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1 Data structures

1.1 Segtree Lazy (Atcoder)

```
struct Node {
    // need an empty constructor with the neutral node
    Node() : {}
};

struct Lazy {
    // need an empty constructor with the neutral lazy
    Lazy() : {}
};

// how to merge two nodes
Node op(Node a, Node b) {}

// how to apply the lazy into a node
Node mapping(Lazy a, Node b, int, int) {}

// how to merge two lazy
Lazy comp(Lazy a, Lazy b) {}

template <typename T, auto op, typename L, auto mapping,
          auto composition>
struct SegTreeLazy {
    static_assert(
        is_convertible_v<decltype(op), function<T(T, T)>>,
        "op must be a function T(T, T)");
    static_assert(
        is_convertible_v<decltype(mapping),
        function<T(L, T, int, int)>>,
        "mapping must be a function T(L, T, int, int)");
    static_assert(is_convertible_v<decltype(composition),
        function<L(L, L)>>,
        "composition must be a function L(L, L)");

    int N, size, height;
    const T eT;
    const L eL;
    vector<T> d;
    vector<L> lz;

    SegTreeLazy(const T &eT_ = T(), const L &eL_ = L())
```

```
        : SegTreeLazy(0, eT_, eL_) {}
    explicit SegTreeLazy(int n, const T &eT_ = T(),
        const L &eL_ = L())
        : SegTreeLazy(vector<T>(n, eT_), eT_, eL_) {}
    explicit SegTreeLazy(const vector<T> &v,
        const T &eT_ = T(),
        const L &eL_ = L())
        : N(int(v.size())), eT(eT_), eL(eL_) {
        size = 1;
        height = 0;
        while (size < N) size <= 1, height++;
        d = vector<T>(2 * size, eT);
        lz = vector<L>(size, eL);
        for (int i = 0; i < N; i++) d[size + i] = v[i];
        for (int i = size - 1; i >= 1; i--) {
            update(i);
        }
    }

    void set(int p, T x) {
        assert(0 <= p && p < N);
        p += size;
        for (int i = height; i >= 1; i--) push(p >> i);
        d[p] = x;
        for (int i = 1; i <= height; i++) update(p >> i);
    }

    T get(int p) {
        assert(0 <= p && p < N);
        p += size;
        for (int i = height; i >= 1; i--) push(p >> i);
        return d[p];
    }

    T query(int l, int r) {
        assert(0 <= l && l <= r && r < N);

        l += size;
        r += size;

        for (int i = height; i >= 1; i--) {
            if (((l >> i) << i) != l) push(l >> i);
            if (((r + 1) >> i) << i) != (r + 1)) push(r >> i);
        }
    }
};
```

```

T sml = eT, smr = eT;
while (l <= r) {
    if (l & 1) sml = op(sml, d[l++]);
    if (!(r & 1)) smr = op(d[r--], smr);
    l >>= 1;
    r >>= 1;
}

return op(sml, smr);
}

T query_all() { return d[1]; }

void update(int p, L f) {
    assert(0 <= p && p < N);
    p += size;
    for (int i = height; i >= 1; i--) push(p >> i);
    d[p] = mapping(f, d[p]);
    for (int i = 1; i <= height; i++) update(p >> i);
}

void update(int l, int r, L f) {
    assert(0 <= l && l <= r && r < N);

    l += size;
    r += size;

    for (int i = height; i >= 1; i--) {
        if (((l >> i) << i) != l) push(l >> i);
        if (((r + 1) >> i) << i) != (r + 1)) push(r >> i);
    }

    {
        int l2 = l, r2 = r;
        while (l <= r) {
            if (l & 1) all_apply(l++, f);
            if (!(r & 1)) all_apply(r--, f);
            l >>= 1;
            r >>= 1;
        }
        l = l2;
        r = r2;
    }

    for (int i = 1; i <= height; i++) {
        if (((l >> i) << i) != l) update(l >> i);
    }
}

```

```

        if (((r + 1) >> i) << i) != (r + 1)) update(r >> i);
    }
}

pair<int, int> node_range(int k) const {
    int remain = height;
    for (int kk = k; kk >>= 1; --remain)
        ;
    int fst = k << remain;
    int lst = min(fst + (1 << remain) - 1, size + N - 1);
    return {fst - size, lst - size};
}

private:
void update(int k) { d[k] = op(d[2 * k], d[2 * k + 1]); }
void all_apply(int k, L f) {
    auto [fst, lst] = node_range(k);
    d[k] = mapping(f, d[k], fst, lst);
    if (k < size) lz[k] = composition(f, lz[k]);
}

void push(int k) {
    all_apply(2 * k, lz[k]);
    all_apply(2 * k + 1, lz[k]);
    lz[k] = eL;
}

};

1.2 Hash module  $2^{61} - 1$ 

const ll MOD = (1ll << 61) - 1;
ll mulmod(ll a, ll b) {
    const static ll LOWER = (1ll << 30) - 1,
                  GET31 = (1ll << 31) - 1;
    ll l1 = a & LOWER, h1 = a >> 30, l2 = b & LOWER,
       h2 = b >> 30;
    ll m = l1 * h2 + l2 * h1, h = h1 * h2;
    ll ans = l1 * l2 + (h >> 1) + ((h & 1) << 60) +
            (m >> 31) + ((m & GET31) << 30) + 1;
    ans = (ans & MOD) + (ans >> 61);
    ans = (ans & MOD) + (ans >> 61);
    return ans - 1;
}

mt19937_64 rng(
    chrono::steady_clock::now().time_since_epoch().count());

```

```

11 uniform(ll l, ll r) {
    uniform_int_distribution<ll> uid(l, r);
    return uid(rng);
}

struct str_hash {
    static ll P;
    vector<ll> h, p;
    str_hash(string s) : h(s.size()), p(s.size()) {
        p[0] = 1, h[0] = s[0];
        for (int i = 1; i < s.size(); i++)
            p[i] = mulmod(p[i - 1], P),
            h[i] = (mulmod(h[i - 1], P) + s[i]) % MOD;
    }
    11 operator()(int l, int r) { // retorna hash s[l...r]
        ll hash =
            h[r] - (l ? mulmod(h[l - 1], p[r - l + 1]) : 0);
        return hash < 0 ? hash + MOD : hash;
    }
};

11 str_hash::P = uniform(256, MOD - 1); // l > |sigma|

```

1.3 Bitree 2D

Given a 2d array allow you to sum *val* to the position (x,y) and find the sum of the rectangle with left top corner $(x1,y1)$ and right bottom corner $(x2,y2)$

Update and query 1 indexed !

Time: update $O(\log n^2)$, query $O(\log n^2)$

```

struct Bit2d {
    int n;
    vll2d bit;
    Bit2d(int ni) : n(ni), bit(n + 1, vll(n + 1)) {}
    Bit2d(int ni, vll2d &xs) : n(ni), bit(n + 1, vll(n + 1)) {
        for (int i = 1; i <= n; i++) {
            for (int j = 1; j <= n; j++) {
                update(i, j, xs[i][j]);
            }
        }
    }
    void update(int x, int y, ll val) {
        for (; x <= n; x += (x & (-x))) {
            for (int i = y; i <= n; i += (i & (-i))) {
                bit[x][i] += val;
            }
        }
    }
};

```

```

    }
}
11 sum(int x, int y) {
    ll ans = 0;

    for (int i = x; i; i -= (i & (-i))) {
        for (int j = y; j; j -= (j & (-j))) {
            ans += bit[i][j];
        }
    }
    return ans;
}
11 query(int x1, int y1, int x2, int y2) {
    return sum(x2, y2) - sum(x2, y1 - 1) - sum(x1 - 1, y2) +
        sum(x1 - 1, y1 - 1);
}
};

```

1.4 Bitree

```

template <typename T>
struct BITree {
    int N;
    vector<T> v;

    BITree(int n) : N(n), v(n + 1, 0) {}

    void update(int i, const T& x) {
        if (i == 0) return;
        for (; i <= N; i += i & -i) v[i] += x;
    }

    T range_sum(int i, int j) {
        return range_sum(j) - range_sum(i - 1);
    }

    T range_sum(int i) {
        T sum = 0;
        for (; i > 0; i -= i & -i) sum += v[i];
        return sum;
    }
};

```

1.5 Convex Hull Trick / Line Container

Container where you can add lines of the form $mx + b$, and query maximum value at point x .

insert_line(m, b) inserts the line $m \cdot x + b$ in the container.
eval(x) find the highest value among all lines in the point x .
both in $O(\log N)$

```
const ll LLINF = 1e18;
const ll is_query = -LLINF;
struct Line {
    ll m, b;
    mutable function<const Line*> succ;
    bool operator<(const Line& rhs) const {
        if (rhs.b != is_query) return m < rhs.m;
        const Line* s = succ();
        if (!s) return 0;
        ll x = rhs.m;
        return b - s->b < (s->m - m) * x;
    }
};

struct Cht : public multiset<Line> { // maintain max m*x+b
    bool bad(iterator y) {
        auto z = next(y);
        if (y == begin()) {
            if (z == end()) return 0;
            return y->m == z->m && y->b <= z->b;
        }
        auto x = prev(y);
        if (z == end()) return y->m == x->m && y->b <= x->b;
        return (ld)(x->b - y->b) * (z->m - y->m) >=
            (ld)(y->b - z->b) * (y->m - x->m);
    }
}

void insert_line(
    ll m, ll b) { // min -> insert (-m, -b) -> -eval()
    auto y = insert({m, b});
    y->succ = [=] {
        return next(y) == end() ? 0 : &*next(y);
    };
    if (bad(y)) {
        erase(y);
        return;
    }
    while (next(y) != end() && bad(next(y))) erase(next(y));
    while (y != begin() && bad(prev(y))) erase(prev(y));
}

ll eval(ll x) {
    auto l = *lower_bound((Line){x, is_query});
    return l.m * x + l.b;
}
```

```
};
```

1.6 Disjoint Sparse Table

Answers queries of any monoid operation (i.e. has identity element and is associative)
Build: $O(N \log N)$, Query: $O(1)$

```
#define F(expr) [](auto a, auto b) { return expr; }
template <typename T>
struct DisjointSparseTable {
    using Operation = T (*)(T, T);

    vector<vector<T>> st;
    Operation f;
    T identity;

    static constexpr int log2_floor(
        unsigned long long i) noexcept {
        return i ? __builtin_clzll(1) - __builtin_clzll(i) : -1;
    }

    // Lazy loading constructor. Needs to call build!
    DisjointSparseTable(Operation op, const T neutral = T())
        : st(), f(op), identity(neutral) {}

    DisjointSparseTable(vector<T> v)
        : DisjointSparseTable(v, F(min(a, b))) {}

    DisjointSparseTable(vector<T> v, Operation op,
        const T neutral = T())
        : st(), f(op), identity(neutral) {
        build(v);
    }

    void build(vector<T> v) {
        st.resize(log2_floor(v.size()) + 1,
            vector<T>(1ll << (log2_floor(v.size()) + 1)));
        v.resize(st[0].size(), identity);
        for (int level = 0; level < (int)st.size(); ++level) {
            for (int block = 0; block < (1 << level); ++block) {
                const auto l = block << (st.size() - level);
                const auto r = (block + 1) << (st.size() - level);
                const auto m = l + (r - l) / 2;

                st[level][m] = v[m];
                for (int i = m + 1; i < r; i++)
```

```

        st[level][i] = f(st[level][i - 1], v[i]);
    st[level][m - 1] = v[m - 1];
    for (int i = m - 2; i >= 1; i--)
        st[level][i] = f(st[level][i + 1], v[i]);
    }
}
}

T query(int l, int r) const {
    if (l > r) return identity;
    if (l == r) return st.back()[1];

    const auto k = log2_floor(l ^ r);
    const auto level = (int)st.size() - 1 - k;
    return f(st[level][l], st[level][r]);
}
};

```

1.7 Dsu

```

struct DSU {
    vi ps, sz;

    // vector<unordered_set<int>> sts;

    DSU(int N) : ps(N + 1), sz(N, 1) /*, sts(N) */ {
        iota(all(ps), 0);
        // for (int i = 0; i < N; i++) sts[i].insert(i);
    }
    int find_set(int x) {
        return ps[x] == x ? x : ps[x] = find_set(ps[x]);
    }
    int size(int u) { return sz[find_set(u)]; }
    bool same_set(int x, int y) {
        return find_set(x) == find_set(y);
    }
    void union_set(int x, int y) {
        if (same_set(x, y)) return;

        int px = find_set(x);
        int py = find_set(y);

        if (sz[px] < sz[py]) swap(px, py);

        ps[py] = px;
    }
};

```

```

        sz[px] += sz[py];
        // sts[px].merge(sts[py]);
    }
};

```

1.8 Lichao Tree (dynamic)

Lichao Tree that creates the nodes dynamically, allowing to query and update from range $[MAXL, MAXR]$
query(x) : find the highest point among all lines in the structure
add(a, b) : add a line of form $y = ax + b$ in the structure
addSegment(a, b, l, r) : add a line segment of form $y = ax + b$ which covers from range $[l, r]$
 time: $O(\log N)$

```

template <typename T = ll, T MAXL = 0,
          T MAXR = 1'000'000'001>
struct LiChaoTree {
    static const T inf = -numeric_limits<T>::max() / 2;
    bool first_best(T a, T b) { return a > b; }
    T get_best(T a, T b) { return first_best(a, b) ? a : b; }
    struct line {
        T m, b;
        T operator()(T x) { return m * x + b; }
    };
    struct node {
        line li;
        node *left, *right;
        node(line _li = {0, inf})
            : li(_li), left(nullptr), right(nullptr) {}
        ~node() {
            delete left;
            delete right;
        }
    };
    node *root;
    LiChaoTree(line li = {0, inf}) : root(new node(li)) {}
    ~LiChaoTree() { delete root; }
    T query(T x, node *cur, T l, T r) {
        if (cur == nullptr) return inf;
        if (x < l or x > r) return inf;
        T mid = midpoint(l, r);
        T ans = cur->li(x);
        ans = get_best(ans, query(x, cur->left, l, mid));
        ans = get_best(ans, query(x, cur->right, mid + 1, r));
        return ans;
    }
    T query(T x) { return query(x, root, MAXL, MAXR); }
    void add(line li, node *&cur, T l, T r) {

```

```

    if (cur == nullptr) {
        cur = new node(li);
        return;
    }
    T mid = midpoint(l, r);
    if (first_best(li(mid), cur->li(mid)))
        swap(li, cur->li);
    if (first_best(li(l), cur->li(l)))
        add(li, cur->left, l, mid);
    if (first_best(li(r), cur->li(r)))
        add(li, cur->right, mid + 1, r);
}

void add(T m, T b) { add({m, b}, root, MAXL, MAXR); }
void addSegment(line li, node *&cur, T l, T r, T lseg,
                T rseg) {
    if (r < lseg || l > rseg) return;
    if (cur == nullptr) cur = new node;
    if (lseg <= l && r <= rseg) {
        add(li, cur, l, r);
        return;
    }
    T mid = midpoint(l, r);
    if (l != r) {
        addSegment(li, cur->left, l, mid, lseg, rseg);
        addSegment(li, cur->right, mid + 1, r, lseg, rseg);
    }
}

void addSegment(T a, T b, T l, T r) {
    addSegment({a, b}, root, MAXL, MAXR, l, r);
}
};

```

1.9 Merge Sort Tree

Like a segment tree but each node st_i stores a sorted subarray

- $\text{inrange}(l, r, a, b)$: counts the number of elements $x \in [l, r]$ such that $a \leq x \leq b$.

Memory: $O(n \log N)$ Time: build $O(N \log N)$, inrange $O(\log N)$

```

template <class T>
struct MergeSortTree {
    int n;
    vector<vector<T>> st;
    MergeSortTree(vector<T> &xs) : n(len(xs)), st(n << 1) {
        for (int i = 0; i < n; i++)
            st[i + n] = vector<T>({xs[i]});
    }
};

```

```

        for (int i = n - 1; i > 0; i--) {
            st[i].resize(len(st[i << 1]) + len(st[i << 1 | 1]));
            merge(all(st[i << 1]), all(st[i << 1 | 1]),
                  st[i].begin());
        }
    }

    int count(int i, T a, T b) {
        return upper_bound(all(st[i]), b) -
               lower_bound(all(st[i]), a);
    }

    int inrange(int l, int r, T a, T b) {
        int ans = 0;

        for (l += n, r += n + 1; l < r; l >>= 1, r >>= 1) {
            if (l & 1) ans += count(l++, a, b);
            if (r & 1) ans += count(--r, a, b);
        }

        return ans;
    }
};

```

1.10 Ordered Set

If you need an ordered **multiset** you may add an id to each value. Using `greater_equal`, or `less_equal` is considered undefined behavior.

- **order_of_key(k)** : Number of items strictly smaller/greater than k .
- **find_by_order(k)** : K -th element in a set (counting from zero).

```

#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/tree_policy.hpp>
using namespace __gnu_pbds;

```

```

template <typename T>
using ordered_set = tree<T, null_type, less<T>, rb_tree_tag,
                        tree_order_statistics_node_update>;

```

1.11 Prefix Sum 2D

Given an 2d array with n lines and m columns, find the sum of the subarray that have the left upper corner at $(x1, y1)$ and right bottom corner at $(x2, y2)$.

Time: build $O(n \cdot m)$, query $O(1)$.

```

struct psum2d {

```



```

vll2d s;
vll2d psum;
psum2d(vll2d &grid, int n, int m)
: s(n + 1, vll(m + 1)), psum(n + 1, vll(m + 1)) {
    for (int i = 1; i <= n; i++)
        for (int j = 1; j <= m; j++)
            s[i][j] = s[i][j - 1] + grid[i][j];

    for (int i = 1; i <= n; i++)
        for (int j = 1; j <= m; j++)
            psum[i][j] = psum[i - 1][j] + s[i][j];
}

ll query(int x1, int y1, int x2, int y2) {
    ll ans = psum[x2][y2] + psum[x1 - 1][y1 - 1];
    ans -= psum[x2][y1 - 1] + psum[x1 - 1][y2];
    return ans;
}
};

```

1.12 SegTree Range Sum Query Range PA sum/set Update

Makes arithmetic progression updates in range and sum queries.

Considering $PA(A, R) = [A + R, A + 2R, A + 3R, \dots]$

- **update_set(l, r, A, R)**: sets [l, r] to $PA(A, R)$
- **update_add(l, r, A, R)**: sum $PA(A, R)$ in [l, r]
- **query(l, r)**: sum in range [l, r]

0 indexed !

Time: build $O(n)$, updates and queries $O(\log n)$

```

const ll oo = 1e18;
struct SegTree {
    struct Data {
        ll sum;
        ll set_a, set_r, add_a, add_r;
        Data()
        : sum(0), set_a(oo), set_r(0), add_a(0), add_r(0) {}
    };
    int n;
    vector<Data> seg;
    SegTree(int n_) : n(n_), seg(vector<Data>(4 * n)) {}

    void prop(int p, int l, int r) {
        int sz = r - l + 1;
        ll &sum = seg[p].sum, &set_a = seg[p].set_a,
            &set_r = seg[p].set_r, &add_a = seg[p].add_a,

```

```

        &add_r = seg[p].add_r;

        if (set_a != oo) {
            set_a += add_a, set_r += add_r;
            sum = set_a * sz + set_r * sz * (sz + 1) / 2;
            if (l != r) {
                int m = (l + r) / 2;

                seg[2 * p].set_a = set_a;
                seg[2 * p].set_r = set_r;
                seg[2 * p].add_a = seg[2 * p].add_r = 0;

                seg[2 * p + 1].set_a = set_a + set_r * (m - l + 1);
                seg[2 * p + 1].set_r = set_r;
                seg[2 * p + 1].add_a = seg[2 * p + 1].add_r = 0;
            }
            set_a = oo, set_r = 0;
            add_a = add_r = 0;
        } else if (add_a or add_r) {
            sum += add_a * sz + add_r * sz * (sz + 1) / 2;
            if (l != r) {
                int m = (l + r) / 2;

                seg[2 * p].add_a += add_a;
                seg[2 * p].add_r += add_r;

                seg[2 * p + 1].add_a += add_a + add_r * (m - l + 1);
                seg[2 * p + 1].add_r += add_r;
            }
            add_a = add_r = 0;
        }
    }

    int inter(pii a, pii b) {
        if (a.first > b.first) swap(a, b);
        return max(0, min(a.second, b.second) - b.first + 1);
    }

    ll set(int a, int b, ll aa, ll rr, int p, int l, int r) {
        prop(p, l, r);
        if (b < l or r < a) return seg[p].sum;
        if (a <= l and r <= b) {
            seg[p].set_a = aa;
            seg[p].set_r = rr;
            prop(p, l, r);
            return seg[p].sum;

```

```

}
int m = (l + r) / 2;
int tam_l = inter({l, m}, {a, b});
return seg[p].sum = set(a, b, aa, rr, 2 * p, l, m) +
                    set(a, b, aa + rr * tam_l, rr,
                        2 * p + 1, m + 1, r);
}

void update_set(int l, int r, ll aa, ll rr) {
    set(l, r, aa, rr, 1, 0, n - 1);
}

ll add(int a, int b, ll aa, ll rr, int p, int l, int r) {
    prop(p, l, r);
    if (b < l or r < a) return seg[p].sum;
    if (a <= l and r <= b) {
        seg[p].add_a += aa;
        seg[p].add_r += rr;
        prop(p, l, r);
        return seg[p].sum;
    }
    int m = (l + r) / 2;
    int tam_l = inter({l, m}, {a, b});
    return seg[p].sum = add(a, b, aa, rr, 2 * p, l, m) +
                        add(a, b, aa + rr * tam_l, rr,
                            2 * p + 1, m + 1, r);
}

void update_add(int l, int r, ll aa, ll rr) {
    add(l, r, aa, rr, 1, 0, n - 1);
}

ll query(int a, int b, int p, int l, int r) {
    prop(p, l, r);
    if (b < l or r < a) return 0;
    if (a <= l and r <= b) return seg[p].sum;
    int m = (l + r) / 2;
    return query(a, b, 2 * p, l, m) +
           query(a, b, 2 * p + 1, m + 1, r);
}

ll query(int l, int r) {
    return query(l, r, 1, 0, n - 1);
}
};

```

1.13 SegTree Point Update (dynamic function)

Answers queries of any monoid operation (i.e. has identity element and is associative)
 Build: $O(N)$, Query: $O(\log N)$

```

#define F(expr) [](auto a, auto b) { return expr; }
template <typename T>
struct SegTree {
    using Operation = T (*)(T, T);

    int N;
    vector<T> ns;
    Operation operation;
    T identity;

    SegTree(int n, Operation op = F(a + b), T neutral = T())
        : N(n),
          ns(2 * N, neutral),
          operation(op),
          identity(neutral) {}

    SegTree(const vector<T> &v, Operation op = F(a + b),
            T neutral = T())
        : SegTree((int)v.size(), op, neutral) {
        copy(v.begin(), v.end(), ns.begin() + N);

        for (int i = N - 1; i > 0; --i)
            ns[i] = operation(ns[2 * i], ns[2 * i + 1]);
    }

    T query(size_t i) const { return ns[i + N]; }

    T query(size_t l, size_t r) const {
        auto a = l + N, b = r + N;
        auto ans = identity;
        // Non-associative operations needs to be processed
        // backwards
        stack<T> st;
        while (a <= b) {
            if (a & 1) ans = operation(ans, ns[a++]);
            if (not(b & 1)) st.push(ns[b--]);

            a >>= 1;
            b >>= 1;
        }

        for (; !st.empty(); st.pop())
            ans = operation(ans, st.top());

        return ans;
    }
};

```

```

}

void update(size_t i, T value) {
    update_set(i, operation(ns[i + N], value));
}

void update_set(size_t i, T value) {
    auto a = i + N;

    ns[a] = value;
    while (a >= 1)
        ns[a] = operation(ns[2 * a], ns[2 * a + 1]);
}
};

