```

#include "../data_structures/union_find.h"
typedef long long ll;
struct Edge{
    int u, v; ll w;
    Edge(){}
    Edge(int u, int v, ll w):u(u), v(v), w(w){}
};
ll kruskal(vector<Edge> v, int nVet){
    ll cost = 0;
    UnionFind uf(nVet);
    sort(v.begin(), v.end(), [&](Edge a, Edge b){
        return a.w < b.w;
    });
    for(Edge &e: v){
        if(!uf.isSame(e.u, e.v)){

```

```

    cost += e.w;
    uf.join(e.u, e.v);
}
}
return cost;
}

```

2.18 LCA

```

#include <bits/stdc++.h>
using namespace std;
namespace LCA{
    typedef long long lca_t;
    typedef pair<int, lca_t> lca_p;
    const lca_t neutral = 0;
    vector<vector<lca_p>> adj;
    vector<int> level;
    vector<vector<lca_t>> D;
    vector<vector<int>> P;
    int n, mxLogN;
    void init(int _n, int _mxLogN = 20){
        n = _n;
        mxLogN = _mxLogN;
        adj.assign(n, vector<lca_p>());
        D.resize(n, vector<lca_t>(mxLogN));
        level.resize(n);
    }
    lca_t join(lca_t a, lca_t b){
        return a + b;
    }
    void addEdge(int a, int b, lca_t w = 1){
        adj[a].emplace_back(b, w);
        adj[b].emplace_back(a, w);
    }
    void dfs(int u){
        for (auto to : adj[u]){
            int v = to.first;
            lca_t w = to.second;
            if (v == P[u][0])
                continue;
            P[v][0] = u;
            D[v][0] = w;
            level[v] = level[u] + 1;
            dfs(v);
        }
    }
    void build(int root = 0){
        P.assign(n, vector<int>(mxLogN, -1));
        level[root] = 0;
        P[root][0] = root;
        D[root][0] = neutral;
        dfs(root);
        for (int j = 1; j < mxLogN; j++){
            for (int i = 0; i < n; i++){
                P[i][j] = P[P[i][j - 1]][j - 1];
                D[i][j] = join(D[P[i][j - 1]][j - 1], D[i][j - 1]);
            }
        }
    }
    lca_p lca(int u, int v){
        if (level[u] > level[v])

```

```

        swap(u, v);
        int d = level[v] - level[u];
        lca_t ans = neutral;
        for (int i = 0; i < mxLogN; i++){
            if (d & (1 << i)){
                ans = join(ans, D[v][i]);
                v = P[v][i];
            }
        }
        if (u == v)
            return lca_p(u, ans);
        for (int i = mxLogN - 1; i >= 0; i--){
            while (P[u][i] != P[v][i]){
                ans = join(ans, D[v][i]);
                ans = join(ans, D[u][i]);
                u = P[u][i];
                v = P[v][i];
            }
        }
        ans = join(ans, D[v][0]);
        ans = join(ans, D[u][0]);
        return lca_p(P[u][0], ans);
    }
};

```

2.19 Min-Cut

```

#include <bits/stdc++.h>
using namespace std;
typedef long long ll;
//This algorithm finds the Global Min-Cut in O(|V|^3)
namespace MinCut{
    const int MAXN = 510;
    bool exist[MAXN], in_a[MAXN];
    ll g[MAXN][MAXN], w[MAXN];
    vector<int> v[MAXN];
    int n;
    void init(int n1){
        n = n1;
        memset(g, 0, sizeof(g));
    }
    void addEdge(int a, int b, int w1){
        if(a == b) return;
        g[a][b] += w1;
        g[b][a] += w1;
    }
    pair<ll, vector<int>> mincut() {
        ll best_cost = 0x3f3f3f3f3f3f3fLL;
        vector<int> best_cut;
        for (int i=0; i<n; ++i)
            v[i].assign(1, i);
        memset(exist, true, sizeof(exist));
        for(int ph=0; ph<n-1; ++ph) {
            memset(in_a, false, sizeof in_a);
            memset(w, 0, sizeof w);
            for(int it=0, prev=0; it<n-ph; ++it){
                int sel = -1;
                for(int i=0; i<n; ++i)
                    if(exist[i] && !in_a[i] && (sel == -1 || w[i] > w[sel]))
                        sel = i;

```

```

    if(it == n-ph-1){
        if(w[sel] < best_cost)
            best_cost = w[sel], best_cut = v[sel];
        v[prev].insert (v[prev].end(), v[sel].begin(), v[sel].end())
        ;
        for(int i=0; i<n; ++i)
            g[prev][i] = g[i][prev] += g[sel][i];
        exist[sel] = false;
    }else{
        in_a[sel] = true;
        for(int i=0; i<n; ++i)
            w[i] += g[sel][i];
        prev = sel;
    }
}
}
return {best_cost, best_cut};
};

```

2.20 Minimum Cost Maximum Flow

```

#include <bits/stdc++.h>
using namespace std;
template <class T = int>
class MCMF{
private:
    struct Edge{
        int to;
        T cap, cost;
        Edge(int a, T b, T c) : to(a), cap(b), cost(c) {}
    };
    int n;
    vector<vector<int>> edges;
    vector<Edge> list;
    vector<int> from;
    vector<T> dist, pot;
    vector<bool> visit;
    pair<T, T> augment(int src, int sink){
        pair<T, T> flow = {list[from[sink]].cap, 0};
        for (int v = sink; v != src; v = list[from[v]] ^ 1).to){
            flow.first = std::min(flow.first, list[from[v]].cap);
            flow.second += list[from[v]].cost;
        }
        for (int v = sink; v != src; v = list[from[v]] ^ 1).to){
            list[from[v]].cap -= flow.first;
            list[from[v] ^ 1].cap += flow.first;
        }
        return flow;
    }
    queue<int> q;
    bool SPFA(int src, int sink){
        T INF = numeric_limits<T>::max();
        dist.assign(n, INF);
        from.assign(n, -1);
        q.push(src);
        dist[src] = 0;
        while (!q.empty()){
            int on = q.front();
            q.pop();

```

```

            visit[on] = false;
            for (auto e : edges[on]){
                auto ed = list[e];
                if (ed.cap == 0)
                    continue;
                T toDist = dist[on] + ed.cost + pot[on] - pot[ed.to];
                if (toDist < dist[ed.to]){
                    dist[ed.to] = toDist;
                    from[ed.to] = e;
                    if (!visit[ed.to]){
                        visit[ed.to] = true;
                        q.push(ed.to);
                    }
                }
            }
        }
        return dist[sink] < INF;
    }
    void fixPot(){
        T INF = numeric_limits<T>::max();
        for (int i = 0; i < n; i++){
            if (dist[i] < INF)
                pot[i] += dist[i];
        }
    }
public:
    MCMF(int size){
        n = size;
        edges.resize(n);
        pot.assign(n, 0);
        dist.resize(n);
        visit.assign(n, false);
    }
    pair<T, T> solve(int src, int sink){
        pair<T, T> ans(0, 0);
        // Can use dijkstra to speed up depending on the graph
        if (!SPFA(src, sink))
            return ans;
        fixPot();
        // Can use dijkstra to speed up depending on the graph
        while (SPFA(src, sink)){
            auto flow = augment(src, sink);
            ans.first += flow.first;
            ans.second += flow.first * flow.second;
            fixPot();
        }
        return ans;
    }
    void addEdge(int u, int to, T cap, T cost){
        edges[u].push_back(list.size());
        list.push_back(Edge(to, cap, cost));
        edges[to].push_back(list.size());
        list.push_back(Edge(u, 0, -cost));
    }
};

```

2.21 Strongly Connected Component

```

#include "topological_sort.h"
using namespace std;

```



```

namespace SCC{
    typedef pair<int, int> pii;
    vector<vector<int>> revAdj;
    vector<int> component;
    void dfs(int u, int c){
        component[u] = c;
        for (int to : revAdj[u]){
            if (component[to] == -1)
                dfs(to, c);
        }
    }
    vector<int> scc(int n, vector<pii> &edges){
        revAdj.assign(n, vector<int>());
        for (pii p : edges)
            revAdj[p.second].push_back(p.first);
        vector<int> tp = TopologicalSort::order(n, edges);
        component.assign(n, -1);
        int comp = 0;
        for (int u : tp){
            if (component[u] == -1)
                dfs(u, comp++);
        }
        return component;
    }
} // namespace SCC

```

2.22 Topological Sort

```

#include <bits/stdc++.h>
using namespace std;
namespace TopologicalSort{
    typedef pair<int, int> pii;
    vector<vector<int>> adj;
    vector<bool> visited;
    vector<int> vAns;
    void dfs(int u){
        visited[u] = true;
        for (int to : adj[u]){
            if (!visited[to])
                dfs(to);
        }
        vAns.push_back(u);
    }
    vector<int> order(int n, vector<pii> &edges){
        adj.assign(n, vector<int>());
        for (pii p : edges)
            adj[p.first].push_back(p.second);
        visited.assign(n, false);
        vAns.clear();
        for (int i = 0; i < n; i++){
            if (!visited[i])
                dfs(i);
        }
        reverse(vAns.begin(), vAns.end());
        return vAns;
    }
} // namespace TopologicalSort

```

2.23 Tree ID

```

#include "centroid.h"
#define F first
#define S second
namespace TreeID{
    int id=0;
    map<map<int, int>, int> mpId;
    vector<int> adj[MAXN];
    int treeID(int u, int p){
        map<int, int> mp;
        for(int to: adj[u]){
            if(to != p)
                mp[treeID(to, u)]++;
        }
        if(!mpId.count(mp))
            mpId[mp] = ++id;
        return mpId[mp];
    }
    //Returns a pair of values that represents a tree only. O((N+M)*log(M))
    //0-indexed
    pii getTreeID(vector<pii> &edges, int n){
        for(int i=0; i<n; i++)
            adj[i].clear();
        Centroid::init(n);
        for(pii e: edges){
            adj[e.F].push_back(e.S);
            adj[e.S].push_back(e.F);
            Centroid::addEdge(e.F, e.S);
        }
        pii c = Centroid::findCentroid();
        pii ans(treeID(c.F, -1), treeID(c.S, -1));
        if(ans.F > ans.S)
            swap(ans.F, ans.S);
        return ans;
    }
    bool isomorphic(vector<pii> &tree1, vector<pii> &tree2, int n){
        return getTreeID(tree1, n) == getTreeID(tree2, n);
    }
};

```

2.24 Vertex Cover In Tree

```

#include <bits/stdc++.h>
using namespace std;
const int MAXN = 200010;
int dp[MAXN][2];
vector<int> adj[MAXN];
// vertexCover(node current, free to choose, dad)
int vertexCover(int u, bool color=true, int p=-1){
    if(dp[u][color] != -1)
        return dp[u][color];
    int case1 = 1, case2 = 0;
    for(int to: adj[u]){
        if(to == p) continue;
        case1 += vertexCover(to, true, u);
        case2 += vertexCover(to, false, u);
    }
}

```

```

}
if(color)
    return dp[u][color] = min(case1, case2);
else
    return dp[u][color] = case1;
}

```

3 Dynamic Programming

3.1 Divide and Conquer Optimization

Reduces the complexity from $O(n^2k)$ to $O(nk \log n)$ of PD's in the following ways (and other variants):

$$dp[n][k] = \max_{0 \leq i < n} (dp[i][k-1] + C[i+1][n]), \text{ base case : } dp[0][j], dp[i][0] \quad (1)$$

- $C[i][j]$ = the cost only depends on i and j .
- $opt[n][k] = i$ is the optimal value that maximizes $dp[n][k]$.

It is necessary that opt is increasing along each column: $opt[j][k] \leq opt[j+1][k]$.

3.2 Divide and Conquer Optimization Implementation

```

#include <bits/stdc++.h>
using namespace std;
int C(int i, int j);
const int MAXN = 100010;
const int MAXK = 110;
const int INF = 0x3f3f3f3f;
int dp[MAXN][MAXK];
void calculateDP(int l, int r, int k, int opt_l, int opt_r){
    if (l > r)
        return;
    int mid = (l + r) >> 1;
    int ans = -INF, opt = mid;
    // int ans = dp[mid][k-1], opt=mid; //If you accept empty subsegment
    for (int i = opt_l; i <= min(opt_r, mid - 1); i++){
        if (ans < dp[i][k-1] + C(i+1, mid)){
            opt = i;
            ans = dp[i][k-1] + C(i+1, mid);
        }
    }
    dp[mid][k] = ans;
    calculateDP(l, mid - 1, k, opt_l, opt);
    calculateDP(mid + 1, r, k, opt, opt_r);
}
int solve(int n, int k){
    for (int i = 0; i <= n; i++)
        dp[i][0] = -INF;
    for (int j = 0; j <= k; j++)
        dp[0][j] = -INF;
    dp[0][0] = 0;
    for (int j = 1; j <= k; j++)
        calculateDP(1, n, j, 0, n - 1);
    return dp[n][k];
}

```

3.3 Knuth Optimization

Reduces the complexity from $O(n^3)$ to $O(n^2)$ of PD's in the following ways (and other variants):

$$dp[i][j] = C[i][j] + \min_{i < k < j} (dp[i][k] + dp[k][j]), \text{ caso base : } dp[i][i] \quad (2)$$

$$dp[i][j] = \min_{i < k < j} (dp[i][k] + C[i][k]), \text{ caso base : } dp[i][i] \quad (3)$$

- $C[i][j]$ = the cost only depends on i and j .
- $opt[i][j] = k$ is the optimal value that maximizes $dp[i][j]$.

The following conditions must be met:

- Foursquare inequality on C : $C[a][c] + C[b][d] \leq C[a][d] + C[b][c]$, $a \leq b \leq c \leq d$.
- Monotonicity on C : $C[b][c] \leq C[a][d]$, $a \leq b \leq c \leq d$.

Or the following condition:

- opt increasing in rows and columns: $opt[i][j-1] \leq opt[i][j] \leq opt[i+1][j]$.

3.4 Knuth Optimization Implementation

```

#include <bits/stdc++.h>
using namespace std;
typedef long long ll;
const int MAXN = 1009;
const ll INFLL = 0x3f3f3f3f3f3f3f3f;
ll C(int a, int b);
ll dp[MAXN][MAXN];
int opt[MAXN][MAXN];
ll knuth(int n){
    for (int i = 0; i < n; i++){
        dp[i][i] = 0;
        opt[i][i] = i;
    }
    for (int s = 1; s < n; s++){
        for (int i = 0, j; (i + s) < n; i++){
            j = i + s;
            dp[i][j] = INFLL;
            for (int k = opt[i][j-1]; k < min(j, opt[i+1][j]+1); k++){
                ll cur = dp[i][k] + dp[k+1][j] + C(i, j);
                if (dp[i][j] > cur){
                    dp[i][j] = cur;
                    opt[i][j] = k;
                }
            }
        }
    }
    return dp[0][n-1];
}

```

4 Math

4.1 Basic Math

```
#include <bits/stdc++.h>
using namespace std;
typedef long long ll;
typedef unsigned long long ull;

ull fastPow(ull base, ull exp, ull mod){
    base %= mod;
    //exp %= phi(mod) if base and mod are relatively prime
    ull ans = 1LL;
    while (exp > 0){
        if (exp & 1LL)
            ans = (ans * (__int128_t)base) % mod;
        base = (base * (__int128_t)base) % mod;
        exp >>= 1;
    }
    return ans;
}

int fastPow(int base, string bigExp, int mod){
    int ans = 1;
    for(char c: bigExp){
        ans = fastPow(ans, 10, mod);
        ans = (ans*1LL*fastPow(base, c-'0', mod))%mod;
    }
    return ans;
}

ll gcd(ll a, ll b){ return __gcd(a, b); }
ll lcm(ll a, ll b){ return (a / gcd(a, b)) * b; }
void enumeratingAllSubmasks(int mask){
    for (int s = mask; s; s = (s - 1) & mask)
        cout << s << endl;
}

//MOD to Hash
namespace ModHash{
    const uint64_t MOD = (1ll<<61) - 1;
    uint64_t modmul(uint64_t a, uint64_t b){
        uint64_t l1 = (uint32_t)a, h1 = a>>32, l2 = (uint32_t)b, h2 = b
            >>32;
        uint64_t l = l1*l2, m = l1*h2 + l2*h1, h = h1*h2;
        uint64_t ret = (l&MOD) + (l>>61) + (h << 3) + (m >> 29) + ((m <<
            35) >> 3) + 1;
        ret = (ret & MOD) + (ret>>61);
        ret = (ret & MOD) + (ret>>61);
        return ret-1;
    }
};
```

