Teamnote of 2mic1cup

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Contents

1 Helpers

1.1 Stress Tester

Overview

Simple .bat file for stress testing.

Implementation

```
@echo off
g++ -std=c++20 -o solution test.cpp
g++ -std=c++20 -o brute brute.cpp
g++ -std=c++20 -o gen gen.cpp

for /l %%x in (1, 1, 1000) do (
    gen > input.in
    solution < input.in > output.out
    brute < input.in > output2.out
    fc output.out output2.out > nul

    if ERRORLEVEL 1 (
        echo INPUT
        type input.in
        echo.
        echo SOLUTION OUTOUT
        type output.out
        echo.
        echo CORRECT OUTPUT
        type output2.out
        echo.
    )
)
echo all tests passed
```

1.2 Random

Overview

Self explanatory.

Implementation

```
#define uid(a, b) uniform_int_distribution<long long>(a, b)(rng)
mt19937 rng(chrono::steady_clock::now().time_since_epoch().count());
```

Usage

- $uid(a, b)$ returns random integer between $[a, b]$

2 Data Structure

2.1 Iterative Segment Tree

Overview

For-loop implementation of segment tree, faster than recursive. Note: Operation that depends on ordering is not supported (For example: Minimum prefix sum)

Time complexity: $\mathcal{O}(n)$ for constructor, $\mathcal{O}(\log n)$ for query

Implementation

```
template<typename T>
struct SegmentTreeFast{
    vector<T> a;
    T defv;
    int n;

    SegmentTreeFast(int n, T defv) : n(n), defv(defv){
        a = vector<T>(2 * n, defv);
    }

    T cmb(T a, T b){ //change if needed
        return a + b;
    }

    void build(){ //array is at i + n index
        for (int i = n - 1; i > 0; --i)
            a[i] = cmb(a[i << 1], a[i << 1 | 1]);
    }

    void update(int i, T v){
        for (a[i += n] = v; i > 1; i >>= 1)
            a[i >> 1] = cmb(a[i], a[i ^ 1]);
    }

    T get(int l, int r){
        r++;
        T res = defv;
        for (l += n, r += n; l < r; l >>= 1, r >>= 1){
            if (l&1) res = cmb(res, a[l++]);
            if (r&1) res = cmb(res, a[--r]);
        }

        return res;
    }
};
```

2.2 Lazy Segment Tree

Overview

Segment tree that supports ranged update.

Time complexity: $\mathcal{O}(n)$ for constructor, $\mathcal{O}(\log n)$ for query

Implementation

```
template<typename T>
class SegmentTreeLazy{
public:
    vector<T> st, lazy;
    T defv;
    int n;

    SegmentTreeLazy(int n, T defv) : n(n), defv(defv){
        st = vector<T>(n * 4, defv);
        lazy = vector<T>(n * 4, defv);
    }

    void update(int l, int r, T v){
        _update(0, n - 1, 0, l, r, v);
    }

    T get(int l, int r){
        return _get(0, n - 1, l, r, 0);
```

```cpp
    }

private:
    T cmb(T l, T r){
        return l + r;
    }

    void push(int i, int l, int r){
        int mid = (l + r) / 2;
        lazy[i * 2 + 1] += lazy[i];
        lazy[i * 2 + 2] += lazy[i];

        st[i * 2 + 1] += (mid - l + 1) * lazy[i];
        st[i * 2 + 2] += (r - mid) * lazy[i];

        lazy[i] = 0;
    }

    void _update(int l, int r, int crr, int ql, int qr, T v){
        if (qr < l || ql > r)
            return;

        if (l >= ql && r <= qr){
            st[crr] += (r - l + 1) * v;
            lazy[crr] += v;
            return;
        }

        push(crr, l, r);
        int mid = (l + r) / 2;
        _update(l, mid, crr * 2 + 1, ql, qr, v);
        _update(mid + 1, r, crr * 2 + 2, ql, qr, v);

        st[crr] = cmb(st[crr * 2 + 1], st[crr * 2 + 2]);
    }

    T _get(int l, int r, int ql, int qr, int crr){
        if (qr < l || ql > r)
            return defv;
        if (l >= ql && r <= qr)
            return st[crr];

        push(crr, l, r);
        int mid = (l + r) / 2;
        return cmb(_get(l, mid, ql, qr, crr * 2 + 1), _get(mid + 1, r, ql, qr, crr * 2 + 2));
    }
};
```

2.3 Sparse Table

Overview

Uses binary lifting for efficient queries, offline only.

Time complexity: $\mathcal{O}(n \log n)$ for constructor, $\mathcal{O}(1)$ for query

Implementation

```cpp
template <typename T, class Combine = function<T(const T &, const T &)>>
struct SparseTable{
    vector<vector<T>> f;
    vector<int> lg;
    Combine cmb;
    int n;

    SparseTable(vector<T> &init, const Combine &cmb) : n(init.size()), cmb(cmb){
        lg = vector<int>(n + 1, 0);
        for (int i = 2; i <= n; i++)
            lg[i] = lg[i / 2] + 1;
        for (int i = 0; i < n; i++){
            f.push_back(vector<int>(lg[n] + 1, -1));
            f[i][0] = init[i];
        }
        for (int j = 1; (1 << j) <= n; j++){
            for (int i = 0; (i + (1 << j) - 1) < n; i++)
                f[i][j] = cmb(f[i][j - 1], f[i + (1 << (j - 1))][j - 1]);
        }
    }

    T get(int l, int r){
        int k = lg[r - l + 1];
        return cmb(f[l][k], f[r - (1 << k) + 1][k]);
    }
};
```

Usage

- Init minimum range query and uses integer type

```cpp
SparseTable<int> rmq(a, [](int a, int b){
    return min(a, b);
});
```

2.4 Implicit Treap

Overview

Implicit treap implementation with range add update and range sum query. push() and upd() functions should be changed accordingly like lazy segment tree.

Time complexity: $\mathcal{O}(\log n)$ on average for all operations, large constant!!

Implementation

```cpp
typedef node* pnode;
struct ImplicitTreap{
public:
    pnode root;
    ImplicitTreap(){
        root = new node(-1, 0);
    }
    void insert(int i, ll val){
        pnode t1, t2;
        split(root, i + 1, 0, t1, t2);
        merge(t1, t1, new node(val));
        merge(root, t1, t2);
    }
    void erase(int i){
        _erase(root, i + 1, 0);
    }
    ll query(int l, int r){
        pnode t1, t2, t3;
        split(root, r + 2, 0, t2, t3);
        split(t2, l + 1, 0, t1, t2);

        ll res = t2->sum;
        merge(root, t1, t2);
        merge(root, root, t3);

```

```cpp
        return res;
    }
    void update(int l, int r, ll val){
        pnode t1, t2, t3;
        split(root, r + 2, 0, t2, t3);
        split(t2, l + 1, 0, t1, t2);

        t2->add += val;
        merge(root, t1, t2);
        merge(root, root, t3);
    }
    void split(pnode t, int key, int add, pnode &l,
    ↪  pnode &r){
        if (!t){
            l = r = nullptr;
            return;
        }
        push(t);
        int impl_key = add + _cnt(t->l);
        if (key <= impl_key)
            split(t->l, key, add, l, t->l), r = t;
        else
            split(t->r, key, add + _cnt(t->l) + 1, t->r,
            ↪  r), l = t;
        upd(t);
    }

    void merge(pnode &t, pnode l, pnode r){
        push(l); push(r);
        if (!l || !r)
            t = l? l : r;
        else if (l->prior > r->prior)
            merge(r->l, l, r->l), t = r;
        else
            merge(l->r, l->r, r), t = l;
        upd(t);
    }
private:
    void _erase(pnode &t, int key, int add){
        push(t);
        int impl_key = add + _cnt(t->l);
        if (impl_key == key){
            pnode it = t;
            merge(t, t->l, t->r);
            delete it;
        }
        else if (key < impl_key)
            _erase(t->l, key, add);
        else
            _erase(t->r, key, add + _cnt(t->l) + 1);
        upd(t);
    }
    void push(pnode t){
        if (!t) return;
        t->sum += t->add * (ll)_cnt(t);
        t->val += t->add;
        if (t->l) t->l->add += t->add;
        if (t->r) t->r->add += t->add;

        t->add = 0;
    }
    int _cnt(pnode t){
        if (!t) return 0;
        return t->cnt;
    }
    ll _sum(pnode t){
        if (!t) return 0;
        push(t);
        return t->sum;
    }
    void upd(pnode t){
        if (!t) return;
        t->sum = t->val + _sum(t->l) + _sum(t->r);
        t->cnt = _cnt(t->l) + _cnt(t->r) + 1;
    }
};
```

2.5 Dynamic Segment Tree

Overview

Range queries and updates on larger range ($1 \le l \le r \le 10^9$)

Time complexity: $\mathcal{O}(\log M)$ for every operations, where M is max range