```

1.14 Segtree Range Max Query Point Max Assign Update (dynamic)

Answers range queries in ranges until 10^9 (maybe more)
 Time: query and update $O(n \cdot \log n)$

```

struct node;
node *newNode();

struct node {
    node *left, *right;
    int lv, rv;
    ll val;

    node() : left(NULL), right(NULL), val(-oo) {}

    inline void init(int l, int r) {
        lv = l;
        rv = r;
    }

    inline void extend() {
        if (!left) {
            int m = (lv + rv) / 2;
            left = newNode();
            right = newNode();
            left->init(lv, m);
            right->init(m + 1, rv);
        }
    }
};

```

```

ll query(int l, int r) {
    if (r < lv || rv < l) {
        return 0;
    }

    if (l <= lv && rv <= r) {
        return val;
    }

    extend();
    return max(left->query(l, r), right->query(l, r));
}

void update(int p, ll newVal) {
    if (lv == rv) {
        val = max(val, newVal);
        return;
    }

    extend();
    (p <= left->rv ? left : right)->update(p, newVal);
    val = max(left->val, right->val);
}

};

const int BUFFSZ(1e7);
node *newNode() {
    static int bufSize = BUFFSZ;
    static node buf[(int)BUFFSZ];
    assert(bufSize);
    return &buf[--bufSize];
}

struct SegTree {
    int n;
    node *root;
    SegTree(int _n) : n(_n) {
        root = newNode();
        root->init(0, n);
    }
    ll query(int l, int r) { return root->query(l, r); }
    void update(int p, ll v) { root->update(p, v); }
};

```

1.15 Segtree Range Max Query Range Max Update

```
template <typename T = ll>
struct SegTree {
    int N;
    T nu, nq;
    vector<T> st, lazy;
    SegTree(const vector<T> &xs)
        : N(len(xs)),
          nu(numeric_limits<T>::min()),
          nq(numeric_limits<T>::min()),
          st(4 * N + 1, nu),
          lazy(4 * N + 1, nu) {
        for (int i = 0; i < len(xs); ++i) update(i, i, xs[i]);
    }

    void update(int l, int r, T value) {
        update(1, 0, N - 1, l, r, value);
    }

    T query(int l, int r) { return query(1, 0, N - 1, l, r); }

    void update(int node, int nl, int nr, int ql, int qr,
                T v) {
        propagation(node, nl, nr);

        if (ql > nr or qr < nl) return;

        st[node] = max(st[node], v);
        if (ql <= nl and nr <= qr) {
            if (nl < nr) {
                lazy[left(node)] = max(lazy[left(node)], v);
                lazy[right(node)] = max(lazy[right(node)], v);
            }
            return;
        }
        update(left(node), nl, mid(nl, nr), ql, qr, v);
        update(right(node), mid(nl, nr) + 1, nr, ql, qr, v);

        st[node] = max(st[left(node)], st[right(node)]);
    }

    T query(int node, int nl, int nr, int ql, int qr) {
        propagation(node, nl, nr);
```

```
        if (ql > nr or qr < nl) return nq;

        if (ql <= nl and nr <= qr) return st[node];

        T x = query(left(node), nl, mid(nl, nr), ql, qr);
        T y = query(right(node), mid(nl, nr) + 1, nr, ql, qr);

        return max(x, y);
    }

    void propagation(int node, int nl, int nr) {
        if (lazy[node] != nu) {
            st[node] = max(st[node], lazy[node]);

            if (nl < nr) {
                lazy[left(node)] =
                    max(lazy[left(node)], lazy[node]);
                lazy[right(node)] =
                    max(lazy[right(node)], lazy[node]);
            }

            lazy[node] = nu;
        }
    }

    int left(int p) { return p << 1; }
    int right(int p) { return (p << 1) + 1; }
    int mid(int l, int r) { return (r - l) / 2 + 1; }
};

int main() {
    int n;
    cin >> n;
    vector<array<int, 3>> xs(n);
    for (int i = 0; i < n; ++i) {
        for (int j = 0; j < 3; ++j) {
            cin >> xs[i][j];
        }
    }
    vi aux(n, 0);
    SegTree<int> st(aux);
    for (int i = 0; i < n; ++i) {
        int a = min(i + xs[i][1], n);
        int b = min(i + xs[i][2], n);
        st.update(i, i, st.query(i, i) + xs[i][0]);
        int cur = st.query(i, i);
```

```

    st.update(a, b, cur);
}

cout << st.query(0, n) << '\n';
}

```

1.16 SegTree Range Min Query Point Assign Update

```

template <typename T = ll>
struct SegTree {
    int n;
    T nu, nq;
    vector<T> st;
    SegTree(const vector<T> &v)
        : n(len(v)),
          nu(0),
          nq(numeric_limits<T>::max()),
          st(n * 4 + 1, nu) {
        for (int i = 0; i < n; ++i) update(i, v[i]);
    }
    void update(int p, T v) { update(1, 0, n - 1, p, v); }
    T query(int l, int r) { return query(1, 0, n - 1, l, r); }

    void update(int node, int nl, int nr, int p, T v) {
        if (p < nl or p > nr) return;

        if (nl == nr) {
            st[node] = v;
            return;
        }

        update(left(node), nl, mid(nl, nr), p, v);
        update(right(node), mid(nl, nr) + 1, nr, p, v);

        st[node] = min(st[left(node)], st[right(node)]);
    }

    T query(int node, int nl, int nr, int ql, int qr) {
        if (ql <= nl and qr >= nr) return st[node];
        if (nl > qr or nr < ql) return nq;
        if (nl == nr) return st[node];

        return min(
            query(left(node), nl, mid(nl, nr), ql, qr),
            query(right(node), mid(nl, nr) + 1, nr, ql, qr));
    }
}

```

```

}

int left(int p) { return p << 1; }
int right(int p) { return (p << 1) + 1; }
int mid(int l, int r) { return (r - l) / 2 + l; }
};

```

1.17 Segtree Range Sum Query Point Sum Update (dynamic)

Answers range queries in ranges until 10^9 (maybe more)
 Time: query and update $O(n \cdot \log n)$

```

struct node;
node *newNode();

struct node {
    node *left, *right;
    int lv, rv;
    ll val;

    node() : left(NULL), right(NULL), val(0) {}

    inline void init(int l, int r) {
        lv = l;
        rv = r;
    }

    inline void extend() {
        if (!left) {
            int m = (rv - lv) / 2 + lv;
            left = newNode();
            right = newNode();
            left->init(lv, m);
            right->init(m + 1, rv);
        }
    }

    ll query(int l, int r) {
        if (r < lv || rv < l) {
            return 0;
        }

        if (l <= lv && rv <= r) {
            return val;
        }

        extend();
    }
}

```

```

    return left->query(l, r) + right->query(l, r);
}

void update(int p, ll newVal) {
    if (lv == rv) {
        val += newVal;
        return;
    }

    extend();
    (p <= left->rv ? left : right)->update(p, newVal);
    val = left->val + right->val;
}

};

const int BUFSIZE(1.3e7);
node *newNode() {
    static int bufSize = BUFSIZE;
    static node buf[(int)BUFSIZE];
    // assert(bufSize);
    return &buf[--bufSize];
}

struct SegTree {
    int n;
    node *root;
    SegTree(int _n) : n(_n) {
        root = newNode();
        root->init(0, n);
    }
    ll query(int l, int r) { return root->query(l, r); }
    void update(int p, ll v) { root->update(p, v); }
};

```

1.18 SegTree Range Xor query Point Assign Update

```

template <typename T = ll>
struct SegTree {
    int n;
    T nu, nq;
    vector<T> st;
    SegTree(const vector<T> &v)
        : n(len(v)), nu(0), nq(0), st(n * 4 + 1, nu) {
        for (int i = 0; i < n; ++i) update(i, v[i]);
    }
};

```

```

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

void update(int node, int nl, int nr, int p, T v) {
    if (p < nl or p > nr) return;

    if (nl == nr) {
        st[node] = v;
        return;
    }

    update(left(node), nl, mid(nl, nr), p, v);
    update(right(node), mid(nl, nr) + 1, nr, p, v);

    st[node] = st[left(node)] ^ st[right(node)];
}

T query(int node, int nl, int nr, int ql, int qr) {
    if (ql <= nl and qr >= nr) return st[node];
    if (nl > qr or nr < ql) return nq;
    if (nl == nr) return st[node];

    return query(left(node), nl, mid(nl, nr), ql, qr) ^
        query(right(node), mid(nl, nr) + 1, nr, ql, qr);
}

int left(int p) { return p << 1; }
int right(int p) { return (p << 1) + 1; }
int mid(int l, int r) { return (r - 1) / 2 + 1; }
};

```

1.19 SegTree Range Min Query Range Sum Update

```

template <typename t = ll>
struct SegTree {
    int n;
    t nu;
    t nq;
    vector<t> st, lazy;
    SegTree(const vector<t> &xs)
        : n(len(xs)),
          nu(0),
          nq(numeric_limits<t>::max()),
          st(4 * n, nu),
          lazy(4 * n, nu) {
};

```

```

    for (int i = 0; i < len(xs); ++i) update(i, i, xs[i]);
}

SegTree(int n) : n(n), st(4 * n, nu), lazy(4 * n, nu) {}

void update(int l, int r, ll value) {
    update(1, 0, n - 1, l, r, value);
}

t query(int l, int r) { return query(1, 0, n - 1, l, r); }

void update(int node, int nl, int nr, int ql, int qr,
            ll v) {
    propagation(node, nl, nr);

    if (ql > nr or qr < nl) return;

    if (ql <= nl and nr <= qr) {
        st[node] += (nr - nl + 1) * v;

        if (nl < nr) {
            lazy[left(node)] += v;
            lazy[right(node)] += v;
        }

        return;
    }

    update(left(node), nl, mid(nl, nr), ql, qr, v);
    update(right(node), mid(nl, nr) + 1, nr, ql, qr, v);

    st[node] = min(st[left(node)], st[right(node)]);
}

t query(int node, int nl, int nr, int ql, int qr) {
    propagation(node, nl, nr);

    if (ql > nr or qr < nl) return nq;

    if (ql <= nl and nr <= qr) return st[node];

    t x = query(left(node), nl, mid(nl, nr), ql, qr);
    t y = query(right(node), mid(nl, nr) + 1, nr, ql, qr);

    return min(x, y);
}

```

```

}

void propagation(int node, int nl, int nr) {
    if (lazy[node]) {
        st[node] += lazy[node];

        if (nl < nr) {
            lazy[left(node)] += lazy[node];
            lazy[right(node)] += lazy[node];
        }

        lazy[node] = nu;
    }
}

int left(int p) { return p << 1; }
int right(int p) { return (p << 1) + 1; }
int mid(int l, int r) { return (r - l) / 2 + l; }
};

```

1.20 SegTree Range Sum Query Range Sum Update

```

template <typename T = ll>
struct SegTree {
    int N;
    T nu;
    T nq;
    vector<T> st, lazy;
    SegTree(const vector<T> &xs)
        : N(len(xs)),
          nu(0),
          nq(0),
          st(4 * N, nu),
          lazy(4 * N, nu) {
        for (int i = 0; i < len(xs); ++i) update(i, i, xs[i]);
    }

    SegTree(int n)
        : N(n), nu(0), nq(0), st(4 * N, nu), lazy(4 * N, nu) {}

    void update(int l, int r, ll value) {
        update(1, 0, N - 1, l, r, value);
    }

    T query(int l, int r) { return query(1, 0, N - 1, l, r); }
}

```

```

void update(int node, int nl, int nr, int ql, int qr,
           ll v) {
    propagation(node, nl, nr);

    if (ql > nr or qr < nl) return;

    if (ql <= nl and nr <= qr) {
        st[node] += (nr - nl + 1) * v;

        if (nl < nr) {
            lazy[left(node)] += v;
            lazy[right(node)] += v;
        }

        return;
    }

    update(left(node), nl, mid(nl, nr), ql, qr, v);
    update(right(node), mid(nl, nr) + 1, nr, ql, qr, v);

    st[node] = st[left(node)] + st[right(node)];
}

T query(int node, int nl, int nr, int ql, int qr) {
    propagation(node, nl, nr);

    if (ql > nr or qr < nl) return nq;

    if (ql <= nl and nr <= qr) return st[node];

    T x = query(left(node), nl, mid(nl, nr), ql, qr);
    T y = query(right(node), mid(nl, nr) + 1, nr, ql, qr);

    return x + y;
}

void propagation(int node, int nl, int nr) {
    if (lazy[node]) {
        st[node] += (nr - nl + 1) * lazy[node];

        if (nl < nr) {
            lazy[left(node)] += lazy[node];
            lazy[right(node)] += lazy[node];
        }
    }
}

```

```

        lazy[node] = nu;
    }
}

int left(int p) { return p << 1; }
int right(int p) { return (p << 1) + 1; }
int mid(int l, int r) { return (r - 1) / 2 + 1; }
};

```

1.21 Sparse Table

Answer the range query defined at the function `op`.

Build: $O(N \log N)$, Query: $O(1)$

```

template <typename T>
struct SparseTable {
    vector<T> v;
    int n;
    static const int b = 30;
    vi mask, t;

    int op(int x, int y) { return v[x] < v[y] ? x : y; }
    int msb(int x) {
        return __builtin_clz(1) - __builtin_clz(x);
    }
    SparseTable() {}
    SparseTable(const vector<T>& v_)
        : v(v_), n(v.size()), mask(n), t(n) {
        for (int i = 0, at = 0; i < n; mask[i++] = at |= 1) {
            at = (at << 1) & ((1 << b) - 1);
            while (at and op(i, i - msb(at & -at)) == i)
                at ^= at & -at;
        }
        for (int i = 0; i < n / b; i++)
            t[i] = b * i + b - 1 - msb(mask[b * i + b - 1]);
        for (int j = 1; (1 << j) <= n / b; j++)
            for (int i = 0; i + (1 << j) <= n / b; i++)
                t[n / b * j + i] =
                    op(t[n / b * (j - 1) + i],
                       t[n / b * (j - 1) + i + (1 << (j - 1))]);
    }
    int small(int r, int sz = b) {
        return r - msb(mask[r] & ((1 << sz) - 1));
    }
    T query(int l, int r) {
        if (r - l + 1 <= b) return small(r, r - l + 1);
    }
}

```



```

int ans = op(small(l + b - 1), small(r));
int x = l / b + 1, y = r / b - 1;
if (x <= y) {
    int j = msb(y - x + 1);
    ans = op(ans, op(t[n / b * j + x],
                    t[n / b * j + y - (1 << j) + 1]));
}
return ans;
}
};

```

2 Dynamic programming

2.1 Binary Knapsack (bottom up)

Given N items, each with its own value V_i and weight W_i and a maximum knapsack weight W , compute the maximum value of the items that we can carry, if we can either ignore or take a particular item.

Assume that $1 \leq n \leq 1000$, $1 \leq S \leq 10000$.

Time and space: $O(N * W)$

the vectors VS and WS starts at one, so it need an empty value at index 0.

```

const int MAXN(2010), MAXM(2010);
ll st[MAXN + 1][MAXM + 1];
char ps[MAXN + 1][MAXM + 1];
pair<ll, vi> knapsack(int M, const vll &VS, const vi &WS) {
    memset(st, 0, sizeof(st));
    memset(ps, 0, sizeof(ps));
    int N = len(VS) - 1; // ELEMENTS START AT INDEX 1 !

    for (int i = 0; i <= N; ++i) st[i][0] = 0;

    for (int m = 0; m <= M; ++m) st[0][m] = 0;

    for (int i = 1; i <= N; ++i) {
        for (int m = 1; m <= M; ++m) {
            st[i][m] = st[i - 1][m];
            ps[i][m] = 0;
            int w = WS[i];
            ll v = VS[i];

            if (w <= m and st[i - 1][m - w] + v > st[i][m]) {
                st[i][m] = st[i - 1][m - w] + v;
                ps[i][m] = 1;
            }
        }
    }
}

```

```

int m = M;
vi is;
for (int i = N; i >= 1; --i) {
    if (ps[i][m]) {
        is.emplace_back(i - 1);
        m -= WS[i];
    }
}

return {st[N][M], is};
}

```

2.2 Binary Knapsack (top down)

Given N items, each with its own value V_i and weight W_i and a maximum knapsack weight W , compute the maximum value of the items that we can carry, if we can either ignore or take a particular item.

Assume that $1 \leq n \leq 1000$, $1 \leq S \leq 10000$.

Time and space: $O(N * W)$

the bottom up version is 5 times faster !

```

const int MAXN(2000), MAXM(2000);
ll memo[MAXN][MAXM + 1];
char choosen[MAXN][MAXM + 1];
ll knapSack(int u, int w, vll &VS, vi &WS) {
    if (u < 0) return 0;
    if (memo[u][w] != -1) return memo[u][w];

    ll a = 0, b = 0;
    a = knapSack(u - 1, w, VS, WS);
    if (WS[u] <= w)
        b = knapSack(u - 1, w - WS[u], VS, WS) + VS[u];
    if (b > a) {
        choosen[u][w] = true;
    }
    return memo[u][w] = max(a, b);
}

pair<ll, vi> knapSack(int W, vll &VS, vi &WS) {
    memset(memo, -1, sizeof(memo));
    memset(choosen, 0, sizeof(choosen));
    int n = len(VS);
    ll v = knapSack(n - 1, W, VS, WS);
    ll cw = W;
    vi choosed;
    for (int i = n - 1; i >= 0; i--) {
        if (choosen[i][cw]) {
            cw -= WS[i];
        }
    }
}

```

```

        choosed.emplace_back(i);
    }
}
return {v, choosed};
}

```

2.3 Edit Distance

$O(N * M)$

```

int edit_distance(const string &a, const string &b) {
    int n = a.size();
    int m = b.size();
    vector<vi> dp(n + 1, vi(m + 1, 0));

    int ADD = 1, DEL = 1, CHG = 1;
    for (int i = 0; i <= n; ++i) {
        dp[i][0] = i * DEL;
    }
    for (int i = 1; i <= m; ++i) {
        dp[0][i] = ADD * i;
    }

    for (int i = 1; i <= n; ++i) {
        for (int j = 1; j <= m; ++j) {
            int add = dp[i][j - 1] + ADD;
            int del = dp[i - 1][j] + DEL;
            int chg = dp[i - 1][j - 1] +
                (a[i - 1] == b[j - 1] ? 0 : 1) * CHG;
            dp[i][j] = min({add, del, chg});
        }
    }

    return dp[n][m];
}

```

2.4 Kadane

Find the maximum subarray sum in a given array.

```

int kadane(const vi &as) {
    vi s(len(as));
    s[0] = as[0];

    for (int i = 1; i < len(as); ++i)
        s[i] = max(as[i], s[i - 1] + as[i]);
}

```

```

return *max_element(all(s));
}

```

2.5 Longest Increasing Subsequence (LIS)

Finds the length of the longest subsequence in

$O(n \log n)$

```

int LIS(const vi& as) {
    const ll oo = 1e18;
    int n = len(as);
    vll lis(n + 1, oo);
    lis[0] = -oo;

    auto ans = 0;

    for (int i = 0; i < n; ++i) {
        auto it = lower_bound(all(lis), as[i]);
        auto pos = (int)(it - lis.begin());

        ans = max(ans, pos);
        lis[pos] = as[i];
    }

    return ans;
}

```

2.6 Money Sum (Bottom Up)

Find every possible sum using the given values only once.

```

set<int> money_sum(const vi &xs) {
    using vc = vector<char>;
    using vvc = vector<vc>;
    int _m = accumulate(all(xs), 0);
    int _n = xs.size();
    vvc _dp(_n + 1, vc(_m + 1, 0));
    set<int> _ans;
    _dp[0][xs[0]] = 1;
    for (int i = 1; i < _n; ++i) {
        for (int j = 0; j <= _m; ++j) {
            if (j == 0 or _dp[i - 1][j]) {
                _dp[i][j + xs[i]] = 1;
                _dp[i][j] = 1;
            }
        }
    }
    for (int i = 0; i < _n; ++i)
        _ans.insert(xs[i]);
    return _ans;
}

```

```

    }
}
}

for (int i = 0; i < _n; ++i)
    for (int j = 0; j <= _m; ++j)
        if (_dp[i][j]) _ans.insert(j);
return _ans;
}

```

2.7 Travelling Salesman Problem

```

using vi = vector<int>;
vector<vi> dist;
vector<vi> memo;
/* O ( N^2 * 2^N )*/
int tsp(int i, int mask, int N) {
    if (mask == (1 << N) - 1) return dist[i][0];
    if (memo[i][mask] != -1) return memo[i][mask];
    int ans = INT_MAX << 1;
    for (int j = 0; j < N; ++j) {
        if (mask & (1 << j)) continue;
        auto t = tsp(j, mask | (1 << j), N) + dist[i][j];
        ans = min(ans, t);
    }
    return memo[i][mask] = ans;
}

```

3 Geometry

3.1 Convex Hull

Given a set of points find the smallest convex polygon that contains all the given points.

