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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 Dynamic Wavelet Tree

```

#include <bits/stdc++.h>
using namespace std;
struct SplayTree{
    struct Node{
        int x, y, s;
        Node *p = 0;
        Node *l = 0;
        Node *r = 0;
        Node(int v){

```

```

    x = v;
    y = v;
    s = 1;
}
void upd(){
    s = 1;
    y = x;
    if (l){
        y += l->y;
        s += l->s;
    }
    if (r){
        y += r->y;
        s += r->s;
    }
}
int left_size(){
    return l ? l->s : 0;
}
};
Node *root = 0;
void rot(Node *c){
    auto p = c->p;
    auto g = p->p;
    if (g)
        (g->l == p ? g->l : g->r) = c;
    if (p->l == c){
        p->l = c->r;
        c->r = p;
        if (p->l)
            p->l->p = p;
    }
    else{
        p->r = c->l;
        c->l = p;
        if (p->r)
            p->r->p = p;
    }
    p->p = c;
    c->p = g;
    p->upd();
    c->upd();
}
void splay(Node *c){
    while (c->p){
        auto p = c->p;
        auto g = p->p;
        if (g)
            rot((g->l == p) == (p->l == c) ? p : c);
        rot(c);
    }
    c->upd();
    root = c;
}
Node *join(Node *l, Node *r){
    if (not l)
        return r;
    if (not r)
        return l;
    while (l->r)
        l = l->r;

```

```

    splay(l);
    r->p = l;
    l->r = r;
    l->upd();
    return l;
}
pair<Node *, Node *> split(Node *p, int idx){
    if (not p)
        return make_pair(nullptr, nullptr);
    if (idx < 0)
        return make_pair(nullptr, p);
    if (idx >= p->s)
        return make_pair(p, nullptr);
    for (int lf = p->left_size(); idx != lf; lf = p->left_size()){
        if (idx < lf)
            p = p->l;
        else
            p = p->r, idx -= lf + 1;
    }
    splay(p);
    Node *l = p;
    Node *r = p->r;
    if (r){
        l->r = r->p = 0;
        l->upd();
    }
    return make_pair(l, r);
}
Node *get(int idx){
    auto p = root;
    for (int lf = p->left_size(); idx != lf; lf = p->left_size()){
        if (idx < lf)
            p = p->l;
        else
            p = p->r, idx -= lf + 1;
    }
    splay(p);
    return p;
}
int insert(int idx, int x){
    Node *l, *r;
    tie(l, r) = split(root, idx - 1);
    int v = l ? l->y : 0;
    root = join(l, join(new Node(x), r));
    return v;
}
void erase(int idx){
    Node *l, *r;
    tie(l, r) = split(root, idx);
    root = join(l->l, r);
    delete l;
}
int rank(int idx){
    Node *l, *r;
    tie(l, r) = split(root, idx);
    int x = (l && l->l ? l->l->y : 0);
    root = join(l, r);
    return x;
}
int operator[](int idx){
    return rank(idx);
}

```

```

}
~SplayTree(){
    if (!root)
        return;
    vector<Node *> nodes{root};
    while (nodes.size()){
        auto u = nodes.back();
        nodes.pop_back();
        if (u->l)
            nodes.emplace_back(u->l);
        if (u->r)
            nodes.emplace_back(u->r);
        delete u;
    }
};
class WaveletTree{
private:
    int lo, hi;
    WaveletTree *l = 0;
    WaveletTree *r = 0;
    SplayTree b;
public:
    WaveletTree(int min_value, int max_value){
        lo = min_value;
        hi = max_value;
        b.insert(0, 0);
    }
    ~WaveletTree(){
        delete l;
        delete r;
    }
    //0-indexed
    void insert(int idx, int x){
        if (lo >= hi)
            return;
        int mid = (lo + hi - 1) / 2;
        if (x <= mid){
            l = l ? new WaveletTree(lo, mid);
            l->insert(b.insert(idx, 1), x);
        } else {
            r = r ? new WaveletTree(mid + 1, hi);
            r->insert(idx - b.insert(idx, 0), x);
        }
    }
    //0-indexed
    void erase(int idx){
        if (lo == hi)
            return;
        auto p = b.get(idx);
        int lf = p->l ? p->l->y : 0;
        int x = p->x;
        b.erase(idx);
        if (x == 1)
            l->erase(lf);
        else
            r->erase(idx - lf);
    }
    //kth smallest element in range [i, j]
    //0-indexed
    int kth(int i, int j, int k){