4.2 BigInt

```
#include <bits/stdc++.h>
using namespace std;
typedef int32_t intB;
typedef int64_t longB;
typedef vector<intB> vib;
```

```
class BigInt{
private:
    vib vb;
    bool neg;
    const int BASE_DIGIT = 9;
    const intB base = 1000000LL*1000; //000LL*1000000LL;
    void fromString(string &s){
        if(s[0] == '-'){
            neg = true;
            s = s.substr(1);
        }else{
            neg = false;
        }
        vb.clear();
        vb.reserve((s.size()+BASE_DIGIT-1)/BASE_DIGIT);
        for(int i=(int)s.length(); i>0; i-=BASE_DIGIT){
            if(i < BASE_DIGIT)
                vb.push_back(stol(s.substr(0, i)));
            else
                vb.push_back(stol(s.substr(i-BASE_DIGIT, BASE_DIGIT)));
        }
        fix(vb);
    }

    void fix(vib &v){
        while(v.size()>1 && v.back()==0)
            v.pop_back();
        if(v.size() == 0)
            neg = false;
    }

    bool comp(vib &a, vib &b){
        fix(a); fix(b);
        if(a.size() != b.size()) return a.size() < b.size();
        for(int i=(int)a.size()-1; i>=0; i--) {
            if(a[i] != b[i]) return a[i] < b[i];
        }
        return false;
    }

    vib sum(vib a, vib b){
        int carry = 0;
        for(size_t i=0; i<max(a.size(), b.size()) or carry; i++){
            if(i == a.size())
                a.push_back(0);
            a[i] += carry + (i<b.size() ? b[i] : 0);
            carry = (a[i] >= base);
            if(carry) a[i] -= base;
        }
        fix(a);
        return a;
    }

    vib sub(vib a, vib b){
        int carry = 0;
        for(size_t i=0; i<b.size() or carry; i++){
            a[i] -= carry + (i<b.size() ? b[i] : 0);
            carry = a[i] < 0;
            if(carry) a[i] += base;
        }
        fix(a);
        return a;
    }

public:
```

```

BigInt(){}
BigInt(intB n){
    neg = (n<0);
    vb.push_back(abs(n));
    fix(vb);
}
BigInt(string s){
    fromString(s);
}
BigInt operator =(BigInt oth){
    this->neg = oth.neg;
    this->vb = oth.vb;
    return *this;
}
BigInt operator +(BigInt &oth){
    vib &a = vb, &b = oth.vb;
    BigInt ans;
    if(neg == oth.neg){
        ans.vb = sum(vb, oth.vb);
        ans.neg = neg;
    }else{
        if(comp(a, b)){
            ans.vb = sub(b, a);
            ans.neg = oth.neg;
        }else{
            ans.vb = sub(a, b);
            ans.neg = neg;
        }
    }
    return ans;
}
BigInt operator -(BigInt oth){
    oth.neg ^= true;
    return (*this) + oth;
}
BigInt operator *(intB b){
    bool negB = false;
    if(b < 0){
        negB = true;
        b = -b;
    }
    BigInt ans = *this;
    auto &a = ans.vb;
    intB carry = 0;
    for(size_t i=0; i<a.size() or carry; i++){
        if(i == a.size()) a.push_back(0);
        longB cur = carry + a[i] *(longB) b;
        a[i] = intB(cur%base);
        carry = intB(cur/base);
    }
    ans.neg ^= negB;
    fix(ans.vb);
    return ans;
}
BigInt operator *(BigInt &oth){
    BigInt ans;
    auto a = vb, &b = oth.vb, &c = ans.vb;
    c.assign(a.size() + b.size(), 0);
    for(size_t i=0; i<a.size(); i++){
        intB carry=0;
        for(size_t j=0; j<b.size() or carry; j++){
            longB cur = c[i+j] + a[i]*(longB)(j<b.size() ? b[j] : 0);
            cur += carry;
            c[i+j] = intB(cur%base);
            carry = intB(cur/base);
        }
    }
    ans.neg = neg^oth.neg;
    fix(ans.vb);
    return ans;
}
BigInt operator /(intB b){
    bool negB = false;
    if(b < 0){
        negB = true;
        b = -b;
    }
    BigInt ans = *this;
    auto &a = ans.vb;
    intB carry = 0;
    for(int i=(int)a.size()-1; i>=0; i--){
        longB cur = a[i] + (longB)carry * base;
        a[i] = intB(cur/b);
        carry = intB(cur%b);
    }
    ans.neg ^= negB;
    fix(ans.vb);
    return ans;
}
void shiftL(int b){
    vb.resize(vb.size() + b);
    for(int i=(int)vb.size()-1; i>=0; i--){
        if(i>=b) vb[i] = vb[i-b];
        else vb[i] = 0;
    }
    fix(vb);
}
void shiftR(int b){
    if((int)vb.size() <= b){
        vb.clear();
        vb.push_back(0);
        return;
    }
    for(int i=0; i<((int)vb.size() - b); i++){
        vb[i] = vb[i+b];
        vb.resize((int)vb.size() - b);
        fix(vb);
    }
}
void divide(BigInt a, BigInt b, BigInt &q, BigInt &r){
    BigInt z(0), p(1);
    while(b < a){
        p.shiftL(max(1, (int)(a.vb.size()-b.vb.size())));
        b.shiftL(max(1, (int)(a.vb.size()-b.vb.size())));
    }
    while(true){
        while ((a < b) && (z < p)) {
            p = p/10;
            b = b/10;
        }
        if(!(z < p)) break;
        a = a - b;
        q = q + p;
    }
}

```

```

    }
    r = a;
}
BigInt operator / (BigInt &oth){
    BigInt q, r;
    divide(*this, oth, q, r);
    return q;
}
BigInt operator % (BigInt &oth){
    BigInt q, r;
    divide(*this, oth, q, r);
    return r;
}
bool operator < (BigInt &oth){
    BigInt ans = (*this) - oth;
    return ans.neg;
}
bool operator == (BigInt &oth){
    BigInt ans = (*this) - oth;
    return (ans.vb.size()==1) and (ans.vb.back()==0);
}
friend ostream &operator<<(ostream &out, const BigInt &D){
    if(D.neg)
        out << '-';
    out << (D.vb.empty() ? 0 : D.vb.back());
    for(int i=(int)D.vb.size()-2; i>=0; i--){
        out << setfill('0') << setw(D.BASE_DIGIT) << D.vb[i];
    }
    return out;
}
string to_string(){
    std::stringstream ss;
    ss << (*this);
    return ss.str();
}
friend istream &operator>>(istream &input, BigInt &D) {
    string s;
    input >> s;
    D.fromString(s);
    return input;
}
};

```

4.3 Binomial Coefficients

```

#include <bits/stdc++.h>
#include "../basic_math.h"
#include "../modular.h"
using namespace std;
typedef long long ll;
//O(k)
ll C1(int n, int k){
    ll res = 1LL;
    for (int i = 1; i <= k; ++i)
        res = (res * (n - k + i)) / i;
    return res;
}
//O(n^2)
vector<vector<ll>> C2(int maxn, int mod){
    vector<vector<ll>> mat(maxn + 1, vector<ll>(maxn + 1, 0));
    mat[0][0] = 1;

```

```

    for (int n = 1; n <= maxn; n++){
        mat[n][0] = mat[n][n] = 1;
        for (int k = 1; k < n; k++)
            mat[n][k] = (mat[n - 1][k - 1] + mat[n - 1][k]) % mod;
    }
    return mat;
}
//O(N)
vector<int> factorial, inv_factorial;
void prevC3(int maxn, int mod){
    factorial.resize(maxn + 1);
    factorial[0] = 1;
    for (int i = 1; i <= maxn; i++)
        factorial[i] = (factorial[i - 1] * 1LL * i) % mod;
    inv_factorial.resize(maxn + 1);
    inv_factorial[maxn] = fastPow(factorial[maxn], mod - 2, mod);
    for (int i = maxn - 1; i >= 0; i--){
        inv_factorial[i] = (inv_factorial[i + 1] * 1LL * (i + 1)) % mod;
    }
int C3(int n, int k, int mod){
    if (n < k)
        return 0;
    return ((factorial[n] * 1LL * inv_factorial[k]) % mod) * 1LL *
        inv_factorial[n - k]) % mod;
}
//O(P*log(P))
//C4(n, k, p) = Comb(n, k)%p
vector<int> changeBase(int n, int p){
    vector<int> v;
    while (n > 0){
        v.push_back(n % p);
        n /= p;
    }
    return v;
}
int C4(int n, int k, int p){
    auto vn = changeBase(n, p);
    auto vk = changeBase(k, p);
    int mx = max(vn.size(), vk.size());
    vn.resize(mx, 0);
    vk.resize(mx, 0);
    prevC3(p - 1, p);
    int ans = 1;
    for (int i = 0; i < mx; i++){
        ans = (ans * 1LL * C3(vn[i], vk[i], p)) % p;
    }
    return ans;
}
//O(P^k)
//C5(n, k, p, pk) = Comb(n, k)%(p^k)
int fat_p(ll n, int p, int pk){
    vector<int> fat1(pk, 1);
    int res = 1;
    for(int i=1; i<pk; i++){
        if(i%p == 0)
            fat1[i] = fat1[i-1];
        else
            fat1[i] = (fat1[i-1]*1LL*i)%pk;
    }
    while(n > 1){
        res = (res*1LL*fastPow(fat1[pk-1], n/pk, pk))%pk;
        res = (res*1LL*fat1[n%pk])%pk;
    }
}

```

```

    n /= p;
}
return res;
}
ll cnt(ll n, int p){
    ll ans = 0;
    while(n > 1){
        ans += n/p;
        n/=p;
    }
    return ans;
}
int C5(ll n, ll k, int p, int pk){
    ll exp = cnt(n, p) - cnt(n-k, p) - cnt(k, p);
    int d = (fat_p(n-k, p, pk)*1LL*fat_p(k, p, pk))%pk;
    int ans = (fat_p(n, p, pk)*1LL*inv(d, pk))%pk;
    return (ans*1LL*fastPow(p, exp, pk))%pk;
}

```

4.4 Chinese Remainder Theorem

```

#include <bits/stdc++.h>
#include "extended_euclidean.h"
using namespace std;
typedef long long ll;
namespace CRT{
    inline ll normalize(ll x, ll mod){
        x %= mod;
        if (x < 0)
            x += mod;
        return x;
    }
    ll solve(vector<ll> a, vector<ll> m){
        int n = a.size();
        for (int i = 0; i < n; i++)
            normalize(a[i], m[i]);
        ll ans = a[0];
        ll lcm1 = m[0];
        for (int i = 1; i < n; i++){
            ll x, y;
            ll g = extGcd(lcm1, m[i], x, y);
            if ((a[i] - ans) % g != 0)
                return -1;
            ans = normalize(ans + (((a[i] - ans) / g) * x) % (m[i] / g)) *
                        lcm1, (lcm1 / g) * m[i]);
            lcm1 = (lcm1 / g) * m[i]; //lcm(lcm1, m[i]);
        }
        return ans;
    }
} // namespace CRT

```

4.5 Determinant

```

#include <bits/stdc++.h>
using namespace std;
typedef long double ld;
const ld EPS = 1e-9;
ld determinant(vector<vector<ld>> a) {

```

```

    int n = a.size();
    ld det = 1;
    for(int i=0; i<n; i++) {
        int b = i;
        for(int j=i+1; j<n; j++)
            if(abs (a[j][i]) > abs (a[b][i]))
                b = j;
        if(abs(a[b][i]) < EPS)
            return 0;
        swap(a[i], a[b]);
        if(i != b)
            det = -det;
        det *= a[i][i];
        for(int j=i+1; j<n; ++j)
            a[i][j] /= a[i][i];
        for(int j=0; j<n; ++j)
            if(j != i && abs (a[j][i]) > EPS)
                for(int k=i+1; k<n; k++)
                    a[j][k] -= a[i][k] * a[j][i];
    }
    return det;
}

```

4.6 Division Trick

```

#include <bits/stdc++.h>
using namespace std;
using ll = long long;
using pll = pair<ll, ll>;
// O(N)
pll bruteForce(ll n){
    ll ans1 = 0, ans2 = 0;
    for(ll i = 1; i <= n; i++){
        ans1 += n/i;
        ans2 += (n/i)*i; // n - (n mod i);
    }
    return pll(ans1, ans2);
}
ll AP(ll a1, ll an){
    ll n = (an-a1+1);
    return ((a1+an)*n)/2LL;
}
// O(sqrt(N))
pll divisionTrick(ll n){
    ll ans1 = 0, ans2 = 0;
    for(ll l = 1, r; l <= n; l = r + 1) {
        r = n / (n / l);
        // n / i has the same value for l <= i <= r
        ans1 += (n/l)*(r-l+1);
        ans2 += (n/l)*AP(l, r);
    }
    return pll(ans1, ans2);
}

```

4.7 Euler's totient

```

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

```

```

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

vector<int> phiFrom1toN(int n){
    vector<int> vPhi(n + 1);
    vPhi[0] = 0;
    vPhi[1] = 1;
    for (int i = 2; i <= n; i++){
        vPhi[i] = i;
        for (int j = 2; j <= n; j += i){
            if (vPhi[j] == i){
                vPhi[j] -= vPhi[j] / i;
            }
        }
    }
    return vPhi;
}

```

4.8 Extended Euclidean

```

#include <bits/stdc++.h>
using namespace std;
typedef long long ll;
ll extGcd(ll a, ll b, ll &x, ll &y){
    if (b == 0){
        x = 1, y = 0;
        return a;
    }else{
        ll g = extGcd(b, a % b, y, x);
        y -= (a / b) * x;
        return g;
    }
}
//a*x + b*y = g
//a*(x-(b/g)*k) + b*(y+(a/g)*k) = g
bool dioEq(ll a, ll b, ll c, ll &x0, ll &y0, ll &g){
    g = extGcd(abs(a), abs(b), x0, y0);
    if (c % g) return false;
    x0 *= c / g;
    y0 *= c / g;
    if (a < 0) x0 = -x0;
    if (b < 0) y0 = -y0;
    return true;
}
inline void shift(ll &x, ll &y, ll a, ll b, ll cnt){
    x += cnt * b;
    y -= cnt * a;
}
// a1 + m1*x = a2 + m2*y
// Find the first moment that both are equal

```

```

ll findMinimum(ll a1, ll m1, ll a2, ll m2){
    ll a = m1, b = -m2, c = a2 - a1;
    ll x, y, g;
    if (!dioEq(a, b, c, x, y, g))
        return -1;
    a /= g;
    b /= g;
    int sa = a > 0 ? +1 : -1;
    int sb = b > 0 ? +1 : -1;
    shift(x, y, a, b, -x/b);
    if (x < 0)
        shift(x, y, a, b, sb);
    if (y < 0){
        shift(x, y, a, b, y/a);
        if (y < 0)
            shift(x, y, a, b, -sa);
        if (x < 0)
            return -1;
    }
    return a*x*g;
}

ll findAllSolutions(ll a, ll b, ll c, ll minx, ll maxx, ll miny, ll maxy){
    ll x, y, g;
    if (a==0 or b==0){
        if (a==0 and b==0)
            return (c==0)*(maxx-minx+1)*(maxy-miny+1);
        if (a == 0)
            return (c%b == 0)*(maxx-minx+1)*(miny<=c/b and c/b<=maxy);
        return (c%a == 0)*(minx<=c/a and c/a<=maxx)*(maxy-miny+1);
    }
    if (!dioEq(a, b, c, x, y, g))
        return 0;
    a /= g;
    b /= g;
    int sign_a = a > 0 ? +1 : -1;
    int sign_b = b > 0 ? +1 : -1;
    shift(x, y, a, b, (minx - x) / b);
    if (x < minx)
        shift(x, y, a, b, sign_b);
    if (x > maxx)
        return 0;
    ll lx1 = x;
    shift(x, y, a, b, (maxx - x) / b);
    if (x > maxx)
        shift(x, y, a, b, -sign_b);
    ll rx1 = x;
    shift(x, y, a, b, -(miny - y) / a);
    if (y < miny)
        shift(x, y, a, b, -sign_a);
    if (y > maxy)
        return 0;
    ll lx2 = x;
    shift(x, y, a, b, -(maxy - y) / a);
    if (y > maxy)
        shift(x, y, a, b, sign_a);
    ll rx2 = x;
    if (lx2 > rx2)
        swap(lx2, rx2);
    ll lx = max(lx1, lx2);
    ll rx = min(rx1, rx2);
}