Time: $O(N \log N)$

By default it removes the collinear points, set the boolean to true if you don't want that

```

struct pt {
    double x, y;
    int id;
};

int orientation(pt a, pt b, pt c) {
    double v = a.x * (b.y - c.y) + b.x * (c.y - a.y) +
              c.x * (a.y - b.y);
    if (v < 0) return -1; // clockwise
    if (v > 0) return +1; // counter-clockwise
}

```

```

return 0;
}

bool cw(pt a, pt b, pt c, bool include_collinear) {
    int o = orientation(a, b, c);
    return o < 0 || (include_collinear && o == 0);
}

bool collinear(pt a, pt b, pt c) {
    return orientation(a, b, c) == 0;
}

void convex_hull(vector<pt>& pts,
                bool include_collinear = false) {
    pt p0 = *min_element(all(pts), [](pt a, pt b) {
        return make_pair(a.y, a.x) < make_pair(b.y, b.x);
    });
    sort(all(pts), [p0](const pt& a, const pt& b) {
        int o = orientation(p0, a, b);
        if (o == 0)
            return (p0.x - a.x) * (p0.x - a.x) +
                   (p0.y - a.y) * (p0.y - a.y) <
                   (p0.x - b.x) * (p0.x - b.x) +
                   (p0.y - b.y) * (p0.y - b.y);
        return o < 0;
    });
    if (include_collinear) {
        int i = len(pts) - 1;
        while (i >= 0 && collinear(p0, pts[i], pts.back())) i--;
        reverse(pts.begin() + i + 1, pts.end());
    }

    vector<pt> st;
    for (int i = 0; i < len(pts); i++) {
        while (st.size() > 1 && !cw(st[len(st) - 2], st.back(),
                                   pts[i], include_collinear))
            st.pop_back();
        st.push_back(pts[i]);
    }

    pts = st;
}

```

3.2 Determinant

```
#include "Point.cpp"
```

```

template <typename T>
T D(const Point<T> &P, const Point<T> &Q,
    const Point<T> &R) {
    return (P.x * Q.y + P.y * R.x + Q.x * R.y) -
           (R.x * Q.y + R.y * P.x + Q.x * P.y);
}

```

3.3 Equals

```

template <typename T>
bool equals(T a, T b) {
    const double EPS{1e-9};
    if (is_floating_point<T>::value)
        return fabs(a - b) < EPS;
    else
        return a == b;
}

```

3.4 Line

```

#include <bits/stdc++.h>

#include "point-struct-and-utils.cpp"
using namespace std;

struct line {
    ld a, b, c;
};

// the answer is stored in the third parameter (pass by
// reference)
void pointsToLine(const point &p1, const point &p2,
                  line &l) {
    if (fabs(p1.x - p2.x) < EPS)
        // vertical line
        l = {1.0, 0.0, -p1.x};
    // default values
    else
        l = {-(ld)(p1.y - p2.y) / (p1.x - p2.x), 1.0,
            -(ld)(l.a * p1.x) - p1.y};
}

```

3.5 Point Struct And Utils (2d)

```

#include <bits/stdc++.h>

```

```

using namespace std;
using ld = long double;

struct point {
    ld x, y;
    int id;
    point(ld x = 0.0, ld y = 0.0, int id = -1)
        : x(x), y(y), id(id) {}

    point& operator+=(const point& t) {
        x += t.x;
        y += t.y;
        return *this;
    }
    point& operator-=(const point& t) {
        x -= t.x;
        y -= t.y;
        return *this;
    }
    point& operator*=(ld t) {
        x *= t;
        y *= t;
        return *this;
    }
    point& operator/=(ld t) {
        x /= t;
        y /= t;
        return *this;
    }
    point operator+(const point& t) const {
        return point(*this) += t;
    }
    point operator-(const point& t) const {
        return point(*this) -= t;
    }
    point operator*(ld t) const {
        return point(*this) *= t;
    }
    point operator/(ld t) const {
        return point(*this) /= t;
    }
};

ld dot(point& a, point& b) {
    return a.x * b.x + a.y * b.y;
}

ld norm(point& a) {
    return dot(a, a);
}

ld abs(point a) {
    return sqrt(norm(a));
}

```

```
ld proj(point a, point b) { return dot(a, b) / abs(b); }
```

```
ld angle(point a, point b) {
    return acos(dot(a, b) / abs(a) / abs(b));
}
```

```
ld cross(point a, point b) { return a.x * b.y - a.y * b.x; }
```

3.6 Polygon Lattice Points (Pick's Theorem)

Given a polygon with N points finds the number of lattice points inside and on boundaries. Time : $O(N)$

```
ll cross(ll x1, ll y1, ll x2, ll y2) {
    return x1 * y2 - x2 * y1;
}
```

```
ll polygonArea(vector<pll>& pts) {
    ll ats = 0;
    for (int i = 2; i < len(pts); i++)
        ats += cross(pts[i].first - pts[0].first,
                     pts[i].second - pts[0].second,
                     pts[i - 1].first - pts[0].first,
                     pts[i - 1].second - pts[0].second);
    return abs(ats / 2ll);
}
```

```
ll boundary(vector<pll>& pts) {
    ll ats = pts.size();
    for (int i = 0; i < len(pts); i++) {
        ll deltax =
            (pts[i].first - pts[(i + 1) % pts.size()].first);
        ll deltax =
            (pts[i].second - pts[(i + 1) % pts.size()].second);
        ats += abs(__gcd(deltax, deltax)) - 1;
    }
    return ats;
}
```

```
pll latticePoints(vector<pll>& pts) {
    ll bounds = boundary(pts);
    ll area = polygonArea(pts);
    ll inside = area + 1ll - bounds / 2ll;

    return {inside, bounds};
}
```

3.7 Segment

```
#include "Line.cpp"
#include "Point.cpp"
#include "equals.cpp"
```

```
template <typename T>
struct segment {
    Point<T> A, B;
```

```
    bool contains(const Point<T> &P) const;
```

```
    Point<T> closest(const Point<T> &p) const;
};
```

```
template <typename T>
bool segment<T>::contains(const Point<T> &P) const {
    // verifica se P está contido na reta
    double dAB = Point<T>::dist(A, B),
           dAP = Point<T>::dist(A, P),
           dPB = Point<T>::dist(P, B);

    return equals(dAP + dPB, dAB);
}
```

```
template <typename T>
Point<T> segment<T>::closest(const Point<T> &P) const {
    Line<T> R(A, B);
    auto Q = R.closest(P);

    if (this->contains(Q)) return Q;

    auto distA = Point<T>::dist(P, A);
    auto distB = Point<T>::dist(P, B);

    if (distA <= distB)
        return A;
    else
        return B;
}
```

3.8 Template Line

```
#include "template-point.cpp"
```

```
template <typename T>
```

```

struct Line {
    T a, b, c;

    Line(T av, T bv, T cv) : a(av), b(bv), c(cv) {}

    Line(const Point<T> &P, const Point<T> &Q)
        : a(P.y - Q.y),
          b(Q.x - P.x),
          c(P.x * Q.y - Q.x * P.y) {}

    // verify if a point belongs to the line
    bool contains(const Point<T> &P) {
        return equals(a * P.x + b * P.y + c, 0);
    }

    // shortest distance between P and a point Q that belongs
    // to this line
    double distance(const Point<T> &P) const {
        return fabs(a * P.x + b * P.y + c) / hypot(a, b);
    }

    // the closest point in this line to the given point
    Point<T> closest(const Point<T> &P) const {
        auto den = (a * a) + (b * b);

        auto x = (b * (b * P.x - a * P.y) - a * c) / den;
        auto y = (a * (-b * P.x + a * P.y) - b * c) / den;

        return Point<T>{x, y};
    }
};

```

3.9 Template Point

```

template <typename T>
struct Point {
    T x, y;

    Point(T xv = 0, T yv = 0) : x(xv), y(yv) {}

    double distance(const Point<T> &P) const {
        return hypot(static_cast<double>(P.x - this->x),
                     static_cast<double>(P.y - this->y));
    }
};

```

3.10 Template Segment

```

#include "equals.cpp"
#include "template-line.cpp"
#include "template-point.cpp"

template <typename T>
struct Segment {
    Point<T> A, B;

    Segment(const Point<T> &a, const Point<T> &b)
        : A(a), B(b) {}

    /*
     * Verify if a given point P belongs to the segment,
     * considering that P belongs to the line defined with A
     * and B
     */
    bool contains(const Point<T> &P) const {
        return equals(A.x, B.x)
            ? min(A.y, B.y) <= P.y and P.y <= max(A.y, B.y)
            : min(A.x, B.x) <= P.x and
              P.x <= max(A.x, B.x);
    }

    /*
     * Verify if P belongs to the segment AB,
     * even if P don't belong to the line defined with A and B
     */
    bool contains2(const Point<T> &P) const {
        double dAB = dist(A, B), dAP = dist(A, P),
              dPB = dist(P, B);
        return equals(dAP + dPB, dAB);
    }

    /*
     * Find the closest point in P that belongs to the segment
     */
    Point<T> closest(const Point<T> &P) {
        Line<T> r(A, B);
        auto Q = r.closest(P);

        if (this->contains(Q)) return Q;

        auto distA = P.distance(A);

```

```

    auto distB = P.distance(B);

    return distA <= distB ? A : B;
}

double distToClosest(const Point<T> &P) {
    return closest(P).distance(P);
}
};

```

4 Graphs

4.1 2 SAT

```

struct SAT {
    int n;
    vi2d g, tg;
    vi vis;
    vi order, comp;
    vc assignment;
    bool solvable;
    int qtdcomp;

    SAT(int _n)
        : n(2 * _n),
          g(n),
          tg(n),
          vis(n),
          comp(n, -1),
          assignment(n / 2) {}

    void dfs1(int u) {
        vis[u] = 1;
        for (auto v : g[u]) {
            if (!vis[v]) {
                dfs1(v);
            }
        }
        order.emplace_back(u);
    }

    void dfs2(int u) {
        comp[u] = qtdcomp;
        for (auto v : tg[u]) {
            if (comp[v] == -1) {

```

```

                dfs2(v);
            }
        }
    }

    bool solve2sat() {
        for (int i = 0; i < n; i++) {
            if (!vis[i]) dfs1(i);
        }

        reverse(all(order));
        qtdcomp = 0;
        for (auto u : order) {
            if (comp[u] == -1) {
                dfs2(u);
                qtdcomp++;
            }
        }

        assignment.assign(n / 2, false);
        for (int i = 0; i < n; i += 2) {
            if (comp[i] == comp[i + 1]) {
                solvable = false;
                return false;
            }

            assignment[i / 2] = comp[i] < comp[i + 1];
        }

        solvable = 1;
        return solvable;
    }

    void add_dis(int a, bool va, int b, bool vb) { // a V b
        va = !va, vb = !vb;
        a = (2 * a) ^ va, b = (2 * b) ^ vb;
        int nota = a ^ 1, notb = b ^ 1;
        g[nota].emplace_back(b), g[notb].emplace_back(a),
        tg[b].emplace_back(nota), tg[a].emplace_back(notb);
    }

    void add_impl(int a, bool va, int b, int vb) { // a -> b
        add_dis(a, !va, b, vb);
    }
}

```

```

void add_equiv(int a, bool va, int b,
              bool vb) { // a <-> b
    add_impl(a, 1, b, 1);
    add_impl(b, 1, a, 1);
    add_impl(a, 0, b, 0);
    add_impl(b, 0, a, 0);
}

void add_xor(int a, bool va, int b, bool vb) { // a xor b
    add_impl(a, 1, b, 0);
    add_impl(a, 0, b, 1);
    add_impl(b, 1, a, 0);
    add_impl(b, 0, a, 1);
}
};

```

4.2 Cycle Distances

Given a vertex s finds the longest cycle that end's in s , note that the vector **dist** will contain the distance that each vertex u needs to reach s .

Time: $O(N)$

```

using adj = vector<vector<pair<int, ll>>>;
ll cycleDistances(int u, int n, int s, vc &vis, adj &g,
                  vll &dist) {
    vis[u] = 1;

    for (auto [v, d] : g[u]) {
        if (v == s) {
            dist[u] = max(dist[u], d);
            continue;
        }

        if (vis[v] == 1) {
            continue;
        }

        if (vis[v] == 2) {
            dist[u] = max(dist[u], dist[v] + d);
        } else {
            ll d2 = cycleDistances(v, n, s, vis, g, dist);
            if (d2 != -oo) {
                dist[u] = max(dist[u], d2 + d);
            }
        }
    }
    vis[u] = 2;
}

```

```

return dist[u];
}

```

4.3 SCC (struct)

Build the condensation graph based in the strongly connected components.

tiem: $O(V + E)$

```

struct SCC {
    int N, totscc;
    vi2d g, tg;
    vi todo, comp;
    vector<set<ll>> gsc;
    vc vis;
    SCC(int _N)
        : N(_N),
          totscc(0),
          g(_N),
          tg(_N),
          comp(_N, -1),
          gsc(_N),
          vis(_N) {}

    void add_edge(int x, int y) { g[x].eb(y), tg[y].eb(x); }

    void dfs(int x) {
        vis[x] = 1;
        for (auto y : g[x])
            if (!vis[y]) dfs(y);
        todo.pb(x);
    }

    void dfs2(ll x) {
        comp[x] = totscc;
        for (auto y : tg[x])
            if (comp[y] == -1) dfs2(y);
    }

    void build() {
        for (int i = 0; i < N; ++i)
            if (!vis[i]) dfs(i);

        reverse(all(todo));
        for (auto &x : todo)
            if (comp[x] == -1) {
                dfs2(x);
            }
    }
}

```



```

        totscc++;
    }

    for (int i = 0; i < N; ++i)
        for (auto j : g[i])
            if (comp[i] != comp[j])
                gsc[comp[i]].insert(comp[j]);
    }
};

```

4.4 Bellman-Ford (find negative cycle)

Given a directed graph find a negative cycle by running n iterations, and if the last one produces a relaxation than there is a cycle.

Time: $O(V \cdot E)$

```

const ll oo = 2500 * 1e9;

using graph = vector<vector<pair<int, ll>>>;
vi negative_cycle(graph &g, int n) {
    vll d(n, oo);
    vi p(n, -1);
    int x = -1;
    d[0] = 0;
    for (int i = 0; i < n; i++) {
        x = -1;
        for (int u = 0; u < n; u++) {
            for (auto &[v, l] : g[u]) {
                if (d[u] + l < d[v]) {
                    d[v] = d[u] + l;
                    p[v] = u;
                    x = v;
                }
            }
        }
    }

    if (x == -1)
        return {};
    else {
        for (int i = 0; i < n; i++) x = p[x];
        vi cycle;
        for (int v = x;; v = p[v]) {
            cycle.eb(v);
            if (v == x and len(cycle) > 1) break;
        }
    }
}

```

```

        reverse(all(cycle));
        return cycle;
    }
}

```

4.5 Bellman Ford

Find shortest path from a single source to all other nodes. Can detect negative cycles.

Time: $O(V \cdot E)$

```

bool bellman_ford(const vector<vector<pair<int, ll>>> &g,
                  int s, vector<ll> &dist) {
    int n = (int)g.size();
    dist.assign(n, LLONG_MAX);

    vector<int> count(n);
    vector<char> in_queue(n);
    queue<int> q;

    dist[s] = 0;
    q.push(s);
    in_queue[s] = true;

    while (not q.empty()) {
        int cur = q.front();
        q.pop();
        in_queue[cur] = false;

        for (auto [to, w] : g[cur]) {
            if (dist[cur] + w < dist[to]) {
                dist[to] = dist[cur] + w;
                if (not in_queue[to]) {
                    q.push(to);
                    in_queue[to] = true;
                    count[to]++;
                    if (count[to] > n) return false;
                }
            }
        }
    }

    return true;
}

```

4.6 BFS 01

Similar to a Dijkstra given a weighted graph finds the distance from source s to every other node (SSSP).

Applicable only when the weight of the edges $\in \{0, x\}$

Time: $O(V + E)$

```
vector<pair<ll, int>> adj[maxn];
ll dists[maxn];
int s, n;
void bfs_01() {
    fill(dists, dists + n, oo);
    dist[s] = 0;

    deque<int> q;
    q.emplace_back(s);

    while (not q.empty()) {
        auto u = q.front();
        q.pop_front();

        for (auto [v, w] : adj[u]) {
            if (dist[v] <= dist[u] + w) continue;
            dist[v] = dist[u] + w;
            w ? q.emplace_back(v) : q.emplace_front(v);
        }
    }
}
```

4.7 Binary Lifting/Jumping

Given a function/successor graph answers queries of the form which is the node after k moves starting from u .

Time: build $O(N \cdot \text{MAXLOG2})$, query $O(\text{MAXLOG2})$.

```
const int MAXN(2e5), MAXLOG2(30);
int bl[MAXN][MAXLOG2 + 1];
int N;

int jump(int u, ll k) {
    for (int i = 0; i <= MAXLOG2; i++) {
        if (k & (1ll << i)) u = bl[u][i];
    }
    return u;
}

void build() {
    for (int i = 1; i <= MAXLOG2; i++) {
        for (int j = 0; j < N; j++) {
            bl[j][i] = bl[bl[j][i - 1]][i - 1];
        }
    }
}
```

```
    }
}
}
```

4.8 Block Cut Tree

```
// O(n + m)
struct BlockCutTree {
    vector<vector<int>> blocks, tree;
    vector<vector<pair<int, int>>> block_edges;
    vector<int> articulation, pos;

    BlockCutTree(const vector<vector<int>> &g)
        : articulation(g.size()), pos(g.size()) {
        int t = 0;
        vector<int> id(g.size(), -1);
        stack<int> s1;
        stack<pair<int, int>> s2;
        for (int i = 0; i < (int)g.size(); i++)
            if (id[i] == -1) dfs(g, i, -1, t, id, s1, s2);

        tree.resize(blocks.size());
        for (int i = 0; i < (int)g.size(); i++)
            if (articulation[i])
                pos[i] = (int)tree.size(), tree.emplace_back();

        for (int i = 0; i < (int)blocks.size(); i++) {
            for (auto j : blocks[i]) {
                if (not articulation[j])
                    pos[j] = i;
                else
                    tree[i].push_back(pos[j]),
                    tree[pos[j]].push_back(i);
            }
        }
    }

private:
    int dfs(const vector<vector<int>> &g, int i, int p,
            int &t, vector<int> &id, stack<int> &s1,
            stack<pair<int, int>> &s2) {
        int lo = id[i] = t++;
        s1.push(i);

        if (p != -1) s2.emplace(i, p);
    }
}
```

```

for (auto j : g[i])
    if (j != p and id[j] != -1) s2.emplace(i, j);

for (auto j : g[i])
    if (j != p) {
        if (id[j] == -1) {
            int val = dfs(g, j, i, t, id, s1, s2);
            lo = min(lo, val);

            if (val >= id[i]) {
                articulation[i]++;
                blocks.emplace_back(1, i);
                for (; blocks.back().back() != j; s1.pop())
                    blocks.back().push_back(s1.top());

                block_edges.emplace_back(1, s2.top());
                s2.pop();
                for (; block_edges.back().back() !=
                    make_pair(j, i);
                    s2.pop())
                    block_edges.back().push_back(s2.top());
            }
        } else {
            lo = min(lo, id[j]);
        }
    }

if (p == -1 and articulation[i]) --articulation[i];
return lo;
}
};

```

4.9 Check Bipartite

$O(V)$

```

vi2d G;
int N, M;

bool check() {
    vi side(N, -1);
    queue<int> q;
    for (int st = 0; st < N; st++) {
        if (side[st] == -1) {
            q.emplace(st);
            side[st] = 0;
            while (not q.empty()) {

```

```

                int u = q.front();
                q.pop();
                for (auto v : G[u]) {
                    if (side[v] == -1) {
                        side[v] = side[u] ^ 1;
                        q.push(v);
                    } else if (side[u] == side[v])
                        return false;
                }
            }
        }
    }
    return true;
}

```

4.10 Dijkstra (k Shortest Paths)

```

const ll oo = 1e9 * 1e5 + 1;
using adj = vector<vector<pll>>;
vector<priority_queue<ll>> dijkstra(
    const vector<vector<pll>> &g, int n, int s, int k) {
    priority_queue<pll, vector<pll>, greater<pll>> pq;

    vector<priority_queue<ll>> dist(n);
    dist[0].emplace(0);
    pq.emplace(0, s);
    while (!pq.empty()) {
        auto [d1, v] = pq.top();
        pq.pop();

        if (not dist[v].empty() and dist[v].top() < d1)
            continue;

        for (auto [d2, u] : g[v]) {
            if (len(dist[u]) < k) {
                pq.emplace(d2 + d1, u);
                dist[u].emplace(d2 + d1);
            } else {
                if (dist[u].top() > d1 + d2) {
                    dist[u].pop();
                    dist[u].emplace(d1 + d2);
                    pq.emplace(d2 + d1, u);
                }
            }
        }
    }
}

```

```

}
return dist;
}

```

4.11 Dijkstra

Finds the shortest path from s to every other node, and keep the 'parent' tracking.
Time: $O(E \cdot \log V)$

```

pair<vll, vi> dijkstra(const vector<vector<pll>> &g, int n,
                      int s) {
    priority_queue<pll, vector<pll>, greater<pll>> pq;
    vll dist(n, oo);
    vi p(n, -1);
    pq.emplace(0, s);
    dist[s] = 0;
    while (!pq.empty()) {
        auto [d1, v] = pq.top();
        pq.pop();
        if (dist[v] < d1) continue;

        for (auto [d2, u] : g[v]) {
            if (dist[u] > d1 + d2) {
                dist[u] = d1 + d2;
                p[u] = v;
                pq.emplace(dist[u], u);
            }
        }
    }
    return {dist, p};
}

```

4.12 Disjoint Edges Path (Maxflow)

Given a directed graph find's every path with disjoint edges that starts at s and ends at t
Time: $O(E \cdot V^2)$

```

struct DisjointPaths {
    int n;
    vi2d g, capacity;
    vector<vc> isedge;

    DisjointPaths(int _n)
        : n(_n), g(n), capacity(n, vi(n)), isedge(n, vc(n)) {}

    void add(int u, int v, int w = 1) {
        g[u].emplace_back(v);
        g[v].emplace_back(u);
    }
}

```

```

capacity[u][v] += w;
isedge[u][v] = true;
}

```

```

// finds the new flow to insert
int bfs(int s, int t, vi &parent) {
    fill(all(parent), -1);
    parent[s] = -2;
    queue<pair<int, int>> q;
    q.push({oo, s});

    while (!q.empty()) {
        auto [flow, cur] = q.front();
        q.pop();

        for (auto next : g[cur]) {
            if (parent[next] == -1 and capacity[cur][next]) {
                parent[next] = cur;
                ll new_flow = min(flow, capacity[cur][next]);
                if (next == t) return new_flow;
                q.push({new_flow, next});
            }
        }
    }

    return 0;
}

int maxflow(int s, int t) {
    int flow = 0;
    vi parent(n);
    int new_flow;

    while ((new_flow = bfs(s, t, parent))) {
        flow += new_flow;
        int cur = t;
        while (cur != s) {
            int prev = parent[cur];
            capacity[prev][cur] -= new_flow;
            capacity[cur][prev] += new_flow;
            cur = prev;
        }
    }

    return flow;
}

```

```

}

// build the distinct routes based in the capacity set by
// maxflow
void dfs(int u, int t, vc2d &vis, vi &route,
        vi2d &routes) {
    route.eb(u);
    if (u == t) {
        routes.emplace_back(route);
        route.pop_back();
        return;
    }

    for (auto &v : g[u]) {
        if (capacity[u][v] == 0 and isedge[u][v] and
            not vis[u][v]) {
            vis[u][v] = true;
            dfs(v, t, vis, route, routes);
            route.pop_back();
            return;
        }
    }
}

vi2d disjoint_paths(int s, int t) {
    int mf = maxflow(s, t);
    vi2d routes;
    vi route;
    vc2d vis(n, vc(n));
    for (int i = 0; i < mf; i++)
        dfs(s, t, vis, route, routes);
    return routes;
}
};

```

4.13 Euler Path (directed)

Given a **directed** graph finds a path that visits every edge exactly once.
 Time: $O(E)$

```

vector<int> euler_cycle(vector<vector<int>> &g, int u) {
    vector<int> res;

    stack<int> st;
    st.push(u);

```

```

    while (!st.empty()) {
        auto cur = st.top();
        if (g[cur].empty()) {
            res.push_back(cur);
            st.pop();
        } else {
            auto next = g[cur].back();
            st.push(next);

            g[cur].pop_back();
        }
    }

    for (auto &x : g)
        if (!x.empty()) return {};

    return res;
}

vector<int> euler_path(vector<vector<int>> &g, int first) {
    {
        int n = (int)g.size();
        vector<int> in(n), out(n);
        for (int i = 0; i < n; i++)
            for (auto x : g[i]) in[x]++, out[i]++;

        int a = 0, b = 0, c = 0;
        for (int i = 0; i < n; i++)
            if (in[i] == out[i])
                c++;
            else if (in[i] - out[i] == 1)
                b++;
            else if (in[i] - out[i] == -1)
                a++;

        if (c != n - 2 or a != 1 or b != 1) return {};
    }

    auto res = euler_cycle(g, first);
    if (res.empty()) return res;

    reverse(all(res));
    return res;
}

```

4.14 Euler Path (undirected)

Given a **undirected** graph finds a path that visits every edge exactly once.