Implementation

```cpp
struct Node{
    ll sum, tl, tr;
    Node *l = nullptr, *r = nullptr;

    Node (ll _tl, ll _tr){
        tl = _tl;
        tr = _tr;
        sum = 0;
    }

    void extend(){
        if (tl == tr) return;
        ll mid = (tl + tr) / 2;

        if (!l)
            l = new Node(tl, mid);
        if (!r)
            r = new Node(mid + 1, tr);
    }
};

class funkysegtree{
    void _upd(Node *node, ll x, ll val){
        node->sum += val;
        if (node->tl > x || node->tr < x)
            return;
        if (node->tl == node->tr)
            return;

        ll mid = (node->tl + node->tr) / 2;
        node->extend();

        if (x <= mid)
            _upd(node->l, x, val);
        else
            _upd(node->r, x, val);
    }

    ll _get(Node *node, ll ql, ll qr){
        if (qr < node->tl || ql > node->tr)
            return 0;

        else if (ql <= node->tl && qr >= node->tr)
            return node->sum;

        ll mid = (node->tl + node->tr) / 2;
        node->extend();

        if (ql > mid)
            return _get(node->r, ql, qr);
        else if (qr <= mid)
            return _get(node->l, ql, qr);
        else
            return _get(node->l, ql, mid) +
            ↪  _get(node->r, mid + 1, qr);
    }

public:
    Node *root = nullptr;
```

```
    ll _size;

    funkysegtree(ll __size){
        root = new Node(0, __size);
        _size = __size;
    };

    void upd(ll x, ll val){
        _upd(root, x, val);
    }

    ll get(ll l, ll r){
        return _get(root, l, r);
    }
};
```

2.6 Persistent Segment Tree

Overview

Preserving history for every segment tree updates.

Time complexity: $\mathcal{O}(\log N)$ for every operations

Implementation

```
 struct Vertex {
    Vertex *l, *r;
    int sum;

    Vertex(int val) : l(nullptr), r(nullptr), sum(val) {}
    Vertex(Vertex *l, Vertex *r) : l(l), r(r), sum(0) {
        if (l) sum += l->sum;
        if (r) sum += r->sum;
    }
};

Vertex* build(ll a[], int tl, int tr) {
    if (tl == tr)
        return new Vertex(a[tl]);
    int tm = (tl + tr) / 2;
    return new Vertex(build(a, tl, tm), build(a, tm+1, tr));
}

int get_sum(Vertex* v, int tl, int tr, int l, int r) {
    if (l > r)
        return 0;
    if (l == tl && tr == r)
        return v->sum;
    int tm = (tl + tr) / 2;
    return get_sum(v->l, tl, tm, l, min(r, tm))
         + get_sum(v->r, tm+1, tr, max(l, tm+1), r);
}

Vertex* update(Vertex* v, int tl, int tr, int pos, int new_val) {
    if (tl == tr)
        return new Vertex(new_val);
    int tm = (tl + tr) / 2;
    if (pos <= tm)
        return new Vertex(update(v->l, tl, tm, pos, new_val), v->r);
    else
        return new Vertex(v->l, update(v->r, tm+1, tr, pos, new_val));
}
```

Usage

- Init and update segment tree with n nodes, each function returns a pointer, save if needed for later.

```
vector<Vertex*> roots;
roots.push_back(build(a, 0, n - 1)); //init
(...)
roots.push_back(update(roots.back(), 0, n - 1, x, 1)); //update at the last moment
(...)
roots.push_back(update(roots[a], 0, n - 1, x, 1)); //update at some specific moment
```

- Query the segment tree at a specific moment.

```
ll res = get_sum(roots[x], 0, n - 1, l, r);
```

2.7 2D Fenwick Tree

Overview

Query and update on a 2D array.

Time complexity: $\mathcal{O}(\log^2 n)$ for every operations

Implementation

```
ll bit[1001][1001];
ll n, m;

void update(ll x, ll y, ll val){
        for (; y <= n; y += (y & (-y))){
                for (ll i = x; i <= m; i += (i & (-i)))
                        bit[y][i] += val;
        }
}

ll query(ll x, ll y){
        ll res = 0;
        for (ll i = y; i; i -= (i & (-i)))
                for (ll j = x; j; j -= (j & (-j)))
                        res += bit[i][j];
        return res;
}

ll query(ll x1, ll y1, ll x2, ll y2){
        ll res = query(x2, y2) - query(x1 - 1, y2) - query(x2, y1 - 1) + query(x1 - 1, y1 - 1);
        return res;
}
```

Usage

- query(x, y) returns sum of value from $(1, 1)$ to (x, y).
- query(x1, y1, x2, y2) returns sum of value from $(x1, y1)$ to $(x2, y2)$.

2.8 Disjoint Set Union

Overview

Union disjoint set lol.

Time complexity: $\mathcal{O}(\alpha(n))$

Implementation

```cpp
struct DissjointSet{
    vector<int> p;
    int cnt = 0;

    DissjointSet(){}
    DissjointSet(int n){
        cnt = n;
        p = vector<int>(n, -1);
    }

    int find(int n){
        return p[n] < 0 ? n : p[n] = find(p[n]);
    }

    void merge(int u, int v){
        if ((u = find(u)) == (v = find(v)))
            return;

        cnt--;
        if (p[v] < p[u])
            swap(u, v);

        p[u] += p[v];
        p[v] = u;
    }
};
```

2.9 Line Container

Overview

Add lines of the form $y = kx + m$, and query maximum value at point x.

Time complexity: $\mathcal{O}(\log n)$

Implementation

```cpp
struct Line {
        mutable ll k, m, p;
        bool operator<(const Line& o) const { return k < o.k; }
        bool operator<(ll x) const { return p < x; }
};

struct LineContainer : multiset<Line, less<>> {
        // (for doubles, use inf = 1/.0, div(a,b) = a/b)
        ll div(ll a, ll b) { // floored division
                return a / b - ((a ^ b) < 0 && a % b); }
        bool isect(iterator x, iterator y) {
                if (y == end()) return x->p = inf, 0;
                if (x->k == y->k) x->p = x->m > y->m ? inf : -inf;
                else x->p = div(y->m - x->m, x->k - y->k);
                return x->p >= y->p;
        }
    //add line y = kx + m
        void add(ll k, ll m) {
                auto z = insert({k, m, 0}), y = z++, x = y;
                while (isect(y, z)) z = erase(z);
                if (x != begin() && isect(--x, y)) isect(x, y = erase(y));
                while ((y = x) != begin() && (--x)->p >= y->p)
                        isect(x, erase(y));
        }
        ll query(ll x) {
                assert(!empty());
                auto l = *lower_bound(x);
                return l.k * x + l.m;
        }
};
```

2.10 Lichao Tree

Overview

Add lines of the form $y = ax + b$, and query maximum value at point x, segment tree implementation.

Time complexity: $\mathcal{O}(\log n)$

Implementation

```cpp
struct LichaoTree{
    struct Line{
        ll a, b;
        Line() : a(0), b(-inf) {}
        Line(ll a, ll b): a(a), b(b) {}
        ll get(ll x){
            return a * x + b;
        }
    };
public:
    vector<Line> st;
    int n;
    LichaoTree(int n) : n(n){
        st.resize(4 * n);
    }
    void add_line(Line line, int indx = 1, int l = 0, int r = -1){
        if (r == -1) r = n;
        int m = (l + r) / 2;
        bool left = line.get(l) > st[indx].get(l);
        bool mid = line.get(m) > st[indx].get(m);

        if (mid)
            swap(line, st[indx]);
        if (r - l == 1) return;
        else if (left != mid)
            add_line(line, 2 * indx, l, m);
        else
            add_line(line, 2 * indx + 1, m, r);
    }
    ll query(ll x, int indx = 1, int l = 0, int r = -1){
        if (r == -1) r = n;
        if (r - l == 1) return st[indx].get(x);
        int mid = (l + r) / 2;
        if (x < mid)
            return max(st[indx].get(x), query(x, 2 * indx, l, mid));
        else
            return max(st[indx].get(x), query(x, 2 * indx + 1, mid, r));
    }
};
```

2.11 Ordered Set

Overview

A set that supports finding k-th maximum value, or getting the order of an element.

Time complexity: $\mathcal{O}(\log n)$, large constant

Implementation

```
#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/tree_policy.hpp>

using namespace __gnu_pbds;
template<class T> using ordset = tree<T, null_type, less<T>, rb_tree_tag, tree_order_statistics_node_update>;
```

Usage

- Uses just like a normal set, but with some added functions.

```
ordset<int> s;
s.insert(1);
s.insert(2);
s.insert(4);
s.find_by_order(0) //Returns 1
s.order_of_key(4) //Returns 2
```

2.12 Minimum Stack/Deque

Overview

Maintains minimum value in a stack/deque.

