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1 Data structures

1.1 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;
            }
        }
    }
    ll 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;
    }
    ll 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);
    }
};
```

1.2 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 >= l; 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()[l];

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

1.3 Dsu

```
struct DSU {
    vi ps;
    vi size;
    DSU(int N) : ps(N + 1), size(N + 1, 1) { iota(all(ps), 0); }
    int find_set(int x) { return ps[x] == 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) {
        if (same_set(x, y)) return;

        int px = find_set(x);
```

```

    int py = find_set(y);

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

    ps[py] = px;
    size[px] += size[py];
}
};

```

1.4 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>;

```

1.5 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;
    }
};

```

1.6 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;

        while (a <= b) {
            if (a & 1) ans = operation(ans, ns[a++]);
            if (not(b & 1)) ans = operation(ans, ns[b--]);

            a /= 2;
            b /= 2;
        }

        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]);
    }
};

```

1.7 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 + l; }
};

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';
}

```

1.8 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 + 1; }
};

```

1.9 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 - l) / 2 + 1; }
};

```

1.10 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 + 1; }
};

```

1.11 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 - l) / 2 + 1; }
};

```

1.12 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 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];
}

```

2.2 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));
}

```

2.3 Knapsack (value)

Finds the maximum points possible

```

const int MAXN{2010}, MAXM{2010};

ll st[MAXN][MAXM];

```

```

ll dp(int i, int m, int M, const vii &cs) {
    if (i < 0) return 0;

    if (st[i][m] != -1) return st[i][m];

    auto res = dp(i - 1, m, M, cs);
    auto [w, v] = cs[i];

    if (w <= m) res = max(res, dp(i - 1, m - w, M, cs) + v);

    st[i][m] = res;
    return res;
}

ll knapsack(int M, const vii &cs) {
    memset(st, -1, sizeof st);

    return dp((int)cs.size() - 1, M, M, cs);
}

```

2.4 Knapsack (elements)

Finds the maximum possible points carry and which elements to achieve it

```

const int MAXN{2010}, MAXM{2010};
ll st[MAXN][MAXM];
char ps[MAXN][MAXM];

pair<ll, vi> knapsack(int M, const vii &cs) {
    int N = len(cs) - 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;
            auto [w, v] = cs[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.push_back(i);
            m -= cs[i].first;
        }
    }
}

```

```
reverse(all(is));

// max value, items
return {st[N][M], is};
}
```

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)
        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;
/* 0 ( 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 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  est 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;
}

```

4 Graphs

4.1 2 SAT

```

struct SAT2 {
    ll n;
    vll2d adj, adj_t;
    vc used;
    vll order, comp;
    vc assignment;
    bool solvable;
    SAT2(ll _n)
        : n(2 * _n),
          adj(n),
          adj_t(n),
          used(n),
          order(n),
          comp(n, -1),
          assignment(n / 2) {}
    void dfs1(int v) {
        used[v] = true;
        for (int u : adj[v]) {
            if (!used[u]) dfs1(u);
        }
        order.push_back(v);
    }
}

```

```

void dfs2(int v, int c1) {
    comp[v] = c1;
    for (int u : adj_t[v]) {
        if (comp[u] == -1) dfs2(u, c1);
    }
}

bool solve_2SAT() {
    // find and label each SCC
    for (int i = 0; i < n; ++i) {
        if (!used[i]) dfs1(i);
    }
    reverse(all(order));
    ll j = 0;
    for (auto &v : order) {
        if (comp[v] == -1) dfs2(v, j++);
    }

    assignment.assign(n / 2, false);
    for (int i = 0; i < n; i += 2) {
        // x and !x belong to the same SCC
        if (comp[i] == comp[i + 1]) {
            solvable = false;
            return false;
        }

        assignment[i / 2] = comp[i] > comp[i + 1];
    }
    solvable = true;
    return true;
}

void add_disjunction(int a, bool na, int b, bool nb) {
    a = (2 * a) ^ na;
    b = (2 * b) ^ nb;
    int neg_a = a ^ 1;
    int neg_b = b ^ 1;
    adj[neg_a].push_back(b);
    adj[neg_b].push_back(a);
    adj_t[b].push_back(neg_a);
    adj_t[a].push_back(neg_b);
}
};