Time: $O(E)$

```
vector<int> euler_cycle(vector<vector<int>> &g, int u) {
    vector<int> res;
    multiset<pair<int, int>> vis;

    stack<int> st;
    st.push(u);
    while (!st.empty()) {
        auto cur = st.top();

        while (!g[cur].empty()) {
            auto it = vis.find(make_pair(cur, g[cur].back()));
            if (it == vis.end()) break;
            g[cur].pop_back();
            vis.erase(it);
        }

        if (g[cur].empty()) {
            res.push_back(cur);
            st.pop();
        } else {
            auto next = g[cur].back();
            st.push(next);

            vis.emplace(next, cur);
            g[cur].pop_back();
        }
    }

    for (auto &x : g)
        if (!x.empty()) return {};

    return res;
}

vector<int> euler_path(vector<vector<int>> &g, int first) {
    int n = (int)g.size();
    int v1 = -1, v2 = -1;
    {
        bool bad = false;
        for (int i = 0; i < n; i++)
```

```
        if (g[i].size() & 1) {
            if (v1 == -1)
                v1 = i;
            else if (v2 == -1)
                v2 = i;
            else
                bad = true;
        }

        if (bad or (v1 != -1 and v2 == -1)) return {};
    }

    if (v2 != -1) {
        // insert cycle
        g[v1].push_back(v2);
        g[v2].push_back(v1);
    }

    auto res = euler_cycle(g, first);
    if (res.empty()) return res;

    if (v1 != -1) {
        for (int i = 0; i + 1 < (int)res.size(); i++) {
            if ((res[i] == v1 and res[i + 1] == v2) ||
                (res[i] == v2 and res[i + 1] == v1)) {
                vector<int> res2;
                for (int j = i + 1; j < (int)res.size(); j++)
                    res2.push_back(res[j]);
                for (int j = 1; j <= i; j++) res2.push_back(res[j]);
                res = res2;
                break;
            }
        }
    }

    reverse(all(res));
    return res;
}
```

4.15 Extra Edges to Make Digraph Fully Strongly Connected

Given a directed graph G find the necessary edges to add to make the graph a single strongly connected component.

time : $O(N + M)$, memory : $O(N)$

```
struct SCC {
```

```

int num_sccs = 0;
vi scc_id;
SCC(const vi2d& adj) : scc_id(len(adj), -1) {
    int n = len(adj), timer = 1;
    vi tin(n), st;
    st.reserve(n);
    auto dfs = [&](auto&& self, int u) -> int {
        int low = tin[u] = timer++, siz = len(st);
        st.push_back(u);
        for (int v : adj[u])
            if (scc_id[v] < 0)
                low = min(low, tin[v] ? tin[v] : self(self, v));
        if (tin[u] == low) {
            for (int i = siz; i < len(st); i++)
                scc_id[st[i]] = num_sccs;
            st.resize(siz);
            num_sccs++;
        }
        return low;
    };
    for (int i = 0; i < n; i++)
        if (!tin[i]) dfs(dfs, i);
}

vector<array<int, 2>> extra_edges(const vi2d& adj) {
    SCC scc(adj);
    auto scc_id = scc.scc_id;
    auto num_sccs = scc.num_sccs;

    if (num_sccs == 1) return {};

    int n = len(adj);
    vi2d scc_adj(num_sccs);
    vi zero_in(num_sccs, 1);
    for (int u = 0; u < n; u++)
        for (int v : adj[u]) {
            if (scc_id[u] == scc_id[v]) continue;
            scc_adj[scc_id[u]].eb(scc_id[v]);
            zero_in[scc_id[v]] = 0;
        }

    vi vis(num_sccs);
    auto dfs = [&](auto&& self, int u) {
        if (empty(scc_adj[u])) return u;

```

```

        for (int v : scc_adj[u])
            if (!vis[v]) {
                vis[v] = 1;
                int zero_out = self(self, v);
                if (zero_out != -1) return zero_out;
            }
        return -1;
    };

    vector<array<int, 2>> edges;
    vi in_unused;
    for (int i = 0; i < num_sccs; i++)
        if (zero_in[i]) {
            vis[i] = 1;
            int zero_out = dfs(dfs, i);
            if (zero_out != -1)
                edges.push_back({zero_out, i});
            else
                in_unused.push_back(i);
        }

    for (int i = 1; i < len(edges); i++)
        swap(edges[i][0], edges[i - 1][0]);

    for (int i = 0; i < num_sccs; i++)
        if (empty(scc_adj[i]) && !vis[i]) {
            if (!empty(in_unused)) {
                edges.push_back({i, in_unused.back()});
                in_unused.pop_back();
            } else
                edges.push_back({i, num_sccs - 1});
        }

    for (int u : in_unused) edges.push_back({0, u});

    vi to_node(num_sccs);
    for (int i = 0; i < n; i++) to_node[scc_id[i]] = i;
    for (auto& [u, v] : edges) u = to_node[u], v = to_node[v];

    return edges;
}

```

4.16 Find Articulation/Cut Points

Given an **undirected** graph find its articulation points.

articulation point (or cut vertex): is defined as a **vertex** which, when removed along with associated edges, increases the number of connected components in the graph.

A vertex u can be an articulation point if and only if has at least 2 adjacent vertex

Time: $O(N + M)$

```
const int MAXN(100);
int N;
vi2d G;
int timer;
int tin[MAXN], low[MAXN];
set<int> cpoints;

int dfs(int u, int p = -1) {
    int cnt = 0;
    low[u] = tin[u] = timer++;
    for (auto v : G[u]) {
        if (not tin[v]) {
            cnt++;
            dfs(v, u);

            if (low[v] >= tin[u]) cpoints.insert(u);
            low[u] = min(low[u], low[v]);
        } else if (v != p)
            low[u] = min(low[u], tin[v]);
    }

    return cnt;
}

void getCutPoints() {
    memset(low, 0, sizeof(low));
    memset(tin, 0, sizeof(tin));
    cpoints.clear();

    timer = 1;
    for (int i = 0; i < N; i++) {
        if (tin[i]) continue;
        int cnt = dfs(i);
        if (cnt == 1) cpoints.erase(i);
    }
}
```

4.17 Find Bridge Tree Components

$dfs(u, p)$ finds the component of the connected component of u .

time: $O(n + m)$

```
int n;
const int MAXN(3'00'000);
vi g[MAXN], vi stck;
int tin[MAXN], low[MAXN], comp[MAXN], qtdcomps, clk;
void dfsb(int u, int p) {
    low[u] = tin[u] = ++clk;
    stck.emplace_back(u);

    for (auto v : g[u]) {
        if (!tin[v]) {
            dfsb(v, u);
            low[u] = min(low[u], low[v]);
        } else if (v != p) {
            low[u] = min(low[u], tin[v]);
        }
    }

    if (low[u] == tin[u]) {
        qtdcomps++;
        int v2;
        do {
            v2 = stck.back();
            comp[v2] = qtdcomps;
            stck.pop_back();
        } while (v2 != u);
    }
}
```

4.18 Find Bridges (online)

```
// O((n+m)*log(n))
struct BridgeFinder {
    // 2ecc = 2 edge connected component
    // cc = connected component
    vector<int> parent, dsu_2ecc, dsu_cc, dsu_cc_size;
    int bridges, lca_iteration;
    vector<int> last_visit;

    BridgeFinder(int n)
        : parent(n, -1),
          dsu_2ecc(n),
          dsu_cc(n),
          dsu_cc_size(n, 1),
          bridges(0),
          lca_iteration(0),
```



```

    last_visit(n) {
for (int i = 0; i < n; i++) {
    dsu_2ecc[i] = i;
    dsu_cc[i] = i;
}
}

int find_2ecc(int v) {
    if (v == -1) return -1;
    return dsu_2ecc[v] == v
        ? v
        : dsu_2ecc[v] = find_2ecc(dsu_2ecc[v]);
}

int find_cc(int v) {
    v = find_2ecc(v);
    return dsu_cc[v] == v ? v
        : dsu_cc[v] = find_cc(dsu_cc[v]);
}

void make_root(int v) {
    v = find_2ecc(v);
    int root = v;
    int child = -1;
    while (v != -1) {
        int p = find_2ecc(parent[v]);
        parent[v] = child;
        dsu_cc[v] = root;
        child = v;
        v = p;
    }
    dsu_cc_size[root] = dsu_cc_size[child];
}

void merge_path(int a, int b) {
    ++lca_iteration;
    vector<int> path_a, path_b;
    int lca = -1;
    while (lca == -1) {
        if (a != -1) {
            a = find_2ecc(a);
            path_a.push_back(a);
            if (last_visit[a] == lca_iteration) {
                lca = a;
                break;
            }
        }
    }

```

```

    }
    last_visit[a] = lca_iteration;
    a = parent[a];
}
if (b != -1) {
    b = find_2ecc(b);
    path_b.push_back(b);
    if (last_visit[b] == lca_iteration) {
        lca = b;
        break;
    }
    last_visit[b] = lca_iteration;
    b = parent[b];
}
}

for (auto v : path_a) {
    dsu_2ecc[v] = lca;
    if (v == lca) break;
    --bridges;
}
for (auto v : path_b) {
    dsu_2ecc[v] = lca;
    if (v == lca) break;
    --bridges;
}
}

void add_edge(int a, int b) {
    a = find_2ecc(a);
    b = find_2ecc(b);

    if (a == b) return;

    int ca = find_cc(a);
    int cb = find_cc(b);

    if (ca != cb) {
        ++bridges;
        if (dsu_cc_size[ca] > dsu_cc_size[cb]) {
            swap(a, b);
            swap(ca, cb);
        }
        make_root(a);
        parent[a] = dsu_cc[a] = b;
    }
}

```

```

        dsu_cc_size[cb] += dsu_cc_size[a];
    } else {
        merge_path(a, b);
    }
}
};

```

4.19 Find Bridges

Find every bridge in a **undirected** connected graph.

bridge: A bridge is defined as an **edge** which, when removed, increases the number of connected components in the graph.

Remember to read the graph as pair where the second is the id of the edge!

Time: $O(N + M)$

```

const int MAXN(10000), MAXM(100000);
int N, M, clk, tin[MAXN], low[MAXN], isBridge[MAXM];
vector<pii> G[MAXN];

void dfs(int u, int p = -1) {
    tin[u] = low[u] = clk++;

    for (auto [v, i] : G[u]) {
        if (v == p) continue;
        if (tin[v]) {
            low[u] = min(low[u], tin[v]);
        } else {
            dfs(v, u);
            low[u] = min(low[u], low[v]);
            if (low[v] > tin[u]) {
                isBridge[i] = 1;
            }
        }
    }
}

void findBridges() {
    fill(tin, tin + N, 0);
    fill(low, low + N, 0);
    fill(isBridge, isBridge + M, 0);
    clk = 1;
    for (int i = 0; i < N; i++) {
        if (!tin[i]) dfs(i);
    }
}

```

4.20 Find Centroid

Given a tree (don't forget to make it 'undirected'), find it's centroids.

Time: $O(V)$

```

void dfs(int u, int p, int n, vi2d &g, vi &sz,
        vi &centroid) {
    sz[u] = 1;

    bool iscentroid = true;
    for (auto v : g[u])
        if (v != p) {
            dfs(v, u, n, g, sz, centroid);
            if (sz[v] > n / 2) iscentroid = false;
            sz[u] += sz[v];
        }

    if (n - sz[u] > n / 2) iscentroid = false;
    if (iscentroid) centroid.eb(u);
}

vi getCentroid(vi2d &g, int n) {
    vi centroid;
    vi sz(n);
    dfs(0, -1, n, g, sz, centroid);
    return centroid;
}

```

4.21 Floyd Warshall

Simply finds the minimal distance for each node to every other node. $O(V^3)$

```

vector<vll> floyd_warshall(const vector<vll> &adj, ll n) {
    auto dist = adj;

    for (int i = 0; i < n; ++i) {
        for (int j = 0; j < n; ++j) {
            for (int k = 0; k < n; ++k) {
                dist[j][k] =
                    min(dist[j][k], dist[j][i] + dist[i][k]);
            }
        }
    }
    return dist;
}

```

4.22 Functional/Successor Graph

Given a functional graph find the vertex after k moves starting at u and also the distance between u and v , if it's impossible to reach v starting at u returns -1.

Time: build $O(N \cdot \text{MAXLOG2})$, kth $O(\text{MAXLOG2})$, dist $O(\text{MAXLOG2})$

```
const int MAXN(2'000'000), MAXLOG2(24);
int N;
vi2d succ(MAXN, vi(MAXLOG2 + 1));
vi dst(MAXN, 0);

int vis[MAXN];
void dfsbuild(int u) {
    if (vis[u]) return;
    vis[u] = 1;
    int v = succ[u][0];
    dfsbuild(v);
    dst[u] = dst[v] + 1;
}

void build() {
    for (int i = 0; i < N; i++) {
        if (not vis[i]) dfsbuild(i);
    }

    for (int k = 1; k <= MAXLOG2; k++) {
        for (int i = 0; i < N; i++) {
            succ[i][k] = succ[succ[i][k - 1]][k - 1];
        }
    }
}

int kth(int u, ll k) {
    if (k <= 0) return u;
    for (int i = 0; i <= MAXLOG2; i++)
        if ((1ll << i) & k) u = succ[u][i];
    return u;
}

int dist(int u, int v) {
    int cu = kth(u, dst[u]);
    if (kth(u, dst[u] - dst[v]) == v)
        return dst[u] - dst[v];
    else if (kth(cu, dst[cu] - dst[v]) == v)
        return dst[u] + (dst[cu] - dst[v]);
    else
        return -1;
}
```

}

4.23 Graph Cycle (directed)

Given a directed graph finds a cycle (or not).

Time : $O(E)$

```
bool dfs(int v, vi2d &adj, vc &visited, vi &parent,
         vc &color, int &cycle_start, int &cycle_end) {
    color[v] = 1;
    for (int u : adj[v]) {
        if (color[u] == 0) {
            parent[u] = v;
            if (dfs(u, adj, visited, parent, color, cycle_start,
                    cycle_end))
                return true;
        } else if (color[u] == 1) {
            cycle_end = v;
            cycle_start = u;
            return true;
        }
    }
    color[v] = 2;
    return false;
}

vi find_cycle(vi2d &g, int n) {
    vc visited(n);
    vi parent(n);
    vc color(n);
    int cycle_start, cycle_end;
    color.assign(n, 0);
    parent.assign(n, -1);
    cycle_start = -1;

    for (int v = 0; v < n; v++) {
        if (color[v] == 0 && dfs(v, g, visited, parent, color,
                                cycle_start, cycle_end))
            break;
    }

    if (cycle_start == -1) {
        return {};
    } else {
        vector<int> cycle;
        cycle.push_back(cycle_start);
    }
}
```

```

    for (int v = cycle_end; v != cycle_start; v = parent[v])
        cycle.push_back(v);
    cycle.push_back(cycle_start);
    reverse(cycle.begin(), cycle.end());
    return cycle;
}
}

```

4.24 Graph Cycle (undirected)

Detects if a graph contains a cycle. If path parameter is not null, it will contain the cycle if one exists.
Time: $O(V + E)$

```

void graph_cycles(const vector<vector<int>> &g, int u,
                 int p, vector<int> &ps,
                 vector<int> &color, int &cn,
                 vector<vector<int>> &cycles) {
    if (color[u] == 2) {
        return;
    }

    if (color[u] == 1) {
        cn++;
        int cur = p;
        cycles.emplace_back();
        auto &v = cycles.back();
        v.push_back(cur);
        while (cur != u) {
            cur = ps[cur];
            v.push_back(cur);
        }
        reverse(all(v));
        return;
    }

    ps[u] = p;
    color[u] = 1;
    for (auto v : g[u]) {
        if (v != p)
            graph_cycles(g, v, u, ps, color, cn, cycles);
    }

    color[u] = 2;
}

vector<vector<int>> graph_cycles(

```

```

const vector<vector<int>> &g) {
    vector<int> ps(g.size(), -1), color(g.size());
    int cn = 0;
    vector<vector<int>> cycles;
    for (int i = 0; i < (int)g.size(); i++)
        graph_cycles(g, i, -1, ps, color, cn, cycles);
    return cycles;
}

```

4.25 Heavy Light Decomposition

```

struct HeavyLightDecomposition {
    vector<int> parent, depth, size, heavy, head, pos;

    using SegT = int;
    static SegT op(SegT a, SegT b) { return max(a, b); }
    SegTree<SegT, op> seg;

    HeavyLightDecomposition(const vector<vector<int>> &g,
                           const vector<int> &v,
                           int root = 0)
        : parent(g.size()),
          depth(g.size()),
          size(g.size()),
          heavy(g.size(), -1),
          head(g.size()),
          pos(g.size()),
          seg((int)g.size()) {
        dfs(g, root);
        int cur_pos = 0;
        decompose(g, root, root, cur_pos);

        for (int i = 0; i < (int)g.size(); i++) {
            seg.set(pos[i], v[i]);
        }
    }

    SegT query_path(int a, int b) const {
        int res = 0;
        for (; head[a] != head[b]; b = parent[head[b]]) {
            if (depth[head[a]] > depth[head[b]]) swap(a, b);
            res = op(res, seg.query(pos[head[b]], pos[b]));
        }
        if (depth[a] > depth[b]) swap(a, b);
        return op(res, seg.query(pos[a], pos[b]));
    }
}

```

```

}

SegT query_subtree(int a) const {
    return seg.query(pos[a], pos[a] + size[a] - 1);
}

void set(int a, int x) { seg.set(pos[a], x); }

private:
void dfs(const vector<vector<int>> &g, int u) {
    size[u] = 1;
    int mx_child_size = 0;
    for (auto x : g[u])
        if (x != parent[u]) {
            parent[x] = u;
            depth[x] = depth[u] + 1;
            dfs(g, x);
            size[u] += size[x];
            if (size[x] > mx_child_size)
                mx_child_size = size[x], heavy[u] = x;
        }
}

void decompose(const vector<vector<int>> &g, int u, int h,
               int &cur_pos) {
    head[u] = h;
    pos[u] = cur_pos++;
    if (heavy[u] != -1) decompose(g, heavy[u], h, cur_pos);

    for (auto x : g[u])
        if (x != parent[u] and x != heavy[u]) {
            decompose(g, x, x, cur_pos);
        }
}
};

```

4.26 Kruskal

Find the minimum spanning tree of a graph.

Time: $O(E \log E)$

can be used to find the maximum spanning tree by changing the comparison operator in the sort

```

struct UFDS {
    vector<int> ps, sz;
    int components;

    UFDS(int n) : ps(n + 1), sz(n + 1, 1), components(n) {

```

```

        iota(all(ps), 0);
    }

    int find_set(int x) {
        return (x == ps[x] ? x : (ps[x] = find_set(ps[x])));
    }

    bool same_set(int x, int y) {
        return find_set(x) == find_set(y);
    }

    void union_set(int x, int y) {
        x = find_set(x);
        y = find_set(y);

        if (x == y) return;

        if (sz[x] < sz[y]) swap(x, y);

        ps[y] = x;
        sz[x] += sz[y];

        components--;
    }
};

vector<tuple<ll, int, int>> kruskal(
    int n, vector<tuple<ll, int, int>> &edges) {
    UFDS udfs(n);
    vector<tuple<ll, int, int>> ans;

    sort(all(edges));
    for (auto [a, b, c] : edges) {
        if (udfs.same_set(b, c)) continue;

        ans.emplace_back(a, b, c);
        udfs.union_set(b, c);
    }

    return ans;
}

```

4.27 Lowest Common Ancestor (Binary Lifting)

Finds the LCA between two nodes using binary lifting

Time: build $O(N \cdot \text{MAXLOG2})$ query $O(\text{MAXLOG2})$

```
const int MAXLOG2 = 20, MAXN(2'00'000);
int N;
int G[MAXN];
int depth[MAXN];
int up[MAXN][MAXLOG2 + 1];
vi GT[MAXN];

void build(int u = 0) {
    for (int i = 1; i <= MAXLOG2; i++)
        up[u][i] = up[up[u][i - 1]][i - 1];

    for (int v : GT[u])
        if (v != up[u][0]) {
            depth[v] = depth[up[v][0] = u] + 1;
            build(v);
        }
}

int jump(int u, ll k) {
    for (ll i = 0; i <= MAXLOG2; i++)
        if (k & (1ll << i)) u = up[u][i];

    return u;
}

int lca(int a, int b) {
    if (depth[a] < depth[b]) swap(a, b);

    a = jump(a, depth[a] - depth[b]);

    if (b == a) return a;

    for (int i = MAXLOG2; i >= 0; i--) {
        int at = up[a][i], bt = up[b][i];
        if (at != bt) a = at, b = bt;
    }

    return up[a][0];
}
```

4.28 Lowest Common Ancestor

Given two nodes of a tree find their lowest common ancestor, or their distance
Build : $O(V)$, Queries: $O(1)$

```
template <typename T>
struct SparseTable {
    vector<T> v;
    int n;
    static const int b = 30;
    vi mask, t;

    int op(int x, int y) { return v[x] < v[y] ? x : y; }
    int msb(int x) {
        return __builtin_clz(1) - __builtin_clz(x);
    }
    SparseTable() {}
    SparseTable(const vector<T>& v_)
        : v(v_), n(v.size()), mask(n), t(n) {
        for (int i = 0, at = 0; i < n; mask[i++] = at |= 1) {
            at = (at << 1) & ((1 << b) - 1);
            while (at and op(i, i - msb(at & -at)) == i)
                at ^= at & -at;
        }
        for (int i = 0; i < n / b; i++)
            t[i] = b * i + b - 1 - msb(mask[b * i + b - 1]);
        for (int j = 1; (1 << j) <= n / b; j++)
            for (int i = 0; i + (1 << j) <= n / b; i++)
                t[n / b * j + i] =
                    op(t[n / b * (j - 1) + i],
                       t[n / b * (j - 1) + i + (1 << (j - 1))]);
    }
    int small(int r, int sz = b) {
        return r - msb(mask[r] & ((1 << sz) - 1));
    }
    T query(int l, int r) {
        if (r - l + 1 <= b) return small(r, r - l + 1);
        int ans = op(small(l + b - 1), small(r));
        int x = l / b + 1, y = r / b - 1;
        if (x <= y) {
            int j = msb(y - x + 1);
            ans = op(ans, op(t[n / b * j + x],
                             t[n / b * j + y - (1 << j) + 1]));
        }
        return ans;
    }
};

struct LCA {
    SparseTable<int> st;
};
```

```

int n;
vi v, pos, dep;

LCA(const vi2d& g, int root) : n(len(g)), pos(n) {
    dfs(root, 0, -1, g);
    st = SparseTable<int>(vector<int>(all(dep)));
}

void dfs(int i, int d, int p, const vi2d& g) {
    v.eb(len(dep)) = i, pos[i] = len(dep), dep.eb(d);
    for (auto j : g[i])
        if (j != p) {
            dfs(j, d + 1, i, g);
            v.eb(len(dep)) = i, dep.eb(d);
        }
}

int lca(int a, int b) {
    int l = min(pos[a], pos[b]);
    int r = max(pos[a], pos[b]);
    return v[st.query(l, r)];
}

int dist(int a, int b) {
    return dep[pos[a]] + dep[pos[b]] -
        2 * dep[pos[lca(a, b)]];
}
};

```

4.29 Maximum Flow (Edmonds-Karp)

Finds the **maximum flow** in a graph network, given the **source** s and the **sink** t .
Time: $O(V \cdot E^2)$

```

struct maxflow {
    int n;
    vi2d g;
    vll2d cps;
    vi ps;
    vector<vector<char>> isedge;

    maxflow(int _n)
        : n(_n),
          g(n),
          cps(n, vll(n)),
          ps(n),
          isedge(n, vc(n)) {}
};

```

```

void add(int u, int v, ll c, bool set = true) {
    g[u].emplace_back(v);
    g[v].emplace_back(u);
    cps[u][v] = cps[u][v] * (!set) + c;
    isedge[u][v] = true;
}

ll bfs(int s, int t) {
    fill(all(ps), -1);
    ps[s] = -2;
    queue<pair<ll, int>> q;
    q.emplace(oo, s);

    while (!q.empty()) {
        auto [flow, cur] = q.front();
        q.pop();

        for (auto next : g[cur]) {
            if (ps[next] == -1 and cps[cur][next]) {
                ps[next] = cur;
                ll new_flow = min(flow, cps[cur][next]);
                if (next == t) return new_flow;
                q.emplace(new_flow, next);
            }
        }
    }

    return 0ll;
}

ll flow(int s, int t) {
    ll flow = 0;
    ll new_flow;

    while ((new_flow = bfs(s, t))) {
        flow += new_flow;
        int cur = t;
        while (cur != s) {
            int prev = ps[cur];
            cps[prev][cur] -= new_flow;
            cps[cur][prev] += new_flow;
            cur = prev;
        }
    }
}

```

```

    return flow;
}

vector<pii> get_used() {
    vector<pii> used;
    for (int i = 0; i < n; i++) {
        for (int j = 0; j < n; j++) {
            if (isedge[i][j] and cps[i][j] == 0)
                used.emplace_back(i, j);
        }
    }
    return used;
}
};

```

4.30 Minimum Cost Flow

Given a network find the minimum cost to achieve a flow of at most f . Works with **directed** and **undirected** graphs

- **add(u, v, w, c)**: adds an edge from u to v with capacity w and cost c .
- **flow(s, t, f)**: return a pair $(flow, cost)$ with the maximum flow until f with source at s and sink at t , with the minimum cost possible.