Time complexity: $\mathcal{O}(\alpha(\mathrm{n}))$, large constant

Implementation

```
struct minstack {
        stack<pair<int, int>> st;
        int getmin() {return st.top().second;}
        bool empty() {return st.empty();}
        int size() {return st.size();}
        void push(int x) {
                int mn = x;
                if (!empty()) mn = min(mn, getmin());
                st.push({x, mn});
        }
        void pop() {st.pop();}
        int top() {return st.top().first;}
        void swap(minstack &x) {st.swap(x.st);}
};

struct mindeque {
        minstack l, r, t;
        void rebalance() {
                bool f = false;
                if (r.empty()) {f = true; l.swap(r);}
                int sz = r.size() / 2;
                while (sz--) {t.push(r.top()); r.pop();}
                while (!r.empty()) {l.push(r.top()); r.pop();}
                while (!t.empty()) {r.push(t.top()); t.pop();}
                if (f) l.swap(r);
        }
        int getmin() {
                if (l.empty()) return r.getmin();
                if (r.empty()) return l.getmin();
                return min(l.getmin(), r.getmin());
        }
        bool empty() {return l.empty() && r.empty();}
        int size() {return l.size() + r.size();}
        void push_front(int x) {l.push(x);}
        void push_back(int x) {r.push(x);}
        void pop_front() {if (l.empty()) rebalance(); l.pop();}
        void pop_back() {if (r.empty()) rebalance(); r.pop();}
        int front() {if (l.empty()) rebalance(); return l.top();}
        int back() {if (r.empty()) rebalance(); return r.top();}
        void swap(mindeque &x) {l.swap(x.l); r.swap(x.r);}
};
```

2.13 Dynamic Bitset

Overview

Bitset with varied length support. NOTE: This requires relatively new version of GCC, and it might be BUGGED using the shift operator.

Time complexity: $\mathcal{O}$(n / 32)

Implementation

```
#include <tr2/dynamic_bitset>
using namespace tr2;
```

Usage

- Init a dynamic bitset with length n.

```
dynamic_bitset<> bs;
bs.resize(n);
```

3 Graph

3.1 Graph

Overview

Helper class, some implementations below will use this.

Implementation

```
struct Graph{
    vector<vector<int>> edg;
    int n;

    Graph(int n) : n(n){
        edg = vector<vector<int>>(n, vector<int>());
    }
    void add(int u, int v){
```

```cpp
        edg[u].push_back(v);
    }
    void bi_add(int u, int v){
        edg[u].push_back(v);
        edg[v].push_back(u);
    }
    void clear(){
        for (int u = 0; u < n; u++)
            edg[u].clear();
    }
    void remove_dup(){
        for (int u = 0; u < n; u++){
            sort(edg[u].begin(), edg[u].end());
            edg[u].erase(unique(edg[u].begin(), edg[u].end()), edg[u].end());
        }
    }
};
```

3.2 Strongly Connected Components

Overview

Find strongly connected components, compress the graph if needed

Time complexity: $\mathcal{O}(N)$

Implementation

```cpp
struct StronglyConnected{
    Graph &G;
    vector<vector<int>> components;
    vector<int> low, num, new_num;
    vector<bool> deleted;
    stack<int> st;
    int indx, scc, n;

    StronglyConnected(Graph &G) : G(G), n(G.n){
        low = num = new_num = vector<int>(n, 0);
        indx = scc = 0;
        deleted = vector<bool>(n, 0);

        for (int i = 0; i < n; i++){
            if (!num[i])
                dfs(i);
        }
    }

    void dfs(int u){
        low[u] = num[u] = ++indx;
        st.push(u);

        for (int v : G.edg[u]){
            if (deleted[v]) continue;
            if (!num[v]){
                dfs(v);
                low[u] = min(low[u], low[v]);
            }
            else
                low[u] = min(low[u], num[v]);
        }

        if (low[u] == num[u]){
            int crr = -1;
            vector<int> cmp;

            while (crr != u){
                crr = st.top();
                cmp.push_back(crr);
                st.pop();

                new_num[crr] = scc;
                deleted[crr] = 1;
            }

            components.push_back(cmp);
            scc++;
        }
    }

    void compress(){
        Graph _G(scc);
        for (int u = 0; u < n; u++){
            for (int v : G.edg[u]){
                int _u = new_num[u], _v = new_num[v];
                if (_u != _v)
                    _G.add(_u, _v);
            }
        }
        G = _G;
    }
};
```

3.3 Bridges and Articulations

Overview

Find bridges and articulations!!

Time complexity: $\mathcal{O}(N)$

Implementation

```cpp
struct BridgeArt{
    Graph &G;
    vector<int> low, num, arts;
    vector<bool> isart;
    vector<pair<int, int>> bridges;
    int indx, n;

    BridgeArt(Graph &G) : G(G), n(G.n){
        indx = 0;
        low = num = vector<int>(n, 0);
        isart = vector<bool>(n, 0);

        for (int i = 0; i < n; i++){
            if (!num[i])
                dfs(i, i);
        }
        for (int i = 0; i < n; i++){
            if (isart[i])
                arts.push_back(i);
        }
    }

    void dfs(int u, int pre){
        low[u] = num[u] = ++indx;
        int cnt = 0;

        for (int v : G.edg[u]){
            if (v == pre) continue;
            if (!num[v]){
                dfs(v, u);
                low[u] = min(low[u], low[v]);
                cnt++;
                if (u == pre){
                    if (cnt > 1)
                        isart[u] = 1;
                }
                else{
                    if (num[u] <= low[v])
```

```cpp
                    isart[u] = 1;
                }
                if (num[v] == low[v])
                    bridges.push_back({u, v});
            }
            else
                low[u] = min(low[u], num[v]);
        }
    }
};
```

3.4 Two SAT

Overview

Solve a system of boolean formula, where every clause has exactly two literals.

Time complexity: $\mathcal{O}(N+M)$, M can be a slowing factor

Implementation

```cpp
struct TwoSAT{
    vector<vector<int>> edg1, edg2;
    vector<int> scc, res;
    vector<bool> b;
    stack<int> topo;
    int n;

    TwoSAT(int n) : n(n){
        edg1 = edg2 = vector<vector<int>>(2 * n);
        scc = res = vector<int>(2 * n, 0);
        b = vector<bool>(2 * n, 0);
    }

    void dfs1(ll u){
        b[u] = 1;
        for (ll v : edg1[u]){
            if (!b[v])
                dfs1(v);
        }

        topo.push(u);
    }

    void dfs2(ll u, ll root){
        scc[u] = root;
        for (ll v : edg2[u]){
            if (scc[v] == -1)
                dfs2(v, root);
        }
    }

    bool solve(){
        for (int i = 0; i < 2 * n; i++){
            scc[i] = -1;
            if (!b[i])
                dfs1(i);
        }

        int j = 0;
        while (siz(topo)){
            ll u = topo.top();
            topo.pop();

            if (scc[u] == -1)
                dfs2(u, j++);
        }

        for (int i = 0; i < n; i++){
            if (scc[i * 2] == scc[i * 2 + 1])
                return 0;
            res[i] = scc[i * 2] > scc[i * 2 + 1];
        }

        return 1;
    }

    void add(int x, bool a, int y, bool b){
        int X = x * 2 + (a & 1), Y = y * 2 + (b & 1);
        int _X = x * 2 + 1 - (a & 1), _Y = y * 2 + 1 - (b & 1);

        edg1[_X].push_back(Y);
        edg1[_Y].push_back(X);
        edg2[Y].push_back(_X);
        edg2[X].push_back(_Y);
    }
};
```

Usage

- The $add(x, a, y, b)$ function add the clause (x OR y), where a, b signify whether x or y is negated or not.
- The $solve()$ function returns 1 if there exist a valid assignment, and 0 otherwise. The valid assignment will then be stored in res.

3.5 MCMF

Overview

Find a maximum flow with minimum cost, SPFA implementation.

Time complexity: $\mathcal{O}(N^3)$ with a bullshit factor

Implementation

```cpp
struct edge{
    int v;
    ll cost, capacity;
    edge* rv;
    edge(int v, ll cost, ll capacity) : v(v), cost(cost), capacity(capacity){}
};

struct MCMF{
    vector<vector<edge*>> edg;
    vector<pair<int, edge*>> par;
    vector<ll> dis;

    MCMF(int n){
        edg = vector<vector<edge*>>(n);
    }
    void add_edge(int u, int v, ll capacity, ll cost){
        edge* e = new edge(v, cost, capacity);
        edge* re = new edge(u, -cost, 0);

        e->rv = re;
        re->rv = e;

        edg[u].push_back(e);
        edg[v].push_back(re);
    }
    void spfa(int start){
```

```cpp
        int n = edg.size();
        auto inq = vec(n, 0);
        dis = vec(n, inf);
        par = vector<pair<int, edge*>>(n, {-1, nullptr});

        queue<int> q;
        q.push(start);
        dis[start] = 0;

        while (q.size()){
            int u = q.front(); q.pop();
            inq[u] = 0;

            for (auto e : edg[u]){
                if (e->capacity > 0 && dis[e->v] > dis[u] + e->cost){
                    dis[e->v] = dis[u] + e->cost;
                    par[e->v] = {u, e};

                    if (!inq[e->v]){
                        inq[e->v] = 1;
                        q.push(e->v);
                    }
                }
            }
        }
    }
    pl get(int start, int end, ll max_flow = inf){
        ll flow = 0, cost = 0;
        while (flow < max_flow){
            spfa(start);
            if (dis[end] == inf) break;

            ll f = max_flow - flow;
            int u = end;

            while (u != start){
                f = min(f, par[u].y->capacity);
                u = par[u].x;
            }

            flow += f;
            cost += f * dis[end];

            u = end;
            while (u != start){
                par[u].y->capacity -= f;
                par[u].y->rv->capacity += f;
                u = par[u].x;
            }
        }
        if (flow == max_flow || max_flow == inf)
            return {flow, cost};
        else
            return {-1, -1};
    }
};
```

3.6 Maximum Flow (Dinic)

Overview

Maximum flow using Dinic's algorithm.