```

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)

Able to find the component of each node and the total of SCC in $O(V * E)$ and build the SCC graph ($O(V * E)$).

```

struct SCC {
    ll N;
    int totsc;
    vll2d adj, tadj;
    vll todo, comps, comp;
    vector<set<ll>> sccadj;
    vchar vis;
    SCC(ll _N)
        : N(_N), totsc(0), adj(_N), tadj(_N), comp(_N, -1), sccadj(_N), vis(_N)
    {}

    void add_edge(ll x, ll y) { adj[x].eb(y), tadj[y].eb(x); }

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

    void dfs2(ll x, ll v) {
        comp[x] = v;
        for (auto &y : tadj[x])
            if (comp[y] == -1) dfs2(y, v);
    }

    void gen() {
        for (ll i = 0; i < N; ++i)
            if (!vis[i]) dfs(i);
        reverse(all(todo));
        for (auto &x : todo)
            if (comp[x] == -1) {
                dfs2(x, x);
                comps.pb(x);
                totsc++;
            }
    }
}

```

```

}

void genSCCGraph() {
    for (ll i = 0; i < N; ++i) {
        for (auto &j : adj[i]) {
            if (comp[i] != comp[j]) {
                sccadj[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: $O(V * E)$

```

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: $O(V * E)$

```
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 Binary Lifting

$far[h][i]$ = the node that is 2^h distance from node i

Build : $O(N * \log N)$

sometimes is useful invert the order of loops

```
const int maxlog = 20;
int far[maxlog + 1][n + 1];
int n;
for (int h = 1; h <= maxlog; h++) {
    for (int i = 1; i <= n; i++) {
        far[h][i] = far[h - 1][far[h - 1][i]];
    }
}
```

4.7 Check Bipartitie

$O(V)$

```
bool checkBipartite(const ll n, const vector<vll> &adj) {
    ll s = 0;
    queue<ll> q;
```

```
    q.push(s);
    vll color(n, INF);
    color[s] = 0;
    bool isBipartite = true;
    while (!q.empty() && isBipartite) {
        ll u = q.front();
        q.pop();
        for (auto &v : adj[u]) {
            if (color[v] == INF) {
                color[v] = 1 - color[u];
                q.push(v);
            } else if (color[v] == color[u]) {
                return false;
            }
        }
    }
    return true;
}
```

4.8 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;
}
```

4.9 Dijkstra (restore Path)

```
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};
}

```

4.10 Dijkstra

Finds the minimum distance from s to every other node in

$$O(E * \log E)$$

time.

```

vll dijkstra(const vector<vector<pll>> &g, int n, int s) {
    priority_queue<pll, vector<pll>, greater<pll>> pq;
    vll dist(n + 1, oo);
    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;
                pq.emplace(dist[u], u);
            }
        }
    }
    return dist;
}

```

4.11 Disjoint Edges Path (Maxflow)

Given a directed graph find's every path with distinct edges that starts at s and ends at t

When building the graph, if there is an edge (u, v) is necessary to also add the transposed edge (v, u) but only need to add the capacity $c(u, v)$, and mark $isedge(u, v)$ as true.

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

```

ll bfs(int s, int t, vi2d &g, vll2d &capacity, vi &parent) {
    fill(all(parent), -1);
    parent[s] = -2;

```

```

    queue<pair<ll, 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 0ll;
}

ll maxflow(int s, int t, int n, vi2d &g, vll2d &capacity) {
    ll flow = 0;
    vi parent(n);
    ll new_flow;

    while ((new_flow = bfs(s, t, g, capacity, 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;
}

void dfs(int u, int t, vi2d &g, vc2d &vis, vc2d &isedge, vll2d &capacity,
        vi &route, vi2d &routes) {
    route.pb(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, g, vis, isedge, capacity, route, routes);
            route.pop_back();
            return;
        }
    }
}

vi2d disjoint_paths(vi2d &g, vll2d &capacity, vc2d &isedge, int s, int t,
                    int n) {

