

GEMP - UFC Quixadá - ICPC Library

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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){
        for (; i <= nBit; i += (i & -i))
            bit[i] += value;
    }
    t_bit position(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, *r;
    vector<int> a, b;
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 + 1);
        b.reserve(end - begin + 1);
        a.push_back(0);
        b.push_back(0);
        for (auto it = begin; it != end; it++){
            a.push_back(a.back() + f(*it));
            b.push_back(b.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);
    }
    //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;
    int 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);
}
~WaveletTree(){
    delete l;
    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;
typedef long long ll;
class Dinic{
private:
    struct FlowEdge{
        int v, u;
        ll cap, flow = 0;
        FlowEdge(int v, int u, ll cap) : v(v), u(u), cap(cap) {}
    };
    const ll flow_inf = 1e18;
    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;
    }
    ll dfs(int v, ll 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;
            ll 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;
    }
public:
    Dinic(int n) : n(n){
        adj.resize(n);
        level.resize(n);
        ptr.resize(n);
    }
    void addEdge(int v, int u, ll cap){
        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;
    }
    ll maxFlow(int s1, int t1){
        s = s1;
        t = t1;
        ll f = 0;
        while (true){
            fill(level.begin(), level.end(), -1);
            level[s] = 0;
            q.push(s);
            if (!bfs())
                break;
            fill(ptr.begin(), ptr.end(), 0);
            while (ll pushed = dfs(s, flow_inf))
                f += pushed;
        }
        return f;
    }
    typedef pair<int, int> pii;
    vector<pii> recoverCut(){
        fill(level.begin(), level.end(), 0);
        vector<pii> rc;
        q.push(s);
        level[s] = 1;
        while (!q.empty()){
            int v = q.front();
            q.pop();
            for (int id : adj[v]){
                if ((id & 1) == 1)
                    continue;
                if (edges[id].cap == edges[id].flow){
                    rc.push_back(pii(edges[id].v, edges[id].u));
                } else {
                    if (level[edges[id].u] == 0){

```

```

        q.push(edges[id].u);
        level[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 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<std::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;
}*/

```

2.4 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

```

2.5 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 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;
    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];
}

```

4 Math

4.1 Basic Math

```

#include <bits/stdc++.h>
using namespace std;
typedef long long ll;
ll fastPow(ll base, ll exp, ll mod){
    base %= mod;
    //exp %= phi(mod) if base and mod are relatively prime
    ll 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 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;
    }
}
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;
}
bool checkComposite(ll n, ll a, ll d, int s){
    ll x = fastPow(a, d, n);
    if (x == 1 or x == n - 1)
        return false;

```

```

    for (int r = 1; r < s; r++){
        x = (x * (__int128_t)x) % n;
        if (x == n - 1LL)
            return false;
    }
    return true;
};
bool millerRabin(ll n){
    if (n < 2)
        return false;
    int r = 0;
    ll d = n - 1LL;
    while ((d & 1LL) == 0){
        d >>= 1;
        r++;
    }
    for (int 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;
}

```

4.2 Binomial Coefficients

```

#include <bits/stdc++.h>
#include "../basic_math.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;
}

```

4.3 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

```

4.4 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++){
            if (vPhi[j] == i){
                for (int k = i; k <= n; k += i)
                    vPhi[k] -= vPhi[k] / i;
            }
        }
    }
    return vPhi;
}

```

4.5 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;
    }
    ll g = extGcd(b, a % b, y, x);
    y -= (a / b) * x;
    return g;
}

```

4.6 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;
}

```

5 Geometry

6 String Algorithms

7 Miscellaneous

8 Theorems and Formulas

8.1 Binomial Coefficients

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

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

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

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

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

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

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

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

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

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

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

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 Primes

If $n = p_1^{e_1} \cdot p_2^{e_2} \cdot \dots \cdot p_k^{e_k}$ então, then: Number of divisors is $d(n) = (e_1 + 1) \cdot (e_2 + 1) \cdot \dots \cdot (e_k + 1)$.

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