Time complexity: $\mathcal{O}(V^2E)$ **for general graphs, but in practice** $\approx \mathcal{O}(E^{1.5})$

Implementation

```cpp
template<int V, class T=long long>
class max_flow {
        static const T INF = numeric_limits<T>::max();

        struct edge {
                int t, rev;
                T cap, f;
        };

public:
        vector<edge> adj[V];
        ll dist[V];
        int ptr[V];

        bool bfs(int s, int t) {
                memset(dist, -1, sizeof dist);
                dist[s] = 0;
                queue<int> q({ s });
                while (!q.empty() && dist[t] == -1) {
                        int n = q.front();
                        q.pop();
                        for (auto& e : adj[n]) {
                                if (dist[e.t] == -1 && e.cap != e.f) {
                                        dist[e.t] = dist[n] + 1;
                                        q.push(e.t);
                                }
                        }
                }
                return dist[t] != -1;
        }

        T augment(int n, T amt, int t) {
                if (n == t) return amt;
                for (; ptr[n] < adj[n].size(); ptr[n]++) {
                        edge& e = adj[n][ptr[n]];
                        if (dist[e.t] == dist[n] + 1 && e.cap != e.f) {
                                T flow = augment(e.t, min(amt, e.cap - e.f), t);
                                if (flow != 0) {
                                        e.f += flow;
                                        adj[e.t][e.rev].f -= flow;
                                        return flow;
                                }
                        }
                }
                return 0;
        }

        void add(int u, int v, T cap=1, T rcap=0) {
                adj[u].push_back({ v, (int) adj[v].size(), cap, 0 });
                adj[v].push_back({ u, (int) adj[u].size() - 1, rcap, 0 });
        }

        T calc(int s, int t) {
                T flow = 0;
                while (bfs(s, t)) {
                        memset(ptr, 0, sizeof ptr);
                        while (T df = augment(s, INF, t))
                                flow += df;
                }
                return flow;
        }

        void clear() {
                for (int n = 0; n < V; n++)
                        adj[n].clear();
        }
};
```

3.7 Maximum Matching (Hopcroft Karp)

Overview

Find maximum matching on bipartite graph.

Time complexity: $\mathcal{O}(m\sqrt{n})$ worst case

Implementation

```cpp
struct HopcroftKarp{
    vector<vector<int>> edg;
    vector<int> U, V;
    vector<int> pu, pv;
    vector<int> dist;

    //NOTE: This graph is 1-indexed!!!
    HopcroftKarp(int n, int m){
        edg = vector<vector<int>>(n + 1);
        for (int i = 0; i < n; i++)
            U.push_back(i + 1);
        for (int i = 0; i < m; i++)
            V.push_back(i + 1);

        pu = vector<int>(n + 1, 0);
        pv = vector<int>(m + 1, 0);
        dist = vector<int>(n + 1, inf);
    }

    void add_edge(int u, int v){
        edg[u].push_back(v);
    }

    bool bfs(){
        queue<int> q;
        for (int u : U){
            if (!pu[u]){
                q.push(u);
                dist[u] = 0;
            }

            else
                dist[u] = inf;
        }

        dist[0] = inf;
        while (q.size() > 0){
            int u = q.front();
            q.pop();

            if (dist[u] < dist[0]){
                for (int v : edg[u]){
                    if (dist[pv[v]] == inf){
                        q.push(pv[v]);
                        dist[pv[v]] = dist[u] + 1;
                    }
                }
            }
        }

        if (dist[0] == inf)
            return 0;
        return 1;
    }

    bool dfs(ll u){
        if (u == 0) return 1;
        for (int v : edg[u]){
            if (dist[pv[v]] == (dist[u] + 1)){
                if (dfs(pv[v])){
                    pu[u] = v;
                    pv[v] = u;
                    return 1;
                }
            }
        }

        dist[u] = 0;
        return 0;
    }

    int solve(){
        int res = 0;
        while (bfs()){
            for (int u : U){
                if (!pu[u])
                    if (dfs(u))
                        res++;
            }
        }

        return res;
    }
};
```

3.8 General Matching (Blossom)

Overview

Find maximum matching on general graph.

Time complexity: $\mathcal{O}(n^3)$ worst case

Implementation

```cpp
struct Matching {
    int n;
    vector<vector<int>> g;
    vector<int> mt;
    vector<int> is_ev, gr_buf;
    vector<pi> nx;
    int st;
    int group(int x) {
        if(gr_buf[x] == -1 || is_ev[gr_buf[x]] != st) return gr_buf[x];
        return gr_buf[x] = group(gr_buf[x]);
    }
    void match(int p, int b) {
        int d = mt[p];
        mt[p] = b;
        if(d == -1 || mt[d] != p) return;
        if(nx[p].second == -1) {
            mt[d] = nx[p].first;
            match(nx[p].first, d);
        } else {
            match(nx[p].first, nx[p].second);
            match(nx[p].second, nx[p].first);
        }
    }
    bool arg() {
        is_ev[st] = st;
        gr_buf[st] = -1;
        nx[st] = pi(-1, -1);
        queue<int> q;
        q.push(st);
        while(q.size()) {
            int a = q.front();
            q.pop();
            for(auto b : g[a]) {
                if(b == st) continue;
                if(mt[b] == -1) {
                    mt[b] = a;
                    match(a, b);
```

```
                    return true;
                }
                if(is_ev[b] == st) {
                    int x = group(a), y = group(b);
                    if(x == y) continue;
                    int z = -1;
                    while(x != -1 || y != -1) {
                        if(y != -1) swap(x, y);
                        if(nx[x] == pi(a, b)) {
                            z = x;
                            break;
                        }
                        nx[x] = pi(a, b);
                        x = group(nx[mt[x]].first);
                    }
                    for(int v : {group(a), group(b)}) {
                        while(v != z) {
                            q.push(v);
                            is_ev[v] = st;
                            gr_buf[v] = z;
                            v = group(nx[mt[v]].first);
                        }
                    }
                } else if(is_ev[mt[b]] != st) {
                    is_ev[mt[b]] = st;
                    nx[b] = pi(-1, -1);
                    nx[mt[b]] = pi(a, -1);
                    gr_buf[mt[b]] = b;
                    q.push(mt[b]);
                }
            }
        }
        return false;
    }
    Matching(const vector<vector<int>> &_g) : n(int(_g.size())), g(_g), mt(n, -1), is_ev(n, -1), gr_buf(n), nx(n) {
        for(st = 0; st < n; st++)
            if(mt[st] == -1) arg();
    }
    vector<pi> max_match() {
        vector<pi> res;
        for (int i = 0; i < n; i++){
            if(i < mt[i])
                res.push_back({i, mt[i]});
        }
        return res;
    }
};
```

4 Math

4.1 Modular Int

Overview

Helper class, some implementations below will use this.

Implementation

```
template<ll mod = 1000000007>
struct modu{
    ll val;
    modu(ll x){
        val = x;
        val %= mod;
        if (val < 0) val += mod;
    }
    modu(){ val = 0; }

    operator ll() const { return val; }
    modu operator+(modu const& other){ return val + other.val; }
    modu operator-(modu const& other){ return val - other.val; }
    modu operator*(modu const& other){ return val * other.val; }
    modu operator/(modu const& other){ return *this * other.inv(); }
    modu operator+=(modu const& other) { *this = *this + other; return *this; }
    modu operator-=(modu const& other) { *this = *this - other; return *this; }
    modu operator*=(modu const& other) { *this = *this * other; return *this; }
    modu operator/=(modu const& other) { *this = *this / other; return *this; }
    modu operator++(int) {modu tmp = *this; *this += 1; return tmp;}
    modu operator++() {*this += 1; return *this;}
    modu operator--(int) {modu tmp = *this; *this -= 1; return tmp;}
    modu operator--() {*this -= 1; return *this;}
    modu operator-() {return modu(-val);}
    friend ostream& operator<<(ostream& os, modu const& m) { return os << m.val; }
    friend istream& operator>>(istream& is, modu & m) { return is >> m.val; }

    modu pow(ll x) const{
        if (x == 0)
            return 1;
        if (x % 2 == 0){
            modu tmp = pow(x / 2);
            return tmp * tmp;
        }
        else
            return pow(x - 1) * *this;
    }

    modu inv() const{ return pow(mod - 2); }
};
```