Time : $O(N \cdot M + f \cdot m \log n)$

```

template <typename T>
struct mcmf {
    struct edge {
        int to, rev, flow, cap;
        bool res; // if it's a reverse edge
        T cost; // cost per unity of flow
        edge()
            : to(0),
              rev(0),
              flow(0),
              cap(0),
              cost(0),
              res(false) {}
        edge(int to_, int rev_, int flow_, int cap_, T cost_,
            bool res_)
            : to(to_),
              rev(rev_),
              flow(flow_),
              cap(cap_),
              res(res_),
              cost(cost_) {}
    };
};

```

```

};

vector<vector<edge>> g;
vector<int> par_idx, par;
T inf;
vector<T> dist;

mcmf(int n)
    : g(n),
      par_idx(n),
      par(n),
      inf(numeric_limits<T>::max() / 3) {}

void add(int u, int v, int w, T cost) {
    edge a = edge(v, g[v].size(), 0, w, cost, false);
    edge b = edge(u, g[u].size(), 0, 0, -cost, true);

    g[u].push_back(a);
    g[v].push_back(b);
}

vector<T> spfa(int s) { // don't code it if there isn't
                        // negative cycles

    deque<int> q;
    vector<bool> is_inside(g.size(), 0);
    dist = vector<T>(g.size(), inf);

    dist[s] = 0;
    q.push_back(s);
    is_inside[s] = true;

    while (!q.empty()) {
        int v = q.front();
        q.pop_front();
        is_inside[v] = false;

        for (int i = 0; i < g[v].size(); i++) {
            auto [to, rev, flow, cap, res, cost] = g[v][i];
            if (flow < cap and dist[v] + cost < dist[to]) {
                dist[to] = dist[v] + cost;

                if (is_inside[to]) continue;
                if (!q.empty() and dist[to] > dist[q.front()])
                    q.push_back(to);
                else

```



```

        q.push_front(to);
        is_inside[to] = true;
    }
}
}
return dist;
}
bool dijkstra(int s, int t, vector<T>& pot) {
    priority_queue<pair<T, int>, vector<pair<T, int>>,
        greater<>>
        q;
    dist = vector<T>(g.size(), inf);
    dist[s] = 0;
    q.emplace(0, s);
    while (q.size()) {
        auto [d, v] = q.top();
        q.pop();
        if (dist[v] < d) continue;
        for (int i = 0; i < g[v].size(); i++) {
            auto [to, rev, flow, cap, res, cost] = g[v][i];
            cost += pot[v] - pot[to];
            if (flow < cap and dist[v] + cost < dist[to]) {
                dist[to] = dist[v] + cost;
                q.emplace(dist[to], to);
                par_idx[to] = i, par[to] = v;
            }
        }
    }
    return dist[t] < inf;
}

pair<int, T> min_cost_flow(int s, int t, int flow = inf) {
    vector<T> pot(g.size(), 0);
    pot = spfa(s); // comment this line if there isn't
                  // negative cycles

    int f = 0;
    T ret = 0;
    while (f < flow and dijkstra(s, t, pot)) {
        for (int i = 0; i < g.size(); i++)
            if (dist[i] < inf) pot[i] += dist[i];

        int mn_flow = flow - f, u = t;
        while (u != s) {
            mn_flow =

```

```

                min(mn_flow, g[par[u]][par_idx[u]].cap -
                    g[par[u]][par_idx[u]].flow);
            u = par[u];
        }

        ret += pot[t] * mn_flow;

        u = t;
        while (u != s) {
            g[par[u]][par_idx[u]].flow += mn_flow;
            g[u][g[par[u]][par_idx[u]].rev].flow -= mn_flow;
            u = par[u];
        }

        f += mn_flow;
    }

    return make_pair(f, ret);
};
};

```

4.31 Minimum Cut (unweighted)

After build the **direct/undirected** graph find the minimum of edges needed to be removed to make the sink t unreachable from the source s .

Time: $O(V \cdot E^2)$

```

struct Mincut {
    int n;
    vi2d g;
    vii edges;
    vll2d capacity;
    vi ps, vis;

    Mincut(int _n)
        : n(_n), g(n), capacity(n, vll(n)), ps(n), vis(n) {}

    void add(int u, int v, ll c = 1, bool directed = false,
        bool set = false) {
        edges.emplace_back(u, v);
        g[u].emplace_back(v);

        if (not set)
            capacity[u][v] += c;
        else
            capacity[u][v] = c;
    }
};

```

```

if (not directed) {
    g[v].emplace_back(u);

    if (not set)
        capacity[v][u] += c;
    else
        capacity[v][u] = c;
}
}

ll bfs(int s, int t) {
    fill(all(ps), -1);
    ps[s] = -2;
    queue<pair<ll, int>> q;
    q.push({0, s});

    while (!q.empty()) {
        auto [flow, cur] = q.front();
        q.pop();

        for (auto next : g[cur]) {
            if (ps[next] == -1 and capacity[cur][next]) {
                ps[next] = cur;
                ll new_flow = min(flow, capacity[cur][next]);
                if (next == t) return new_flow;
                q.push({new_flow, next});
            }
        }
    }

    return 0;
}

ll maxflow(int s, int t) {
    ll flow = 0;
    ll new_flow;

    while ((new_flow = bfs(s, t))) {
        flow += new_flow;
        int cur = t;
        while (cur != s) {
            int prev = ps[cur];
            capacity[prev][cur] -= new_flow;
            capacity[cur][prev] += new_flow;

```

```

        cur = prev;
    }
}

return flow;
}

void dfs(int u) {
    vis[u] = true;

    for (auto v : g[u]) {
        if (capacity[u][v] > 0 and not vis[v]) {
            dfs(v);
        }
    }
}

vii mincut(int s, int t) {
    maxflow(s, t);
    fill(all(vis), 0);
    dfs(s);

    vii removed;
    for (auto &[u, v] : edges) {
        if ((vis[u] and not vis[v]) or
            (vis[v] and not vis[u]))
            removed.emplace_back(u, v);
    }

    return removed;
}
};

```

4.32 Prim (MST)

Given a graph with N vertex finds the minimum spanning tree, if there is no such tree returns inf, it starts using the edges that connect with each $s_i \in s$, if none is provided than it starts with the edges of node 0.
Time: $O(V \log E)$

```

const int MAXN(1'000'000);
int N;
vector<pair<ll, int>> G[MAXN];
ll prim(vi s = vi(1, 0)) {
    priority_queue<pair<ll, int>, vector<pair<ll, int>>,
        greater<pair<ll, int>>>
        pq;
    vector<char> ingraph(MAXN);

```

```

int ingraphcnt(0);
for (auto si : s) {
    ingraphcnt++;
    ingraph[si] = true;
    for (auto &[w, v] : G[si]) pq.emplace(w, v);
}

ll mstcost = 0;
while (ingraphcnt < N and !pq.empty()) {
    ll w;
    int v;

    do {
        tie(w, v) = pq.top();
        pq.pop();
    } while (not pq.empty() and ingraph[v]);

    mstcost += w, ingraph[v] = true, ingraphcnt++;

    for (auto &[w2, v2] : G[v]) {
        pq.emplace(w2, v2);
    }
}

return ingraphcnt == N ? mstcost : oo;
}

```

4.33 Small to Large

Answer queries of the form "How many vertices in the subtree of vertex v have property P ?"
 * this implementation answers how many distinct $values[i]$ are in the subtree starting at u .
 Build: $O(N)$, Query: $O(N \log N)$

```

struct SmallToLarge {
    int n;
    vi2d tree, vis_chlds;
    vi sizes, values, ans;
    set<int> cnt;

    SmallToLarge(vi2d &g, vi &v)
        : tree(g),
          vis_chlds(len(g)),
          sizes(len(g)),
          values(v),
          ans(len(g)) {
        get_size(0);
    }
}

```

```

dfs(0);
}

inline void add_value(int u) { cnt.insert(values[u]); }

inline void remove_value(int u) { cnt.erase(values[u]); }

inline void update_ans(int u) { ans[u] = len(cnt); }

void dfs(int u, int p = -1, bool keep = true) {
    int mx = -1;
    for (auto x : tree[u]) {
        if (x == p) continue;

        if (mx == -1 or sizes[mx] < sizes[x]) mx = x;
    }

    for (auto x : tree[u]) {
        if (x != p and x != mx) dfs(x, u, false);
    }

    if (mx != -1) {
        dfs(mx, u, true);
        swap(vis_chlds[u], vis_chlds[mx]);
    }

    vis_chlds[u].push_back(u);
    add_value(u);

    for (auto x : tree[u]) {
        if (x != p and x != mx) {
            for (auto y : vis_chlds[x]) {
                add_value(y);
                vis_chlds[u].push_back(y);
            }
        }
    }

    update_ans(u);

    if (!keep) {
        for (auto x : vis_chlds[u]) remove_value(x);
    }
}

```

```

void get_size(int u, int p = -1) {
    sizes[u] = 1;
    for (auto x : tree[u])
        if (x != p) {
            get_size(x, u);
            sizes[u] += sizes[x];
        }
}
};

```

4.34 Successor Graph-(struct)

```

struct SuccessorGraph {
    vector<vector<int>> paths;
    vector<int> path_num, pos;
    vector<char> is_cycle;

    SuccessorGraph(const vector<int> &v)
        : path_num(v.size()), pos(v.size()) {
        paths.reserve(v.size());
        is_cycle.reserve(v.size());

        vector<char> vis(v.size());
        for (auto i : topological_order(v)) {
            if (vis[i]) continue;

            vector<int> path;
            int cur;
            for (cur = i; not vis[cur]; cur = v[cur]) {
                path.push_back(cur);
                vis[cur] = 1;
            }

            int cycle_start = 0;
            for (; cycle_start < (int)path.size() and
                path[cycle_start] != cur;
                cycle_start++);

            if (cycle_start > 0) {
                paths.emplace_back();
                for (int j = 0; j < cycle_start; j++) {
                    paths.back().push_back(path[j]);
                    pos[path[j]] = j;
                    path_num[path[j]] = (int)paths.size() - 1;
                }
            }
        }
    }
};

```

```

}
paths.back().push_back(cur);
is_cycle.push_back(false);
}

if (cycle_start < (int)path.size()) {
    paths.emplace_back();
    for (int j = cycle_start; j < (int)path.size();
        j++) {
        paths.back().push_back(path[j]);
        pos[path[j]] = j - cycle_start;
        path_num[path[j]] = (int)paths.size() - 1;
    }
    is_cycle.push_back(true);
}
}

const vector<int> &path(int cur) const {
    return paths[path_num[cur]];
}

int kth_pos(int cur, ll k) const {
    while (not is_cycle[path_num[cur]]) {
        auto &p = path(cur);
        int remain = (int)p.size() - pos[cur] - 1;
        if (k <= remain) return p[pos[cur] + k];
        cur = p.back();
        k -= remain;
    }

    auto &p = path(cur);
    return p[(pos[cur] + k) % p.size()];
}

// {element, number_of_moves}
pair<int, int> go_to_cycle(int cur) const {
    int moves = 0;
    while (not is_cycle[path_num[cur]]) {
        auto &p = path(cur);
        moves += (int)p.size() - pos[cur] - 1;
        cur = p.back();
    }
    return {cur, moves};
}

```

```

// min cost to reach dest from cur
int reach(int cur, int dest) const {
    int moves = 0;
    while (not is_cycle[path_num[cur]] and
           path_num[cur] != path_num[dest]) {
        auto &p = path(cur);
        moves += (int)p.size() - pos[cur] - 1;
        cur = p.back();
    }

    if (path_num[cur] != path_num[dest]) return -1;

    if (pos[cur] <= pos[dest])
        return moves + pos[dest] - pos[cur];

    if (not is_cycle[path_num[cur]]) return -1;

    return moves + pos[dest] + (int)path(cur).size() -
           pos[cur];
}

private:
void topological_order(const vector<int> &g,
                      vector<char> &vis,
                      vector<int> &order, int u) {
    vis[u] = true;
    if (not vis[g[u]])
        topological_order(g, vis, order, g[u]);
    order.push_back(u);
}

vector<int> topological_order(const vector<int> &g) {
    vector<char> vis(g.size(), false);
    vector<int> order;
    for (auto i = 0; i < (int)g.size(); i++)
        if (not vis[i]) topological_order(g, vis, order, i);
    reverse(order.begin(), order.end());
    return order;
}
};

```

4.35 Sum every node distance

Given a **tree**, for each node i find the sum of distance from i to every other node.
 don't forget to set the tree as undirected, that's needed to choose an arbitrary root

Time: $O(N)$

```

void getRoot(int u, int p, vi2d &g, vll &d, vll &cnt) {
    for (int i = 0; i < len(g[u]); i++) {
        int v = g[u][i];
        if (v == p) continue;
        getRoot(v, u, g, d, cnt);
        d[u] += d[v] + cnt[v];
        cnt[u] += cnt[v];
    }
}

void dfs(int u, int p, vi2d &g, vll &cnt, vll &ansd,
         int n) {
    for (int i = 0; i < len(g[u]); i++) {
        int v = g[u][i];
        if (v == p) continue;

        ansd[v] = ansd[u] - cnt[v] + (n - cnt[v]);
        dfs(v, u, g, cnt, ansd, n);
    }
}

vll fromToAll(vi2d &g, int n) {
    vll d(n);
    vll cnt(n, 1);
    getRoot(0, -1, g, d, cnt);

    vll ansdist(n);
    ansdist[0] = d[0];

    dfs(0, -1, g, cnt, ansdist, n);
    return ansdist;
}

```

4.36 Topological Labelling (Kahn)

The same thing as topological sorting but over every possible order gives lexicographically smaller
 Time: $O(E + V \cdot \log V)$

```

const int MAXN(1'000'000);
int OUTCNT[MAXN];
vi2d GIN(MAXN);
int N;

vi toposort() {

```

```

vi order;
priority_queue<int> q;

for (int i = 0; i < N; i++)
    if (!OUTCNT[i]) q.emplace(i);

while (!q.empty()) {
    auto u = q.top();
    q.pop();
    order.emplace_back(u);
    for (auto v : GIN[u]) {
        OUTCNT[v]--;
        if (OUTCNT[v] == 0) q.emplace(v);
    }
}

reverse(all(order));
return len(order) == N ? order : vi();
}

```

4.37 Topological Sorting (Kahn)

Finds the topological sorting in a **DAG**, if the given graph is not a **DAG** than an empty vector is returned, need to 'initialize' the **INCNT** as you build the graph.
Time: $O(V + E)$

```

const int MAXN(2'00'000);
int INCNT[MAXN];
vi2d GOUT(MAXN);
int N;

vi toposort() {
    vi order;
    queue<int> q;

    for (int i = 0; i < N; i++)
        if (!INCNT[i]) q.emplace(i);

    while (!q.empty()) {
        auto u = q.front();
        q.pop();
        order.emplace_back(u);
        for (auto v : GOUT[u]) {
            INCNT[v]--;
            if (INCNT[v] == 0) q.emplace(v);
        }
    }
}

```

```

}

return len(order) == N ? order : vi();
}

```

4.38 Topological Sorting (Tarjan)

Finds a the topological order for the graph, if there is no such order it means the graph is cyclic, then it returns an empty vector
 $O(V + E)$

```

const int maxn(1'00'000);
int n, m;
vi g[maxn];

int not_found = 0, found = 1, processed = 2;
int state[maxn];

bool dfs(int u, vi &order) {
    if (state[u] == processed) return true;
    if (state[u] == found) return false;

    state[u] = found;

    for (auto v : g[u]) {
        if (not dfs(v, order)) return false;
    }

    state[u] = processed;
    order.emplace_back(u);

    return true;
}

vi topo_sort() {
    vi order;
    memset(state, 0, sizeof state);

    for (int u = 0; u < n; u++) {
        if (state[u] == not_found and not dfs(u, order))
            return {};
    }

    reverse(all(order));
    return order;
}

```

4.39 Tree Diameter (DP)

```
const int MAXN(1'000'000);
int N;
vi G[MAXN];

int diameter, toLeaf[MAXN];
void calcDiameter(int u = 0, int p = -1) {
    int d1, d2;
    d1 = d2 = -1;

    for (auto v : G[u]) {
        if (v != p) {
            calcDiameter(v, u);
            d1 = max(d1, toLeaf[v]);
            tie(d1, d2) = minmax({d1, d2});
        }
    }
    toLeaf[u] = d2 + 1;
    diameter = max(diameter, d1 + d2 + 2);
}
```

4.40 Tree Isomorphism (not rooted)

Two trees are considered **isomorphic** if the hash given by *thash()* is the same.
Time: $O(V \cdot \log V)$

```
map<vi, int> mphash;
```

```
struct Tree {
    int n;
    vi2d g;
    vi sz, cs;

    Tree(int n_) : n(n_), g(n), sz(n) {}

    void add_edge(int u, int v) {
        g[u].emplace_back(v);
        g[v].emplace_back(u);
    }

    void dfs_centroid(int v, int p) {
        sz[v] = 1;
        bool cent = true;
        for (int u : g[v])
            if (u != p) {
                dfs_centroid(u, v);
            }
    }
}
```

```
        sz[v] += sz[u];
        cent &= not(sz[u] > n / 2);
    }
    if (cent and n - sz[v] <= n / 2) cs.push_back(v);
}

int fhash(int v, int p) {
    vi h;
    for (int u : g[v])
        if (u != p) h.push_back(fhash(u, v));
    sort(all(h));
    if (!mphash.count(h)) mphash[h] = mphash.size();
    return mphash[h];
}

ll thash() {
    cs.clear();
    dfs_centroid(0, -1);
    if (cs.size() == 1) return fhash(cs[0], -1);
    ll h1 = fhash(cs[0], cs[1]), h2 = fhash(cs[1], cs[0]);
    return (min(h1, h2) << 30ll) + max(h1, h2);
}
};
```

4.41 Tree Isomorphism (rooted)

Given a rooted tree find the hash of each subtree, if two roots of two distinct trees have the same hash they are considered isomorphic
hash first time in $O(\log N_v \cdot N_v)$ where (N_v) is the of the subtree of v

```
map<vi, int> hasher;
int hs = 0;
struct RootedTreeIso {
    int n;
    vi2d adj;
    vi hashes;
    RootedTreeIso(int n_) : n(n_), adj(n), hashes(n, -1){};

    void add_edge(int u, int v) {
        adj[u].emplace_back(v);
        adj[v].emplace_back(u);
    }

    int hash(int u, int p = -1) {
        if (hashes[u] != -1) return hashes[u];
    }
}
```

```

vi children;
for (auto v : adj[u])
    if (v != p) children.emplace_back(hash(v, u));

sort(all(children));
if (!hasher.count(children)) hasher[children] = hs++;

return hashes[u] = hasher[children];
}
};

```

4.42 Tree Maximum Distance

Returns the maximum distance from every node to any other node in the tree.
 $O(6V) = O(V)$

```

pll mostDistantFrom(const vector<vll> &adj, ll n, ll root) {
    // O(V)
    // 0 indexed
    ll mostDistantNode = root;
    ll nodeDistance = 0;
    queue<pll> q;
    vector<char> vis(n);
    q.emplace(root, 0);
    vis[root] = true;
    while (!q.empty()) {
        auto [node, dist] = q.front();
        q.pop();
        if (dist > nodeDistance) {
            nodeDistance = dist;
            mostDistantNode = node;
        }
        for (auto u : adj[node]) {
            if (!vis[u]) {
                vis[u] = true;
                q.emplace(u, dist + 1);
            }
        }
    }
    return {mostDistantNode, nodeDistance};
}

ll twoNodesDist(const vector<vll> &adj, ll n, ll a, ll b) {
    queue<pll> q;
    vector<char> vis(n);
    q.emplace(a, 0);

```

```

while (!q.empty()) {
    auto [node, dist] = q.front();
    q.pop();
    if (node == b) return dist;
    for (auto u : adj[node]) {
        if (!vis[u]) {
            vis[u] = true;
            q.emplace(u, dist + 1);
        }
    }
}
return -1;
}

tuple<ll, ll, ll> tree_diameter(const vector<vll> &adj,
                                ll n) {
    // returns two points of the diameter and the diameter
    // itself
    auto [node1, dist1] = mostDistantFrom(adj, n, 0); // O(V)
    auto [node2, dist2] =
        mostDistantFrom(adj, n, node1); // O(V)
    auto diameter =
        twoNodesDist(adj, n, node1, node2); // O(V)
    return make_tuple(node1, node2, diameter);
}

vll everyDistanceFromNode(const vector<vll> &adj, ll n,
                           ll root) {
    // Single Source Shortest Path, from a given root
    queue<pair<ll, ll>> q;
    vll ans(n, -1);
    ans[root] = 0;
    q.emplace(root, 0);
    while (!q.empty()) {
        auto [u, d] = q.front();
        q.pop();

        for (auto w : adj[u]) {
            if (ans[w] != -1) continue;
            ans[w] = d + 1;
            q.emplace(w, d + 1);
        }
    }
    return ans;
}

```



```

vll maxDistances(const vector<vll> &adj, ll n) {
    auto [node1, node2, diameter] =
        tree_diameter(adj, n); // O(3V)
    auto distances1 =
        everyDistanceFromNode(adj, n, node1); // O(V)
    auto distances2 =
        everyDistanceFromNode(adj, n, node2); // O(V)
    vll ans(n);
    for (int i = 0; i < n; ++i)
        ans[i] = max(distances1[i], distances2[i]); // O(V)
    return ans;
}

```

4.43 Tree Flatten

```

void tree_flatten(const vector<vector<int>> &g, int u,
                 int p, vector<int> &pre, vector<int> &pos,
                 int &idx) {
    ++idx;
    pre.push_back(u);
    for (auto x : g[u])
        if (x != p) tree_flatten(g, x, u, pre, pos, idx);
    pos[u] = idx;
}

```

```

pair<vector<int>, vector<int>> tree_flatten(
    const vector<vector<int>> &g, int root = 0) {
    vector<int> first(g.size()), last(g.size()), pre;
    int timer = -1;
    tree_flatten(g, root, -1, pre, last, timer);
    for (int i = 0; i < (int)g.size(); i++) first[pre[i]] = i;
    return {first, last};
}

```

5 Math

5.1 GCD (with factorization)

$O(\sqrt{n})$ due to factorization.

```

ll gcd_with_factorization(ll a, ll b) {
    map<ll, ll> fa = factorization(a);
    map<ll, ll> fb = factorization(b);
    ll ans = 1;
    for (auto fai : fa) {

```

```

        ll k = min(fai.second, fb[fai.first]);
        while (k--) ans *= fai.first;
    }
    return ans;
}

```

5.2 GCD

```

ll gcd(ll a, ll b) { return b ? gcd(b, a % b) : a; }

```

5.3 LCM (with factorization)

$O(\sqrt{n})$ due to factorization.

```

ll lcm_with_factorization(ll a, ll b) {
    map<ll, ll> fa = factorization(a);
    map<ll, ll> fb = factorization(b);
    ll ans = 1;
    for (auto fai : fa) {
        ll k = max(fai.second, fb[fai.first]);
        while (k--) ans *= fai.first;
    }
    return ans;
}

```

5.4 LCM

```

ll gcd(ll a, ll b) { return b ? gcd(b, a % b) : a; }
ll lcm(ll a, ll b) { return a / gcd(a, b) * b; }

```

5.5 Arithmetic Progression Sum

- s : first term
- d : common difference
- n : number of terms

```

ll arithmeticProgressionSum(ll s, ll d, ll n) {
    return (s + (s + d * (n - 1))) * n / 2ll;
}

```

5.6 Binomial MOD

Precompute every factorial until $maxn$ ($O(maxn)$) allowing to answer the $\binom{n}{k}$ in $O(\log mod)$ time, due to the fastpow. Note that it needs $O(maxn)$ in memory.

```

const ll MOD = 1e9 + 7;
const ll MAXN = 1'00'000;
ll FACT[MAXN + 1];

```

```

void precompute() {
#warning Remember to call precompute before use binommod !
    FACT[0] = 1;
    for (ll i = 1; i <= MAXN; i++) {
        FACT[i] = (FACT[i - 1] * i) % MOD;
    }
}

ll fpow(ll a, ll k) {
    ll ret = 1;
    while (k) {
        if (k & 1) ret = (ret * a) % MOD;
        a = (a * a) % MOD;
        k >>= 1;
    }
    return ret;
}

ll binommod(ll n, ll k) {
    ll upper = FACT[n];
    ll lower = (FACT[k] * FACT[n - k]) % MOD;
    return (upper * fpow(lower, MOD - 2)) % MOD;
}