```

```

if (lx > rx)
    return 0;
return (rx - lx) / abs(b) + 1;
}

```

4.9 Fraction

```

#include <bits/stdc++.h>
using namespace std;
typedef long long f_type;
//Representation of the a/b
struct Fraction {
    f_type a, b;
    Fraction(f_type _a = 0): a(_a), b(1){}
    Fraction(f_type _a, f_type _b) {
        f_type g = __gcd(_a, _b);
        a = _a/g;
        b = _b/g;
        if(b < 0){
            a = -a;
            b = -b;
        }
    }
    Fraction operator+(Fraction oth) {
        return Fraction(a*oth.b + oth.a*b, b*oth.b);
    }
    Fraction operator-(Fraction oth) {
        return Fraction(a*oth.b - oth.a*b, b*oth.b);
    }
    Fraction operator*(Fraction oth) {
        return Fraction(a*oth.a, b*oth.b);
    }
    Fraction operator/(Fraction oth) {
        return Fraction(a*oth.b, b*oth.a);
    }
    bool operator>=(Fraction oth){
        return ((*this) - oth).a >= 0;
    }
    bool operator==(Fraction oth){
        return a == oth.a and b == oth.b;
    }
    operator f_type() {return a/b;}
    operator double() {return double(a)/b;}
};

```

4.10 FFT

```

#include <bits/stdc++.h>
using namespace std;
struct complex_t {
    double a {0.0}, b {0.0};
    complex_t(){}
    complex_t(double na) : a{na}{}
    complex_t(double na, double nb) : a{na}, b{nb} {}
    const complex_t operator+(const complex_t &c) const {
        return complex_t(a + c.a, b + c.b);
    }
    const complex_t operator-(const complex_t &c) const {

```

```

        return complex_t(a - c.a, b - c.b);
    }
    const complex_t operator*(const complex_t &c) const {
        return complex_t(a*c.a - b*c.b, a*c.b + b*c.a);
    }
    const complex_t operator/(const int &c) const {
        return complex_t(a/c, b/c);
    }
};
//using cd = complex<double>;
using cd = complex_t;
const double PI = acos(-1);
void fft(vector<cd> &a, bool invert) {
    int n = a.size();
    for (int i = 1, j = 0; i < n; i++) {
        int bit = n >> 1;
        for (; j & bit; bit >>= 1)
            j ^= bit;
        j ^= bit;
        if (i < j)
            swap(a[i], a[j]);
    }
    for (int len = 2; len <= n; len <= 1) {
        double ang = 2 * PI / len * (invert ? -1 : 1);
        cd wlen(cos(ang), sin(ang));
        for (int i = 0; i < n; i += len) {
            cd w(1);
            for (int j = 0; j < len / 2; j++) {
                cd u = a[i+j], v = a[i+j+len/2] * w;
                a[i+j] = u + v;
                a[i+j+len/2] = u - v;
                w = w * wlen;
            }
        }
    }
    if (invert){
        for (cd &x : a)
            x = x / n;
    }
}
typedef long long ll;
vector<ll> multiply(vector<int> &a, vector<int> &b) {
    vector<cd> fa(a.begin(), a.end()), fb(b.begin(), b.end());
    int n = 1;
    while(n < int(a.size() + b.size()) )
        n <= 1;
    fa.resize(n);
    fb.resize(n);
    fft(fa, false);
    fft(fb, false);
    for (int i = 0; i < n; i++)
        fa[i] = fa[i]*fb[i];
    fft(fa, true);
    vector<ll> result(n);
    for (int i = 0; i < n; i++)
        result[i] = ll(fa[i].a + 0.5);
    return result;
}
vector<ll> scalarProdut(vector<int> t, vector<int> p, bool isCyclic=
    false) {
    int nt = t.size();

```



```

int np = p.size();
t.resize(nt+np, 0);
reverse(p.begin(), p.end());
if(isCyclic)
    for(int i=nt; i<nt+np; i++)
        t[i] = t[i%nt];
vector<ll> ans = multiply(t, p);
for(int i=0; i<nt; i++)
    ans[i] = ans[np-1+i];
ans.resize(nt);
return ans;
}
inline int getID(char c){
    return c - 'a';
}
// Find p in text t. Wildcard character *
vector<bool> stringMatchingWithWildcards(string t, string p){
    int nt = t.size();
    int np = p.size();
    vector<cd> fa(nt), fb(np);
    for(int i=0; i<nt; i++){
        double apha = (2*PI*getID(t[i]))/26;
        fa[i] = cd(cos(apha), sin(apha));
    }
    reverse(p.begin(), p.end());
    int k = 0;
    for(int i=0; i<np; i++){
        if(p[i] != '*'){
            double apha = (2*PI*getID(p[i]))/26;
            fb[i] = cd(cos(apha), -sin(apha));
            k++;
        }else{
            fb[i] = cd(0, 0);
        }
    }
    int n = 1;
    while(n < int(nt + np) )
        n <<= 1;
    fa.resize(n);
    fb.resize(n);
    fft(fa, false);
    fft(fb, false);
    for (int i = 0; i < n; i++)
        fa[i] = fa[i]*fb[i];
    fft(fa, true);
    vector<bool> result(nt - np+1);
    for (int i = 0; i < (nt - np+1); i++)
        result[i] = (int(fa[np-1+i].a + 1e-9) == k);
    return result;
}

```

4.11 Floyd Cycle Finding

```

#include <bits/stdc++.h>
using namespace std;
int f(int x);
typedef pair<int, int> pii;
pii floydCycleFinding(int x0){
    int tortoise = f(x0), hare = f(f(x0));
    while(tortoise != hare){

```

```

        tortoise = f(tortoise);
        hare = f(f(hare));
    }
    int mu = 0;
    hare = x0;
    while(tortoise != hare){
        tortoise = f(tortoise);
        hare = f(hare);
        mu++;
    }
    int lambda = 1;
    hare = f(tortoise);
    while(tortoise != hare){
        hare = f(hare);
        lambda++;
    }
    return pii(mu, lambda);
}

```

4.12 Function Root Using Newton

```

#include <bits/stdc++.h>
using namespace std;
typedef long double ld;
struct Poly{
    vector<ld> v;
    Poly(vector<ld> &v1):v(v1){}
    //return f(x)
    ld f(ld x){
        ld ans = 0;
        ld e = 1;
        int n = v.size();
        for(int i=0; i<n; i++){
            ans += v[i] * e;
            e *= x;
        }
        return ans;
    }
    //return f'(x)
    ld df(ld x){
        ld ans = 0;
        ld e = 1;
        int n = v.size();
        for(int i=1; i<n; i++){
            ans += i * v[i] * e;
            e *= x;
        }
        return ans;
    }
}
// takes some root of the polynomial
ld root(ld x0=1){
    const ld eps = 1E-10;
    ld x = x0;
    for (;;) {
        ld nx = x - (f(x)/df(x));
        if (abs(x - nx) < eps)
            break;
        x = nx;
    }
    return x;
}

```

```

}
//div f(x) by (x-a)
void div(ld a){
    int g = (int)v.size() - 1;
    vector<ld> aux(g);
    for(int i=g; i>=1; i--){
        aux[i-1] = v[i];
        v[i-1] += a*aux[i-1];
    }
    v = aux;
}
};

```

4.13 Gauss

```

#include <bits/stdc++.h>
using namespace std;
const int INF = 0x3f3f3f3f;
typedef long double ld;
const ld EPS = 1e-9;
int gauss(vector<vector<ld>> a, vector<ld> &ans) {
    int n = (int) a.size();
    int m = (int) a[0].size() - 1;
    vector<int> where (m, -1);
    for (int col=0, row=0; col<m && row<n; col++) {
        int sel = row;
        for (int i=row; i<n; i++)
            if (abs(a[i][col]) > abs(a[sel][col]))
                sel = i;
        if (abs(a[sel][col]) < EPS)
            continue;
        for (int i=col; i<=m; i++)
            swap(a[sel][i], a[row][i]);
        where[col] = row;
        for (int i=0; i<n; i++){
            if (i != row) {
                ld c = a[i][col] / a[row][col];
                for (int j=col; j<=m; j++)
                    a[i][j] -= a[row][j] * c;
            }
        }
        row++;
    }
    ans.assign(m, 0);
    for (int i=0; i<m; i++)
        if (where[i] != -1)
            ans[i] = a[where[i]][m] / a[where[i]][i];
    for (int i=0; i<n; i++) {
        ld sum = 0;
        for (int j=0; j<m; j++)
            sum += ans[j] * a[i][j];
        if (abs (sum - a[i][m]) > EPS)
            return 0;
    }
    for (int i=0; i<m; i++)
        if (where[i] == -1)
            return INF;
    return 1;
}

```

4.14 Gauss Xor

```

#include <bits/stdc++.h>
using namespace std;
const int MAXB = 30;
struct GaussXOR {
    int table[MAXB];
    GaussXOR() {
        for(int i = 0; i < MAXB; i++) {
            table[i] = 0;
        }
    }
    int size() {
        int ans = 0;
        for(int i = 0; i < MAXB; i++) {
            if(table[i]) ans++;
        }
        return ans;
    }
    bool isComb(int x) {
        for(int i = MAXB-1; i >= 0; i--) {
            x = std::min(x, x ^ table[i]);
        }
        return x == 0;
    }
    void add(int x) {
        for(int i = MAXB-1; i >= 0; i--) {
            if((table[i] == 0) and ((x>>i) & 1)){
                table[i] = x;
                x = 0;
            } else {
                x = std::min(x, x ^ table[i]);
            }
        }
    }
    int max(){
        int ans = 0;
        for(int i = MAXB-1; i >= 0; i--) {
            ans = std::max(ans, ans ^ table[i]);
        }
        return ans;
    }
};

```

4.15 Gray Code

```

int grayCode(int nth){
    return nth ^ (nth >> 1);
}
int revGrayCode(int g){
    int nth = 0;
    for (; g > 0; g >>= 1)
        nth ^= g;
    return nth;
}

```

4.16 Matrix

```
#include <bits/stdc++.h>
#include "modular.h"
using namespace std;
const int D = 3;
struct Matrix{
    int m[D][D];
    Matrix(bool identify = false){
        memset(m, 0, sizeof(m));
        for (int i = 0; i < D; i++)
            m[i][i] = identify;
    }
    Matrix(vector<vector<int>> mat){
        for(int i=0; i<D; i++)
            for(int j=0; j<D; j++)
                m[i][j] = mat[i][j];
    }
    int * operator[] (int pos){
        return m[pos];
    }
    Matrix operator*(Matrix oth){
        Matrix ans;
        for (int i = 0; i < D; i++){
            for (int j = 0; j < D; j++){
                int &sum = ans[i][j];
                for (int k = 0; k < D; k++)
                    sum = modSum(sum, modMul(m[i][k], oth[k][j]));
            }
        }
        return ans;
    }
};
Matrix fastPow(Matrix base, ll exp){
    Matrix ans(true);
    while(exp){
        if(exp&1LL)
            ans = ans * base;
        base = base*base;
        exp>>=1;
    }
    return ans;
}
```

4.17 Modular Arithmetic

```
#include <bits/stdc++.h>
#include "extended_euclidean.h"
using namespace std;
const int MOD = 1000000007;
inline int modSum(int a, int b, int mod = MOD){
    int ans = a+b;
    if(ans >= mod) ans -= mod;
    return ans;
}
inline int modSub(int a, int b, int mod = MOD){
    int ans = a-b;
    if(ans < 0) ans += mod;
```

```
    return ans;
}
inline int modMul(int a, int b, int mod = MOD){
    return (a*1LL*b)%mod;
}
int inv(int a, int mod=MOD){
    assert(a > 0);
    ll inv_x, y;
    extGcd(a, mod, inv_x, y);
    return (inv_x%mod + mod)%mod;
}
int modDiv(int a, int b, int mod = MOD){
    return modMul(a, inv(b, mod));
}
```

4.18 Modular Integer

```
#include <bits/stdc++.h>
using namespace std;
typedef long long ll;
const int MOD = 1e9 + 7;
struct modInt{
    int val;
    modInt(long long v = 0) {
        if (v < 0)
            v = (v % MOD) + MOD;
        if (v >= MOD)
            v %= MOD;
        val = v;
    }
    static int modInv(int a, int m = MOD) {
        int g = m, r = a, x = 0, y = 1;
        while (r != 0) {
            int q = g / r;
            g %= r; swap(g, r);
            x -= q * y; swap(x, y);
        }
        return x < 0 ? x + m : x;
    }
    explicit operator int() const {
        return val;
    }
    modInt& operator+=(const modInt &other) {
        val += other.val;
        if (val >= MOD)
            val -= MOD;
        return *this;
    }
    modInt& operator-=(const modInt &other) {
        val -= other.val;
        if (val < 0) val += MOD;
        return *this;
    }
    modInt& operator*=(const modInt &other) {
        val = ((uint64_t) val * other.val) % MOD;
        return *this;
    }
    modInt& operator/=(const modInt &other) {
        return *this *= other.inv();
    }
}
```

```

friend modInt operator+(const modInt &a, const modInt &b) {
    return modInt(a) += b;
}
friend modInt operator-(const modInt &a, const modInt &b) {
    return modInt(a) -= b;
}
friend modInt operator*(const modInt &a, const modInt &b) {
    return modInt(a) *= b;
}
friend modInt operator/(const modInt &a, const modInt &b) {
    return modInt(a) /= b;
}
modInt& operator++() {
    val = (val == (MOD - 1)) ? 0 : val + 1;
    return *this;
}
modInt operator++(int) {
    modInt before = *this;
    ++*this;
    return before;
}
modInt& operator--() {
    val = val == 0 ? MOD - 1 : val - 1;
    return *this;
}
modInt operator--(int) {
    modInt before = *this;
    --*this;
    return before;
}
modInt operator-() const {
    return (val == 0) ? 0 : MOD - val;
}
bool operator==(const modInt &other) const {
    return val == other.val;
}
bool operator!=(const modInt &other) const {
    return val != other.val;
}
modInt inv() const {
    return modInv(val);
}
modInt pow(long long p) const {
    assert(p >= 0);
    modInt a = *this, result = 1;
    while (p > 0) {
        if (p & 1)
            result *= a;
        a *= a;
        p >>= 1;
    }
    return result;
}
};

```

4.19 Montgomery Multiplication

```

#include <bits/stdc++.h>
using namespace std;
using u64 = uint64_t;

```

```

using u128 = __uint128_t;
using i128 = __int128_t;
struct u256{
    u128 high, low;
    static u256 mult(u128 x, u128 y){
        u64 a = x >> 64, b = x;
        u64 c = y >> 64, d = y;
        u128 ac = (u128)a * c;
        u128 ad = (u128)a * d;
        u128 bc = (u128)b * c;
        u128 bd = (u128)b * d;
        u128 carry = (u128)(u64)ad + (u128)(u64)bc + (bd >> 64u);
        u128 high = ac + (ad >> 64u) + (bc >> 64u) + (carry >> 64u);
        u128 low = (ad << 64u) + (bc << 64u) + bd;
        return {high, low};
    }
};
//x_m := x*r mod n
struct Montgomery{
    u128 mod, inv, r2;
    //the N will be an odd number
    Montgomery(u128 n) : mod(n), inv(1), r2(-n % n){
        for (int i = 0; i < 7; i++)
            inv = 2 - n * inv;
        for (int i = 0; i < 4; i++){
            r2 <<= 1;
            if (r2 >= mod)
                r2 -= mod;
        }
        for (int i = 0; i < 5; i++)
            r2 = mult(r2, r2);
    }
    u128 init(u128 x){
        return mult(x, r2);
    }
    u128 reduce(u256 x){
        u128 q = x.low * inv;
        i128 a = x.high - u256::mult(q, mod).high;
        if (a < 0)
            a += mod;
        return a;
    }
    u128 mult(u128 a, u128 b){
        return reduce(u256::mult(a, b));
    }
};

```

4.20 NTT

```

#include <bits/stdc++.h>
using namespace std;
typedef long long ll;
const int MOD = 998244353;
inline int modMul(int a, int b) {
    return (int) ((a*(ll)b) % MOD);
}
namespace ntt {
    int base = 1;
    vector<int> roots = {0, 1};
    vector<int> rev = {0, 1};