```

```

ll mf = maxflow(s, t, n, g, capacity);
vi2d routes;
vi route;
vc2d vis(n + 1, vc(n + 1));
for (int i = 0; i < (int)mf; i++)
    dfs(s, t, g, vis, isedge, capacity, route, routes);
return routes;
}

```

4.12 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;
}

```

4.13 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;
}

```

4.14 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;
}

```

4.15 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;
}

```

4.16 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;
}
}

```

4.17 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: $O(V + E)$

```

bool has_cycle(const vector<vector<int>> &g, int s, vector<char> &vis,
               vector<char> &in_path, vector<int> *path = nullptr) {
    vis[s] = in_path[s] = 1;
    if (path != nullptr) path->push_back(s);
    for (auto x : g[s]) {
        if (!vis[x] && has_cycle(g, x, vis, in_path, path))
            return true;
        else if (in_path[x]) {
            if (path != nullptr) path->push_back(x);
            return true;
        }
    }
    in_path[s] = 0;
    if (path != nullptr) path->pop_back();
    return false;
}

```

4.18 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 ufds(n);
    vector<tuple<ll, int, int>> ans;

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

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

    return ans;
}

```

4.19 Lowest Common Ancestor

Given two nodes of a tree find their lowest common ancestor, or their distance

Build : $O(V)$, Queries: $O(1)$

0 indexed !

```

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.pb(len(dep)) = i, pos[i] = len(dep), dep.pb(d);
        for (auto j : g[i])
            if (j != p) {
                dfs(j, d + 1, i, g);
                v.pb(len(dep)) = i, dep.pb(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)]];
    }
};

```

4.20 Tree Maximum Distance

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

```

ll mostDistantFrom(const vector<vll> &adj, ll n, ll root) {
    // 0(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); // 0(V)
    auto [node2, dist2] = mostDistantFrom(adj, n, node1); // 0(V)
    auto diameter = twoNodesDist(adj, n, node1, node2); // 0(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); // 0(3V)
    auto distances1 = everyDistanceFromNode(adj, n, node1); // 0(V)
    auto distances2 = everyDistanceFromNode(adj, n, node2); // 0(V)
    vll ans(n);
    for (int i = 0; i < n; ++i)

```

```

    ans[i] = max(distances1[i], distances2[i]); // O(V)
return ans;
}

```

4.21 Maximum Flow (Edmonds-Karp)

Finds the **maximum flow** in a graph network, given the **source** s and the **sink** t .

When building the graph, if there is an edge (u, v) is necessary to also add the transposed edge (v, u) but only need to add the capacity $c(u, v)$.

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

```

const ll oo = 1e17;

ll bfs(int s, int t, vi2d &g, vll2d &capacity, vi &parent) {
    fill(all(parent), -1);
    parent[s] = -2;
    queue<pair<ll, 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 0ll;
}

ll maxflow(int s, int t, int n, vi2d &g, vll2d &capacity) {
    ll flow = 0;
    vi parent(n);
    ll new_flow;

    while ((new_flow = bfs(s, t, g, capacity, 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;
}

```

4.22 Minimum Cut (unweighted)

Given the edges of a directed/undirected graph find the minum of edges that needs to be removed to make the sink t unreachable from the source s .