```

5.7 Binomial

$O(nm)$ time, $O(m)$ space
 Equal to n choose k

```

ll binom(ll n, ll k) {
    if (k > n) return 0;
    vll dp(k + 1, 0);
    dp[0] = 1;
    for (ll i = 1; i <= n; i++)
        for (ll j = k; j > 0; j--) dp[j] = dp[j] + dp[j - 1];
    return dp[k];
}

```

5.8 Chinese Remainder Theorem

Finds the solution x to the n modular equations.

$$x \equiv a_1 \pmod{m_1}$$

...

$$x \equiv a_n \pmod{m_n}$$

The m_i don't need to be coprime, if there is no solution then it returns -1.

```

tuple<ll, ll, ll> ext_gcd(ll a, ll b) {
    if (!a) return {b, 0, 1};
    auto [g, x, y] = ext_gcd(b % a, a);
    return {g, y - b / a * x, x};
}

template <typename T = ll>
struct crt {
    T a, m;

    crt() : a(0), m(1) {}
    crt(T a_, T m_) : a(a_), m(m_) {}
    crt operator*(crt C) {
        auto [g, x, y] = ext_gcd(m, C.m);
        if ((a - C.a) % g != 0) a = -1;
        if (a == -1 or C.a == -1) return crt(-1, 0);
        T lcm = m / g * C.m;
        T ans = a + (x * (C.a - a) / g % (C.m / g)) * m;
        return crt((ans % lcm + lcm) % lcm, lcm);
    }
};

template <typename T = ll>
struct Congruence {
    T a, m;
};

template <typename T = ll>
T chinese_remainder_theorem(
    const vector<Congruence<T>> &equations) {
    crt<T> ans;

    for (auto &[a_, m_] : equations) {
        ans = ans * crt<T>(a_, m_);
    }

    return ans.a;
}

```

5.9 Derangement / Matching Problem

Computes the derangement of N , which is given by the formula :

$$D_N = N! \left(1 - \frac{1}{1!} + \frac{1}{2!} - \frac{1}{3!} + \dots + (-1)^N \frac{1}{N!} \right)$$

time: $O(N)$

#warning Remember to call precompute !

```

const ll MOD = 1e9 + 7;
const int MAXN(1'000'000);
ll fats[MAXN + 1];
void precompute() {
    fats[0] = 1;
    for (ll i = 1; i <= MAXN; i++) {
        fats[i] = (fats[i - 1] * i) % MOD;
    }
}

ll fastpow(ll a, ll p, ll m) {
    ll ret = 1;
    while (p) {
        if (p & 1) ret = (ret * a) % MOD;
        p >>= 1;
        a = (a * a) % MOD;
    }
    return ret;
}

ll divmod(ll a, ll b) {
    return (a * fastpow(b, MOD - 2, MOD)) % MOD;
}

ll derangement(const ll n) {
    ll ans = fats[n];
    for (ll i = 1; i <= n; i++) {
        ll k = divmod(fats[n], fats[i]);
        if (i & 1) {
            ans = (ans - k + MOD) % MOD;
        } else {
            ans = (ans + k) % MOD;
        }
    }
    return ans;
}

```

5.10 Euler phi $\varphi(n)$ (in range)

Computes the number of positive integers less than n that are coprimes with n , in the range $[1, n]$, in $O(N \log N)$.

```

const int MAX = 1e6;
vi range_phi(int n) {
    bitset<MAX> sieve;
    vi phi(n + 1);

```

```

    iota(phi.begin(), phi.end(), 0);
    sieve.set();

    for (int p = 2; p <= n; p += 2) phi[p] /= 2;
    for (int p = 3; p <= n; p += 2) {
        if (sieve[p]) {
            for (int j = p; j <= n; j += p) {
                sieve[j] = false;
                phi[j] /= p;
                phi[j] *= (p - 1);
            }
        }
    }

    return phi;
}

```

5.11 Euler phi $\varphi(n)$

Computes the number of positive integers less than n that are coprimes with n , in $O(\sqrt{N})$.

```

int phi(int n) {
    if (n == 1) return 1;

    auto fs = factorization(n); // a vector of pair or a map
    auto res = n;

    for (auto [p, k] : fs) {
        res /= p;
        res *= (p - 1);
    }

    return res;
}

```

5.12 Factorial Factorization

Computes the factorization of $n!$ in $\pi(N) * \log n$

```

// O(logN)
ll E(ll n, ll p) {
    ll k = 0, b = p;
    while (b <= n) {
        k += n / b;
        b *= p;
    }

```

```

}
return k;
}

// O(pi(N)*logN)
map<ll, ll> factorial_factorization(ll n,
                                   const vll &primes) {

    map<ll, ll> fs;
    for (const auto &p : primes) {
        if (p > n) break;
        fs[p] = E(n, p);
    }
    return fs;
}

```

5.13 Factorial

```

const ll MAX = 18;
vll fv(MAX, -1);
ll factorial(ll n) {
    if (fv[n] != -1) return fv[n];
    if (n == 0) return 1;
    return n * factorial(n - 1);
}

```

5.14 Factorization (Pollard Rho)

Factorizes a number into its prime factors in $O(n^{\frac{1}{4}} * \log(n))$.

```

ll mul(ll a, ll b, ll m) {
    ll ret = a * b - (ll)((ld)1 / m * a * b + 0.5) * m;
    return ret < 0 ? ret + m : ret;
}

ll pow(ll a, ll b, ll m) {
    ll ans = 1;
    for (; b > 0; b /= 211, a = mul(a, a, m)) {
        if (b % 211 == 1) ans = mul(ans, a, m);
    }
    return ans;
}

```

```

bool prime(ll n) {
    if (n < 2) return 0;
    if (n <= 3) return 1;
    if (n % 2 == 0) return 0;
}

```

```

ll r = __builtin_ctzll(n - 1), d = n >> r;
for (int a :
     {2, 325, 9375, 28178, 450775, 9780504, 795265022}) {
    ll x = pow(a, d, n);
    if (x == 1 or x == n - 1 or a % n == 0) continue;

    for (int j = 0; j < r - 1; j++) {
        x = mul(x, x, n);
        if (x == n - 1) break;
    }
    if (x != n - 1) return 0;
}
return 1;
}

ll rho(ll n) {
    if (n == 1 or prime(n)) return n;
    auto f = [n](ll x) { return mul(x, x, n) + 1; };

    ll x = 0, y = 0, t = 30, prd = 2, x0 = 1, q;
    while (t % 40 != 0 or gcd(prd, n) == 1) {
        if (x == y) x = ++x0, y = f(x);
        q = mul(prd, abs(x - y), n);
        if (q != 0) prd = q;
        x = f(x), y = f(f(y)), t++;
    }
    return gcd(prd, n);
}

vll fact(ll n) {
    if (n == 1) return {};
    if (prime(n)) return {n};
    ll d = rho(n);
    vll l = fact(d), r = fact(n / d);
    l.insert(l.end(), r.begin(), r.end());
    return l;
}

```

5.15 Factorization

Computes the factorization of n in $O(\sqrt{n})$.

```

map<ll, ll> factorization(ll n) {
    map<ll, ll> ans;
    for (ll i = 2; i * i <= n; i++) {

```

```

    ll count = 0;
    for (; n % i == 0; count++, n /= i)
        ;
    if (count) ans[i] = count;
}
if (n > 1) ans[n]++;
return ans;
}

```

5.16 Fast pow

Computes $a^b \pmod m$ in $O(\log N)$.

```

ll fpow(ll a, ll b, ll m) {
    ll ret = 1;
    while (b) {
        if (b & 1) ret = (ret * a) % m;
        b >>= 1;
        a = (a * a) % m;
    }
    return ret;
}

ll fpow(ll a, ll b, ll m) {
    if (!b) return 1;
    ll ans = fpow2((a * a) % m, b / 2ll, m);
    return b & 1 ? (a * ans) % m : ans;
}

```

5.17 FFT Convolution

Performs convolution in a vector duh !

```

const ld PI = acos(-1);

/* change the ld to doulbe may increase performance =D */
struct num {
    ld a{0.0}, b{0.0};
    num() {}
    num(ld na) : a{na} {}
    num(ld na, ld nb) : a{na}, b{nb} {}

    const num operator+(const num& c) const {
        return num(a + c.a, b + c.b);
    }
    const num operator-(const num& c) const {

```

```

        return num(a - c.a, b - c.b);
    }
    const num operator*(const num& c) const {
        return num(a * c.a - b * c.b, a * c.b + b * c.a);
    }
    const num operator/(const ll& c) const {
        return num(a / c, b / c);
    }
};

```

```

void fft(vector<num>& a, bool invert) {
    int n = len(a);
    for (int i = 1, j = 0; i < n; i++) {
        int bit = n >> 1;
        for (; j & bit; bit >>= 1) j ^= bit;
        j ^= bit;
        if (i < j) swap(a[i], a[j]);
    }
    for (int sz = 2; sz <= n; sz <= 1) {
        ld ang = 2 * PI / sz * (invert ? -1 : 1);
        num wsz(cos(ang), sin(ang));
        for (int i = 0; i < n; i += sz) {
            num w(1);
            rep(j, 0, sz / 2) {
                num u = a[i + j], v = a[i + j + sz / 2] * w;
                a[i + j] = u + v;
                a[i + j + sz / 2] = u - v;
                w = w * wsz;
            }
        }
    }
    if (invert)
        for (num& x : a) x = x / n;
}

```

```

vi conv(vi const a, vi const b) {
    vector<num> fa(all(a));
    vector<num> fb(all(b));
    int n = 1;
    while (n < len(a) + len(b)) n <= 1;
    fa.resize(n);
    fb.resize(n);
    fft(fa, false);
    fft(fb, false);
    rep(i, 0, n) fa[i] = fa[i] * fb[i];

```

```

fft(fa, true);
vi result(n);
rep(i, 0, n) result[i] = round(fa[i].a);
while (len(result) and result.back() == 0)
    result.pop_back();

/* Uncomment this line if you want a boolean convolution*/
for (auto& xi : result) xi = min(xi, 1ll);

return result;
}

vll poly_exp(vll& ps, int k) {
    vll ret(len(ps));
    auto base = ps;
    ret[0] = 1;

    while (k) {
        if (k & 1) ret = conv(ret, base);
        k >>= 1;
        base = conv(base, base);
    }

    return ret;
}

```

5.18 Find Multiplicative Inverse

```

ll inv(ll a, ll m) {
    return a > 1ll ? m - inv(m % a, a) * m / a : 1ll;
}

```

5.19 Linear Diophantine Equation: Find any solution

Given a, b, c finds the solution to the equation $ax + by = c$, the result will be stored in the reference variables $x0$ and $y0$
time: $O(\log \min(a, b))$

```

template <typename T>
tuple<T, T, T> ext_gcd(T a, T b) {
    if (b == 0) return {a, 1, 0};

    auto [d, x1, y1] = ext_gcd(b, a % b);

    return {d, y1, x1 - y1 * (a / b)};
}

template <typename T>

```

```

tuple<bool, T, T> find_any_solution(T a, T b, T c) {
    assert(a != 0 or b != 0);
    #warning Be careful with overflow, use __int128 if needed !

    auto [d, x0, y0] =
        ext_gcd(a < 0 ? -a : a, b < 0 ? -b : b);

    if (c % d) return {false, 0, 0};

    x0 *= c / d;
    y0 *= c / d;
    if (a < 0) x0 = -x0;
    if (b < 0) y0 = -y0;

    return {true, x0, y0};
}

// optional if you want to use __int128
void print(__int128 x) {
    if (x < 0) {
        cout << '-';
        x = -x;
    }
    if (x > 9) print(x / 10);
    cout << (char)((x % 10) + '0');
}

__int128 read() {
    string s;
    cin >> s;
    __int128 x = 0;
    for (auto c : s) {
        if (c != '-') x += c - '0';
        x *= 10;
    }
    x /= 10;
    if (s[0] == '-') x = -x;
    return x;
}

```

5.20 Gauss Elimination

```

template <size_t Dim>
struct GaussianElimination {
    vector<ll> basis;

```

```

size_t size;

GaussianElimination() : basis(Dim + 1), size(0) {}

void insert(ll x) {
    for (ll i = Dim; i >= 0; i--) {
        if ((x & 1ll << i) == 0) continue;

        if (!basis[i]) {
            basis[i] = x;
            size++;
            break;
        }

        x ^= basis[i];
    }
}

void normalize() {
    for (ll i = Dim; i >= 0; i--)
        for (ll j = i - 1; j >= 0; j--)
            if (basis[i] & 1ll << j) basis[i] ^= basis[j];
}

bool check(ll x) {
    for (ll i = Dim; i >= 0; i--) {
        if ((x & 1ll << i) == 0) continue;

        if (!basis[i]) return false;

        x ^= basis[i];
    }

    return true;
}

auto operator [] (ll k) { return at(k); }

ll at(ll k) {
    ll ans = 0;
    ll total = 1ll << size;
    for (ll i = Dim; ~i; i--) {
        if (!basis[i]) continue;

        ll mid = total >> 1ll;

```

```

        if ((mid < k and (ans & 1ll << i) == 0) ||
            (k <= mid and (ans & 1ll << i)))
            ans ^= basis[i];

        if (mid < k) k -= mid;

        total >>= 1ll;
    }
    return ans;
}

ll at_normalized(ll k) {
    ll ans = 0;
    k--;
    for (size_t i = 0; i <= Dim; i++) {
        if (!basis[i]) continue;
        if (k & 1) ans ^= basis[i];
        k >>= 1;
    }
    return ans;
}
};

```

5.21 Integer Partition

Find the total of ways to partition a given number N in such way that none of the parts is greater than K .

Remember to memset everything to -1 before using it

time: $O(N \cdot \min(N, K))$

memory: $O(N)$

```

const ll MOD = 1000000007;
const int MAXN(100);
ll memo[MAXN + 1];
ll dp(ll n, ll k = oo) {
    if (n == 0) return 1;
    ll &ans = memo[n];
    if (ans != -1) return ans;

    ans = 0;
    for (int i = 1; i <= min(n, k); i++) {
        ans = (ans + dp(n - i, k)) % MOD;
    }

    return ans;
}

```

5.22 Integer Mod

```
const ll INF = 1e18;
const ll mod = 998244353;
template <ll MOD = mod>
struct Modular {
    ll value;
    static const ll MOD_value = MOD;

    Modular(ll v = 0) {
        value = v % MOD;
        if (value < 0) value += MOD;
    }

    Modular(ll a, ll b) : value(0) {
        *this += a;
        *this /= b;
    }

    Modular& operator+=(Modular const& b) {
        value += b.value;
        if (value >= MOD) value -= MOD;
        return *this;
    }

    Modular& operator-=(Modular const& b) {
        value -= b.value;
        if (value < 0) value += MOD;
        return *this;
    }

    Modular& operator*=(Modular const& b) {
        value = (ll)value * b.value % MOD;
        return *this;
    }

    friend Modular mexp(Modular a, ll e) {
        Modular res = 1;
        while (e) {
            if (e & 1) res *= a;
            a *= a;
            e >>= 1;
        }
        return res;
    }

    friend Modular inverse(Modular a) {
        return mexp(a, MOD - 2);
    }
};
```

```
Modular& operator/=(Modular const& b) {
    return *this *= inverse(b);
}

friend Modular operator+(Modular a, Modular const b) {
    return a += b;
}

Modular operator++(int) {
    return this->value = (this->value + 1) % MOD;
}

Modular operator++() {
    return this->value = (this->value + 1) % MOD;
}

friend Modular operator-(Modular a, Modular const b) {
    return a -= b;
}

friend Modular operator-(Modular const a) {
    return 0 - a;
}

Modular operator--(int) {
    return this->value = (this->value - 1 + MOD) % MOD;
}

Modular operator--() {
    return this->value = (this->value - 1 + MOD) % MOD;
}

friend Modular operator*(Modular a, Modular const b) {
    return a *= b;
}

friend Modular operator/(Modular a, Modular const b) {
    return a /= b;
}

friend std::ostream& operator<<(std::ostream& os,
                                Modular const& a) {
    return os << a.value;
}

friend bool operator==(Modular const& a,
                        Modular const& b) {
    return a.value == b.value;
}

friend bool operator!=(Modular const& a,
                        Modular const& b) {
    return a.value != b.value;
}

};
```


5.23 Matrix Exponentiation

```
ll MOD = 1'000'000'007;
```

```
template <typename T>
vector<vector<T>> prod(vector<vector<T>> &a,
                      vector<vector<T>> &b) {
    int n = len(a);
    vector<vector<T>> c(n, vector<T>(n));

    for (int i = 0; i < n; i++) {
        for (int j = 0; j < n; j++) {
            for (int k = 0; k < n; k++) {
                c[i][j] =
                    (c[i][j] + ((a[i][k] * b[k][j]) % MOD)) % MOD;
            }
        }
    }

    return c;
}
```

```
template <typename T>
vector<vector<T>> fpow(vector<vector<T>> &xs, ll p) {
    vector<vector<T>> ans(len(xs), vector<T>(len(xs)));
    for (int i = 0; i < len(xs); i++) ans[i][i] = 1;

    auto b = xs;
    while (p) {
        if (p & 1) ans = prod(ans, b);
        p >>= 1;
        b = prod(b, b);
    }
    return ans;
}
```

5.24 N Choose K (elements)

process every possible combination of K elements from N elements, those index marked as 1 in the index vector says which elements are chosen at that moment.
Time : $O(\binom{N}{K} \cdot O(\text{process}))$

```
void process(vi &index) {
    for (int i = 0; i < len(index); i++) {
        if (index[i]) cout << i << " \n"[i == len(index) - 1];
    }
}
```

```
void n_choose_k(int n, in k) {
    vi index(n);
    fill(index.end() - k, index.end(), 1);

    do {
        process(index);
    } while (next_permutation(all(index)));
}
```

5.25 NTT integer convolution and exponentiation

Convolution finds the product a and b , and exp finds a^k
time: convolution $O(N \cdot \log N)$, exponentiation: $O(\log K \cdot N \cdot \log N)$

```
/*
=====
*/

/*===== MINT ===== */
template <int _mod>
struct mint {
    ll expo(ll b, ll e) {
        ll ret = 1;
        while (e) {
            if (e % 2) ret = ret * b % _mod;
            e /= 2, b = b * b % _mod;
        }
        return ret;
    }
    ll inv(ll b) { return expo(b, _mod - 2); }

    using m = mint;
    ll v;
    mint() : v(0) {}
    mint(ll v_) {
        if (v_ >= _mod or v_ <= -_mod) v_ %= _mod;
        if (v_ < 0) v_ += _mod;
        v = v_;
    }
    m& operator+=(const m& a) {
        v += a.v;
        if (v >= _mod) v -= _mod;
        return *this;
    }
    m& operator-=(const m& a) {
        v -= a.v;

```

```

    if (v < 0) v += _mod;
    return *this;
}

m& operator*=(const m& a) {
    v = v * ll(a.v) % _mod;
    return *this;
}

m& operator/=(const m& a) {
    v = v * inv(a.v) % _mod;
    return *this;
}

m operator-() { return m(-v); }

m& operator^=(ll e) {
    if (e < 0) {
        v = inv(v);
        e = -e;
    }
    v = expo(v, e);
    // possivel otimizacao:
    // cuidado com 0^0
    // v = expo(v, e%(p-1));
    return *this;
}

bool operator==(const m& a) { return v == a.v; }
bool operator!=(const m& a) { return v != a.v; }

friend istream& operator>>(istream& in, m& a) {
    ll val;
    in >> val;
    a = m(val);
    return in;
}

friend ostream& operator<<(ostream& out, m a) {
    return out << a.v;
}

friend m operator+(m a, m b) { return a += b; }
friend m operator-(m a, m b) { return a -= b; }
friend m operator*(m a, m b) { return a *= b; }
friend m operator/(m a, m b) { return a /= b; }
friend m operator^(m a, ll e) { return a ^= e; }
};

/*===== END MINT ===== */

/*===== ntt int convolution =====*/
const ll MOD1 = 998244353;

```

```

const ll MOD2 = 754974721;
const ll MOD3 = 167772161;

template <int _mod>
void ntt(vector<mint<_mod>>& a, bool rev) {
    int n = len(a);
    auto b = a;
    assert(!(n & (n - 1)));
    mint<_mod> g = 1;
    while ((g ^ (_mod / 2)) == 1) g += 1;
    if (rev) g = 1 / g;

    for (int step = n / 2; step; step /= 2) {
        mint<_mod> w = g ^ (_mod / (n / step)), wn = 1;
        for (int i = 0; i < n / 2; i += step) {
            for (int j = 0; j < step; j++) {
                auto u = a[2 * i + j], v = wn * a[2 * i + j + step];
                b[i + j] = u + v;
                b[i + n / 2 + j] = u - v;
            }
            wn = wn * w;
        }
        swap(a, b);
    }
    if (rev) {
        auto n1 = mint<_mod>(1) / n;
        for (auto& x : a) x *= n1;
    }
}

template <ll _mod>
vector<mint<_mod>> convolution(
    const vector<mint<_mod>>& a,
    const vector<mint<_mod>>& b) {
    vector<mint<_mod>> l(all(a)), r(all(b));
    int N = len(l) + len(r) - 1, n = 1;
    while (n <= N) n *= 2;
    l.resize(n), r.resize(n);
    ntt(l, false), ntt(r, false);
    for (int i = 0; i < n; i++) l[i] *= r[i];
    ntt(l, true);
    l.resize(N);

    // Uncomment for a boolean convolution :)
    /*

```

```

for (auto& li : l) {
    li.v = min(li.v, lll);
}
*/

return l;
}

template <ll _mod>
vector<mint<_mod>> poly_exp(vector<mint<_mod>>& ps, int k) {
    vector<mint<_mod>> ret(len(ps));
    auto base = ps;
    ret[0] = 1;

    while (k) {
        if (k & 1) ret = convolution(ret, base);
        k >>= 1;
        base = convolution(base, base);
    }

    return ret;
}

```

5.26 NTT Integer Convolution (combine 2 modules)

Computes the convolution between polynomials (vectors) a and b

This is pure magic !

time: $O(N \log N)$

```

/*
=====
*/
/*===== MINT ===== */
template <int _mod>
struct mint {
    ll expo(ll b, ll e) {
        ll ret = 1;
        while (e) {
            if (e % 2) ret = ret * b % _mod;
            e /= 2, b = b * b % _mod;
        }
        return ret;
    }
    ll inv(ll b) { return expo(b, _mod - 2); }
}

```

```

using m = mint;
ll v;
mint() : v(0) {}
mint(ll v_) {
    if (v_ >= _mod or v_ <= -_mod) v_ %= _mod;
    if (v_ < 0) v_ += _mod;
    v = v_;
}
m& operator+=(const m& a) {
    v += a.v;
    if (v >= _mod) v -= _mod;
    return *this;
}
m& operator-=(const m& a) {
    v -= a.v;
    if (v < 0) v += _mod;
    return *this;
}
m& operator*=(const m& a) {
    v = v * ll(a.v) % _mod;
    return *this;
}
m& operator/=(const m& a) {
    v = v * inv(a.v) % _mod;
    return *this;
}
m operator-() { return m(-v); }
m& operator^=(ll e) {
    if (e < 0) {
        v = inv(v);
        e = -e;
    }
    v = expo(v, e);
    // possivel otimizacao:
    // cuidado com 0^0
    // v = expo(v, e%(p-1));
    return *this;
}
bool operator==(const m& a) { return v == a.v; }
bool operator!=(const m& a) { return v != a.v; }

friend istream& operator>>(istream& in, m& a) {
    ll val;
    in >> val;
    a = m(val);
}