```

```

int max_base = -1;
int root = -1;
inline int power(int a, long long b) {
    int res = 1;
    while (b > 0) {
        if (b & 1)
            res = modMul(res, a);
        a = modMul(a, a);
        b >>= 1;
    }
    return res;
}
inline int inv(int a) {
    a %= MOD;
    if (a < 0) a += MOD;
    int b = MOD, u = 0, v = 1;
    while(a) {
        int t = b / a;
        b -= t * a; swap(a, b);
        u -= t * v; swap(u, v);
    }
    assert(b == 1);
    if (u < 0) u += MOD;
    return u;
}
void init() {
    int tmp = MOD - 1;
    max_base = 0;
    while (tmp % 2 == 0) {
        tmp /= 2;
        max_base++;
    }
    root = 2;
    while (true) {
        if (power(root, 1 << max_base) == 1) {
            if (power(root, 1 << (max_base - 1)) != 1) {
                break;
            }
        }
        root++;
    }
}
void ensure_base(int nbase) {
    if (max_base == -1)
        init();
    if (nbase <= base)
        return;
    assert(nbase <= max_base);
    rev.resize(1 << nbase);
    for (int i = 0; i < (1 << nbase); i++)
        rev[i] = (rev[i >> 1] >> 1) + ((i & 1) << (nbase - 1));
    roots.resize(1 << nbase);
    while (base < nbase) {
        int z = power(root, 1 << (max_base - 1 - base));
        for (int i = 1 << (base - 1); i < (1 << base); i++) {
            roots[i << 1] = roots[i];
            roots[(i << 1) + 1] = modMul(roots[i], z);
        }
        base++;
    }
}

```

```

void fft(vector<int> &a) {
    int n = (int) a.size();
    assert((n & (n - 1)) == 0);
    int zeros = __builtin_ctz(n);
    ensure_base(zeros);
    int shift = base - zeros;
    for (int i = 0; i < n; i++) {
        if (i < (rev[i] >> shift)) {
            swap(a[i], a[rev[i] >> shift]);
        }
    }
    for (int k = 1; k < n; k <= 1) {
        for (int i = 0; i < n; i += 2 * k) {
            for (int j = 0; j < k; j++) {
                int x = a[i + j];
                int y = modMul(a[i + j + k], roots[j + k]);
                a[i + j] = x + y - MOD;
                if (a[i + j] < 0) a[i + j] += MOD;
                a[i + j + k] = x - y + MOD;
                if (a[i + j + k] >= MOD) a[i + j + k] -= MOD;
            }
        }
    }
}
vector<int> multiply(vector<int> a, vector<int> b, int eq = 0) {
    int need = (int) (a.size() + b.size() - 1);
    int nbase = 0;
    while ((1 << nbase) < need) nbase++;
    ensure_base(nbase);
    int sz = 1 << nbase;
    a.resize(sz);
    b.resize(sz);
    fft(a);
    if (eq)
        b = a;
    else
        fft(b);
    int inv_sz = inv(sz);
    for (int i = 0; i < sz; i++)
        a[i] = modMul(modMul(a[i], b[i]), inv_sz);
    reverse(a.begin() + 1, a.end());
    fft(a);
    a.resize(need);
    return a;
}
vector<int> square(vector<int> a) {
    return multiply(a, a, 1);
}
vector<int> pow(vector<int> a, ll e) {
    int need = (int) ((a.size() - 1) * e + 1);
    int nbase = 0;
    while ((1 << nbase) < need) nbase++;
    ensure_base(nbase);
    int sz = 1 << nbase;
    a.resize(sz);
    fft(a);
    int inv_sz = ntt::inv(sz);
    for (int i = 0; i < sz; i++)
        a[i] = modMul(power(a[i], e), inv_sz);
    reverse(a.begin() + 1, a.end());
    fft(a);
}

```

```

    a.resize(need);
    return a;
}
};

```

4.21 Prime Number

```

#include <bits/stdc++.h>
#include "basic_math.h"
using namespace std;
typedef unsigned long long ull;
ull modMul(ull a, ull b, ull mod){
    return (a * (__uint128_t)b) % mod;
}
bool checkComposite(ull n, ull a, ull d, int s){
    ull x = fastPow(a, d, n);
    if (x == 1 or x == n - 1)
        return false;
    for (int r = 1; r < s; r++){
        x = modMul(x, x, n);
        if (x == n - 1LL)
            return false;
    }
    return true;
};
bool millerRabin(ull n){
    if (n < 2)
        return false;
    int r = 0;
    ull d = n - 1LL;
    while ((d & 1LL) == 0){
        d >>= 1;
        r++;
    }
    for (ull a : {2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37}){
        if (n == a)
            return true;
        if (checkComposite(n, a, d, r))
            return false;
    }
    return true;
}
ull pollard(ull n){
    auto f = [n](ull x) { return modMul(x, x, n) + 1; };
    ull x = 0, y = 0, t = 0, prd = 2, i = 1, q;
    while (t++ % 40 || __gcd(prd, n) == 1){
        if (x == y)
            x = ++i, y = f(x);
        if ((q = modMul(prd, max(x, y) - min(x, y), n))
            prd = q;
        x = f(x), y = f(y));
    }
    return __gcd(prd, n);
}
vector<ull> factor(ull n){
    if (n == 1)
        return {};
    if (millerRabin(n))
        return {n};
    ull x = pollard(n);

```

```

    auto l = factor(x), r = factor(n / x);
    l.insert(l.end(), r.begin(), r.end());
    return l;
}

```

4.22 Rank Matrix

```

#include <bits/stdc++.h>
using namespace std;
typedef long double ld;
const ld EPS = 1e-9;
int compute_rank(vector<vector<ld>> A) {
    int n = A.size();
    int m = A[0].size();
    int rank = max(n, m);
    vector<bool> row_selected(n, false);
    for (int i = 0; i < m; ++i) {
        int j;
        for (j = 0; j < n; ++j) {
            if (!row_selected[j] && abs(A[j][i]) > EPS)
                break;
        }
        if (j == n) {
            rank--;
        } else {
            row_selected[j] = true;
            for (int p = i + 1; p < m; p++)
                A[j][p] /= A[j][i];
            for (int k = 0; k < n; k++) {
                if (k != j && abs(A[k][i]) > EPS) {
                    for (int p = i + 1; p < m; p++)
                        A[k][p] -= A[j][p] * A[k][i];
                }
            }
        }
    }
    return rank;
}

```

4.23 Simpson Integration

```

#include <bits/stdc++.h>
using namespace std;
double f(double x);
const int N = 1000000;
double simpson_integration(double a, double b){
    double h = (b - a) / N;
    double s = f(a) + f(b); // a = x_0 and b = x_{2n}
    for (int i = 1; i <= N - 1; ++i) { // Refer to final Simpson's
        formula
        double x = a + h * i;
        s += f(x) * ((i & 1) ? 4 : 2);
    }
    s *= h / 3;
    return s;
}

```

4.24 Sieve And Primes

```
#include <bits/stdc++.h>
using namespace std;
typedef long long ll;
ll ns;
int np;
bitset<10000010> bs;
vector<ll> primes;
void sieve(ll l) {
    ns = l+1;
    bs.set();
    primes.clear();
    bs[0] = bs[1] = 0;
    for (ll i = 2; i < ns; i++) if (bs[i]) {
        for (ll j = i*i; j < ns; j += i)
            bs[j] = 0;
        primes.push_back(i);
    }
    np = primes.size();
}
bool isPrime(ll n) {
    if (n < ns)
        return bs[n];
    for (ll p: primes) {
        if (p*p > n) break;
        if (n%p == 0)
            return false;
    }
    return true;
}
vector<ll> primeFactors(ll n) {
    vector<ll> factors;
    for (ll p: primes) {
        if (p*p > n) break;
        while (n%p == 0LL) {
            n /= p;
            factors.push_back(p);
        }
    }
    if (n != 1LL) factors.push_back(n);
    return factors;
}
ll numDiv(ll n) {
    ll ans = 1;
    for (ll p: primes) {
        if (p*p > n) break;
        ll f = 0;
        while (n%p == 0LL) {
            n /= p;
            f++;
        }
        ans *= (f+1LL);
    }
    return (n != 1LL) ? 2LL*ans : ans;
}
ll sumDiv(ll n) {
    ll ans = 1;
    for (ll p: primes) {
        if (p*p > n) break;
```

```
ll power = p;
while (n%p == 0LL) {
    n /= p;
    power *= p;
}
ans *= (power - 1LL) / (p - 1LL);
}
if (n != 1LL)
    ans *= (n*n - 1LL) / (n - 1LL);
return ans;
}
int mobius[1000010];
void sieveMobius(ll l) {
    sieve(l);
    mobius[1] = 1;
    for (int i=2; i<=l; i++)
        mobius[i] = 0;
    for (ll p: primes) {
        if (p > l) break;
        for (ll j = p; j <= l; j += p) {
            if (mobius[j] != -1) {
                mobius[j]++;
                if (j%(p*p) == 0)
                    mobius[j] = -1;
            }
        }
    }
    for (int i=2; i<=l; i++) {
        if (mobius[i] == -1)
            mobius[i] = 0;
        else if (mobius[i]%2 == 0)
            mobius[i] = 1;
        else
            mobius[i] = -1;
    }
}
```

5 Geometry

5.1 Basic Geometry

```
#include <bits/stdc++.h>
using namespace std;
#define POINT_DOUBLE
#ifndef POINT_DOUBLE
    // Se necessario, apelar para __float128
    typedef double ftype;
    typedef long double ftLong;
    const double EPS = 1e-9;
    #define eq(a, b) (abs(a - b) < EPS)
    #define lt(a, b) ((a + EPS) < b)
    #define gt(a, b) (a > (b + EPS))
    #define le(a, b) (a < (b + EPS))
    #define ge(a, b) ((a + EPS) > b)
#else
    typedef int32_t ftype;
    typedef int64_t ftLong;
    #define eq(a, b) (a == b)
```

```

#define lt(a, b) (a < b)
#define gt(a, b) (a > b)
#define le(a, b) (a <= b)
#define ge(a, b) (a >= b)
#endif
//Begin Point 2D
struct Point2d{
    ftype x, y;
    Point2d() {}
    Point2d(ftype x1, ftype y1) : x(x1), y(y1) {}
    Point2d operator+(const Point2d &t){
        return Point2d(x + t.x, y + t.y);
    }
    Point2d operator-(const Point2d &t){
        return Point2d(x - t.x, y - t.y);
    }
    Point2d operator*(ftype t){
        return Point2d(x * t, y * t);
    }
    Point2d operator/(ftype t){
        return Point2d(x / t, y / t);
    }
    bool operator<(const Point2d &o) const{
        return lt(x, o.x) or (eq(x, o.x) and lt(y, o.y));
    }
    bool operator==(const Point2d &o) const{
        return eq(x, o.x) and eq(y, o.y);
    }
    friend std::istream& operator >> (std::istream &is, Point2d &p) {
        return is >> p.x >> p.y;
    }
    friend std::ostream& operator << (std::ostream &os, const Point2d &p
        ) {
        return os << p.x << ' ' << p.y;
    }
};
ftLong pw2(ftype a){
    return a * (ftLong)a;
}
//Scalar product
ftLong dot(Point2d a, Point2d b){
    return a.x*(ftLong)b.x + a.y*(ftLong)b.y;
}
ftLong norm(Point2d a){
    return dot(a, a);
}
double len(Point2d a){
    return sqrtl(dot(a, a));
}
double dist(Point2d a, Point2d b){
    return len(a - b);
}
//Vector product
ftLong cross(Point2d a, Point2d b){
    return a.x * (ftLong)b.y - a.y * (ftLong)b.x;
}
//Projection size from A to B
double proj(Point2d a, Point2d b){
    return dot(a, b) / len(b);
}
//The angle between A and B

```

```

double angle(Point2d a, Point2d b){
    return acos(dot(a, b) / len(a) / len(b));
}
//Left rotation. Angle in radian
Point2d rotateL(Point2d p, double ang){
    return Point2d(p.x * cos(ang) - p.y * sin(ang), p.x * sin(ang) + p.y
        * cos(ang));
}
//90 degree left rotation
Point2d perpL(Point2d a){
    return Point2d(-a.y, a.x);
}
//0-> 1o,2o quadrant, 1-> 3o,4o
int half(Point2d &p){
    if (gt(p.y, 0) or (eq(p.y, 0) and ge(p.x, 0)))
        return 0;
    else
        return 1;
}
//angle(a) < angle(b)
bool cmpByAngle(Point2d a, Point2d b){
    int ha = half(a), hb = half(b);
    if (ha != hb){
        return ha < hb;
    }else{
        ftLong c = cross(a, b);
        if(eq(c, 0))
            return lt(norm(a), norm(b));
        else
            return gt(c, 0);
    }
}
inline int sgn(ftLong x){
    return ge(x, 0) ? (eq(x, 0) ? 0 : 1) : -1;
}
// -1: angle(a, b) < angle(b, c)
// 0: angle(a, b) = angle(b, c)
// +1: angle(a, b) > angle(b, c)
int cmpAngleBetweenVectors(Point2d a, Point2d b, Point2d c){
    ftLong dotAB = dot(a, b), dotBC = dot(b, c);
    int sgnAB = sgn(dotAB), sgnBC = sgn(dotBC);
    if(sgnAB == sgnBC){
        //Careful with overflow
        ftLong l = pw2(dotAB)*dot(c, c), r = pw2(dotBC)*dot(a, a);
        if(l == r)
            return 0;
        if(sgnAB == 1)
            return gt(l, r)? -1 : +1;
        return lt(l, r)? -1 : +1;
    }else{
        return (sgnAB > sgnBC)? -1 : +1;
    }
}
//Line parameterized: r1 = a1 + d1*t
//This function can be generalized to 3D
Point2d intersect(Point2d a1, Point2d d1, Point2d a2, Point2d d2){
    return a1 + d1 * (cross(a2 - a1, d2) / cross(d1, d2));
}
//Distance between the point(a) and segment(ps1, ps2)
//This function can be generalized to 3D
ftLong distance_point_to_segment(Point2d a, Point2d ps1, Point2d ps2)

```



```

    {
        if(ps1 == ps2)
            return dist(ps1, a);
        Point2d d = ps2 - ps1;
        ftLong t = max(ftLong(0), min(ftLong(1), dot(a-ps1, d)/len(d)));
        Point2d proj = ps1 + Point2d(d.x*t, d.y*t);
        return dist(a, proj);
    }
    //Distance between the point(a) and line(pl1, pl2)
    //This function can be generalized to 3D
    double dist(Point2d a, Point2d pl1, Point2d pl2){
        //crs = parallelogram area
        double crs = cross(Point2d(a - pl1), Point2d(pl2 - pl1));
        //h = area/base
        return abs(crs / dist(pl1, pl2));
    }
    long double area(vector<Point2d> p){
        long double ret = 0;
        for (int i = 2; i < (int)p.size(); i++)
            ret += cross(p[i] - p[0], p[i - 1] - p[0]) / 2.0;
        return abs(ret);
    }
    ftLong signed_area_parallelogram(Point2d p1, Point2d p2, Point2d p3){
        return cross(p2 - p1, p3 - p2);
    }
    long double triangle_area(Point2d p1, Point2d p2, Point2d p3){
        return abs(signed_area_parallelogram(p1, p2, p3)) / 2.0;
    }
    bool pointInTriangle(Point2d a, Point2d b, Point2d c, Point2d p){
        ftLong s1 = abs(cross(b - a, c - a));
        ftLong s2 = abs(cross(a - p, b - p)) + abs(cross(b - p, c - p)) +
            abs(cross(c - p, a - p));
        return eq(s1, s2);
    }
    bool clockwise(Point2d p1, Point2d p2, Point2d p3){
        return lt(signed_area_parallelogram(p1, p2, p3), 0);
    }
    bool counter_clockwise(Point2d p1, Point2d p2, Point2d p3){
        return gt(signed_area_parallelogram(p1, p2, p3), 0);
    }
    //End Point 2D

    //Begin Line
    ftLong det(ftype a, ftype b, ftype c, ftype d){
        return a * (ftLong)d - b * (ftLong)c;
    }
    struct Line{
        ftype a, b, c;
        Line() {}
        Line(ftype a1, ftype b1, ftype c1) : a(a1), b(b1), c(c1){
            normalize();
        }
        Line(Point2d p1, Point2d p2){
            a = p1.y - p2.y;
            b = p2.x - p1.x;
            c = -a * p1.x - b * p1.y;
            normalize();
        }
        void normalize(){
#ifdef POINT_DOUBLE
            ftype z = sqrt(pw2(a) + pw2(b));