4.2 Modular Square Root

Overview

Operations on field

$$\langle u, v \rangle = u + v\sqrt{k} \mod p$$

Implementation

```
ll MOD = 999999893;
ll sq = 2;

class EX {
  int re, im;
  static int trim(int a) {
    if (a >= MOD) a -= MOD;
    if (a < 0) a += MOD;
    return a;
  }
  static int inv(const int a) {
    int ans = 1;
    for (int cur = a, p = MOD - 2; p; p >>= 1, cur = 1ll * cur * cur % MOD) {
      if (p&1) ans = 1ll * ans * cur % MOD;
```

```cpp
    }
    return ans;
  };
public:
  EX(int re = 0, int im = 0) : re(re), im(im) {}
  EX& operator=(EX oth) { return re = oth.re, im = oth.im, *this; }
  int norm() const {
    return trim((1ll * re * re - 1ll * sq * im % MOD * im) % MOD);
  }
  EX conj() const {
    return EX(re, trim(MOD - im));
  }
  EX operator*(EX oth) const {
    return EX((1ll * re * oth.re + 1ll * sq * im % MOD * oth.im) % MOD,
              (1ll * re * oth.im + 1ll * im * oth.re) % MOD);
  };
  EX operator/(int n) const {
    return EX(1ll * re * inv(n) % MOD, 1ll * im * inv(n) % MOD);
  }
  EX operator/(EX oth) const { return *this * oth.conj() / oth.norm(); }
  EX operator+(EX oth) const { return EX(trim(re + oth.re), trim(im + oth.im)); }
  EX operator-(EX oth) const {
    return EX(trim(re - oth.re), trim(im - oth.im));
  }
  EX pow(long long n) const {
    EX ans(1);
    for (EX a = *this; n; n >>= 1, a = a * a) {
      if (n&1) ans = a * ans;
    }
    return ans;
  }
  bool operator==(EX oth) const { return re == oth.re and im == oth.im; }
  bool operator!=(EX oth) const { return not (*this == oth); }
  int real() const& { return re; }
  int imag() const& { return im; }
};
```

4.3 Discrete Log

Overview

Given a, b, m, find any x that satisfy

$$a^x = b \mod m$$

Time complexity: $\mathcal{O}(N \log\log N)$

Implementation

```cpp
// Returns minimum x for which a ^ x % m = b % m.
int solve(int a, int b, int m) {
    a %= m, b %= m;
    int k = 1, add = 0, g;
    while ((g = gcd(a, m)) > 1) {
        if (b == k)
            return add;
        if (b % g)
            return -1;
        b /= g, m /= g, ++add;
        k = (k * 1ll * a / g) % m;
    }

    int n = sqrt(m) + 1;
    int an = 1;
    for (int i = 0; i < n; ++i)
        an = (an * 1ll * a) % m;

    unordered_map<int, int> vals;
    for (int q = 0, cur = b; q <= n; ++q) {
        vals[cur] = q;
        cur = (cur * 1ll * a) % m;
    }

    for (int p = 1, cur = k; p <= n; ++p) {
        cur = (cur * 1ll * an) % m;
        if (vals.count(cur)) {
            int ans = n * p - vals[cur] + add;
            return ans;
        }
    }
    return -1;
}
```

4.4 Primite Root

Overview

Given a, n, find g so that for any a such that $gcd(a, n) = 1$, there exists k such that

$$g^k = a \mod n$$

Time complexity: $\mathcal{O}(Ans \cdot \log \phi(n) \cdot \log n)$

Implementation

```cpp
int powmod (int a, int b, int p) {
    int res = 1;
    while (b)
        if (b & 1)
            res = int (res * 1ll * a % p),  --b;
        else
            a = int (a * 1ll * a % p),  b >>= 1;
    return res;
}

int generator (int p) {
    vector<int> fact;
    int phi = p-1,  n = phi;
    for (int i=2; i*i<=n; ++i)
        if (n % i == 0) {
            fact.push_back (i);
            while (n % i == 0)
                n /= i;
        }
    if (n > 1)
        fact.push_back (n);

    for (int res=2; res<=p; ++res) {
        bool ok = true;
        for (size_t i=0; i<fact.size() && ok; ++i)
            ok &= powmod (res, phi / fact[i], p) != 1;
        if (ok)  return res;
    }
    return -1;
}
```

4.5 Euler's Totient Funnction

Overview

Find $\phi(i)$ for i from 1 to N.

Time complexity: $\mathcal{O}(N \log \log N)$

Implementation

```
int phi[def];
void phi(int n) {
    phi[0] = 0;
    phi[1] = 1;
    for (int i = 2; i <= n; i++)
        phi[i] = i - 1;

    for (int i = 2; i <= n; i++)
        for (int j = 2 * i; j <= n; j += i)
              phi[j] -= phi[i];
}
```

4.6 Chinese Remainder Theorem

Overview

Given a system of congruences

$$a = a_1 \mod M_1, a = a_2 \mod M_2, ...$$

where M_i might not be pairwise coprime, find any a that satisfy it.

Time complexity: $\mathcal{O}(N \log \max(M_i))$

Implementation

```
typedef __int128_t i128;
i128 exeuclid(i128 a, i128 b, i128& x, i128& y){
    if (b == 0) {
        x = 1;
        y = 0;
        return a;
    }
    i128 x1, y1;
    i128 d = exeuclid(b, a % b, x1, y1);
    x = y1;
    y = x1 - y1 * (a / b);
    return d;
}

struct CBT{
    i128 A = 0, M = 0;
    void add(i128 a, i128 m){
        a = ((a % m) + m) % m;
        i128 _M = M;
        if (M == 0){
            A = a, M = m;
            return;
        }
        if (A == -1) return;
        i128 p, q;
        i128 g = exeuclid(M, m, p, q);
        if ((a - A) % g != 0){
            A = -1, M = -1;
            return;
        }
        i128 mul = (a - A) / g;
        M = m * M / g;
        A = (((_M * p * mul + A) % M) + M) % M;
    }
};
```

Usage

- The $add(x, y)$ function add the condition $a = x \mod y$.
- If $a \neq -1$, the solution a will satisfy $a = A \mod M$.

4.7 Extended Euclidean

Overview

Given a, b, find any x, y that satisfy

$$ax + by = gcd(a, b)$$

Note that the function pass x, y by reference and returns $gcd(a, b)$.

Time complexity: $\mathcal{O}(\log n)$)

Implementation

```
int extended_euclid(int a, int b, int& x, int& y) {
    if (b == 0) {
        x = 1;
        y = 0;
        return a;
    }
    int x1, y1;
    int d = extended_euclid(b, a % b, x1, y1);
    x = y1;
    y = x1 - y1 * (a / b);
    return d;
}
```

4.8 Linear Diophantine

Overview

Given a, b, c, find any x, y that satisfy

$$ax + by = c$$

Time complexity: $\mathcal{O}(\log n)$)

Implementation

```
bool find_any_solution(int a, int b, int c, int &x0, int
↪ &y0, int &g) {
    g = extended_euclid(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;
}
```

4.9 Matrix

Overview

Matrix helper class.

Implementation

```
template <typename T>
struct Matrix{
    vector<vector<T>> m;
    Matrix (vector<vector<T>> &m) : T(m){}
    Matrix (int r, int c) {
        m = vector<vector<T>>(r, vector<T>(c));
    }

    int row() const {return m.size();}
    int col() const {return m[0].size();}

    static Matrix identity(int n){
        Matrix res = Matrix(n, n);
        for (int i = 0; i < n; i++)
            res[i][i] = 1;
        return res;
    }

    auto & operator [] (int i) { return m[i]; }
    const auto & operator[] (int i) const { return m[i]; }

    Matrix operator * (const Matrix &b){
        Matrix a = *this;
        assert(a.col() == b.row());

        Matrix c(a.row(), b.col());
        for (int i = 0; i < a.row(); i++)
            for (int j = 0; j < b.col(); j++)
                for (int k = 0; k < a.col(); k++)
                    c[i][j] += a[i][k] * b[k][j];
        return c;
    }

    Matrix pow(ll x){
        assert(row() == col());
        Matrix crr = *this, res = identity(row());
        while (x > 0){
            if (x % 2 == 1)
                res = res * crr;
            crr = crr * crr;
            x /= 2;
        }
        return res;
    }
};
```

4.10 Miller Rabin Primality Test

Overview

Deterministic implementation of Miller Rabin.

Time complexity: Should be fast

Implementation

```
ll binpower(ll base, ll e, ll mod) {
    ll result = 1;
    base %= mod;
    while (e) {
        if (e & 1)
            result = (__int128_t)result * base % mod;
        base = (__int128_t)base * base % mod;
        e >>= 1;
    }
    return result;
}

bool check_composite(ll n, ll a, ll d, int s) {
    ll x = binpower(a, d, n);
    if (x == 1 || x == n - 1)
        return false;
    for (int r = 1; r < s; r++) {
        x = (__int128_t)x * x % n;
        if (x == n - 1)
            return false;
    }
    return true;
};

bool MillerRabin(ll n) { // returns true if n is prime, else returns false.
    if (n < 2)
        return false;

    int r = 0;
    ll d = n - 1;
    while ((d & 1) == 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 (check_composite(n, a, d, r))
            return false;
    }
    return true;
}
```

4.11 Fast Fourier Transform

Overview

$multiplymod(A, B, M)$ returns C where

$$C[u] = \sum_{i=1}^{|A|} \sum_{j=1}^{|B|} A_i \cdot B_j \mod M \ (i + j = u)$$

Time complexity: $\mathcal{O}(n \log n)$)