```

```

    return in;
}
friend ostream& operator<<(ostream& out, m a) {
    return out << a.v;
}
friend m operator+(m a, m b) { return a += b; }
friend m operator-(m a, m b) { return a -= b; }
friend m operator*(m a, m b) { return a *= b; }
friend m operator/(m a, m b) { return a /= b; }
friend m operator^(m a, ll e) { return a ^= e; }
};

/*===== END MINT ===== */

/*===== ntt int convolution =====*/
const ll MOD1 = 998244353;
const ll MOD2 = 754974721;
const ll MOD3 = 167772161;

template <int _mod>
void ntt(vector<mint<_mod>>& a, bool rev) {
    int n = len(a);
    auto b = a;
    assert(!(n & (n - 1)));
    mint<_mod> g = 1;
    while ((g ^ (_mod / 2)) == 1) g += 1;
    if (rev) g = 1 / g;

    for (int step = n / 2; step; step /= 2) {
        mint<_mod> w = g ^ (_mod / (n / step)), wn = 1;
        for (int i = 0; i < n / 2; i += step) {
            for (int j = 0; j < step; j++) {
                auto u = a[2 * i + j], v = wn * a[2 * i + j + step];
                b[i + j] = u + v;
                b[i + n / 2 + j] = u - v;
            }
            wn = wn * w;
        }
        swap(a, b);
    }
    if (rev) {
        auto n1 = mint<_mod>(1) / n;
        for (auto& x : a) x *= n1;
    }
}

```

```

tuple<ll, ll, ll> ext_gcd(ll a, ll b) {
    if (!a) return {b, 0, 1};
    auto [g, x, y] = ext_gcd(b % a, a);
    return {g, y - b / a * x, x};
}

template <typename T = ll>
struct crt {
    T a, m;

    crt() : a(0), m(1) {}
    crt(T a_, T m_) : a(a_), m(m_) {}
    crt operator*(crt C) {
        auto [g, x, y] = ext_gcd(m, C.m);
        if ((a - C.a) % g != 0) a = -1;
        if (a == -1 or C.a == -1) return crt(-1, 0);
        T lcm = m / g * C.m;
        T ans = a + (x * (C.a - a) / g % (C.m / g)) * m;
        return crt((ans % lcm + lcm) % lcm, lcm);
    }
};

template <typename T = ll>
struct Congruence {
    T a, m;
};

template <typename T = ll>
T chinese_remainder_theorem(
    const vector<Congruence<T>>& equations) {
    crt<T> ans;

    for (auto& [a_, m_] : equations) {
        ans = ans * crt<T>(a_, m_);
    }

    return ans.a;
}

#define int long long
template <ll m1, ll m2>
vll merge_two_mods(const vector<mint<m1>>& a,
                    const vector<mint<m2>>& b) {
    int n = len(a);
    vll ans(n);
}

```

```

for (int i = 0; i < n; i++) {
    auto cur = crt<ll>();
    auto ai = a[i].v;
    auto bi = b[i].v;
    cur = cur * crt<ll>(ai, m1);
    cur = cur * crt<ll>(bi, m2);
    ans[i] = cur.a;
}

return ans;
}

vll convolution_2mods(const vll& a, const vll& b) {
    vector<mint<MOD1>> l(all(a)), r(all(b));
    int N = len(l) + len(r) - 1, n = 1;
    while (n <= N) n *= 2;
    l.resize(n), r.resize(n);
    ntt(l, false), ntt(r, false);
    for (int i = 0; i < n; i++) l[i] *= r[i];
    ntt(l, true);
    l.resize(N);

    vector<mint<MOD2>> l2(all(a)), r2(all(b));
    l2.resize(n), r2.resize(n);
    ntt(l2, false), ntt(r2, false);
    rep(i, 0, n) l2[i] *= r2[i];
    ntt(l2, true);
    l2.resize(N);

    return merge_two_mods(l, l2);
}

vll poly_exp(const vll& xs, ll k) {
    vll ret(len(xs));
    ret[0] = 1;
    auto base = xs;
    while (k) {
        if (k & 1) ret = convolution_2mods(ret, base);
        k >>= 1;
        base = convolution_2mods(base, base);
    }

    return ret;
}

```

5.27 Number Of Divisors (sieve)

```

ll divisors(ll n) {
    ll ans = 1;
    for (auto p : primes) {
        if (p * p * p > n) break;

        int count = 1;
        while (n % p == 0) {
            n /= p;
            count++;
        }

        ans *= count;
    }

    if (is_prime[n])
        ans *= 2;
    else if (is_prime_square[n])
        ans *= 3;
    else if (n != 1)
        ans *= 4;

    return ans;
}

```

5.28 Number of Divisors $\tau(n)$

Find the total of divisors of N in $O(\sqrt{N})$

```

ll number_of_divisors(ll n) {
    ll res = 0;

    for (ll d = 1; d * d <= n; ++d) {
        if (n % d == 0) res += (d == n / d ? 1 : 2);
    }

    return res;
}

```

5.29 Power Sum

Calculates $K^0 + K^1 + \dots + K^n$

```

ll powersum(ll n, ll k) {
    return (fastpow(n, k + 1) - 1) / (n - 1);
}

```

5.30 Sieve list primes

List every prime until MAXN, $O(N \log N)$ in time and $O(MAXN)$ in memory.

```
const ll MAXN = 2e5;
vll list_primes(ll n = MAXN) {
    vll ps;
    bitset<MAXN + 1> sieve;
    sieve.set();
    sieve.reset(1);
    for (ll i = 2; i <= n; ++i) {
        if (sieve[i]) ps.push_back(i);
        for (ll j = i * 2; j <= n; j += i) {
            sieve.reset(j);
        }
    }
    return ps;
}
```

5.31 Sum of Divisors $\sigma(n)$

Computes the sum of each divisor of n in $O(\sqrt{n})$.

```
ll sum_of_divisors(long long n) {
    ll res = 0;

    for (ll d = 1; d * d <= n; ++d) {
        if (n % d == 0) {
            ll k = n / d;

            res += (d == k ? d : d + k);
        }
    }

    return res;
}
```

5.32 To Any Base

```
vll to_otherbase(ll x, ll b) {
    vll result;

    while (x) {
        auto [quot, rem] = std::div(x, b);

        x = rem < 0 ? quot + 1 : quot;
```

```
        rem = rem < 0 ? rem + -b : rem;

        result.eb(rem);
    }

    if (!len(result)) return {0ll};

    reverse(all(result));

    // [msb, ..., lsb]
    return result;
}
```

6 Primitives

6.1 Bigint

```
const int maxn = 1e2 + 14, lg = 15;
const int base = 1000000000;
const int base_digits = 9;
struct bigint {
    vi a;
    int sign;

    int size() {
        if (a.empty()) return 0;
        int ans = (a.size() - 1) * base_digits;
        int ca = a.back();
        while (ca) ans++, ca /= 10;
        return ans;
    }

    bigint operator^(const bigint &v) {
        bigint ans = 1, a = *this, b = v;
        while (!b.isZero()) {
            if (b % 2) ans *= a;
            a *= a, b /= 2;
        }
        return ans;
    }

    string to_string() {
        stringstream ss;
        ss << *this;
        string s;
        ss >> s;
        return s;
    }
}
```

```

}
int sumof() {
    string s = to_string();
    int ans = 0;
    for (auto c : s) ans += c - '0';
    return ans;
}
/*</arpa>*/
bigint() : sign(1) {}

bigint(long long v) { *this = v; }

bigint(const string &s) { read(s); }

void operator=(const bigint &v) {
    sign = v.sign;
    a = v.a;
}

void operator=(long long v) {
    sign = 1;
    a.clear();
    if (v < 0) sign = -1, v = -v;
    for (; v > 0; v = v / base) a.push_back(v % base);
}

bigint operator+(const bigint &v) const {
    if (sign == v.sign) {
        bigint res = v;

        for (int i = 0, carry = 0;
             i < (int)max(a.size(), v.a.size()) || carry;
             ++i) {
            if (i == (int)res.a.size()) res.a.push_back(0);
            res.a[i] += carry + (i < (int)a.size() ? a[i] : 0);
            carry = res.a[i] >= base;
            if (carry) res.a[i] -= base;
        }
        return res;
    }
    return *this - (-v);
}

bigint operator-(const bigint &v) const {
    if (sign == v.sign) {

```

```

        if (abs() >= v.abs()) {
            bigint res = *this;
            for (int i = 0, carry = 0;
                 i < (int)v.a.size() || carry; ++i) {
                res.a[i] -=
                    carry + (i < (int)v.a.size() ? v.a[i] : 0);
                carry = res.a[i] < 0;
                if (carry) res.a[i] += base;
            }
            res.trim();
            return res;
        }
        return -(v - *this);
    }
    return *this + (-v);
}

void operator*=(int v) {
    if (v < 0) sign = -sign, v = -v;
    for (int i = 0, carry = 0; i < (int)a.size() || carry;
         ++i) {
        if (i == (int)a.size()) a.push_back(0);
        long long cur = a[i] * (long long)v + carry;
        carry = (int)(cur / base);
        a[i] = (int)(cur % base);
        // asm("divl %%ecx" : "=a"(carry), "=d"(a[i]) :
        // "A"(cur), "c"(base));
    }
    trim();
}

bigint operator*(int v) const {
    bigint res = *this;
    res *= v;
    return res;
}

void operator*=(long long v) {
    if (v < 0) sign = -sign, v = -v;
    if (v > base) {
        *this =
            *this * (v / base) * base + *this * (v % base);
        return;
    }
    for (int i = 0, carry = 0; i < (int)a.size() || carry;

```

```

        ++i) {
    if (i == (int)a.size()) a.push_back(0);
    long long cur = a[i] * (long long)v + carry;
    carry = (int)(cur / base);
    a[i] = (int)(cur % base);
    // asm("divl %%ecx" : "=a"(carry), "=d"(a[i]) :
    // "A"(cur), "c"(base));
}
trim();
}

bigint operator*(long long v) const {
    bigint res = *this;
    res *= v;
    return res;
}

friend pair<bigint, bigint> divmod(const bigint &a1,
                                const bigint &b1) {

    int norm = base / (b1.a.back() + 1);
    bigint a = a1.abs() * norm;
    bigint b = b1.abs() * norm;
    bigint q, r;
    q.a.resize(a.a.size());

    for (int i = a.a.size() - 1; i >= 0; i--) {
        r *= base;
        r += a.a[i];
        int s1 =
            r.a.size() <= b.a.size() ? 0 : r.a[b.a.size()];
        int s2 = r.a.size() <= b.a.size() - 1
            ? 0
            : r.a[b.a.size() - 1];
        int d = ((long long)base * s1 + s2) / b.a.back();
        r -= b * d;
        while (r < 0) r += b, --d;
        q.a[i] = d;
    }

    q.sign = a1.sign * b1.sign;
    r.sign = a1.sign;
    q.trim();
    r.trim();
    return make_pair(q, r / norm);
}

```

```

bigint operator/(const bigint &v) const {
    return divmod(*this, v).first;
}

bigint operator%(const bigint &v) const {
    return divmod(*this, v).second;
}

void operator/=(int v) {
    if (v < 0) sign = -sign, v = -v;
    for (int i = (int)a.size() - 1, rem = 0; i >= 0; --i) {
        long long cur = a[i] + rem * (long long)base;
        a[i] = (int)(cur / v);
        rem = (int)(cur % v);
    }
    trim();
}

bigint operator/(int v) const {
    bigint res = *this;
    res /= v;
    return res;
}

int operator%(int v) const {
    if (v < 0) v = -v;
    int m = 0;
    for (int i = a.size() - 1; i >= 0; --i)
        m = (a[i] + m * (long long)base) % v;
    return m * sign;
}

void operator+=(const bigint &v) { *this = *this + v; }
void operator-=(const bigint &v) { *this = *this - v; }
void operator*=(const bigint &v) { *this = *this * v; }
void operator/=(const bigint &v) { *this = *this / v; }

bool operator<(const bigint &v) const {
    if (sign != v.sign) return sign < v.sign;
    if (a.size() != v.a.size())
        return a.size() * sign < v.a.size() * v.sign;
    for (int i = a.size() - 1; i >= 0; i--)
        if (a[i] != v.a[i])
            return a[i] * sign < v.a[i] * sign;
}

```



```

    return false;
}

bool operator>(const bigint &v) const {
    return v < *this;
}

bool operator<=(const bigint &v) const {
    return !(v < *this);
}

bool operator>=(const bigint &v) const {
    return !(*this < v);
}

bool operator==(const bigint &v) const {
    return !(*this < v) && !(v < *this);
}

bool operator!=(const bigint &v) const {
    return *this < v || v < *this;
}

void trim() {
    while (!a.empty() && !a.back()) a.pop_back();
    if (a.empty()) sign = 1;
}

bool isZero() const {
    return a.empty() || (a.size() == 1 && !a[0]);
}

bigint operator-() const {
    bigint res = *this;
    res.sign = -sign;
    return res;
}

bigint abs() const {
    bigint res = *this;
    res.sign *= res.sign;
    return res;
}

long long longValue() const {
    long long res = 0;
    for (int i = a.size() - 1; i >= 0; i--)
        res = res * base + a[i];
    return res * sign;
}

```

```

}

friend bigint gcd(const bigint &a, const bigint &b) {
    return b.isZero() ? a : gcd(b, a % b);
}

friend bigint lcm(const bigint &a, const bigint &b) {
    return a / gcd(a, b) * b;
}

void read(const string &s) {
    sign = 1;
    a.clear();
    int pos = 0;
    while (pos < (int)s.size() &&
           (s[pos] == '-' || s[pos] == '+')) {
        if (s[pos] == '-') sign = -sign;
        ++pos;
    }
    for (int i = s.size() - 1; i >= pos; i -= base_digits) {
        int x = 0;
        for (int j = max(pos, i - base_digits + 1); j <= i;
             j++)
            x = x * 10 + s[j] - '0';
        a.push_back(x);
    }
    trim();
}

friend istream &operator>>(istream &stream, bigint &v) {
    string s;
    stream >> s;
    v.read(s);
    return stream;
}

friend ostream &operator<<(ostream &stream,
                           const bigint &v) {
    if (v.sign == -1) stream << '-';
    stream << (v.a.empty() ? 0 : v.a.back());
    for (int i = (int)v.a.size() - 2; i >= 0; --i)
        stream << setw(base_digits) << setfill('0') << v.a[i];
    return stream;
}

static vector<int> convert_base(const vector<int> &a,

```

```

        int old_digits,
        int new_digits) {
vector<long long> p(max(old_digits, new_digits) + 1);
p[0] = 1;
for (int i = 1; i < (int)p.size(); i++)
    p[i] = p[i - 1] * 10;
vector<int> res;
long long cur = 0;
int cur_digits = 0;
for (int i = 0; i < (int)a.size(); i++) {
    cur += a[i] * p[cur_digits];
    cur_digits += old_digits;
    while (cur_digits >= new_digits) {
        res.push_back((int)(cur % p[new_digits]));
        cur /= p[new_digits];
        cur_digits -= new_digits;
    }
}
res.push_back((int)cur);
while (!res.empty() && !res.back()) res.pop_back();
return res;
}

typedef vector<long long> vll;

static vll karatsubaMultiply(const vll &a, const vll &b) {
    int n = a.size();
    vll res(n + n);
    if (n <= 32) {
        for (int i = 0; i < n; i++)
            for (int j = 0; j < n; j++)
                res[i + j] += a[i] * b[j];
        return res;
    }

    int k = n >> 1;
    vll a1(a.begin(), a.begin() + k);
    vll a2(a.begin() + k, a.end());
    vll b1(b.begin(), b.begin() + k);
    vll b2(b.begin() + k, b.end());

    vll a1b1 = karatsubaMultiply(a1, b1);
    vll a2b2 = karatsubaMultiply(a2, b2);

    for (int i = 0; i < k; i++) a2[i] += a1[i];

```

```

    for (int i = 0; i < k; i++) b2[i] += b1[i];

    vll r = karatsubaMultiply(a2, b2);
    for (int i = 0; i < (int)a1b1.size(); i++)
        r[i] -= a1b1[i];
    for (int i = 0; i < (int)a2b2.size(); i++)
        r[i] -= a2b2[i];

    for (int i = 0; i < (int)r.size(); i++)
        res[i + k] += r[i];
    for (int i = 0; i < (int)a1b1.size(); i++)
        res[i] += a1b1[i];
    for (int i = 0; i < (int)a2b2.size(); i++)
        res[i + n] += a2b2[i];
    return res;
}

bigint operator*(const bigint &v) const {
    vector<int> a6 = convert_base(this->a, base_digits, 6);
    vector<int> b6 = convert_base(v.a, base_digits, 6);
    vll a(a6.begin(), a6.end());
    vll b(b6.begin(), b6.end());
    while (a.size() < b.size()) a.push_back(0);
    while (b.size() < a.size()) b.push_back(0);
    while (a.size() & (a.size() - 1))
        a.push_back(0), b.push_back(0);
    vll c = karatsubaMultiply(a, b);
    bigint res;
    res.sign = sign * v.sign;
    for (int i = 0, carry = 0; i < (int)c.size(); i++) {
        long long cur = c[i] + carry;
        res.a.push_back((int)(cur % 1000000));
        carry = (int)(cur / 1000000);
    }
    res.a = convert_base(res.a, 6, base_digits);
    res.trim();
    return res;
}
};

```

6.2 Integer Mod

```

const ll MOD = 1'000'000'000 + 7;
template <ll _mod = MOD>
struct mint {

```

```

ll value;
static const ll MOD_value = _mod;

mint(ll v = 0) {
    value = v % _mod;
    if (value < 0) value += _mod;
}

mint(ll a, ll b) : value(0) {
    *this += a;
    *this /= b;
}

mint& operator+=(mint const& b) {
    value += b.value;
    if (value >= _mod) value -= _mod;
    return *this;
}

mint& operator-=(mint const& b) {
    value -= b.value;
    if (value < 0) value += _mod;
    return *this;
}

mint& operator*=(mint const& b) {
    value = (ll)value * b.value % _mod;
    return *this;
}

friend mint mexp(mint a, ll e) {
    mint res = 1;
    while (e) {
        if (e & 1) res *= a;
        a *= a;
        e >>= 1;
    }
    return res;
}

friend mint inverse(mint a) { return mexp(a, _mod - 2); }

mint& operator/=(mint const& b) {
    return *this *= inverse(b);
}

friend mint operator+(mint a, mint const b) {
    return a += b;
}

mint operator++(int) {

```

```

    return this->value = (this->value + 1) % _mod;
}

mint operator++() {
    return this->value = (this->value + 1) % _mod;
}

friend mint operator-(mint a, mint const b) {
    return a -= b;
}

friend mint operator-(mint const a) { return 0 - a; }

mint operator--(int) {
    return this->value = (this->value - 1 + _mod) % _mod;
}

mint operator--() {
    return this->value = (this->value - 1 + _mod) % _mod;
}

friend mint operator*(mint a, mint const b) {
    return a *= b;
}

friend mint operator/(mint a, mint const b) {
    return a /= b;
}

friend std::ostream& operator<<(std::ostream& os,
                                mint const& a) {
    return os << a.value;
}

friend bool operator==(mint const& a, mint const& b) {
    return a.value == b.value;
}

friend bool operator!=(mint const& a, mint const& b) {
    return a.value != b.value;
}
};

```

6.3 Matrix

```

template <typename T>
struct Matrix {
    vector<vector<T>> d;

    Matrix() : Matrix(0) {}
    Matrix(int n) : Matrix(n, n) {}
    Matrix(int n, int m)
        : Matrix(vector<vector<T>>(n, vector<T>(m))) {}
    Matrix(const vector<vector<T>> &v) : d(v) {}

```

```

constexpr int n() const { return (int)d.size(); }
constexpr int m() const {
    return n() ? (int)d[0].size() : 0;
}

void rotate() { *this = rotated(); }

Matrix<T> rotated() const {
    Matrix<T> res(m(), n());
    for (int i = 0; i < m(); i++) {
        for (int j = 0; j < n(); j++) {
            res[i][j] = d[n() - j - 1][i];
        }
    }
    return res;
}

Matrix<T> pow(int power) const {
    assert(n() == m());

    auto res = Matrix<T>::identity(n());
    auto b = *this;
    while (power) {
        if (power & 1) res *= b;
        b *= b;
        power >>= 1;
    }
    return res;
}

Matrix<T> submatrix(int start_i, int start_j,
                    int rows = INT_MAX,
                    int cols = INT_MAX) const {
    rows = min(rows, n() - start_i);
    cols = min(cols, m() - start_j);
    if (rows <= 0 or cols <= 0) return {};

    Matrix<T> res(rows, cols);
    for (int i = 0; i < rows; i++)
        for (int j = 0; j < cols; j++)
            res[i][j] = d[i + start_i][j + start_j];
    return res;
}

```

```

Matrix<T> translated(int x, int y) const {
    Matrix<T> res(n(), m());
    for (int i = 0; i < n(); i++) {
        for (int j = 0; j < m(); j++) {
            if (i + x < 0 or i + x >= n() or j + y < 0 or
                j + y >= m())
                continue;
            res[i + x][j + y] = d[i][j];
        }
    }
    return res;
}

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

vector<T> &operator[](int i) { return d[i]; }
const vector<T> &operator[](int i) const { return d[i]; }
Matrix<T> &operator+=(T value) {
    for (auto &row : d) {
        for (auto &x : row) x += value;
    }
    return *this;
}

Matrix<T> operator+(T value) const {
    auto res = *this;
    for (auto &row : res) {
        for (auto &x : row) x = x + value;
    }
    return res;
}

Matrix<T> &operator-=(T value) {
    for (auto &row : d) {
        for (auto &x : row) x -= value;
    }
    return *this;
}

Matrix<T> operator-(T value) const {
    auto res = *this;
    for (auto &row : res) {
        for (auto &x : row) x = x - value;
    }
}

```

```

    return res;
}
Matrix<T> &operator*=(T value) {
    for (auto &row : d) {
        for (auto &x : row) x *= value;
    }
    return *this;
}
Matrix<T> operator*(T value) const {
    auto res = *this;
    for (auto &row : res) {
        for (auto &x : row) x = x * value;
    }
    return res;
}
Matrix<T> &operator/=(T value) {
    for (auto &row : d) {
        for (auto &x : row) x /= value;
    }
    return *this;
}
Matrix<T> operator/(T value) const {
    auto res = *this;
    for (auto &row : res) {
        for (auto &x : row) x = x / value;
    }
    return res;
}
Matrix<T> &operator+=(const Matrix<T> &o) {
    assert(n() == o.n() and m() == o.m());
    for (int i = 0; i < n(); i++) {
        for (int j = 0; j < m(); j++) {
            d[i][j] += o[i][j];
        }
    }
    return *this;
}
Matrix<T> operator+(const Matrix<T> &o) const {
    assert(n() == o.n() and m() == o.m());
    auto res = *this;
    for (int i = 0; i < n(); i++) {
        for (int j = 0; j < m(); j++) {
            res[i][j] = res[i][j] + o[i][j];
        }
    }
}

```

```

    return res;
}
Matrix<T> &operator--=(const Matrix<T> &o) {
    assert(n() == o.n() and m() == o.m());
    for (int i = 0; i < n(); i++) {
        for (int j = 0; j < m(); j++) {
            d[i][j] -= o[i][j];
        }
    }
    return *this;
}
Matrix<T> operator-(const Matrix<T> &o) const {
    assert(n() == o.n() and m() == o.m());
    auto res = *this;
    for (int i = 0; i < n(); i++) {
        for (int j = 0; j < m(); j++) {
            res[i][j] = res[i][j] - o[i][j];
        }
    }
    return res;
}
Matrix<T> &operator*=(const Matrix<T> &o) {
    *this = *this * o;
    return *this;
}
Matrix<T> operator*(const Matrix<T> &o) const {
    assert(m() == o.n());
    Matrix<T> res(n(), o.m());
    for (int i = 0; i < res.n(); i++) {
        for (int j = 0; j < res.m(); j++) {
            auto &x = res[i][j];
            for (int k = 0; k < m(); k++) {
                x += (d[i][k] * o[k][j]);
            }
        }
    }
    return res;
}
friend istream &operator>>(istream &is, Matrix<T> &mat) {
    for (auto &row : mat)
        for (auto &x : row) is >> x;
    return is;
}
friend ostream &operator<<(ostream &os,

```

```

        const Matrix<T> &mat) {
    bool frow = 1;
    for (auto &row : mat) {
        if (not frow) os << '\n';
        bool first = 1;
        for (auto &x : row) {
            if (not first) os << ' ';
            os << x;
            first = 0;
        }

        frow = 0;
    }
    return os;
}

auto begin() { return d.begin(); }
auto end() { return d.end(); }
auto rbegin() { return d.rbegin(); }
auto rend() { return d.rend(); }

auto begin() const { return d.begin(); }
auto end() const { return d.end(); }
auto rbegin() const { return d.rbegin(); }
auto rend() const { return d.rend(); }
};

```

7 Problems

7.1 Hanoi Tower

Let T_n be the total of moves to solve a hanoi tower, we know that $T_n \geq 2 \cdot T_{n-1} + 1$, for $n > 0$, and $T_0 = 0$. By induction it's easy to see that $T_n = 2^n - 1$, for $n > 0$.