```

```

#else
        ftype z = __gcd(abs(a), __gcd(abs(b), abs(c)));
#endif
        if(eq(z, 0)) return;
        a /= z;
        b /= z;
        c /= z;
        if (lt(a, 0) or (eq(a, 0) and lt(b, 0))){
            a = -a;
            b = -b;
            c = -c;
        }
    }
};

bool intersect(Line m, Line n, Point2d &res){
    ftype zn = det(m.a, m.b, n.a, n.b);
    if (eq(zn, 0))
        return false;
    res.x = -det(m.c, m.b, n.c, n.b) / zn;
    res.y = -det(m.a, m.c, n.a, n.c) / zn;
    return true;
}

bool parallel(Line m, Line n){
    return eq(det(m.a, m.b, n.a, n.b), 0);
}

bool equivalent(Line m, Line n){
    return eq(det(m.a, m.b, n.a, n.b), 0) &&
        eq(det(m.a, m.c, n.a, n.c), 0) &&
        eq(det(m.b, m.c, n.b, n.c), 0);
}

//Distance from a point(x, y) to a line m
double dist(Line m, ftype x, ftype y){
    return abs(m.a * (ftLong)x + m.b * (ftLong)y + m.c) /
        sqrt(m.a * (ftLong)m.a + m.b * (ftLong)m.b);
}

//End Line

//Begin Segment
struct Segment{
    Point2d a, b;
    Segment() {}
    Segment(Point2d a1, Point2d b1) : a(a1), b(b1) {}
};

bool inter1d(ftype a, ftype b, ftype c, ftype d){
    if (gt(a, b)) swap(a, b);
    if (gt(c, d)) swap(c, d);
    return le(max(a, c), min(b, d));
}

bool check_intersection(Segment s1, Segment s2){
    Point2d a = s1.a, b = s1.b, c = s2.a, d = s2.b;
    if (eq(cross(a - c, d - c), 0) && eq(cross(b - c, d - c), 0))
        return inter1d(a.x, b.x, c.x, d.x) && inter1d(a.y, b.y, c.y, d.y);
    return sgn(cross(b - a, c - a)) != sgn(cross(b - a, d - a)) &&
        sgn(cross(d - c, a - c)) != sgn(cross(d - c, b - c));
}

inline bool betw(ftype l, ftype r, ftype x){
    return le(min(l, r), x) and le(x, max(l, r));
}

bool intersect(Segment s1, Segment s2, Segment &ans){
    Point2d a = s1.a, b = s1.b, c = s2.a, d = s2.b;
    if (!inter1d(a.x, b.x, c.x, d.x) || !inter1d(a.y, b.y, c.y, d.y))

```

```

    return false;
Line m(a, b);
Line n(c, d);
if (parallel(m, n)){
    if (!equivalent(m, n))
        return false;
    if (b < a)
        swap(a, b);
    if (d < c)
        swap(c, d);
    ans = Segment(max(a, c), min(b, d));
    return true;
}else{
    Point2d p(0, 0);
    intersect(m, n, p);
    ans = Segment(p, p);
    return betw(a.x, b.x, p.x) && betw(a.y, b.y, p.y) &&
        betw(c.x, d.x, p.x) && betw(c.y, d.y, p.y);
}
}
//End Segment

//Begin Circle
struct Circle{
    ftype x, y, r;
    Circle() {}
    Circle(ftype x1, ftype y1, ftype r1) : x(x1), y(y1), r(r1){};
};
bool pointInCircle(Circle c, Point2d p){
    return ge(c.r, dist(Point2d(c.x, c.y), p));
}
//CircumCircle of a triangle is a circle that passes through all the
//vertices
Circle circumCircle(Point2d a, Point2d b, Point2d c){
    Point2d u((b - a).y, -((b - a).x));
    Point2d v((c - a).y, -((c - a).x));
    Point2d n = (c - b) * 0.5;
    double t = cross(u, n) / cross(v, u);
    Point2d ct = ((a + c) * 0.5) + (v * t);
    double r = dist(ct, a);
    return Circle(ct.x, ct.y, r);
}
//InCircle is the largest circle contained in the triangle
Circle inCircle(Point2d a, Point2d b, Point2d c){
    double m1 = dist(a, b);
    double m2 = dist(a, c);
    double m3 = dist(b, c);
    Point2d ct = ((c * m1) + (b * m2) + a * (m3)) / (m1 + m2 + m3);
    double sp = 0.5 * (m1 + m2 + m3);
    double r = sqrt(sp * (sp - m1) * (sp - m2) * (sp - m3)) / sp;
    return Circle(ct.x, ct.y, r);
}
//Minimum enclosing circle, O(n)
Circle minimumCircle(vector<Point2d> p){
    random_shuffle(p.begin(), p.end());
    Circle c = Circle(p[0].x, p[0].y, 0.0);
    for (int i = 0; i < (int)p.size(); i++){
        if (pointInCircle(c, p[i]))
            continue;
        c = Circle(p[i].x, p[i].y, 0.0);
        for (int j = 0; j < i; j++){

```

```

            if (pointInCircle(c, p[j]))
                continue;
            c = Circle((p[j].x + p[i].x) * 0.5, (p[j].y + p[i].y) * 0.5, 0.5
                * dist(p[j], p[i]));
            for (int k = 0; k < j; k++){
                if (pointInCircle(c, p[k]))
                    continue;
                c = circumCircle(p[j], p[i], p[k]);
            }
        }
    }
    return c;
}
//Return the number of the intersection
int circle_line_intersection(Circle circ, Line line, Point2d &p1,
    Point2d &p2){
    ftLong r = circ.r;
    ftLong a = line.a, b = line.b, c = line.c + line.a * circ.x + line.b
        * circ.y; //take a circle to the (0, 0)
    ftLong x0 = -a * c / (pw2(a) + pw2(b)), y0 = -b * c / (pw2(a) + pw2(
        b)); // (x0, y0) is the shortest distance point of the line
    for (0, 0)
    if (gt(pw2(c), pw2(r) * (pw2(a) + pw2(b)))){
        return 0;
    }
    else if (eq(pw2(c), pw2(r) * (pw2(a) + pw2(b)))){
        p1.x = p2.x = x0 + circ.x;
        p1.y = p2.y = y0 + circ.y;
        return 1;
    }
    else{
        ftLong d_2 = pw2(r) - pw2(c) / (pw2(a) + pw2(b));
        ftLong mult = sqrt(d_2 / (pw2(a) + pw2(b)));
        p1.x = x0 + b * mult + circ.x;
        p2.x = x0 - b * mult + circ.x;
        p1.y = y0 - a * mult + circ.y;
        p2.y = y0 + a * mult + circ.y;
        return 2;
    }
}
//Return the number of the intersection
int circle_intersection(Circle c1, Circle c2, Point2d &p1, Point2d &p2
    ){
    if (eq(c1.x, c2.x) and eq(c1.y, c2.y)){
        if (eq(c1.r, c2.r))
            return -1; //INF
        else
            return 0;
    }
    else{
        Circle circ(0, 0, c1.r);
        Line line;
        line.a = -2 * (c2.x - c1.x);
        line.b = -2 * (c2.y - c1.y);
        line.c = pw2(c2.x - c1.x) + pw2(c2.y - c1.y) + pw2(c1.r) - pw2(c2.
            r);
        int sz = circle_line_intersection(circ, line, p1, p2);
        p1.x += c1.x;
        p2.x += c1.x;
        p1.y += c1.y;
        p2.y += c1.y;
        return sz;
    }
}

```

```

}

bool checkIfTheSegmentIsCompletelyCoveredByCircles(vector<Circle> &vc,
    Segment s){
    vector<Point2d> v = {s.a, s.b};
    Line l(s.a, s.b);
    for (Circle c : vc){
        Point2d p1, p2;
        int inter = circle_line_intersection(c, l, p1, p2);
        if (inter >= 1 and betw(s.a.x, s.b.x, p1.x) and betw(s.a.y, s.b.y,
            p1.y))
            v.push_back(p1);
        if (inter == 2 and betw(s.a.x, s.b.x, p2.x) and betw(s.a.y, s.b.y,
            p2.y))
            v.push_back(p2);
    }
    sort(v.begin(), v.end());
    bool ans = true;
    for (int i = 1; i < (int)v.size(); i++){
        bool has = false;
        for (Circle c : vc){
            if (pointInCircle(c, v[i - 1]) and pointInCircle(c, v[i])){
                has = true;
                break;
            }
        }
        ans = ans && has;
    }
    return ans;
}

void tangents(Point2d c, double r1, double r2, vector<Line> &ans){
    double r = r2 - r1;
    double z = pw2(c.x) + pw2(c.y);
    double d = z - pw2(r);
    if (lt(d, 0))
        return;
    d = sqrt(abs(d));
    Line l;
    l.a = (c.x * r + c.y * d) / z;
    l.b = (c.y * r - c.x * d) / z;
    l.c = r1;
    ans.push_back(l);
}

vector<Line> tangents(Circle a, Circle b){
    vector<Line> ans;
    for (int i = -1; i <= 1; i += 2)
        for (int j = -1; j <= 1; j += 2)
            tangents(Point2d(b.x - a.x, b.y - a.y), a.r * i, b.r * j, ans);
    for (size_t i = 0; i < ans.size(); ++i){
        ans[i].c -= ans[i].a * a.x + ans[i].b * a.y;
        ans[i].normalize();
    }
    return ans;
}
//End Circle

```

```

using namespace std;

const double PI = acos(-1);
pair<double, double> isCC(Circle circ1, Circle circ2){
    Point2d c1(circ1.x, circ1.y), c2(circ2.x, circ2.y);
    double r1 = circ1.r, r2 = circ2.r;
    double d = dist(c1, c2);
    double x1 = c1.x, x2 = c2.x, y1 = c1.y, y2 = c2.y;
    double mid = atan2(y2 - y1, x2 - x1);
    double a = r1, c = r2;
    double t = acos((a * a + d * d - c * c) / (2 * a * d));
    return make_pair(mid - t, mid + t);
}

int testCC(Circle circ1, Circle circ2){
    Point2d c1(circ1.x, circ1.y), c2(circ2.x, circ2.y);
    double r1 = circ1.r, r2 = circ2.r;
    double d = dist(c1, c2);
    if (le(r1 + r2, d))
        return 1; // not intersected or tged
    if (le(r1 + d, r2))
        return 2; // C1 inside C2
    if (le(r2 + d, r1))
        return 3; // C2 inside C1
    return 0; // intersected
}

struct event_t{
    double theta;
    int delta;
    event_t(double t, int d) : theta(t), delta(d) {}
    bool operator<(const event_t &r) const{
        if (fabs(theta - r.theta) < EPS)
            return delta > r.delta;
        return theta < r.theta;
    }
};

vector<event_t> e;
void add(double begin, double end){
    if (begin <= -PI)
        begin += 2 * PI, end += 2 * PI;
    if (end > PI){
        e.push_back(event_t(begin, 1));
        e.push_back(event_t(PI, -1));
        e.push_back(event_t(-PI, 1));
        e.push_back(event_t(end - 2 * PI, -1));
    }else{
        e.push_back(event_t(begin, 1));
        e.push_back(event_t(end, -1));
    }
}

double calc(Point2d c, double r, double a1, double a2){
    double da = a2 - a1;
    double aa = r * r * (da - sin(da)) / 2;
    Point2d p1 = Point2d(cos(a1), sin(a1)) * r + c;
    Point2d p2 = Point2d(cos(a2), sin(a2)) * r + c;
    return cross(p1, p2) / 2 + aa;
}

/* O(n^2 logn), please remove coincided circles first. */
double circle_union(vector<Circle> &vc){
    int n = vc.size();
    for (int i = n - 1; i >= 0; i--){
        if (eq(vc[i].r, 0)){

```

5.2 Circle Area Union

```
#include "basic_geometry.h"
```

```

    swap(vc[i], vc[n - 1]);
    n--;
    continue;
}
for (int j = 0; j < i; j++){
    if (eq(vc[i].x, vc[j].x) and eq(vc[i].y, vc[j].y) and eq(vc[i].r
        , vc[j].r)){
        swap(vc[i], vc[n - 1]);
        n--;
    }
}
}
if (n == 0)
    return 0;
vc.resize(n);
vector<double> cntarea(2 * n, 0);
for (int c = 0; c < n; c++){
    int cvrcnt = 0;
    e.clear();
    for (int i = 0; i < n; i++){
        if (i != c){
            int r = testCC(vc[c], vc[i]);
            if (r == 2){
                cvrcnt++;
            } else if (r == 0){
                auto paa = isCC(vc[c], vc[i]);
                add(paa.first, paa.second);
            }
        }
    }
    if (e.size() == 0){
        double a = PI * vc[c].r * vc[c].r;
        cntarea[cvrcnt] -= a;
        cntarea[cvrcnt + 1] += a;
    } else {
        e.push_back(event_t(-PI, 1));
        e.push_back(event_t(PI, -2));
        sort(e.begin(), e.end());
        for (int i = 0; i < int(e.size()) - 1; i++){
            cvrcnt += e[i].delta;
            double a = calc(Point2d(vc[c].x, vc[c].y), vc[c].r, e[i].theta
                , e[i + 1].theta);
            cntarea[cvrcnt - 1] -= a;
            cntarea[cvrcnt] += a;
        }
    }
}
double ans = 0;
for (int i = 1; i <= n; i++)
    ans += cntarea[i];
return ans;
}

```

5.3 Circles to Tree

```

#include <bits/stdc++.h>
using namespace std;
typedef pair<int, int> pii;
struct Circle{
    int x, y, r, id;

```

```

    Circle(){}
    Circle(int x1, int y1, int r1, int id1): x(x1), y(y1), r(r1), id(id1)
        ){}
};
// a^2 + b^2 == c^2
double findB(double a, double c){
    return sqrt(c*c - a*a);
}
// - There is no intersection between the circles
// - The parent of circle i will be the smallest circle that includes i
namespace CirclesToTree{
    int X = 0;
    int n;
    vector<Circle> vc;
    vector<int> p;
    struct SetElement{
        int id;
        int side; //Up:1, Down:-1
        SetElement(int id1, int side1): id(id1), side(side1){};
        double getY(int x = X) const{
            return vc[id].y + side*findB(vc[id].x - x, vc[id].r);
        }
        bool operator <(const SetElement &o) const{
            auto l = getY(), r = o.getY();
            if (abs(l-r) < 1e-9)
                return vc[id].r*side < vc[o.id].r*o.side;
            else
                return l < r;
        }
    };
    long long pw2(int a){
        return a*1LL*a;
    }
    bool contains(int big, int small){
        if (big == -1 or small == -1) return false;
        Circle &s = vc[small], &b = vc[big];
        if (s.r > b.r) return false;
        return pw2(s.x-b.x) + pw2(s.y-b.y) <= pw2(b.r-s.r);
    }
    void updateParent(int id, int par){
        if (par != -1 and p[id] == -1) p[id] = par;
    }
    //Public
    vector<vector<int>> solve(vector<Circle> circles){
        vc = circles; n = vc.size();
        p.assign(n, -1);
        vector<vector<int>> adj(n, vector<int>());
        vector<pii> events;
        for (auto c: vc){
            events.emplace_back(c.x-c.r, ~c.id);
            events.emplace_back(c.x+c.r, c.id);
        }
        sort(events.begin(), events.end());
        set<SetElement> st;
        for (auto e: events){
            X = e.first;
            int id = e.second;
            if (id < 0){
                id = ~id;
                auto it = st.lower_bound(SetElement(id, -2));
                if (it != st.end()){

```

```

    int id2 = it->id;
    if(contains(id2, id)) updateParent(id, id2);
    if(contains(p[id2], id)) updateParent(id, p[id2]);
}
if(it != st.begin()){
    it--;
    int id2 = it->id;
    if(contains(id2, id)) updateParent(id, id2);
    if(contains(p[id2], id)) updateParent(id, p[id2]);
}
st.emplace(id, 1);
st.emplace(id, -1);
if(p[id] != -1){
    adj[p[id]].push_back(id);
}
}
else{
    st.erase(SetElement(id, 1));
    st.erase(SetElement(id, -1));
}
}
return adj;
}
};

```

5.4 Count Lattices

```

#include "../code/math/fraction.h"
Fraction f_1 = 1;
//Calculates number of integer points (x,y) such for 0<=x<n and 0<y<=
//floor(k*x+b)
//O((log(N))*log(MAXV))
f_type count_lattices(Fraction k, Fraction b, f_type n) {
    auto fk = (f_type)k;
    auto fb = (f_type)b;
    auto cnt = 0LL;

    if (k >= f_1 || b >= f_1) {
        cnt += (fk * (n - 1) + 2 * fb) * n / 2;
        k = k - Fraction(fk, 1);
        b = b - Fraction(fb, 1);
    }
    auto t = k * Fraction(n, 1) + b;
    auto ft = (f_type)t;
    if (ft >= 1) {
        cnt += count_lattices(f_1 / k, (t - Fraction((f_type)t, 1)) / k, (
            f_type)t);
    }
    return cnt;
}