Implementation

```
using cpx = complex<double>;
const double PI = acos(-1);
vector<cpx> roots = {{0, 0}, {1, 0}};

void ensure_capacity(int min_capacity) {
    for (int len = roots.size(); len < min_capacity; len *= 2) {
```

```
        for (int i = len >> 1; i < len; i++) {
            roots.emplace_back(roots[i]);
            double angle = 2 * PI * (2 * i + 1 - len) / (len * 2);
            roots.emplace_back(cos(angle), sin(angle));
        }
    }
}

void fft(vector<cpx> &z, bool inverse) {
    int n = z.size();
    assert((n & (n - 1)) == 0);
    ensure_capacity(n);
    for (unsigned i = 1, j = 0; i < n; i++) {
        int bit = n >> 1;
        for (; j >= bit; bit >>= 1)
            j -= bit;
        j += bit;
        if (i < j)
            swap(z[i], z[j]);
    }
    for (int len = 1; len < n; len <<= 1) {
        for (int i = 0; i < n; i += len * 2) {
            for (int j = 0; j < len; j++) {
                cpx root = inverse ? conj(roots[j + len]) : roots[j + len];
                cpx u = z[i + j];
                cpx v = z[i + j + len] * root;
                z[i + j] = u + v;
                z[i + j + len] = u - v;
            }
        }
    }
    if (inverse)
        for (int i = 0; i < n; i++)
            z[i] /= n;
}
vector<int> multiply_mod(const vector<int> &a, const vector<int> &b, int m) {
    int need = a.size() + b.size() - 1;
    int n = 1;
    while (n < need)
        n <<= 1;
    vector<cpx> A(n);
    for (size_t i = 0; i < a.size(); i++) {
        int x = (a[i] % m + m) % m;
        A[i] = cpx(x & ((1 << 15) - 1), x >> 15);
    }
    fft(A, false);

    vector<cpx> B(n);
    for (size_t i = 0; i < b.size(); i++) {
        int x = (b[i] % m + m) % m;
        B[i] = cpx(x & ((1 << 15) - 1), x >> 15);
    }
    fft(B, false);

    vector<cpx> fa(n);
    vector<cpx> fb(n);
    for (int i = 0, j = 0; i < n; i++, j = n - i) {
        cpx a1 = (A[i] + conj(A[j])) * cpx(0.5, 0);
        cpx a2 = (A[i] - conj(A[j])) * cpx(0, -0.5);
        cpx b1 = (B[i] + conj(B[j])) * cpx(0.5, 0);
        cpx b2 = (B[i] - conj(B[j])) * cpx(0, -0.5);
        fa[i] = a1 * b1 + a2 * b2 * cpx(0, 1);
        fb[i] = a1 * b2 + a2 * b1;
    }

    fft(fa, true);
    fft(fb, true);
    vector<int> res(need);
    for (int i = 0; i < need; i++) {
        long long aa = (long long)(fa[i].real() + 0.5);
        long long bb = (long long)(fb[i].real() + 0.5);
        long long cc = (long long)(fa[i].imag() + 0.5);
        res[i] = (aa % m + (bb % m << 15) + (cc % m << 30)) % m;
    }
    return res;
}
```

4.12 OR Convolution

Overview

$convoluteor(A, B)$ returns C where

$$C[u] = \sum_{i=1}^{|A|} \sum_{j=1}^{|B|} A_i \cdot B_j \mod M \ (i|j = u)$$

Time complexity: $\mathcal{O}(2^N \cdot N)$

Implementation

```
vector<int> convolute_or(vector<int> &a, vector<int> &b){
    int n = a.size();
    for (int i = 0; i < n; i++) for (int j = 0; j < (1 << n); j++){
        if ((j >> i) & 1){
            a[j] += a[j - (1 << i)];
            b[j] += b[j - (1 << i)];
        }
    }
    for (int i = n - 1; i >= 0; i--){
        for (int j = (1 << n) - 1; j >= 0; j--){
            if ((j >> i) & 1)
                a[j] -= a[j - (1 << i)];
        }
    }
    auto c = vector<int>(n, 0);
    for (int i = n - 1; i < (1 << n); i++)
        c[i] = a[i] * b[i];
    for (int i = n - 1; i >= 0; i--){
        for (int j = (1 << n) - 1; j >= 0; j--){
            if ((j >> i) & 1)
                c[j] -= c[j - (1 << i)];
        }
    }
}
```

4.13 XOR Convolution

Overview

idk lol.

Implementation

```
void xorconv(vector<int> &a,int modul){ // chuyen tu dang binh thuong sang dang dac biet, xong cu lay a[i] = b[i] * c[i] ...
    int n = a.size();
    for(int m = n/2; m; m/=2){
        for(int i = 0 ; i < n; i+= 2 * m){
            for(int j = 0;j <m;++ j){
                int x = a[i + j];
                int y = a[i + j + m];
                a[i + j] = (x + y)%modul;
                a[i + j + m] = (x-y+modul) % modul;
            }
```

```cpp
        }
    }
}
void xorconv2(vector<int> &a,int modul){ // chuyen tu dang dac biet ve dang binh thuong => dap an sau khi fft
    int n = a.size();
    for(int m = 1; m<n; m*=2){
        for(int i = 0 ; i < n; i+= 2 * m){
            for(int j = 0;j <m;++ j){
                int x = a[i + j];
                int y = a[i + j + m];
                a[i + j] = (x + y)%modul;
                a[i + j + m] = (x-y+modul) % modul;
            }
        }
    }
    for(int i = 0;i<n;++i){
        a[i] = 1LL * (ll)a[i] * binpow(n,modul - 2, modul) %modul;
    }
}
```

5 String

5.1 Rolling Hash

Overview

Rolling hash implementation, use multiple mod if necessary.

Time complexity: $\mathcal{O}(N)$

Implementation

```cpp
struct hashu{
        ll n;
        vector<dd> p, h;

        hashu(string s){
                n = s.size();
                p = vector<dd>(n + 1);
                h = vector<dd>(n + 1);

                p[0] = {1, 1};
                for (int i = 1; i <= n; i++)
                        p[i] = p[i - 1] * base;
                for (int i = 1; i <= n; i++)
                        h[i] = (h[i - 1] * base) + (s[i - 1] - '0');
        }

        dd get(ll l, ll r){
                return h[r + 1] - (h[l] * p[r - l + 1]);
        }
};
```

5.2 Z-Function

Overview

Return an array where the i-th element corresponds to the longest sub-string starting from i that matches the prefix of s.

Time complexity: $\mathcal{O}(N)$

Implementation

```cpp
vector<int> z_func(string s){
        int n = s.size();
        vector<int> v(n);

        int l = 0, r = 0;
        for (int i = 1; i < n; i++){
                if (i < r)
                        v[i] = min(r - i, v[i - 1]);
                while ((v[i] + i) < n && s[v[i]] == s[v[i] + i])
                        v[i]++;
                if ((v[i] + i) > r)
                        l = i, r = v[i] + i;
        }

        return v;
}
```

5.3 Prefix Function

Overview

Return an array where the i-th element corresponds to the longest sub-string ending at i that matches the prefix of s.

Time complexity: $\mathcal{O}(N)$

Implementation

```cpp
vector<int> pref_func(string s){
    int n = siz(s);
    vector<int> v(n);

    for (int i = 1; i < n; i++){
        ll j = v[i - 1];
        while (j > 0 && s[j] != s[i])
            j = v[j - 1];
        if (s[j] == s[i])
            j++;
        v[i] = j;
    }

    return v;
}
```

5.4 Manacher's Algorithm

Overview

Return an array where the i-th element corresponds to the longest palindrome that has i as the center, note that the algorithm only works for odd length palindrome, even can also be easily handled by inserting a dummy character in every even indicies.

Time complexity: $\mathcal{O}(N)$

Implementation

```
vector<int> manacher(string s) {
    int n = s.size();
    s = "$" + s + "^";
    vector<int> p(n + 2);
    int l = 1, r = 1;
    for(int i = 1; i <= n; i++) {
        p[i] = max(0, min(r - i, p[l + (r - i)]));
        while(s[i - p[i]] == s[i + p[i]]) {
            p[i]++;
        }
        if(i + p[i] > r) {
            l = i - p[i], r = i + p[i];
        }
    }
    return vector<int>(begin(p) + 1, end(p) - 1);
}
```

5.5 Aho-Corasick

Overview

Construct an automaton of `Trie` nodes, where $dp[i][c]$ is the next state of i when adding character c. If no state exists, we repeatedly go through the next longest available suffix j of i, and try to get $dp[j][c]$.

Time complexity: $\mathcal{O}(M * K)$, where M is the number of nodes in the `Trie`, and K is the alphabet size

Implementation

```
struct node{
    int p[26];
    int link;

    node(){
        for (int i = 0; i < 26; i++)
            p[i] = -1;
    }
};

struct Trie{
    int indx = 1;
    int dp[def][26];
    vector<node> p;

    Trie(){
        p.push_back(node());
    }

    int add(string s){
        ll crr = 0;
        for (int i = 0; i < s.size(); i++){
            int c = s[i] - 'a';
            if (p[crr].p[c] == -1){
                p[crr].p[c] = indx++;
                p.push_back(node());
            }

            crr = p[crr].p[c];
        }

        return crr;
    }

    void buildsuffix(){
        int n = p.size();
        queue<int> q;
        q.push(0);

        p[0].link = 0;
        for (int i = 0; i < n; i++) for (int j = 0; j < 26; j++)
            dp[i][j] = 0;

        while (q.size()){
            int u = q.front();
            q.pop();

            for (int i = 0; i < 26; i++){
                int v = p[u].p[i];
                if (v != -1){
                    dp[u][i] = v;
                    p[v].link = (u == 0)? 0 : dp[p[u].link][i];
                    q.push(v);
                }

                else
                    dp[u][i] = dp[p[u].link][i];
            }
        }
    }
};
```

6 Tree

6.1 Tree

Overview

Helper class, some implementations below will use this.