```

```

        if (i >= j)
            return 0;
        if (lo == hi)
            return lo;
        int x = b.rank(i);
        int y = b.rank(j);
        if (k <= y - x)
            return l->kth(x, y, k);
        else
            return r->kth(i - x, j - y, k - (y - x));
    }
    //Amount of numbers in the range [i, j] Less than or equal to k
    //0-indexed
    int lte(int i, int j, int k){
        if (i >= j or k < lo)
            return 0;
        if (hi <= k)
            return j - i;
        int x = b.rank(i);
        int y = b.rank(j);
        return l->lte(x, y, k) + r->lte(i - x, j - y, k);
    }
    //Amount of numbers in the range [i, j] equal to k
    //0-indexed
    int count(int i, int j, int k){
        if (i >= j or k < lo or k > hi)
            return 0;
        if (lo == hi)
            return j - i;
        int mid = (lo + hi - 1) / 2;
        int x = b.rank(i);
        int y = b.rank(j);
        if (k <= mid)
            return l->count(x, y, k);
        return r->count(i - x, j - y, k);
    }
    //0-indexed
    int get(int idx){
        return kth(idx, idx + 1, 1);
    }
};

```

## 1.6 Implicit Treap

```

#include <bits/stdc++.h>
using namespace std;
class ImplicitTreap{
private:
    typedef int t_treap;
    const t_treap neutral = 0;
    inline t_treap join(t_treap a, t_treap b, t_treap c){
        return a + b + c;
    }
    struct Node{
        int y, size;
        t_treap v, op_value;
        bool rev;
        Node *l, *r;
        Node(t_treap _v){
            v = op_value = _v;

```

```

    y = rand();
    size = 1;
    l = r = NULL;
    rev = false;
}
};
Node *root;
int size(Node *t) { return t ? t->size : 0; }
t_treap op_value(Node *t) { return t ? t->op_value : neutral; }
Node *refresh(Node *t){
    if (t == NULL)
        return t;
    t->size = 1 + size(t->l) + size(t->r);
    t->op_value = join(t->v, op_value(t->l), op_value(t->r));
    if (t->l != NULL)
        t->l->rev ^= t->rev;
    if (t->r != NULL)
        t->r->rev ^= t->rev;
    if (t->rev){
        swap(t->l, t->r);
        t->rev = false;
    }
    return t;
}
void split(Node *t, int k, Node *a, Node *b){
    refresh(t);
    Node *aux;
    if (!t){
        a = b = NULL;
    }else if (size(t->l) < k){
        split(t->r, k - size(t->l) - 1, aux, b);
        t->r = aux;
        a = refresh(t);
    }else{
        split(t->l, k, a, aux);
        t->l = aux;
        b = refresh(t);
    }
}
Node *merge(Node *a, Node *b){
    refresh(a);
    refresh(b);
    if (!a || !b)
        return a ? a : b;
    if (a->y < b->y){
        a->r = merge(a->r, b);
        return refresh(a);
    }else{
        b->l = merge(a, b->l);
        return refresh(b);
    }
}
Node *at(Node *t, int n){
    if (!t)
        return t;
    refresh(t);
    if (n < size(t->l))
        return at(t->l, n);
    else if (n == size(t->l))
        return t;
    else

```

```

        return at(t->r, n - size(t->l) - 1);
}
void del(Node *t){
    if (!t)
        return;
    if (t->l)
        del(t->l);
    if (t->r)
        del(t->r);
    delete t;
    t = NULL;
}
public:
    ImplicitTreap() : root(NULL){
        srand(time(NULL));
    }
    ~ImplicitTreap() { clear(); }
    void clear() { del(root); }
    int size() { return size(root); }
    //0-indexed
    bool insert(int n, int v){
        Node *a, *b;
        split(root, n, a, b);
        root = merge(merge(a, new Node(v)), b);
        return true;
    }
    //0-indexed
    bool erase(int n){
        Node *a, *b, *c, *d;
        split(root, n, a, b);
        split(b, 1, c, d);
        root = merge(a, d);
        if (c == NULL)
            return false;
        delete c;
        return true;
    }
    //0-indexed
    t_treap at(int n){
        Node *ans = at(root, n);
        return ans ? ans->v : -1;
    }
    //0-indexed [l, r]
    t_treap query(int l, int r){
        if (l > r)
            swap(l, r);
        Node *a, *b, *c, *d;
        split(root, l, a, d);
        split(d, r - l + 1, b, c);
        t_treap ans = op_value(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);
        Node *a, *b, *c, *d;
        split(root, l, a, d);
        split(d, r - l + 1, b, c);
        if (b != NULL)