```

5.5 Concave Polygon

```

#include "basic_geometry.h"
const int INSIDE=-1, BOUNDARY=0, OUTSIDE=1;
struct ConcavePolygon{
    vector<Point2d> vp;
    ConcavePolygon(vector<Point2d> aux){
        vp = aux;
    }
};

```

```

}
// -1 inside, 0 boundary, 1 outside
int pointInPolygon(Point2d pt) {
    int n = vp.size(), w = 0;
    for(int i=0; i<n; i++){
        if(pt == vp[i])
            return 0;
        int j = (i+1==n?0:i+1);
        if(vp[i].y == pt.y and vp[j].y == pt.y) {
            if (min(vp[i].x, vp[j].x) <= pt.x and pt.x <= max(vp[i].x, vp[
                j].x))
                return 0;
        }else{
            bool below = vp[i].y < pt.y;
            if (below != (vp[j].y < pt.y)) {
                auto orientation = cross(pt-vp[i], vp[j]-vp[i]);
                if (orientation == 0) return 0;
                if (below == (orientation > 0))
                    w += below ? 1 : -1;
            }
        }
    }
    return (w==0?-1:-1);
}
};

```

5.6 Convex Hull

```

#include "basic_geometry.h"
using namespace std;
//If accept collinear points then change for <=
bool cw(Point2d a, Point2d b, Point2d c) {
    return lt(cross(b - a, c - b), 0);
}
//If accept collinear points then change for >=
bool ccw(Point2d a, Point2d b, Point2d c) {
    return gt(cross(b - a, c - b), 0);
}
// Returns the points clockwise
vector<Point2d> convex_hull(vector<Point2d> a){
    if (a.size() == 1)
        return a;
    sort(a.begin(), a.end());
    a.erase(unique(a.begin(), a.end()), a.end());
    vector<Point2d> up, down;
    Point2d p1 = a[0], p2 = a.back();
    up.push_back(p1);
    down.push_back(p1);
    for (int i = 1; i < (int)a.size(); i++){
        if ((i == int(a.size() - 1)) || cw(p1, a[i], p2)){
            while (up.size() >= 2 && !cw(up[up.size() - 2], up[up.size() -
                1], a[i]))
                up.pop_back();
            up.push_back(a[i]);
        }
        if ((i == int(a.size() - 1)) || ccw(p1, a[i], p2)){
            while (down.size() >= 2 && !ccw(down[down.size() - 2], down[down
                .size() - 1], a[i]))
                down.pop_back();
            down.push_back(a[i]);
        }
    }
}

```

```

    }
}
a.clear();
for (int i = 0; i < (int)up.size(); i++)
    a.push_back(up[i]);
for (int i = down.size() - 2; i > 0; i--)
    a.push_back(down[i]);
return a;
}

```

5.7 Convex Hull Trick

```

#include "basic_geometry.h"
using namespace std;
struct LineCHT{
    ftype k, b;
    int id;
    LineCHT() {}
    LineCHT(ftype k, ftype b, int id=-1): k(k), b(b), id(id) {}
};
struct ConvexHullTrick{
    vector<Point2d> hull, vecs;
    ConvexHullTrick(){}
    ConvexHullTrick(vector<LineCHT> v){
        sort(v.begin(), v.end(), [&](LineCHT a, LineCHT b){
            return lt(a.k, b.k);
        });
        for(auto l: v)
            add_line(l.k, l.b);
    }
    //Here we will assume that when linear functions are added, their k
    //only increases and we want to find minimum values.
    void add_line(ftype k, ftype b) {
        Point2d nw(k, b);
        while(!vecs.empty() && lt(dot(vecs.back(), nw - hull.back()), 0))
        {
            hull.pop_back();
            vecs.pop_back();
        }
        if(!hull.empty())
            vecs.push_back(perpL(nw - hull.back()));
        hull.push_back(nw);
    }
    //Find minimum value
    ftLong get(ftype x) {
        Point2d query(x, 1);
        auto it = lower_bound(vecs.begin(), vecs.end(), query, [](Point2d
            a, Point2d b) {
            return gt(cross(a, b), 0);
        });
        return dot(query, hull[it - vecs.begin()]);
    }
};

```

5.8 Convex Polygon

```

#include "convex_hull.h"
using namespace std;

```

```

//Checks if the point P belongs to the segment AB
bool pointInSegment(Point2d &a, Point2d &b, Point2d &p) {
    if(!eq(cross(a-p, b-p), 0))
        return false;
    return betw(a.x, b.x, p.x) && betw(a.y, b.y, p.y);
}
struct ConvexPolygon{
    vector<Point2d> vp;
    ConvexPolygon(vector<Point2d> aux){
        //The points have to be clockwise
        vp = convex_hull(aux);
    }
    //O(log(N))
    //Accepts points on the edge
    bool pointInPolygon(Point2d point){
        if(vp.size() < 3)
            return pointInSegment(vp[0], vp[1], point);
        if(!eq(cross(vp[1]-vp[0], point-vp[0]), 0) and sgn(cross(vp[1]-vp
            [0], point-vp[0])) != sgn(cross(vp[1]-vp[0], vp.back()-vp[0]))
        )
            return false;
        if(!eq(cross(vp.back()-vp[0], point-vp[0]), 0) and sgn(cross(vp.
            back()-vp[0], point-vp[0])) != sgn(cross(vp.back() - vp[0], vp
            [1]-vp[0])) )
            return false;
        if(eq(cross(vp[1]-vp[0], point-vp[0]), 0))
            return ge(norm(vp[1]-vp[0]), norm(point-vp[0]));
        int pos = 1, l = 1, r = vp.size() - 2;
        while(l <= r){
            int mid = (l + r)/2;
            if(le(cross(vp[mid] - vp[0], point - vp[0]), 0)){
                pos = mid;
                l = mid+1;
            }else{
                r = mid-1;
            }
        }
        return pointInTriangle(vp[0], vp[pos], vp[pos+1], point);
    }
};

```

5.9 Nearest Pair Of Points

```

#include <bits/stdc++.h>
using namespace std;
struct pt {
    long long x, y, id;
    pt(){}
    pt(int _x, int _y, int _id=-1):x(_x), y(_y), id(_id){}
};
namespace NearestPairOfPoints{
    struct cmp_x {
        bool operator()(const pt & a, const pt & b) const {
            return a.x < b.x || (a.x == b.x && a.y < b.y);
        }
    };
    struct cmp_y {
        bool operator()(const pt & a, const pt & b) const {
            return a.y < b.y;
        }
    };
}

```

```

};
int n;
vector<pt> v;
vector<pt> t;
double mindist;
pair<int, int> best_pair;
void upd_ans(const pt & a, const pt & b) {
    double dist = sqrt((a.x - b.x)*(a.x - b.x) + (a.y - b.y)*(a.y - b.
        y));
    if (dist < mindist) {
        mindist = dist;
        best_pair = {a.id, b.id};
    }
}
void rec(int l, int r) {
    if (r - l <= 3) {
        for (int i = l; i < r; ++i) {
            for (int j = i + 1; j < r; ++j) {
                upd_ans(v[i], v[j]);
            }
        }
        sort(v.begin() + l, v.begin() + r, cmp_y());
        return;
    }
    int m = (l + r) >> 1;
    int midx = v[m].x;
    rec(l, m);
    rec(m, r);
    merge(v.begin() + l, v.begin() + m, v.begin() + m, v.begin() + r,
        t.begin(), cmp_y());
    copy(t.begin(), t.begin() + r - l, v.begin() + l);
    int tsz = 0;
    for (int i = l; i < r; ++i) {
        if (abs(v[i].x - midx) < mindist) {
            for (int j = tsz - 1; j >= 0 && v[i].y - t[j].y < mindist; --j)
                upd_ans(v[i], t[j]);
            t[tsz++] = v[i];
        }
    }
}
pair<int, int> solve(vector<pt> _v) {
    v = _v;
    n = v.size();
    t.resize(n);
    sort(v.begin(), v.end(), cmp_x());
    mindist = 1E20;
    rec(0, n);
    return best_pair;
}
};

```

5.10 Point 3D

```

#include <bits/stdc++.h>
using namespace std;
// #define POINT_DOUBLE
#ifdef POINT_DOUBLE
    typedef double ftype;
    typedef long double ftLong;

```

```

    const double EPS = 1e-9;
    #define eq(a, b) (abs(a-b)<EPS)
    #define lt(a, b) ((a+EPS)<b)
    #define gt(a, b) (a>(b+EPS))
    #define le(a, b) (a<=(b+EPS))
    #define ge(a, b) ((a+EPS)>b)
#else
    typedef int32_t ftype;
    typedef int64_t ftLong;
    #define eq(a, b) (a==b)
    #define lt(a, b) (a<b)
    #define gt(a, b) (a>b)
    #define le(a, b) (a<=b)
    #define ge(a, b) (a>=b)
#endif
// Point3D
struct Point3d {
    ftype x, y, z;
    Point3d() {}
    Point3d(ftype x, ftype y, ftype z) : x(x), y(y), z(z) {}
    Point3d operator+(Point3d t) {
        return Point3d(x + t.x, y + t.y, z + t.z);
    }
    Point3d operator-(Point3d t) {
        return Point3d(x - t.x, y - t.y, z - t.z);
    }
    Point3d operator*(ftype t) {
        return Point3d(x * t, y * t, z * t);
    }
    Point3d operator/(ftype t) {
        return Point3d(x / t, y / t, z / t);
    }
};
ftLong dot(Point3d a, Point3d b) {
    return a.x * (ftLong)b.x + a.y * (ftLong)b.y + a.z * (ftLong)b.z;
}
double len(Point3d a) {
    return sqrt(dot(a, a));
}
double dist(Point3d a, Point3d b) {
    return len(a-b);
}
double proj(Point3d a, Point3d b) {
    return dot(a, b) / len(b);
}
// theta -> XY; phi -> ZY;
Point3d toVetor(double theta, double phi, double r) {
    return Point3d(r*cos(theta)*sin(phi), r*sin(theta)*sin(phi), r*cos(
        phi));
}
double getAngleTheta(Point3d p) {
    return atan2(p.y, p.x);
}
double getAnglePhi(Point3d p) {
    return acos(p.z/len(p));
}
Point3d rotateX(Point3d p, double ang) {
    return Point3d(p.x, p.y*cos(ang)-p.z*sin(ang), p.y*sin(ang)+p.z*cos(
        ang));
}
Point3d rotateY(Point3d p, double ang) {

```

```

    return Point3d(p.x*cos(ang)+p.z*sin(ang), p.y, -p.x*sin(ang)+p.z*cos
        (ang));
}
Point3d rotateZ(Point3d p, double ang){
    return Point3d(p.x*cos(ang)-p.y*sin(ang), p.x*sin(ang)+p.y*cos(ang),
        p.z);
}
//Rotation in relation to the normal axis
Point3d rotateNormal(Point3d v, Point3d n, double ang){
    double theta = getAngleTheta(n);
    double phi = getAnglePhi(n);
    v = rotateZ(v, -theta);
    v = rotateY(v, -phi);
    v = rotateZ(v, ang);
    v = rotateY(v, phi);
    v = rotateZ(v, theta);
    return v;
}
Point3d cross(Point3d a, Point3d b){
    return Point3d(a.y * b.z - a.z * b.y,
        a.z * b.x - a.x * b.z,
        a.x * b.y - a.y * b.x);
}
ftLong triple(Point3d a, Point3d b, Point3d c){
    return dot(a, cross(b, c));
}
Point3d planeIntersect(Point3d a1, Point3d n1, Point3d a2, Point3d n2,
    Point3d a3, Point3d n3){
    Point3d x(n1.x, n2.x, n3.x);
    Point3d y(n1.y, n2.y, n3.y);
    Point3d z(n1.z, n2.z, n3.z);
    Point3d d(dot(a1, n1), dot(a2, n2), dot(a3, n3));
    return Point3d(triple(d, y, z),
        triple(x, d, z),
        triple(x, y, d)) / triple(n1, n2, n3);
}
struct Sphere{
    ftype x, y, z, r;
    Sphere(){}
    Sphere(ftype x, ftype y, ftype z, ftype r):x(x), y(y), z(z), r(r){}
};
//Minimum enclosing Sphere, O(n*70000)
//It is also possible to do with ternary search in the 3 dimensions
Sphere minimumSphere(vector<Point3d> vp){
    Point3d ans(0, 0, 0);
    int n = vp.size();
    for(Point3d p: vp)
        ans = ans + p;
    ans = ans/n;
    double P = 0.1;
    double d = 0, e = 0;
    for(int i = 0; i < 70000; i++){
        int f = 0;
        d = dist(ans, vp[0]);
        for (int j = 1; j < n; j++) {
            e = dist(ans, vp[j]);
            if (d < e) {
                d = e;
                f = j;
            }
        }
    }
}

```

```

    ans = ans + (vp[f]-ans)*P;
    P *= 0.998;
}
return Sphere(ans.x, ans.y, ans.z, d);
}

```

6 String Algorithms

6.1 Aho Corasick

```

#include <bits/stdc++.h>
#define F first
#define S second
using namespace std;
const int K = 26;
inline int getID(char c){
    return c-'a';
}
namespace Aho{
    struct Vertex {
        int next[K], go[K];
        int leaf = -1; // CAUTION with repeated strings!
        int p = -1, sz, match=-1;
        char pch;
        int suff_link = -1;
        int end_link = -1;
        Vertex(int p1=-1, char ch1='$', int sz1=0) : p(p1), pch(ch1){
            fill(begin(next), end(next), -1);
            fill(begin(go), end(go), -1);
            sz = sz1;
        }
    };
    vector<Vertex> trie;
    void init(){
        trie.clear();
        trie.emplace_back();
    }
    int add_string(string const& s, int id=1) {
        int v = 0;
        for (char ch : s) {
            int c = getID(ch);
            if (trie[v].next[c] == -1) {
                trie[v].next[c] = trie.size();
                trie.emplace_back(v, ch, trie[v].sz+1);
            }
            v = trie[v].next[c];
        }
        trie[v].leaf = id;
        return v;
    }
    int go(int v, char ch);
    int get_suff_link(int v) {
        if (trie[v].suff_link == -1) {
            if (v == 0 || trie[v].p == 0)
                trie[v].suff_link = 0;
            else
                trie[v].suff_link = go(get_suff_link(trie[v].p), trie[v].pch);
        }
    }
}

```



```

    return trie[v].suff_link;
}
int get_end_link(int v) {
    if (trie[v].end_link == -1) {
        if (v == 0 || trie[v].p == 0) {
            trie[v].end_link = 0;
        } else {
            int suff_link = get_suff_link(v);
            if (trie[suff_link].leaf != -1)
                trie[v].end_link = suff_link;
            else
                trie[v].end_link = get_end_link(suff_link);
        }
    }
    return trie[v].end_link;
}
int go(int v, char ch) {
    int c = getID(ch);
    if (trie[v].go[c] == -1) {
        if (trie[v].next[c] != -1)
            trie[v].go[c] = trie[v].next[c];
        else
            trie[v].go[c] = (v == 0) ? 0 : go(get_suff_link(v), ch);
    }
    return trie[v].go[c];
}
};
//Aplication:
typedef pair<int, int> pii;
void addMatch(vector<pii> &ans, int v, int i) {
    // This runs at most sqrt(N) times: 1+2+3+4+...+sqrt(N)=N
    while (v != 0) {
        // The string id is Aho::trie[v].leaf
        ans.emplace_back(i - Aho::trie[v].sz + 1, i);
        v = Aho::get_end_link(v);
    }
}
//Get match positions: O(answer) = O(N * sqrt(N))
vector<pii> whatMatch(string t) {
    int state = 0;
    int i = 0;
    vector<pii> ans;
    for (char c : t) {
        state = Aho::go(state, c);
        if (Aho::trie[state].leaf != -1)
            addMatch(ans, state, i);
        else
            addMatch(ans, Aho::get_end_link(state), i);
        i++;
    }
    sort(ans.begin(), ans.end());
    return ans;
}

int countMatch(int v) {
    if (Aho::trie[v].match == -1) {
        if (v == 0 || Aho::trie[v].p == 0) {
            if (Aho::trie[v].leaf != -1)
                Aho::trie[v].match = 1;
            else
                Aho::trie[v].match = 0;
        }
    }
}

```

```

    } else {
        if (Aho::trie[v].leaf != -1)
            Aho::trie[v].match = 1 + countMatch(Aho::get_end_link(v));
        else
            Aho::trie[v].match = countMatch(Aho::get_end_link(v));
    }
}
return Aho::trie[v].match;
}
//Get match amount: O(t)
long long matchAmount(string t) {
    int state = 0;
    long long ans = 0;
    for (char c : t) {
        state = Aho::go(state, c);
        ans += countMatch(state);
    }
    return ans;
}