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

```

const ll oo = 1e17;

ll bfs(int s, int t, vi2d &g, vll2d &capacity, vi &parent) {
    fill(all(parent), -1);
    parent[s] = -2;
    queue<pair<ll, 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 0ll;
}

ll maxflow(int s, int t, int n, vi2d &g, vll2d &capacity) {
    ll flow = 0;
    vi parent(n);
    ll new_flow;

    while ((new_flow = bfs(s, t, g, capacity, 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;
}

void dfs(int u, vi2d &g, vll2d &capacity, vc &visited) {
    visited[u] = true;

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

```

```

vii mincut(vii &edges, int s, int t, int n, bool directed = false) {
    vll2d capacity(n, vll(n));
    vi2d g(n);
    for (auto &[u, v] : edges) {
        g[u].eb(v);
        capacity[u][v] += 1;
        if (not directed) {
            g[v].eb(u);
            capacity[v][u] += 1;
        }
    }

    maxflow(0, n - 1, n, g, capacity);
    vc vis(n);
    dfs(0, g, capacity, vis);

    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;
}

```

4.23 Small to Large

Answer queries of the form "How many vertices in the subtree of vertex v have property P ?"

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

```

struct SmallToLarge {
    vector<vector<int>> tree, vis_chlds;
    vector<int> sizes, values, ans;
    set<int> cnt;

    SmallToLarge(vector<vector<int>> &g, vector<int> &v)
        : tree(g), vis_chlds(g.size(), sizes(g.size()), values(v), ans(g.size()))
        {
            update_sizes(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] = (int)cnt.size(); }

    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;

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

```

4.24 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;
}

```

4.25 Topological Sorting

Assumes that :

- vertices index $[0, n - 1]$
- is a DAG (else it returns an empty vector)

$O(V)$

```

enum class state { not_visited, processing, done };
bool dfs(const vector<vll> &adj, ll s, vector<state> &states, vll &order) {
    states[s] = state::processing;
    for (auto &v : adj[s]) {
        if (states[v] == state::not_visited) {
            if (not dfs(adj, v, states, order)) return false;
        } else if (states[v] == state::processing)
            return false;
    }
    states[s] = state::done;
    order.pb(s);
    return true;
}

vll topologicalSorting(const vector<vll> &adj) {
    ll n = len(adj);
    vll order;
    vector<state> states(n, state::not_visited);
    for (int i = 0; i < n; ++i) {
        if (states[i] == state::not_visited) {
            if (not dfs(adj, i, states, order)) return {};
        }
    }
    reverse(all(order));
    return order;
}

```

4.26 Tree Diameter

Finds the lenght of the diameter of the tree in $O(V)$, it's easy to recover the nodes at the point of the diameter .

```

pll mostDistantFrom(const vector<vll> &adj, ll n, ll root) {
    // 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) {
    // 0 indexed
    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;
}

ll tree_diameter(const vector<vll> &adj, ll n) {
    // 0 indexed !!!
    auto [node1, dist1] = mostDistantFrom(adj, n, 0); // 0(V)
    auto [node2, dist2] = mostDistantFrom(adj, n, node1); // 0(V)
    auto diameter = twoNodesDist(adj, n, node1, node2); // 0(V)
    return diameter;
}

```

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 = 2 * 1e6;
vll fats(maxn + 1, -1);
void precompute() {
    fats[0] = 1;
    for (ll i = 1; i <= maxn; i++) {

```

```

        fats[i] = (fats[i - 1] * i) % MOD;
    }
}

ll fpow(ll a, ll n, ll mod = LLONG_MAX) {
    if (n == 0ll) return 1ll;
    if (n == 1ll) return a;
    ll x = fpow(a, n / 2ll, mod) % mod;
    return ((x * x) % mod * (n & 1ll ? a : 1ll)) % mod;
}

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

```

5.9 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;
}
```

5.10 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;
}
```

5.11 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);
}
```

5.12 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)a / 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 /= 2ll, a = mul(a, a, m)) {
        if (b % 2ll == 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;
}
```

5.13 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;
}
```

5.14 Fast Fourier Transform

```
template <bool invert = false>
void fft(vector<complex<double>>& xs) {
    int N = (int)xs.size();

    if (N == 1) return;

    vector<complex<double>> es(N / 2), os(N / 2);

    for (int i = 0; i < N / 2; ++i) es[i] = xs[2 * i];
    for (int i = 0; i < N / 2; ++i) os[i] = xs[2 * i + 1];

    fft<invert>(es);
    fft<invert>(os);

    auto signal = (invert ? 1 : -1);
    auto theta = 2 * signal * acos(-1) / N;
    complex<double> S{1}, S1{cos(theta), sin(theta)};

    for (int i = 0; i < N / 2; ++i) {
        xs[i] = (es[i] + S * os[i]);
        xs[i] /= (invert ? 2 : 1);

        xs[i + N / 2] = (es[i] - S * os[i]);
        xs[i + N / 2] /= (invert ? 2 : 1);

        S *= S1;
    }
}
```

5.15 Fast pow

Computes a^n in $O(\log N)$.