```

```

    b->rev ^= 1;
    root = merge(a, merge(b, c));
}
};

```

## 1.7 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);
    }
};

```

## 1.8 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 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 l, ll r, int color) : l(l), r(r), color(color) {}
    };
    struct cmp{
        bool operator()(Node a, Node b){
            return a.r < b.r;
        }
    };
    std::set<Node, cmp> 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));
    }
    //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.insert(Node(b + 1LL, r, oldColor));
                st.erase(p);
                break;
            }else{
                p = st.erase(p);
            }
        }
        ans[newColor] += (b - a + 1LL);
```

```
        st.insert(Node(a, b, newColor));
    }
    ll countColor(int x){
        return ans[x];
    }
};
```

## 1.11 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);
}
};

```

## 1.12 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;
    }
};

```

## 1.13 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 + sz - 1; i > 1; i--)
            st[i >> 1] = join(st[i >> 1], st[i]);
    }
    //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[1 + (i << 1)]);
    }
    //0-indexed [l, r]
    Node query(int l, int r){
        Node ans = neutral;
        for (l += n, r += n + 1; l < r; l >= 1, r >= 1){
            if (l & 1)
                ans = join(ans, st[l++]);
            if (r & 1)
                ans = join(ans, st[--r]);
        }
        return ans;
    }
};

```

## 1.14 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);
            //tree[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);
    }
};

```

## 1.15 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]);
}
};

```

## 1.16 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;
    }
};

```

## 1.17 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 tlz = lg;
        while (tlz > 1){

```

```

            onLayer[tlz] = (int)layers.size();
            layers.push_back(tlz);
            tlz = (tlz + 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);
    }
};

```

## 1.18 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();
    }
};

```

## 1.19 Treap

```

#include <bits/stdc++.h>

```

```

using namespace std;
class Treap{
private:
    typedef int t_treap;
    struct Node{
        t_treap x, y, size;
        Node *l, *r;
        Node(t_treap _x) : x(_x), y(rand()), size(1), l(NULL), r(NULL) {}
    };
    Node *root;
    int size(Node *t) { return t ? t->size : 0; }
    Node *refresh(Node *t){
        if (!t)
            return t;
        t->size = 1 + size(t->l) + size(t->r);
        return t;
    }
    void split(Node *t, t_treap k, Node *&a, Node *&b){
        Node *aux;
        if (!t){
            a = b = NULL;
        } else if (t->x < k){
            split(t->r, k, aux, b);
            t->r = aux;
            a = refresh(t);
        } else{
            split(t->l, k, a, aux);
            t->l = aux;
            b = refresh(t);
        }
    }
    Node *merge(Node *a, Node *b){
        if (!a || !b)
            return a ? a : b;
        if (a->y < b->y){
            a->r = merge(a->r, b);
            return refresh(a);
        } else{
            b->l = merge(a, b->l);
            return refresh(b);
        }
    }
    Node *count(Node *t, t_treap k){
        if (!t)
            return NULL;
        else if (k < t->x)
            return count(t->l, k);
        else if (k == t->x)
            return t;
        else
            return count(t->r, k);
    }
    Node *nth(Node *t, int n){
        if (!t)
            return NULL;
        if (n <= size(t->l))
            return nth(t->l, n);
        else if (n == size(t->l) + 1)
            return t;
        else
            return nth(t->r, n - size(t->l) - 1);
    }

```

```

}
void del(Node *&t){
    if (!t)
        return;
    if (t->l)
        del(t->l);
    if (t->r)
        del(t->r);
    delete t;
    t = NULL;
}
public:
    Treap() : root(NULL) {}
    ~Treap() { clear(); }
    void clear() { del(root); }
    int size() { return size(root); }
    bool count(t_treap k) { return count(root, k) != NULL; }
    bool insert(t_treap k){
        if (count(k))
            return false;
        Node *a, *b;
        split(root, k, a, b);
        root = merge(merge(a, new Node(k)), b);
        return true;
    }
    bool erase(t_treap k){
        Node *f = count(root, k);
        if (!f)
            return false;
        Node *a, *b, *c, *d;
        split(root, k, a, b);
        split(b, k + 1, c, d);
        root = merge(a, d);
        delete f;
        return true;
    }
    //1-indexed
    t_treap nth(int n){
        Node *ans = nth(root, n);
        return ans ? ans->x : -1;
    }
};