Implementation

```
struct Tree{
    vector<vector<int>> edg;
    vector<int> par, depth;
    int n, root;

    Tree(int n, int root) : n(n), root(root){
        edg = vector<vector<int>>(n, vector<int>());
    }
    void add(int u, int v){
        edg[u].push_back(v);
        edg[v].push_back(u);
    }
    void clear(){
        for (int u = 0; u < n; u++)
            edg[u].clear();
    }
    void remove_dup(){
        for (int u = 0; u < n; u++){
            sort(edg[u].begin(), edg[u].end());
            edg[u].erase(unique(edg[u].begin(), edg[u].end()), edg[u].end());
        }
    }
    void get_info(){
        par = depth = vector<int>(n, 0);
        par[root] = -1;
        dfs(root, -1);
    }
    void dfs(int u, int pre){
        for (int v : edg[u]){
            if (v == pre) continue;
            par[v] = u; depth[v] = depth[u] + 1;
```

```cpp
            dfs(v, u);
        }
    }
};
```

6.2 Lowest Common Ancestor

Overview

Uses binary lifting to find the k-th parent of a node.

Time complexity: $\mathcal{O}(n \log n)$ for build, $\mathcal{O}(\log n)$ for query

Implementation

```cpp
struct LCA{
    vector<vector<int>> f;
    Tree T;
    int n, k;

    LCA(Tree &_T) : T(_T){
        n = T.n; k = log2(n) + 2;
        for (int i = 0; i < n; i++)
            f.push_back(vector<int>(k, -1));
        T.get_info();

        for (int i = 0; i < n; i++)
            f[i][0] = T.par[i];
        for (int j = 1; j < k; j++) for (int i = 0; i < n; i++){
            int p = f[i][j - 1];
            if (p != -1)
                f[i][j] = f[p][j - 1];
        }
    }

    int get(int u, int v){
        if (T.depth[u] < T.depth[v])
            swap(u, v);
        for (int i = k - 1; i >= 0; i--){
            if (f[u][i] != -1 && T.depth[f[u][i]] >= T.depth[v])
                u = f[u][i];
        }
        if (u == v) return u;
        for (int i = k - 1; i >= 0; i--){
            if (f[u][i] != -1 && f[u][i] != f[v][i])
                u = f[u][i], v = f[v][i];
        }
        return T.par[u];
    }
};
```

6.3 Heavy Light Decomposition

Overview

Clean implementation of HLD, only uses 1 segment, $pos[u]$ is the position of u on the segment. Change the query function if needed, for now it's just max query using a segment tree

Time complexity: $\mathcal{O}(n \log n)$ for build, $\mathcal{O}(\log^2 n)$ for query

Implementation

```cpp
struct HLD{
    vector<int> head, par, h, pos, big;
    int n, indx = 0;
    Tree T;

    HLD(Tree &_T) : T(_T){
        n = T.n;
        head = par = h = pos = big = vector<int>(n, 0);
        dfs(0, -1);
        decompose(0, 0, -1);
    }
    int dfs(int u, int pre){
        ll res = 1;
        big[u] = -1;

        int crr_size = 0;
        for (int v : T.edg[u]){
            if (v == pre)
                continue;

            par[v] = u; h[v] = h[u] + 1;
            int child_size = dfs(v, u);

            if (child_size > crr_size)
                big[u] = v, crr_size = child_size;
            res += child_size;
        }

        return res;
    }
    void decompose(int u, int root, int pre){
        head[u] = root, pos[u] = indx++;
        if (big[u] != -1)
            decompose(big[u], root, u);
        for (int v : T.edg[u]){
            if (v == pre || v == big[u])
                continue;
            decompose(v, v, u);
        }
    }
    ll query(int u, int v){
        ll res = -inf;
        while (head[u] != head[v]){
            if (h[head[u]] < h[head[v]])
                swap(u, v);
            maxi(res, st.get(pos[head[u]], pos[u]));
            u = par[head[u]];
        }

        if (h[u] < h[v])
            swap(u, v);
        maxi(res, st.get(pos[v], pos[u]));

        return res;
    }
};
```

6.4 Centroid Decomposition

Overview

Uses the centroid of a tree to decompose into smaller subtrees, each node will be recursively decomposed in $\mathcal{O}(log)$ times.

Time complexity: $\mathcal{O}(n \log n)$

Implementation

```
vector<ll> edg[def];
bool dead[def];
ll cnt[def];

void dfs(ll u, ll pre){
        cnt[u] = 1;
        for (ll v : edg[u]){
                if (v == pre || dead[v])
                        continue;
                dfs(v, u);
                cnt[u] += cnt[v];
        }
}

ll centroid(ll u, ll pre, ll n){
        for (ll v : edg[u]){
                if (v == pre || dead[v])
                        continue;
                if (cnt[v] > (n / 2))
                        return centroid(v, u, n);
        }
        return u;
}
long long get(ll u){
        dfs(u, -1);
        ll root = centroid(u, -1, cnt[u]);
        dead[root] = 1;

        for (ll v : edg[root]){
                if (!dead[v])
                        get(v);
        }
        return res;
}
```

7 Geometry (Kactl)

7.1 Kactl template

Overview

Kactl implementation sometimes use their own template, reference this for clarity.

Implementation

```
#define rep(i, a, b) for(int i = a; i < (b); ++i)
#define all(x) begin(x), end(x)
#define sz(x) (int)(x).size()
typedef long long ll;
typedef pair<int, int> pii;
typedef vector<int> vi;
```

7.2 Point

Overview

Helper class, some implementations below will use this.

Implementation

```
template <class T> int sgn(T x) { return (x > 0) - (x <
↪ 0); }
template<class T>
struct Point {
        typedef Point P;
        T x, y;
        explicit Point(T x=0, T y=0) : x(x), y(y) {}
        bool operator<(P p) const { return tie(x,y) <
        ↪ tie(p.x,p.y); }
        bool operator==(P p) const { return
        ↪ tie(x,y)==tie(p.x,p.y); }
        P operator+(P p) const { return P(x+p.x, y+p.y);
        ↪ }
        P operator-(P p) const { return P(x-p.x, y-p.y);
        ↪ }
        P operator*(T d) const { return P(x*d, y*d); }
        P operator/(T d) const { return P(x/d, y/d); }
        T dot(P p) const { return x*p.x + y*p.y; }
        T cross(P p) const { return x*p.y - y*p.x; }
        T cross(P a, P b) const { return
        ↪ (a-*this).cross(b-*this); }
        T dist2() const { return x*x + y*y; }
        double dist() const { return
        ↪ sqrt((double)dist2()); }
        // angle to x-axis in interval [-pi, pi]
        double angle() const { return atan2(y, x); }
        P unit() const { return *this/dist(); } // makes
        ↪ dist()=1
        P perp() const { return P(-y, x); } // rotates
        ↪ +90 degrees
        P normal() const { return perp().unit(); }
        // returns point rotated 'a' radians ccw around
        ↪ the origin
        P rotate(double a) const {
                return P(x*cos(a)-y*sin(a),x*sin(a)+y*co
                ↪ s(a)); }
        friend ostream& operator<<(ostream& os, P p) {
                return os << "(" << p.x << "," << p.y <<
                ↪ ")"; }
};
```

7.3 CCW

Overview

- Returns where p is as seen from s towards e. 1/0/-1 $\Leftrightarrow$ left/on line/right.
- If the optional argument *eps* is given 0 is returned if p is within distance *eps* from the line.
- P is supposed to be Point¡T¿ where T is e.g. double or long long.
- It uses products in intermediate steps so watch out for overflow if using int or long long.

Implementation

```
template<class P>
int sideOf(P s, P e, P p) { return sgn(s.cross(e, p)); }

template<class P>
int sideOf(const P& s, const P& e, const P& p, double
↪ eps) {
        auto a = (e-s).cross(p-s);
        double l = (e-s).dist()*eps;
```

```
        return (a > 1) - (a < -1);
}
```

7.4 Circle Intersection

Overview

Computes the pair of points at which two circles intersect. Returns false in case of no intersection.

Time complexity: $\mathcal{O}(1)$

Implementation

```
typedef Point<double> P;
bool circleInter(P a,P b,double r1,double r2,pair<P, P>* out) {
        if (a == b) { assert(r1 != r2); return false; }
        P vec = b - a;
        double d2 = vec.dist2(), sum = r1+r2, dif = r1-r2,
                p = (d2 + r1*r1 - r2*r2)/(d2*2), h2 = r1*r1 - p*p*d2;
        if (sum*sum < d2 || dif*dif > d2) return false;
        P mid = a + vec*p, per = vec.perp() * sqrt(fmax(0, h2) / d2);
        *out = {mid + per, mid - per};
        return true;
}
```

7.5 Circle Line

Overview

Finds the intersection between a circle and a line. Returns a vector of either 0, 1, or 2 intersection points. P is intended to be Point¡double¿.