```

6.2 KMP

```

#include <bits/stdc++.h>
using namespace std;
// "abcabacd" is [0,0,0,1,2,3,0]
// "aabaaab" is [0,1,0,1,2,2,3]
vector<int> kmp(string s) {
    int n = (int)s.length();
    // pi[i] is the length of the longest proper prefix of the substring
    // s[0..i] which is also a suffix of this substring.
    vector<int> pi(n);
    for (int i = 1; i < n; i++) {
        int j = pi[i-1];
        while (j > 0 and s[i] != s[j])
            j = pi[j-1];
        if (s[i] == s[j])
            j++;
        pi[i] = j;
    }
    return pi;
}
//The ans[i] count the amount of occurrence of the prefix s[0..i] in s
vector<int> prefixOccurrences(string &s) {
    auto pi = kmp(s);
    int n = pi.size();
    vector<int> ans(n + 1);
    for (int i = 0; i < n; i++)
        ans[pi[i]]++;
    for (int i = n-1; i > 0; i--)
        ans[pi[i-1]] += ans[i];
    for (int i = 1; i <= n; i++)
        ans[i-1] = ans[i] + 1;
    ans.pop_back();
    return ans;
}

int K = 26;
inline int getID(char c) {
    return c - 'a';
}

vector<vector<int>> computeAutomaton(string s) {

```

```

s += '#';
int n = s.size();
vector<int> pi = kmp(s);
vector<vector<int>> aut(n, vector<int>(26));
for(int i = 0; i < n; i++){
    for(int c = 0; c < K; c++){
        if(i > 0 and c != getID(s[i]))
            aut[i][c] = aut[pi[i-1]][c];
        else
            aut[i][c] = i + (c == getID(s[i]));
    }
}
return aut;
}

```

6.3 Manacher

```

#include <bits/stdc++.h>
using namespace std;
// source: https://github.com/brunomaletta/Biblioteca/blob/master/
//          Codigo/Strings/manacher.cpp
// ret[2*i] = larger size palindrome centered on i
// ret[2*i+1] = larger size palindrome centered on i and i + 1
vector<int> manacher(const string &s) {
    int l = 0, r = -1, n = s.size();
    vector<int> d1(n), d2(n);
    for (int i = 0; i < n; i++) {
        int k = i > r ? 1 : min(d1[l+r-i], r-i);
        while (i+k < n && i-k >= 0 && s[i+k] == s[i-k]) k++;
        d1[i] = k--;
        if (i+k > r) l = i-k, r = i+k;
    }
    l = 0, r = -1;
    for (int i = 0; i < n; i++) {
        int k = i > r ? 0 : min(d2[l+r-i+1], r-i+1); k++;
        while (i+k <= n && i-k >= 0 && s[i+k-1] == s[i-k]) k++;
        d2[i] = --k;
        if (i+k-1 > r) l = i-k, r = i+k-1;
    }
    vector<int> ret(2*n-1);
    for (int i = 0; i < n; i++) ret[2*i] = 2*d1[i]-1;
    for (int i = 0; i < n-1; i++) ret[2*i+1] = 2*d2[i+1];
    return ret;
}
struct Palindrome {
    vector<int> man;
    Palindrome(const string &s) : man(manacher(s)) {}
    bool isPalindrome(int i, int j) {
        return man[i+j] >= j-i+1;
    }
};

```

6.4 Min Cyclic String

```

#include <bits/stdc++.h>
using namespace std;
string min_cyclic_string(string s){
    s += s;

```

```

int n = s.size();
int i = 0, ans = 0;
while (i < n / 2){
    ans = i;
    int j = i + 1, k = i;
    while (j < n && s[k] <= s[j]){
        if (s[k] < s[j])
            k = i;
        else
            k++;
        j++;
    }
    while (i <= k)
        i += j - k;
}
return s.substr(ans, n / 2);
}

```

6.5 String Hashing

```

#include <bits/stdc++.h>
using namespace std;
struct StringHashing{
    const uint64_t MOD = (1LL<<61) - 1;
    const int base = 31;
    uint64_t modMul(uint64_t a, uint64_t b){
        uint64_t l1 = (uint32_t)a, h1 = a>>32, l2 = (uint32_t)b, h2 = b
        >>32;
        uint64_t l = l1*l2, m = l1*h2 + l2*h1, h = h1*h2;
        uint64_t ret = (l&MOD) + (l>>61) + (h << 3) + (m >> 29) + ((m <<
        35) >> 3) + 1;
        ret = (ret & MOD) + (ret>>61);
        ret = (ret & MOD) + (ret>>61);
        return ret-l;
    }
    int getInt(char c){
        return c-'a'+1;
    }
    vector<uint64_t> hs, p;
//Public:
    StringHashing(string s){
        int n = s.size();
        hs.resize(n); p.resize(n);
        p[0] = 1;
        hs[0] = getInt(s[0]);
        for(int i=1; i<n; i++){
            p[i] = modMul(p[i-1], base);
            hs[i] = (modMul(hs[i-1], base) + getInt(s[i]))%MOD;
        }
    }
    uint64_t getValue(int l, int r){
        if(l > r) return -1;
        uint64_t res = hs[r];
        if(l > 0) res = (res + MOD - modMul(p[r-l+1], hs[l-1]))%MOD;
        return res;
    }
};

```

6.6 Suffix Automaton

```
#include <bits/stdc++.h>
using namespace std;
typedef long long ll;
struct SuffixAutomaton{
    struct state{
        int len, link, first_pos;
        bool is_clone = false;
        map<char, int> next;
    };
    vector<state> st;
    int sz, last;
    SuffixAutomaton(string s){
        st.resize(2 * s.size() + 10);
        st[0].len = 0;
        st[0].link = -1;
        st[0].is_clone = false;
        sz = 1;
        last = 0;
        for (char c : s)
            insert(c);
        preCompute();
    }
    void insert(char c){
        int cur = sz++;
        st[cur].len = st[last].len + 1;
        st[cur].first_pos = st[cur].len - 1;
        st[cur].is_clone = false;
        int p = last;
        while (p != -1 && !st[p].next.count(c)){
            st[p].next[c] = cur;
            p = st[p].link;
        }
        if (p == -1){
            st[cur].link = 0;
        }else{
            int q = st[p].next[c];
            if (st[p].len + 1 == st[q].len){
                st[cur].link = q;
            }else{
                int clone = sz++;
                st[clone].len = st[p].len + 1;
                st[clone].next = st[q].next;
                st[clone].link = st[q].link;
                st[clone].first_pos = st[q].first_pos;
                st[clone].is_clone = true;
                while (p != -1 && st[p].next[c] == q){
                    st[p].next[c] = clone;
                    p = st[p].link;
                }
                st[q].link = st[cur].link = clone;
            }
        }
        last = cur;
    }
    string lcs(string s){
        int v = 0, l = 0, best = 0, bestpos = 0;
        for (int i = 0; i < (int)s.size(); i++){
            while (v && !st[v].next.count(s[i])){
```

```
                v = st[v].link;
                l = st[v].len;
            }
            if (st[v].next.count(s[i])){
                v = st[v].next[s[i]];
                l++;
            }
            if (l > best){
                best = l;
                bestpos = i;
            }
        }
        return s.substr(bestpos - best + 1, best);
    }
    vector<ll> dp;
    vector<int> cnt;
    ll dfsPre(int s){
        if (dp[s] != -1)
            return dp[s];
        dp[s] = cnt[s]; //Accepts repeated substrings
        //dp[s] = 1; //Does not accept repeated substrings
        for (auto p : st[s].next)
            dp[s] += dfsPre(p.second);
        return dp[s];
    }
    void preCompute(){
        cnt.assign(sz, 0);
        vector<pair<int, int>> v(sz);
        for (int i = 0; i < sz; i++){
            cnt[i] = !st[i].is_clone;
            v[i] = make_pair(st[i].len, i);
        }
        sort(v.begin(), v.end(), greater<pair<int, int>>());
        for (int i = 0; i < sz - 1; i++)
            cnt[st[v[i].second].link] += cnt[v[i].second];
        dp.assign(sz, -1);
        dfsPre(0);
    }
};
```

6.7 Suffix Array

```
#include <bits/stdc++.h>
using namespace std;
typedef pair<int, int> pii;
vector<int> sort_cyclic_shifts(string const& s) {
    int n = s.size();
    const int alphabet = 256;
    vector<int> p(n), c(n), cnt(max(alphabet, n), 0);
    for(int i = 0; i < n; i++)
        cnt[s[i]]++;
    for(int i = 1; i < alphabet; i++)
        cnt[i] += cnt[i-1];
    for(int i = 0; i < n; i++)
        p[--cnt[s[i]]] = i;
    c[p[0]] = 0;
    int classes = 1;
    for(int i = 1; i < n; i++) {
        if(s[p[i]] != s[p[i-1]])
            classes++;
```

```

    c[p[i]] = classes - 1;
}
vector<int> pn(n), cn(n);
for(int h = 0; (1 << h) < n; ++h) {
    //Ordenando pelo second no RadixSort
    int h2 = (1 << h);
    for(int i = 0; i < n; i++){
        pn[i] = p[i] - h2;
        if(pn[i] < 0) pn[i] += n;
    }
    fill(cnt.begin(), cnt.begin() + classes, 0);
    for(int i = 0; i < n; i++)
        cnt[c[p[i]]]++;
    for(int i = 1; i < classes; i++)
        cnt[i] += cnt[i-1];
    for(int i = n-1; i >= 0; i--)
        p[--cnt[c[p[i]]]] = pn[i];
    cn[p[0]] = 0;
    classes = 1;
    for(int i = 1; i < n; i++){
        pii cur(c[p[i]], c[(p[i] + h2) % n]);
        pii prev(c[p[i-1]], c[(p[i-1] + h2) % n]);
        if(cur != prev)
            ++classes;
        cn[p[i]] = classes - 1;
    }
    c.swap(cn);
}
return p;
}
// O(N*log(N))
vector<int> sa_construction(string s) {
    s += "$";
    vector<int> sorted_shifts = sort_cyclic_shifts(s);
    sorted_shifts.erase(sorted_shifts.begin());
    return sorted_shifts;
}
// Kasai's algorithm: O(N)
vector<int> lcp_construction(string const& s, vector<int> const& suf)
{
    int n = s.size();
    vector<int> rank(n, 0);
    for(int i = 0; i < n; i++)
        rank[suf[i]] = i;
    int k = 0;
    vector<int> lcp(n-1, 0);
    for(int i = 0; i < n; i++){
        if (rank[i] == n - 1) {
            k = 0; continue;
        }
        int j = suf[rank[i] + 1];
        while (i + k < n && j + k < n && s[i+k] == s[j+k])
            k++;
        lcp[rank[i]] = k;
        if (k) k--;
    }
    return lcp;
}

```

6.8 Suffix Tree

```

#include <bits/stdc++.h>
typedef long long ll;
using namespace std;
namespace SuffixTree {
    const int NS = 60; //Number of strings
    const int MAXN = 100010; //Number of letters
    int cn, cd, ns, en = 1, lst;
    string S[NS]; int lastS = -1;
    /* sufn[si][i] no do sufixo S[si][i...] */
    vector<int> sufn[NS];
    struct Node {
        int l, r, si=0;
        int p, suf=0;
        map<char, int> adj;
        Node() : l(0), r(-1){ suf = p = 0; }
        Node(int ll, int rl, int sl, int pl) : l(ll), r(rl), si(sl), p(pl) {}
        inline int len() { return r - l + 1; }
        inline int operator[](int i) { return S[si][l + i]; }
        inline int& operator()(char c) { return adj[c]; }
    };
    Node t[2*MAXN];
    inline int new_node(int l, int r, int s, int p) {
        t[en] = Node(l, r, s, p);
        return en++;
    }
    void init(){
        t[0] = Node();
        cn=0, cd=0, ns=0, en = 1, lst=0;
        lastS = -1;
    }
    //The strings are inserted independently
    void add_string(string s, char id='$') {
        assert(id < 'A');
        s += id;
        S[++lastS] = s;
        sufn[lastS].resize(s.size() + 1);
        cn = cd = 0;
        int i = 0; const int n = s.size();
        for(int j = 0; j < n; j++){
            for(; i <= j; i++) {
                if(cd == t[cn].len() && t[cn](s[j]))
                    cn = t[cn](s[j]), cd = 0;
                if(cd < t[cn].len() && t[cn][cd] == s[j]) {
                    cd++;
                    if(j < (int)s.size() - 1) break;
                }
                else {
                    if(i) t[lst].suf = cn;
                    for(; i <= j; i++) {
                        sufn[lastS][i] = cn;
                        cn = t[cn].suf;
                    }
                }
            }
            else if(cd == t[cn].len()) {
                sufn[lastS][i] = en;
                if(i) t[lst].suf = en;
                lst = en;
                t[cn](s[j]) = new_node(j, n - 1, lastS, cn);
            }
        }
    }
}

```

```

    cn = t[cn].suf;
    cd = t[cn].len();
} else {
    int mid = new_node(t[cn].l, t[cn].l + cd - 1, t[cn].si, t[cn].
        p);
    t[t[cn].p][t[cn][0]] = mid;
    if(ns) t[ns].suf = mid;
    if(i) t[lst].suf = en;
    lst = en;
    sufn[lastS][i] = en;
    t[mid][s[j]] = new_node(j, n - 1, lastS, mid);
    t[mid][t[cn][cd]] = cn;
    t[cn].p = mid; t[cn].l += cd;
    cn = t[mid].p;
    int g = cn? j - cd : i + 1;
    cn = t[cn].suf;
    while(g < j && g + t[t[cn](S[lastS][g])].len() <= j)
        cn = t[cn](S[lastS][g]), g += t[cn].len();
    if(g == j)
        ns = 0, t[mid].suf = cn, cd = t[cn].len();
    else
        ns = mid, cn = t[cn](S[lastS][g]), cd = j - g;
}
}
}
}
bool match(string &s, int i=0, int no=0, int iEdge=0){
    if(i == (int)s.size())
        return true;
    if(iEdge == t[no].len()){ //I arrived at the Node
        if(t[no].adj.count(s[i]))
            return match(s, i+1, t[no].adj[s[i]], 1);
        else
            return false;
    }
    if(t[no][iEdge] == s[i])
        return match(s, i+1, no, iEdge+1);
    return false;
}
};

```

6.9 Trie

```

#include <bits/stdc++.h>
using namespace std;
const int K = 26;
inline int getId(char c){
    return c - 'a';
}
struct Vertex {
    int next[K];
    int leaf;
    int count;
    Vertex() {
        fill(begin(next), end(next), -1);
        leaf = 0;
        count = 0;
    }
};
struct Trie{

```

```

    vector<Vertex> trie;
    Trie(){
        trie.emplace_back();
    }
    void add(string const& s) {
        int v = 0;
        trie[v].count++;
        for(char ch: s) {
            int c = getId(ch);
            if (trie[v].next[c] == -1) {
                trie[v].next[c] = trie.size();
                trie.emplace_back();
            }
            v = trie[v].next[c];
            trie[v].count++;
        }
        trie[v].leaf++;
    }
    int countStr(string const& s) {
        int v = 0;
        for (char ch : s) {
            int c = getId(ch);
            if (trie[v].next[c] == -1)
                return 0;
            v = trie[v].next[c];
        }
        return trie[v].leaf;
    }
    int countPre(string const& s) {
        int v = 0;
        for (char ch : s) {
            int c = getId(ch);
            if (trie[v].next[c] == -1)
                return 0;
            v = trie[v].next[c];
        }
        return trie[v].count;
    }
    bool remove(string const& s) {
        vector<int> rm;
        int v = 0;
        rm.push_back(v);
        for(char ch: s) {
            int c = getId(ch);
            if (trie[v].next[c] == -1)
                return false;
            v = trie[v].next[c];
            rm.push_back(v);
        }
        if(trie[v].leaf > 0){
            trie[v].leaf--;
            for(int x: rm)
                trie[x].count--;
            return true;
        }
        return false;
    }
};
};

```

6.10 Z Function

```
#include <bits/stdc++.h>
using namespace std;
// z[i] is the length of the longest common prefix between s[0..(n-1)]
// and the suffix of s[i..(n-1)].
// z[0] is generally not well defined.
// "aaabaab" - [0,2,1,0,2,1,0]
// "abacaba" - [0,0,1,0,3,0,1]
vector<int> z_function(string s) {
    int n = (int) s.length();
    vector<int> z(n);
    for (int i = 1, l = 0, r = 0; i < n; i++){
        if (i <= r)
            z[i] = min (r - i + 1, z[i - l]);
        while (i + z[i] < n && s[z[i]] == s[i + z[i]])
            z[i]++;
        if (i + z[i] - 1 > r)
            l = i, r = i + z[i] - 1;
    }
    return z;
}
```