```

## 1.20 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]);
}
void join(int x, int y){
    x = find(x);
    y = find(y);
    if (x == y)
        return;
    if (w[x] > w[y])
        swap(x, y);
    p[x] = y;
    sz[y] += sz[x];
    if (w[x] == w[y])
        w[y]++;
}
bool isSame(int x, int y){
    return find(x) == find(y);
}
int size(int x){
    return sz[find(x)];
}
};

```

## 1.21 Wavelet Tree

```

#include <bits/stdc++.h>
using namespace std;
struct WaveletTree{
private:
    typedef int t_wavelet;
    t_wavelet lo, hi;
    WaveletTree *l = nullptr, *r = nullptr;
    vector<t_wavelet> a;
public:
    template <class MyIterator>
    WaveletTree(MyIterator begin, MyIterator end, t_wavelet minX,
        t_wavelet maxX){
        lo = minX, hi = maxX;
        if (lo == hi or begin >= end)
            return;
        t_wavelet mid = (lo + hi - 1) / 2;
        auto f = [mid](int x) {
            return x <= mid;
        };
        a.reserve(end - begin + 2);
        a.push_back(0);
        for (auto it = begin; it != end; it++)
            a.push_back(a.back() + f(*it));
        auto pivot = stable_partition(begin, end, f);
        l = new WaveletTree(begin, pivot, lo, mid);
        r = new WaveletTree(pivot, end, mid + 1, hi);
    }
    inline int b(int i){
        return i - a[i];
    }
}
//kth smallest element in range [i, j]
//1-indexed
int kth(int i, int j, int k){
    if (i > j)
        return 0;

```

```

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

```

## 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 Dinic

```

#include <bits/stdc++.h>
using namespace std;
template <typename flow_t>
struct Dinic{
    struct FlowEdge{
        int v, u;
        flow_t cap, flow = 0;
        FlowEdge(int v, int u, flow_t cap) : v(v), u(u), cap(cap) {}
    };
    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 v = q.front();
            q.pop();
            for (int id : adj[v]){
                if (edges[id].cap - edges[id].flow < 1)
                    continue;
                if (level[edges[id].u] != -1)
                    continue;
                level[edges[id].u] = level[v] + 1;
                q.push(edges[id].u);
            }
        }
        return level[t] != -1;
    }
    flow_t dfs(int v, flow_t pushed){
        if (pushed == 0)
            return 0;
        if (v == t)
            return pushed;
        for (int &cid = ptr[v]; cid < (int)adj[v].size(); cid++){
            int id = adj[v][cid];
            int u = edges[id].u;
            if (level[v] + 1 != level[u] || edges[id].cap - edges[id].flow < 1)
                continue;
            flow_t tr = dfs(u, min(pushed, edges[id].cap - edges[id].flow));
            if (tr == 0)
                continue;
            edges[id].flow += tr;
            edges[id ^ 1].flow -= tr;
            return tr;
        }
        return 0;
    }
    Dinic(){}
    void init(int _n){
        n = _n;
        adj.resize(n);
        level.resize(n);
        ptr.resize(n);
    }
    void addEdge(int v, int u, flow_t cap){
        assert(n>0);
        edges.push_back(FlowEdge(v, u, cap));
        edges.push_back(FlowEdge(u, v, 0));
        adj[v].push_back(m);
        adj[u].push_back(m + 1);
        m += 2;
    }
    flow_t maxFlow(int s1, int t1){
        s = s1, t = t1;
        flow_t f = 0;
        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;
}
};
typedef pair<int, int> pii;
vector<pii> recoverCut(Dinic<int> &d){
    vector<int> level(d.n, 0);
    vector<pii> rc;
    queue<int> q;
    q.push(d.s);
    level[d.s] = 1;
    while (!q.empty()){
        int v = q.front();
        q.pop();
        for (int id : d.adj[v]){
            if ((id & 1) == 1)
                continue;
            if (d.edges[id].cap == d.edges[id].flow){
                rc.push_back(pii(d.edges[id].v, d.edges[id].u));
            }else{
                if (level[d.edges[id].u] == 0){
                    q.push(d.edges[id].u);
                    level[d.edges[id].u] = 1;
                }
            }
        }
    }
    vector<pii> ans;
    for (pii p : rc)
        if ((level[p.first] == 0) or (level[p.second] == 0))
            ans.push_back(p);
    return ans;
}

```

## 2.3 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;
}
};