Time complexity: $\mathcal{O}(1)$

Implementation

```
template<class P>
vector<P> circleLine(P c, double r, P a, P b) {
        P ab = b - a, p = a + ab * (c-a).dot(ab) / ab.dist2();
        double s = a.cross(b, c), h2 = r*r - s*s / ab.dist2();
        if (h2 < 0) return {};
        if (h2 == 0) return {p};
        P h = ab.unit() * sqrt(h2);
        return {p - h, p + h};
}
```

7.6 Circle Polygon

Overview

Returns the area of the intersection of a circle with a ccw polygon.

Time complexity: $\mathcal{O}(n)$

Implementation

```
#define arg(p, q) atan2(p.cross(q), p.dot(q))
double circlePoly(P c, double r, vector<P> ps) {
        auto tri = [&](P p, P q) {
                auto r2 = r * r / 2;
                P d = q - p;
                auto a = d.dot(p)/d.dist2(), b = (p.dist2()-r*r)/d.dist2();
                auto det = a * a - b;
                if (det <= 0) return arg(p, q) * r2;
                auto s = max(0., -a-sqrt(det)), t = min(1., -a+sqrt(det));
                if (t < 0 || 1 <= s) return arg(p, q) * r2;
                P u = p + d * s, v = q + d * (t-1);
                return arg(p,u) * r2 + u.cross(v)/2 + arg(v,q) * r2;
        };
        auto sum = 0.0;
        rep(i,0,sz(ps))
                sum += tri(ps[i] - c, ps[(i + 1) % sz(ps)] - c);
        return sum;
}
```

7.7 Circle Tagents

Overview

Finds the external tangents of two circles, or internal if r2 is negated. Can return 0, 1, or 2 tangents – 0 if one circle contains the other (or overlaps it, in the internal case, or if the circles are the same); 1 if the circles are tangent to each other (in which case .first = .second and the tangent line is perpendicular to the line between the centers). .first and .second give the tangency points at circle 1 and 2 respectively. To find the tangents of a circle with a point set r2 to 0.

Time complexity: $\mathcal{O}(1)$

Implementation

```
template<class P>
vector<pair<P, P>> tangents(P c1, double r1, P c2, double r2) {
        P d = c2 - c1;
        double dr = r1 - r2, d2 = d.dist2(), h2 = d2 - dr * dr;
        if (d2 == 0 || h2 < 0)  return {};
        vector<pair<P, P>> out;
        for (double sign : {-1, 1}) {
                P v = (d * dr + d.perp() * sqrt(h2) * sign) / d2;
                out.push_back({c1 + v * r1, c2 + v * r2});
        }
        if (h2 == 0) out.pop_back();
        return out;
}
```

7.8 Closest pair of points

Overview

Finds the closest pair of points.

Time complexity: $\mathcal{O}(n \log n)$

Implementation

```cpp
typedef Point<ll> P;
pair<P, P> closest(vector<P> v) {
	assert(sz(v) > 1);
	set<P> S;
	sort(all(v), [](P a, P b) { return a.y < b.y; });
	pair<ll, pair<P, P>> ret{LLONG_MAX, {P(), P()}};
	int j = 0;
	for (P p : v) {
		P d{1 + (ll)sqrt(ret.first), 0};
		while (v[j].y <= p.y - d.x) S.erase(v[j++]);
		auto lo = S.lower_bound(p - d), hi = S.upper_bound(p + d);
		for (; lo != hi; ++lo)
			ret = min(ret, {(*lo - p).dist2(), {*lo, p}});
		S.insert(p);
	}
	return ret.second;
}
```

7.9 Convex Hull

Overview

Returns a vector of the points of the convex hull in counter-clockwise order. Points on the edge of the hull between two other points are not considered part of the hull.

Time complexity: $\mathcal{O}(n \log n)$

Implementation

```cpp
typedef Point<ll> P;
vector<P> convexHull(vector<P> pts) {
	if (sz(pts) <= 1) return pts;
	sort(all(pts));
	vector<P> h(sz(pts)+1);
	int s = 0, t = 0;
	for (int it = 2; it--; s = --t, reverse(all(pts)))
		for (P p : pts) {
			while (t >= s + 2 && h[t-2].cross(h[t-1], p) <= 0) t--;
			h[t++] = p;
		}
	return {h.begin(), h.begin() + t - (t == 2 && h[0] == h[1])};
}
```

7.10 Hull Diameter

Overview

Returns the two points with max distance on a convex hull (ccw, no duplicate/collinear points).

Time complexity: $\mathcal{O}(n)$

Implementation

```cpp
typedef Point<ll> P;
array<P, 2> hullDiameter(vector<P> S) {
	int n = sz(S), j = n < 2 ? 0 : 1;
	pair<ll, array<P, 2>> res({0, {S[0], S[0]}});
	rep(i,0,j)
		for (;; j = (j + 1) % n) {
			res = max(res, {(S[i] - S[j]).dist2(), {S[i], S[j]}});
			if ((S[(j + 1) % n] - S[j]).cross(S[i + 1] - S[i]) >= 0)
				break;
		}
	return res.second;
}
```

7.11 Point inside Hull

Overview

- Determine whether a point t lies inside a convex hull (CCW order, with no collinear points). Returns true if point lies within the hull. If strict is true, points on the boundary aren't included.
- **NOTE:** Requires **7.12** and **7.2**.

Time complexity: $\mathcal{O}(\log n)$

Implementation

```cpp
bool inHull(const vector<P>& l, P p, bool strict = true) {
	int a = 1, b = sz(l) - 1, r = !strict;
	if (sz(l) < 3) return r && onSegment(l[0], l.back(), p);
	if (sideOf(l[0], l[a], l[b]) > 0) swap(a, b);
	if (sideOf(l[0], l[a], p) >= r || sideOf(l[0], l[b], p)<= -r)
		return false;
	while (abs(a - b) > 1) {
		int c = (a + b) / 2;
		(sideOf(l[0], l[c], p) > 0 ? b : a) = c;
	}
	return sgn(l[a].cross(l[b], p)) < r;
}
```

7.12 Point on Segment

Overview

Returns true iff p lies on the line segment from s to e. Use $segDist(s, e, p) <= epsilon$ instead when using Point¡double¿.

Time complexity: $\mathcal{O}(1)$

Implementation

```
template<class P> bool onSegment(P s, P e, P p) {
	return p.cross(s, e) == 0 && (s - p).dot(e - p) <= 0;
}
```

7.13 Segment Distance

Overview

Returns the shortest distance between point p and the line segment from point s to e.

Time complexity: $\mathcal{O}(1)$

Implementation

```
template<class P> bool onSegment(P s, P e, P p) {
	return p.cross(s, e) == 0 && (s - p).dot(e - p) <= 0;
}
```

7.14 Segment Intersection

Overview

- If a unique intersection point between the line segments going from s1 to e1 and from s2 to e2 exists then it is returned.
- If no intersection point exists an empty vector is returned.
- If infinitely many exist a vector with 2 elements is returned, containing the endpoints of the common line segment.
- **NOTE:** Requires **7.12**.

Time complexity: $\mathcal{O}(1)$

Implementation

```
template<class P> vector<P> segInter(P a, P b, P c, P d) {
	auto oa = c.cross(d, a), ob = c.cross(d, b),
	     oc = a.cross(b, c), od = a.cross(b, d);
	// Checks if intersection is single non-endpoint point.
	if (sgn(oa) * sgn(ob) < 0 && sgn(oc) * sgn(od) < 0)
		return {(a * ob - b * oa) / (ob - oa)};
	set<P> s;
	if (onSegment(c, d, a)) s.insert(a);
	if (onSegment(c, d, b)) s.insert(b);
	if (onSegment(a, b, c)) s.insert(c);
	if (onSegment(a, b, d)) s.insert(d);
	return {all(s)};
}
```

7.15 Line Distance

Overview

- Returns the signed distance between point p and the line containing points a and b.
- Positive value on left side and negative on right as seen from a towards b. a==b gives nan.

Time complexity: $\mathcal{O}(1)$

Implementation

```
template<class P>
double lineDist(const P& a, const P& b, const P& p) {
	return (double)(b-a).cross(p-a)/(b-a).dist();
}
```

7.16 Line Intersection

Overview

- If a unique intersection point of the lines going through s1,e1 and s2,e2 exists {1, point} is returned.
- If no intersection point exists {0, (0,0)} is returned and if infinitely many exists {-1, (0,0)} is returned.

Time complexity: $\mathcal{O}(1)$

Implementation

```
template<class P>
pair<int, P> lineInter(P s1, P e1, P s2, P e2) {
	auto d = (e1 - s1).cross(e2 - s2);
	if (d == 0) // if parallel
		return {-(s1.cross(e1, s2) == 0), P(0, 0)};
	auto p = s2.cross(e1, e2), q = s2.cross(e2, s1);
	return {1, (s1 * p + e1 * q) / d};
}
```