7 Miscellaneous

7.1 Counting Inversions

```
#include <bits/stdc++.h>
using namespace std;
typedef long long ll;
const int INF = 0x3f3f3f3f;
// Counting Inversions: O(N*log(N))
ll ci(vector<int> &v){
    int n = v.size();
    ll inv = 0LL;
    if(n==1)
        return 0;
    vector<int> u1, u2;
    for(int i=0; i < n/2; i++)
        u1.push_back(v[i]);
    for(int i=n/2; i < n; i++)
        u2.push_back(v[i]);
    inv += ci(u1);
    inv += ci(u2);
    u1.push_back(INF);
    u2.push_back(INF);
    int ini1=0, ini2=0;
    for(int i=0; i < n; i++){
        if(u1[ini1] <= u2[ini2]){
            v[i] = u1[ini1++];
        }else{
            v[i] = u2[ini2++];
            inv += u1.size() - ini1 - 1;
        }
    }
    return inv;
}
```

7.2 Histogram

```
#include <bits/stdc++.h>
using namespace std;
typedef long long ll;
// Largest Rectangular Area in a Histogram
ll histogram(vector<int> v){
    int n = v.size();
    v.push_back(0);
    ll ans = 0;
    stack<int> st;
    for(int i = 0; i <= n; i++){
        while(st.size() && v[st.top()] >= v[i]){
            int idx = st.top(); st.pop();
            int L = st.size() ? st.top() : -1;
            ans = max(ans, (i-L-1) * (ll)v[idx]);
        }
        st.push(i);
    }
    return ans;
}
```

7.3 Identify Pattern

```
#include <bits/stdc++.h>
using namespace std;
typedef pair<int, int> pii;
// Return the pattern of vector in O(N): pair<cycle start, cycle size>
pii identifyPattern(vector<int> v){
    int n = v.size();
    reverse(v.begin(), v.end());
    vector<int> pi(n);
    for (int i = 1; i < n; i++) {
        int j = pi[i-1];
        while (j > 0 and v[i] != v[j])
            j = pi[j-1];
        if (v[i] == v[j])
            j++;
        pi[i] = j;
    }
    tuple<int, int, int> ans(n, 1, n-1);
    for(int i=1; i<=n; i++){
        int p = i - pi[i-1];
        if(p == 0)
            continue;
        int idx = n-i;
        ans = min(ans, {idx+p, p, idx});
    }
    auto [sum, p, idx] = ans;
    return pii(idx, p);
}
```

7.4 Kadane 1D and 2D

```
#include <bits/stdc++.h>
using namespace std;
typedef long long ll;
```

```
// Largest Sum Contiguous Subarray: O(N)
ll kadane(vector<ll> &v){
    ll ans = 0, bigger = 0;
    for(int i=0; i < (int)v.size(); i++){
        bigger = max(0LL, bigger + v[i]);
        ans = max(ans, bigger);
    }
    return ans;
}

// Largest Sum Submatrix: O(N^3)
ll kadane2d(vector<vector<int>> &mat){
    if(mat.size() == 0) return 0;
    int n = mat.size(), m = mat[0].size();
    ll ans = 0;
    vector<ll> v(m);
    for(int a=0; a<n; a++){
        fill(v.begin(), v.end(), 0);
        for(int b=a; b<n; b++){
            for(int k=0; k<m; k++){
                v[k] += mat[b][k];
                ans = max(ans, kadane(v));
            }
        }
    }
    return ans;
}

ll circularKadane(vector<ll> v){
    ll ans1 = kadane(v);
    ll sum = 0;
    for(int i=0; i < (int)v.size(); i++){
        sum += v[i];
        v[i] = -v[i];
    }
    return max(ans1, sum + kadane(v));
}
```

7.5 Longest Increasing Subsequence

```
#include <bits/stdc++.h>
using namespace std;
vector<int> lis(vector<int> &v){
    vector<int> st, ans;
    vector<int> pos(v.size()+1), dad(v.size()+1);
    for(int i=0; i < (int)v.size(); i++){
        auto it = lower_bound(st.begin(), st.end(), v[i]); // Do not
        // accept repeated values
        //auto it = upper_bound(st.begin(), st.end(), v[i]); //Accept
        // repeated values
        int p = it-st.begin();
        if(it==st.end())
            st.push_back(v[i]);
        else
            *it = v[i];
        pos[p] = i;
        dad[i] = (p==0)? -1 : pos[p-1];
    }
    int p = pos[st.size() - 1];
    while(p >= 0){
        ans.push_back(v[p]);
        p=dad[p];
    }
}
```

```
reverse(ans.begin(), ans.end());
return ans;
}
```

7.6 Mo Algorithm

```
#include <bits/stdc++.h>
using namespace std;
const int BLOCK_SIZE = 700;
void remove(int idx);
void add(int idx);
void clearAnswer();
int getAnswer();
struct Query{
    int l, r, idx;
    bool operator<(Query other) const{
        if (l / BLOCK_SIZE != other.l / BLOCK_SIZE)
            return l < other.l;
        return (l / BLOCK_SIZE & 1) ? (r < other.r) : (r > other.r);
    }
};

vector<int> mo_s_algorithm(vector<Query> queries){
    vector<int> answers(queries.size());
    sort(queries.begin(), queries.end());
    clearAnswer();
    int L = 0, R = 0;
    add(0);
    for(Query q : queries){
        while(q.l < L) add(--L);
        while(R < q.r) add(++R);
        while(L < q.l) remove(L++);
        while(q.r < R) remove(R--);
        answers[q.idx] = getAnswer();
    }
    return answers;
}
```

7.7 Polyominoes

```
#include <bits/stdc++.h>
#define F first
#define S second
using namespace std;
const int MAXP = 10;
typedef pair<int, int> pii;
//This implementation considers the rotations as distinct
// 0, 10, 10+9, 10+9+8...
int pos[11] = {0, 10, 19, 27, 34, 40, 45, 49, 52, 54, 55};
struct Polyominoes{
    pii v[MAXP];
    int64_t id;
    int n;
    Polyominoes(){
        n = 1;
        v[0] = {0, 0};
        normalize();
    }
    pii& operator[](int i){
```

```

    return v[i];
}
bool add(int a, int b){
    for(int i=0; i<n; i++){
        if(v[i].F == a and v[i].S == b)
            return false;
        v[n++] = pii(a, b);
        normalize();
        return true;
    }
    void normalize(){
        int mnx=100, mny=100;
        for(int i=0; i<n; i++){
            mnx = min(mnx, v[i].F), mny = min(mny, v[i].S);
            id = 0;
            for(int i=0; i<n; i++){
                v[i].F -= mnx, v[i].S -= mny;
                id |= (1LL<<(pos[v[i].F] + v[i].S));
            }
        }
    };
    vector<Polyominoes> polyominoes[MAXP+1];
    int dx[] = {0, 0, -1, 1};
    int dy[] = {-1, 1, 0, 0};
    void buildPolyominoes(int mxN=10){
        for(int i=0; i<=mxN; i++){
            polyominoes[i].clear();
            Polyominoes init;
            queue<Polyominoes> q;
            unordered_set<int64_t> used;
            q.push(init);
            used.insert(init.id);
            while(!q.empty()){
                Polyominoes u = q.front(); q.pop();
                polyominoes[u.n].push_back(u);
                if(u.n == mxN)
                    continue;
                for(int i=0; i<u.n; i++){
                    for(int j=0; j<4; j++){
                        Polyominoes to = u;
                        bool ok = to.add(to[i].F + dx[j], to[i].S + dy[j]);
                        if(ok and !used.count(to.id)){
                            q.push(to);
                            used.insert(to.id);
                        }
                    }
                }
            }
        }
    }
}

```

7.8 Scheduling Jobs

```

#include <bits/stdc++.h>
using namespace std;
typedef long long ll;
struct Job {
    int t, c, idx;
    Job(int t1=0, int c1=0, int i=0):t(t1), c(c1), idx(i){}
};
//Penalty functions fi(t) = c[i]*t

```

```

bool cmp1(Job a, Job b){
    return a.c*(1ll)b.t > b.c*(1ll)a.t;
}
//Penalty functions fi(t) = c[i]*e^(alfa*t)
const double alfa = 2;
const double EPS = 1e-9;
bool cmp2(Job a, Job b){
    return (1 - exp(alfa*a.t))/a.c > (1 - exp(alfa*b.t))/b.c + EPS;
}

```

7.9 Sprague Grundy

```

#include <bits/stdc++.h>
using namespace std;
const int MAXN = 1010;
int version;
int used[MAXN];
int mex() {
    for(int i=0; ; ++i)
        if(used[i] != version)
            return i;
}
int g[MAXN];
// Can remove 1, 2 and 3
void grundy() {
    //Base case depends on the problem
    g[0] = 0;
    g[1] = 1;
    g[2] = 2;
    //Inductive case
    for(int i=3; i<MAXN; i++){
        version++;
        used[g[i-1]] = version;
        used[g[i-2]] = version;
        used[g[i-3]] = version;
        g[i] = mex();
    }
}
string solve(vector<int> v){
    grundy();
    int ans = 0;
    for(int x: v)
        ans ^= g[x];
    return ((ans != 0) ? "First" : "Second");
}

```

8 Theorems and Formulas

8.1 Binomial Coefficients

$$(a+b)^n = \binom{n}{0}a^n + \binom{n}{1}a^{n-1}b + \binom{n}{2}a^{n-2}b^2 + \dots + \binom{n}{k}a^{n-k}b^k + \dots + \binom{n}{n}b^n$$

$$\text{Pascal's Triangle: } \binom{n}{k} = \binom{n-1}{k-1} + \binom{n-1}{k}$$

$$\text{Symmetry rule: } \binom{n}{k} = \binom{n}{n-k}$$

$$\text{Factoring in: } \binom{n}{k} = \frac{n}{k} \binom{n-1}{k-1}$$

$$\text{Sum over } k: \sum_{k=0}^n \binom{n}{k} = 2^n$$

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

Sum over n and k : $\sum_{k=0}^m \binom{n+k}{k} = \binom{n+m+1}{m}$

Sum of the squares: $\binom{n}{0}^2 + \binom{n}{1}^2 + \cdots + \binom{n}{n}^2 = \binom{2n}{n}$

Weighted sum: $1\binom{n}{1} + 2\binom{n}{2} + \cdots + n\binom{n}{n} = n2^{n-1}$

Connection with the Fibonacci numbers: $\binom{n}{0} + \binom{n-1}{1} + \cdots + \binom{n-k}{k} + \cdots + \binom{0}{n} = F_{n+1}$

More formulas: $\sum_{k=0}^m (-1)^k \cdot \binom{n}{k} = (-1)^m \cdot \binom{n-1}{m}$ _____

8.2 Catalan Number

Recursive formula: $C_0 = C_1 = 1$

$C_n = \sum_{k=0}^{n-1} C_k C_{n-1-k}, n \geq 2$

Analytical formula: $C_n = \binom{2n}{n} - \binom{2n}{n-1} = \frac{1}{n+1} \binom{2n}{n}, n \geq 0$

The first few numbers Catalan numbers, C_n (starting from zero):
1, 1, 2, 5, 14, 42, 132, 429, 1430, ...

The Catalan number C_n is the solution for:

- Number of correct bracket sequence consisting of n opening and n closing brackets.
- The number of rooted full binary trees with $n + 1$ leaves (vertices are not numbered). A rooted binary tree is full if every vertex has either two children or no children.
- The number of ways to completely parenthesize $n + 1$ factors.
- The number of triangulations of a convex polygon with $n + 2$ sides (i.e. the number of partitions of polygon into disjoint triangles by using the diagonals).
- The number of ways to connect the $2n$ points on a circle to form n disjoint chords.
- The number of non-isomorphic full binary trees with n internal nodes (i.e. nodes having at least one son).
- The number of monotonic lattice paths from point $(0,0)$ to point (n,n) in a square lattice of size $n \times n$, which do not pass above the main diagonal (i.e. connecting $(0,0)$ to (n,n)).
- Number of permutations of length n that can be stack sorted (i.e. it can be shown that the rearrangement is stack sorted if and only if there is no such index $i < j < k$, such that $a_k < a_i < a_j$).
- The number of non-crossing partitions of a set of n elements.
- The number of ways to cover the ladder $1 \dots n$ using n rectangles (The ladder consists of n columns, where i^{th} column has a height i).

8.3 Euler's Totient

If p is a prime number: $\phi(p) = p - 1$ and $\phi(p^k) = p^k - p^{k-1}$

If a and b are relatively prime, then: $\phi(ab) = \phi(a) \cdot \phi(b)$

In general: $\phi(ab) = \phi(a) \cdot \phi(b) \cdot \frac{\gcd(a,b)}{\phi(\gcd(a,b))}$

This interesting property was established by Gauss: $\sum_{d|n} \phi(d) = n$, Here the sum is over all positive divisors d of n .

Euler's theorem: $a^{\phi(m)} \equiv 1 \pmod{m}$, if a and m are relatively prime.

Generalization: $a^n \equiv a^{\phi(m) + [n \bmod \phi(m)]} \pmod{m}$, for arbitrary a , m and $n \geq \log_2(m)$. _____

8.4 Formulas

Count the number of ways to partition a set of n labelled objects into k nonempty labelled subsets.

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

Stirling Number 2nd: Partitions of an n element set into k not-empty set. Or count the number of ways to partition a set of n labelled objects into k nonempty unlabelled subsets.

$$S_{2nd}(n, k) = \left\{ \begin{matrix} n \\ k \end{matrix} \right\} = \frac{1}{k!} \sum_{i=0}^k (-1)^i \binom{k}{i} (k-i)^n$$

Euler's formula: $f = e - v + 2$

Euler's formula to n Lines or Segment if there is no three lines/segments that contains the same point: $R = intersects + component - n$

Number of regions in a planar graph: $R = E - V + C + 1$ where C is the number of connected components

Given a and b co-prime, $n = a \cdot x + b \cdot y$ where $x \geq 0$ and $y \geq 0$. You are required to find the least value of n , such that all currency values greater than or equal to n can be made using any number of coins of denomination a and b : $n = (a-1) * (b-1)$

generalization of the above problem, n is multiple of $\gcd(a, b)$: $n = lcm(a, b) - a - b + \gcd(a, b)$ _____

8.5 Graph

8.6 Manhattan Distance

Transformation of the manhattan distance to 2 dimensions between $P_1 = (x_1, y_1)$ and $P_2 = (x_2, y_2)$:

$|x_1 - x_2| + |y_1 - y_2| = \max(|A_1 - B_1|, |A_2 - B_2|)$ where $A = (x_1 + y_1, x_1 - y_1)$ e $B = (x_2 + y_2, x_2 - y_2)$

Transformation of the manhattan distance to 3 dimensions between $P_1 = (x_1, y_1, z_1)$ and $P_2 = (x_2, y_2, z_2)$:

$|x_1 - x_2| + |y_1 - y_2| + |z_1 - z_2| = \max(|A_1 - B_1|, |A_2 - B_2|, |A_3 - B_3|, |A_4 - B_4|)$ where $A = (x_1 + y_1 + z_1, x_1 + y_1 - z_1, x_1 - y_1 + z_1, -x_1 + y_1 + z_1)$ e $B = (x_2 + y_2 + z_2, x_2 + y_2 - z_2, x_2 - y_2 + z_2, -x_2 + y_2 + z_2)$

Transformation of the manhattan distance to D dimensions between P_1 and P_2 :

$isSet(i, x) = 1$ if the i-th bit is setted in x and 0 otherwise.

$$A[i] = \sum_{j=0}^{d-1} (-1)^{isSet(j,i)} P_1[j]$$

$$B[i] = \sum_{j=0}^{d-1} (-1)^{isSet(j,i)} P_2[j]$$

$$\sum_{i=0}^{d-1} |P_1[i] - P_2[i]| = \max_{i=0}^{2^d-1} |A_i - B_i|$$

8.7 Primes

If $n = p_1^{e_1} \cdot p_2^{e_2} \cdots p_k^{e_k}$, then:

Number of divisors is $d(n) = (e_1 + 1) \cdot (e_2 + 1) \cdots (e_k + 1)$.

Sum of divisors is $\sigma(n) = \frac{p_1^{e_1+1}-1}{p_1-1} \cdot \frac{p_2^{e_2+1}-1}{p_2-1} \cdots \frac{p_k^{e_k+1}-1}{p_k-1}$