```

## 2.4 HLD

```

#include <bits/stdc++.h>
#include "../data_structures/bit_range.h"
using namespace std;
#define F first
#define S second
using pii = pair<int, int>;
struct HLD{
    vector<vector<pii>> adj;
    vector<int> sz, h, dad, pos, val, v;
    int t;
    bool edge;
    //Begin Internal Data Structure
    BitRange *bit;
    int neutral = 0;
    inline int join(int a, int b){
        return a+b;
    }
    inline void update(int a, int b, int x){
        bit->add(a+1, b+1, x);
    }
    inline int query(int a, int b){
        return bit->get(a+1, b+1);
    }
    //End Internal Data Structure
    HLD(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, int w = 0){
    adj[a].emplace_back(b, w);
    adj[b].emplace_back(a, w);
}
void build(int root, bool _edge){
    edge = _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]);
    }
    int 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, int 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);
    }
    int 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, int 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);
    }
}
};

```

## 2.5 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 from, int to, T cap, T cost){
    edges[from].push_back(list.size());
    list.push_back(Edge(to, cap, cost));
    edges[to].push_back(list.size());
    list.push_back(Edge(from, 0, -cost));
}
};
/*bool dij(int src, int sink){
    T INF = numeric_limits<T>::max();
    dist.assign(n, INF);
    from.assign(n, -1);
    visit.assign(n, false);
    dist[src] = 0;
    for(int i = 0; i < n; i++){
        int best = -1;
        for(int j = 0; j < n; j++){
            if(visit[j]) continue;
            if(best == -1 || dist[best] > dist[j]) best = j;
        }
        if(dist[best] >= INF) break;
        visit[best] = true;
        for(auto e : edges[best]){
            auto ed = list[e];
            if(ed.cap == 0) continue;
            T toDist = dist[best] + ed.cost + pot[best] - pot[ed.to];
            assert(toDist >= dist[best]);
            if(toDist < dist[ed.to]){
                dist[ed.to] = toDist;
                from[ed.to] = e;
            }
        }
    }
    return dist[sink] < INF;
}*/

```

## 2.6 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

```

## 2.7 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

```

## 3 Dynamic Programming

### 3.1 Divide and Conquer Optimization

Reduces the complexity from  $O(n^2k)$  to  $O(nk \log n)$  of DP'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;
}
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;
}

```

## 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 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 i = 2; i <= n; i++){
        if (vPhi[i] == i){
            for (int j = i; j <= n; j += i)
                vPhi[j] -= vPhi[j] / i;
        }
    }
    return vPhi;
}

```

## 4.6 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_solution(ll &x, ll &y, ll a, ll b, ll cnt){
    x += cnt * b;
    y -= cnt * a;
}
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_solution(x, y, a, b, (minx - x) / b);
    if (x < minx)
        shift_solution(x, y, a, b, sign_b);
    if (x > maxx)
        return 0;
    ll lx1 = x;
    shift_solution(x, y, a, b, (maxx - x) / b);
    if (x > maxx)
        shift_solution(x, y, a, b, -sign_b);
    ll rx1 = x;
    shift_solution(x, y, a, b, -(miny - y) / a);
    if (y < miny)
        shift_solution(x, y, a, b, -sign_a);
    if (y > maxy)
        return 0;
    ll lx2 = x;
    shift_solution(x, y, a, b, -(maxy - y) / a);
    if (y > maxy)
        shift_solution(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;
}

```

## 4.7 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;
}
```

## 4.8 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;
    }
};
```

## 4.9 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){
    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));
}
```

## 4.10 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));
}
};

```

## 4.11 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(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;
}

```

## 5 Geometry

## 6 String Algorithms

### 6.1 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);
}

```

### 6.2 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 and !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);
}
};

```

## 7 Miscellaneous

### 7.1 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;
}

```

## 8 Theorems and Formulas

### 8.1 Binomial Coefficients

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

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

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

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

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

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

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

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

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

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

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

### 8.2 Catalan Number

$$\text{Recursive formula: } C_0 = C_1 = 1$$

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

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

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:  $\phi(ab) = \phi(a) \cdot \phi(b)$

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

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:  $f = e - v + 2$

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  $\gcd(a, b)$ :  $n = \text{lcm}(a, b) - a - b + \gcd(a, b)$

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## 8.5 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

$P_2$ :

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

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

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

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


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## 8.6 Primes

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

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

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

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