The following algorithm finds the necessary steps to solve the game for 3 stacks and n disks.

```

void move(int a, int b) { cout << a << ' ' << b << endl; }
void solve(int n, int s, int e) {
    if (n == 0) return;
    if (n == 1) {
        move(s, e);
        return;
    }
    solve(n - 1, s, 6 - s - e);
    move(s, e);
    solve(n - 1, 6 - s - e, e);
}

```

8 Searching

8.1 Meet in the middle

Answers the query how many subsets of the vector xs have sum equal x .

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

```

vll get_subset_sums(int l, int r, vll &a) {
    int len = r - l + 1;
    vll res;

    for (int i = 0; i < (1 << len); i++) {
        ll sum = 0;
        for (int j = 0; j < len; j++) {
            if (i & (1 << j)) {
                sum += a[l + j];
            }
        }
        res.push_back(sum);
    }
    return res;
};

ll count(vll &xs, ll x) {
    int n = len(xs);
    vll left = get_subset_sums(0, n / 2 - 1, xs);
    vll right = get_subset_sums(n / 2, n - 1, xs);
    sort(all(left));
    sort(all(right));
    ll ans = 0;
    for (ll i : left) {
        auto start_index =
            lower_bound(right.begin(), right.end(), x - i) -
            right.begin();
        auto end_index =
            upper_bound(right.begin(), right.end(), x - i) -
            right.begin();
        ans += end_index - start_index;
    }
    return ans;
}

```

8.2 Ternary Search Recursive

```

const double eps = 1e-6;

```

```
// IT MUST BE AN UNIMODAL FUNCTION
double f(int x) { return x * x + 2 * x + 4; }
```

```
double ternary_search(double l, double r) {
    if (fabs(f(l) - f(r)) < eps)
        return f((l + (r - l) / 2.0));

    auto third = (r - l) / 3.0;
    auto m1 = l + third;
    auto m2 = r - third;

    // change the signal to find the maximum point.
    return m1 < m2 ? ternary_search(m1, r)
        : ternary_search(l, m2);
}
```

9 Strings

9.1 Count Distinct Anagrams

```
const ll MOD = 1e9 + 7;
const int maxn = 1e6;
vll fs(maxn + 1);
void precompute() {
    fs[0] = 1;
    for (ll i = 1; i <= maxn; i++) {
        fs[i] = (fs[i - 1] * i) % MOD;
    }
}

ll fpow(ll a, int n, ll mod = LLONG_MAX) {
    if (n == 0) return 1;
    if (n == 1) return a;
    ll x = fpow(a, n / 2, mod) % mod;
    return ((x * x) % mod * (n & 1 ? a : 1)) % mod;
}

ll distinctAnagrams(const string &s) {
    precompute();
    vi hist('z' - 'a' + 1, 0);
    for (auto &c : s) hist[c - 'a']++;
    ll ans = fs[len(s)];
    for (auto &q : hist) {
        ans = (ans * fpow(fs[q], MOD - 2, MOD)) % MOD;
    }
}
```

```
return ans;
}
```

9.2 Double Hash Range Query

```
const ll MOD = 1000027957;
const int MOD2 = 1000015187;

struct Hash {
    const ll P = 31;
    int n;
    string s;
    vll h, h2, hi, hi2, p, p2;
    Hash() {}
    Hash(string _s)
        : s(_s),
          n(len(_s)),
          h(n),
          h2(n),
          hi(n),
          hi2(n),
          p(n),
          p2(n) {
        for (int i = 0; i < n; i++)
            p[i] = (i ? P * p[i - 1] : 1) % MOD;
        for (int i = 0; i < n; i++)
            p2[i] = (i ? P * p2[i - 1] : 1) % MOD2;
        for (int i = 0; i < n; i++)
            h[i] = (s[i] + (i ? h[i - 1] : 0) * P) % MOD;
        for (int i = 0; i < n; i++)
            h2[i] = (s[i] + (i ? h2[i - 1] : 0) * P) % MOD2;
        for (int i = n - 1; i >= 0; i--)
            hi[i] =
                (s[i] + (i + 1 < n ? hi[i + 1] : 0) * P) % MOD;
        for (int i = n - 1; i >= 0; i--)
            hi2[i] =
                (s[i] + (i + 1 < n ? hi2[i + 1] : 0) * P) % MOD2;
    }
    pii query(int l, int r) {
        ll hash =
            (h[r] - (l ? h[l - 1] * p[r - l + 1] % MOD : 0));
        ll hash2 =
            (h2[r] - (l ? h2[l - 1] * p2[r - l + 1] % MOD2 : 0));

        return {(hash < 0 ? hash + MOD : hash),
```

```

        (hash2 < 0 ? hash2 + MOD2 : hash2));
    }
    pii query_inv(int l, int r) {
        ll hash =
            (hi[l] -
             (r + 1 < n ? hi[r + 1] * p[r - 1 + 1] % MOD : 0));
        ll hash2 =
            (hi2[l] -
             (r + 1 < n ? hi2[r + 1] * p2[r - 1 + 1] % MOD2 : 0));
        return {(hash < 0 ? hash + MOD : hash),
                (hash2 < 0 ? hash2 + MOD2 : hash2)};
    }
};

```

9.3 Hash Range Query

```

const ll P = 31;
const ll MOD = 1e9 + 9;
const int MAXN(1e6);

ll ppow[MAXN + 1];
void pre_calc() {
    ppow[0] = 1;
    for (int i = 1; i <= MAXN; i++)
        ppow[i] = (ppow[i - 1] * P) % MOD;
}

struct Hash {
    int n;
    vll h, hi;
    Hash(const string &s) : n(s.size()), h(n), hi(n) {
        h[0] = s[0];
        hi[n - 1] = s[n - 1];
        for (int i = 1; i < n; i++) {
            h[i] = (s[i] + h[i - 1] * P) % MOD;
            hi[n - i - 1] =
                (s[n - i - 1] + hi[n - i - 1] * P) % MOD;
        }
    }

    ll qry(int l, int r) {
        ll hash =
            (h[r] - (l ? h[l - 1] * ppow[r - l + 1] % MOD : 0));
        return hash < 0 ? hash + MOD : hash;
    }
}

```

```

ll qry_inv(int l, int r) {
    ll hash =
        (hi[l] -
         (r + 1 < n ? hi[r + 1] * ppow[r - l + 1] % MOD : 0));
    return hash < 0 ? hash + MOD : hash;
}
};

```

9.4 K-th digit in digit string

Find the k-th digit in a *digit string*, only works for $1 \leq k \leq 10^{18}$!
 Time: precompute $O(1)$, query $O(1)$

```

using ull = vector<ull>;
ull pow10;
vector<array<ull, 4>> memo;
void precompute(int maxpow = 18) {
    ull qtd = 1;
    ull start = 1;
    ull end = 9;
    ull curlenght = 9;
    ull startstr = 1;
    ull endstr = 9;

    for (ull i = 0, j = 1ll; (int)i < maxpow; i++, j *= 10ll)
        pow10.eb(j);

    for (ull i = 0; i < maxpow - 1ull; i++) {
        memo.push_back({start, end, startstr, endstr});

        start = end + 1ll;
        end = end + (9ll * pow10[qtd]);
        curlenght = end - start + 1ull;

        qtd++;
        startstr = endstr + 1ull;
        endstr = (endstr + 1ull) + (curlenght)*qtd - 1ull;
    }
}

char kthDigit(ull k) {
    int qtd = 1;
    for (auto [s, e, ss, es] : memo) {
        if (k >= ss and k <= es) {
            ull pos = k - ss;
            ull index = pos / qtd;
            ull nmr = s + index;

```



```

        int i = k - ss - qtd * index;

        return ((nmr / pow10[qtd - i - 1]) % 10) + '0';
    }
    qtd++;
}

return 'X';
}

```

9.5 Longest Palindrome Substring (Manacher)

Finds the longest palindrome substring, manacher returns a vector where the i -th position is how much is possible to grow the string to the left and the right of i and keep it a palindrome.

Time: $O(N)$

```

vi manacher(const string &s) {
    int n = len(s) - 2;
    vi 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];
        p[i]--;
    }
    return p;
}

string longest_palindrome(const string &s) {
    string t("$#");
    for (auto c : s) t.push_back(c), t.push_back('#');
    t.push_back('^');
    vi xs = manacher(t);
    int mpos = max_element(all(xs)) - xs.begin();
    string p;
    for (int k = xs[mpos], i = mpos - k; i <= mpos + k; i++)
        if (t[i] != '#') p.push_back(t[i]);
    return p;
}

```

9.6 Longest Palindrome

```

string longest_palindrome(const string &s) {
    int n = (int)s.size();
    vector<array<int, 2>> dp(n);

```

```

pii odd(0, -1), even(0, -1);
pii ans;
for (int i = 0; i < n; i++) {
    int k = 0;
    if (i > odd.second)
        k = 1;
    else
        k = min(dp[odd.first + odd.second - i][0],
                odd.second - i + 1);
    while (i - k >= 0 and i + k < n and
           s[i - k] == s[i + k])
        k++;
    dp[i][0] = k--;
    if (i + k > odd.second) odd = {i - k, i + k};
    if (2 * dp[i][0] - 1 > ans.second)
        ans = {i - k, 2 * dp[i][0] - 1};

    k = 0;
    if (i <= even.second)
        k = min(dp[even.first + even.second - i + 1][1],
                even.second - i + 1);
    while (i - k - 1 >= 0 and i + k < n and
           s[i - k - 1] == s[i + k])
        k++;
    dp[i][1] = k--;
    if (i + k > even.second) even = {i - k - 1, i + k};
    if (2 * dp[i][1] > ans.second)
        ans = {i - k - 1, 2 * dp[i][1]};
}
return s.substr(ans.first, ans.second);
}

```

9.7 Rabin Karp

```

size_t rabin_karp(const string &s, const string &p) {
    if (s.size() < p.size()) return 0;

    auto n = s.size(), m = p.size();
    const ll p1 = 31, p2 = 29, q1 = 1e9 + 7, q2 = 1e9 + 9;
    const ll p1_1 = fpow(p1, q1 - 2, q1),
              p1_2 = fpow(p1, m - 1, q1);
    const ll p2_1 = fpow(p2, q2 - 2, q2),
              p2_2 = fpow(p2, m - 1, q2);

    pair<ll, ll> hs, hp;

```

```

for (int i = (int)m - 1; ~i; --i) {
    hs.first = (hs.first * p1) % q1;
    hs.first = (hs.first + (s[i] - 'a' + 1)) % q1;
    hs.second = (hs.second * p2) % q2;
    hs.second = (hs.second + (s[i] - 'a' + 1)) % q2;

    hp.first = (hp.first * p1) % q1;
    hp.first = (hp.first + (p[i] - 'a' + 1)) % q1;
    hp.second = (hp.second * p2) % q2;
    hp.second = (hp.second + (p[i] - 'a' + 1)) % q2;
}

size_t occ = 0;
for (size_t i = 0; i < n - m; i++) {
    occ += (hs == hp);

    int fi = s[i] - 'a' + 1;
    int fm = s[i + m] - 'a' + 1;

    hs.first = (hs.first - fi + q1) % q1;
    hs.first = (hs.first * p1_1) % q1;
    hs.first = (hs.first + fm * p1_2) % q1;
    hs.second = (hs.second - fi + q2) % q2;
    hs.second = (hs.second * p2_1) % q2;
    hs.second = (hs.second + fm * p2_2) % q2;
}
occ += hs == hp;

return occ;
}

```

9.8 String Psum

```

struct strPsum {
    ll n;
    ll k;
    vector<vll> psum;
    strPsum(const string &s)
        : n(s.size()), k(100), psum(k, vll(n + 1)) {
        for (ll i = 1; i <= n; ++i) {
            for (ll j = 0; j < k; ++j) {
                psum[j][i] = psum[j][i - 1];
            }
            psum[s[i - 1]][i]++;
        }
    }
}

```

```

}

ll qtd(ll l, ll r, char c) { // [0,n-1]
    return psum[c][r + 1] - psum[c][l];
}
}

```

9.9 Suffix Automaton (complete)

```

struct state {
    int len, link, cnt, firstpos;
    // this can be optimized using a vector with the alphabet
    // size
    map<char, int> next;
    vi inv_link;
};

struct SuffixAutomaton {
    vector<state> st;
    int sz = 0;
    int last;
    vc cloned;

    SuffixAutomaton(const string &s, int maxlen)
        : st(maxlen * 2), cloned(maxlen * 2) {
        st[0].len = 0;
        st[0].link = -1;
        sz++;
        last = 0;
        for (auto &c : s) add_char(c);

        // precompute for count occurrences
        for (int i = 1; i < sz; i++) {
            st[i].cnt = !cloned[i];
        }
        vector<pair<state, int>> aux;
        for (int i = 0; i < sz; i++) {
            aux.push_back({st[i], i});
        }

        sort(all(aux), [](const pair<state, int> &a,
                           const pair<state, int> &b) {
            return a.fst.len > b.fst.len;
        });

        for (auto &[stt, id] : aux) {

```

```

        if (stt.link != -1) {
            st[stt.link].cnt += st[id].cnt;
        }
    }

    // for find every occurende position
    for (int v = 1; v < sz; v++) {
        st[st[v].link].inv_link.push_back(v);
    }
}

void add_char(char c) {
    int cur = sz++;
    st[cur].len = st[last].len + 1;
    st[cur].firstpos = st[cur].len - 1;
    int p = last;
    // follow the suffix link until find a transition to c
    while (p != -1 and !st[p].next.count(c)) {
        st[p].next[c] = cur;
        p = st[p].link;
    }
    // there was no transition to c so create and leave
    if (p == -1) {
        st[cur].link = 0;
        last = cur;
        return;
    }

    int q = st[p].next[c];
    if (st[p].len + 1 == st[q].len) {
        st[cur].link = q;
    } else {
        int clone = sz++;
        cloned[clone] = true;
        st[clone].len = st[p].len + 1;
        st[clone].next = st[q].next;
        st[clone].link = st[q].link;
        st[clone].firstpos = st[q].firstpos;
        while (p != -1 and st[p].next[c] == q) {
            st[p].next[c] = clone;
            p = st[p].link;
        }
        st[q].link = st[cur].link = clone;
    }
    last = cur;
}

```

```

}

bool checkOccurrence(const string &t) { // O(len(t))
    int cur = 0;
    for (auto &c : t) {
        if (!st[cur].next.count(c)) return false;
        cur = st[cur].next[c];
    }
    return true;
}

ll totalSubstrings() { // distinct, O(len(s))
    ll tot = 0;
    for (int i = 1; i < sz; i++) {
        tot += st[i].len - st[st[i].link].len;
    }
    return tot;
}

// count occurrences of a given string t
int countOccurrences(const string &t) {
    int cur = 0;
    for (auto &c : t) {
        if (!st[cur].next.count(c)) return 0;
        cur = st[cur].next[c];
    }
    return st[cur].cnt;
}

// find the first index where t appears a substring
// O(len(t))
int firstOccurrence(const string &t) {
    int cur = 0;
    for (auto c : t) {
        if (!st[cur].next.count(c)) return -1;
        cur = st[cur].next[c];
    }
    return st[cur].firstpos - len(t) + 1;
}

vi everyOccurrence(const string &t) {
    int cur = 0;
    for (auto c : t) {
        if (!st[cur].next.count(c)) return {};
        cur = st[cur].next[c];
    }
}

```

```

vi ans;
getEveryOccurrence(cur, len(t), ans);
return ans;
}

void getEveryOccurrence(int v, int P_length, vi &ans) {
    if (!cloned[v]) ans.pb(st[v].firstpos - P_length + 1);
    for (int u : st[v].inv_link)
        getEveryOccurrence(u, P_length, ans);
}
};

```

9.10 Trie

- build with the size of the alphabet (*sigma*) and the first char (*norm*)
- *insert(s)* insert the string in the trie $O(|s| * \text{sigma})$
- *erase(s)* remove the string from the trie $O(|s|)$
- *find(s)* return the last node from the string s, 0 if not found $O(|s|)$

```

struct trie {
    vi2d to;
    vi end, pref;
    int sigma;
    char norm;

    trie(int sigma_ = 26, char norm_ = 'a')
        : sigma(sigma_), norm(norm_) {
        to = {vector<int>(sigma)};
        end = {0}, pref = {0};
    }

    int next(int node, char key) {
        return to[node][key - norm];
    }

    void insert(const string &s) {
        int x = 0;
        for (auto c : s) {
            int &nxt = to[x][c - norm];
            if (!nxt) {
                nxt = len(to);
                to.push_back(vi(sigma));
                end.emplace_back(0), pref.emplace_back(0);
            }
            x = nxt, pref[x]++;
        }
    }
};

```

```

end[x]++, pref[0]++;
}

void erase(const string &s) {
    int x = 0;
    for (char c : s) {
        int &nxt = to[x][c - norm];
        x = nxt, pref[x]--;
        if (!pref[x]) nxt = 0;
    }
    end[x]--, pref[0]--;
}

int find(const string &s) {
    int x = 0;
    for (auto c : s) {
        x = to[x][c - norm];
        if (!x) return 0;
    }
    return x;
}
};

```

9.11 Z-function get occurrence positions

$O(\text{len}(s) + \text{len}(p))$

```

vi getOccPos(string &s, string &p) {
    // Z-function
    char delim = '#';
    string t{p + delim + s};
    vi zs(len(t));

    int l = 0, r = 0;
    for (int i = 1; i < len(t); i++) {
        if (i <= r) zs[i] = min(zs[i - 1], r - i + 1);
        while (zs[i] + i < len(t) and t[zs[i]] == t[i + zs[i]])
            zs[i]++;
        if (r < i + zs[i] - 1) l = i, r = i + zs[i] - 1;
    }

    // Iterate over the results of Z-function to get ranges
    vi ans;
    int start = len(p) + 1 + 1 - 1;
    for (int i = start; i < len(zs); i++) {
        if (zs[i] == len(p)) {
            int l = i - start;
            ans.emplace_back(l);
        }
    }
}

```

```

    }
}
return ans;
}

```

10 Settings and macros

10.1 .vimrc

```

set ts=4 sw=4 sta nu rnu sc cindent
set bg=dark ruler clipboard=unnamed,unnamedplus, timeoutlen=100
colorscheme default

```

```

nnoremap <C-j> :botright belowright term bash <CR>
syntax on

```

10.2 macro.cpp

```

#include <bits/stdc++.h>
using namespace std;
#ifdef LOCAL
#include "debug.cpp"
#else
#define dbg(...)
#endif
#define endl '\n'
#define fastio \
    ios_base::sync_with_stdio(0); \
    cin.tie(0);
// #define int long long
#define len(__x) (int)__x.size()
using ll = long long;
using ull = unsigned long long;
using ld = long double;
using vll = vector<ll>;
using pll = pair<ll, ll>;
using vll2d = vector<vll>;
using vi = vector<int>;
using vi2d = vector<vi>;
using pii = pair<int, int>;
using vii = vector<pii>;
using vc = vector<char>;
#define all(a) a.begin(), a.end()
#define rall(a) a.rbegin(), a.rend()
#define pb push_back

```

```

#define eb emplace_back
#define ff first
#define ss second
#define rep(i, begin, end) \
    for (__typeof(begin) i = (begin) - ((begin) > (end)); \
         i != (end) - ((begin) > (end)); \
         i += 1 - 2 * ((begin) > (end)))

int lg2(ll x) {
    return __builtin_clzll(1) - __builtin_clzll(x);
}

// vector<string> dir({"LU", "U", "RU", "R", "RD", "D",
// "LD", "L"}); int dx[] = {-1, -1, -1, 0, 1, 1, 1, 0}; int
// dy[] = {-1, 0, 1, 1, 1, 0, -1, -1};
vector<string> dir({"U", "R", "D", "L"});
int dx[] = {-1, 0, 1, 0};
int dy[] = {0, 1, 0, -1};

const ll OO = 1e18;
const int oo = 1e9;

int T(1);

auto run() {

}

int32_t main(void) {
#ifdef LOCAL
    fastio;
#endif

    // cin >> T;

    for (int t = 1; t <= T; t++) {
        run();
    }
}

```

10.3 debug.cpp

```

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

```

```

template <typename T>
concept Printable = requires(T t) {
    { std::cout << t } -> std::same_as<std::ostream &>;
};
template <Printable T>
void __print(const T &x) {
    cerr << x;
}
template <size_t T>
void __print(const bitset<T> &x) {
    cerr << x;
}
template <typename A, typename B>
void __print(const pair<A, B> &p);
template <typename... A>
void __print(const tuple<A...> &t);
template <typename T>
void __print(stack<T> s);
template <typename T>
void __print(queue<T> q);
template <typename T, typename... U>
void __print(priority_queue<T, U...> q);
template <typename A>
void __print(const A &x) {
    bool first = true;
    cerr << '{';
    for (const auto &i : x) {
        cerr << (first ? "" : ","), __print(i);
        first = false;
    }
    cerr << '}';
}
template <typename A, typename B>
void __print(const pair<A, B> &p) {
    cerr << '(';
    __print(p.first);
    cerr << ',';
    __print(p.second);
    cerr << ')';
}
template <typename... A>
void __print(const tuple<A...> &t) {
    bool first = true;
    cerr << '(';
    apply(

```

```

        [&first](const auto &...args) {
            ((cerr << (first ? "" : ","), __print(args), first
= false), ...);
        },
        t);
    cerr << ')';
}
template <typename T>
void __print(stack<T> s) {
    vector<T> debugVector;
    while (!s.empty()) {
        T t = s.top();
        debugVector.push_back(t);
        s.pop();
    }
    reverse(debugVector.begin(), debugVector.end());
    __print(debugVector);
}
template <typename T>
void __print(queue<T> q) {
    vector<T> debugVector;
    while (!q.empty()) {
        T t = q.front();
        debugVector.push_back(t);
        q.pop();
    }
    __print(debugVector);
}
template <typename T, typename... U>
void __print(priority_queue<T, U...> q) {
    vector<T> debugVector;
    while (!q.empty()) {
        T t = q.top();
        debugVector.push_back(t);
        q.pop();
    }
    __print(debugVector);
}
void _print() { cerr << "]\n"; }
template <typename Head, typename... Tail>
void _print(const Head &H, const Tail &...T) {
    __print(H);
    if (sizeof...(T)) cerr << ", ";
    _print(T...);
}

```

```

#define dbg(x...) \
    cerr << "[" << #x << "]" = ["; \
    _print(x)

```

10.4 .bashrc

```

cpp() {
    g++ -std=c++20 -fsanitize=address,undefined -Wall $1 && time
    ./a.out
}

```

```

cpp() {
    echo ">> COMPILING <<" 1>&2
    g++ -std=c++17 \
        -O2 \
        -g \
        -g3 \
        -Wextra \
        -Wshadow \
        -Wformat=2 \
        -Wconversion \
        -fsanitize=address,undefined \
        -fno-sanitize-recover \
        -Wfatal-errors \
        $1

    if [ $? -ne 0 ]; then
        echo ">> FAILED <<" 1>&2
        return 1
    fi
    echo ">> DONE <<" 1>&2
    time ./a.out ${@:2}
}

```

```

prepare() {
    cp debug.cpp ./
    for i in {a..z}
    do
        cp macro.cpp $i.cpp
        touch $i.py
    done

    for i in {1..10}
    do
        touch in${i}
        touch out${i}
        touch ans${i}
    done
}

```

10.5 short-macro.cpp

```

#include <bits/stdc++.h>
using namespace std;
#define fastio \
    ios_base::sync_with_stdio(0); \
    cin.tie(0);

void run() {}

int32_t main(void) {
    fastio;
    int t;
    t = 1;
    // cin >> t;
    while (t--) run();
}

```