```
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;
}
```

5.16 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;
}
};

```

5.17 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;
}
};

```

5.18 Is prime

$O(\sqrt{N})$

```

bool isprime(ll n) {
    if (n < 2) return false;
    if (n == 2) return true;
    if (n % 2 == 0) return false;
    for (ll i = 3; i * i < n; i += 2)
        if (n % i == 0) return false;
    return true;
}

```

5.19 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;
}

```

5.20 Power Sum

Calculates $K^0 + K^1 + \dots + K^n$

```

ll powersum(ll n, ll k) { return (fastpow(n, k + 1) - 1) / (n - 1); }

```


5.21 Sieve list primes

List every prime until MAXN , $O(N \log N)$ in time and $O(\text{MAXN})$ in memory.

```
const ll MAXN = 1e5;
vll list_primes(ll n) {
    vll ps;
    bitset<MAXN> 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;
}
```

5.22 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;
}
```

6 Problems

6.1 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);
}
```

7 Searching

7.1 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;
}
```

7.2 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);
}
```

8 Strings

8.1 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;
}
```

8.2 Hash Range Query

```
struct Hash {
    const ll P = 31;
    const ll mod = 1e9 + 7;
    string s;
    int n;
    vll h, hi, p;
    Hash() {}
    Hash(string s) : s(s), n(s.size()), h(n), hi(n), p(n) {
        for (int i = 0; i < n; i++) p[i] = (i ? P * p[i - 1] : 1) % mod;
        for (int i = 0; i < n; i++) h[i] = (s[i] + (i ? h[i - 1] : 0) * P) % mod;
        for (int i = n - 1; i >= 0; i--)
            hi[i] = (s[i] + (i + 1 < n ? hi[i + 1] : 0) * P) % mod;
    }
    ll query(int l, int r) {
        ll hash = (h[r] - (l ? h[l - 1] * p[r - l + 1] % mod : 0));
        return hash < 0 ? hash + mod : hash;
    }
    ll query_inv(int l, int r) {
        ll hash = (hi[l] - (r + 1 < n ? hi[r + 1] * p[r - l + 1] % mod : 0));
        return hash < 0 ? hash + mod : hash;
    }
};
```

8.3 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 = 1; (int)i < maxpow; i++, j *= 10) pow10.eb(j);

    for (ull i = 0; i < maxpow - 1; i++) {
        memo.push_back({start, end, startstr, endstr});

        start = end + 1;
        end = end + (9 * pow10[qtd]);
        curlenght = end - start + 1;

        qtd++;
        startstr = endstr + 1;
        endstr = (endstr + 1) + (curlenght)*qtd - 1;
    }
}

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';
}
```

8.4 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(string s) {
    string t2;
    for (auto c : s) t2 += string("#") + c;
    t2 = t2 + '#';
    int n = t2.size();
    t2 = "$" + t2 + "^";
```

```

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 (t2[i - p[i]] == t2[i + p[i]]) {
        p[i]++;
    }
    if (i + p[i] > r) {
        l = i - p[i], r = i + p[i];
    }
    p[i]--;
}
return vi(begin(p) + 1, end(p) - 1);
}

string longest_palindrome(const string &s) {
    vi xs = manacher(s);

    string s2;
    for (auto c : s) s2 += string("#") + c;
    s2 = s2 + '#';

    int mpos = 0;
    for (int i = 0; i < len(xs); i++) {
        if (xs[i] > xs[mpos]) {
            mpos = i;
        }
    }

    string ans;
    int k = xs[mpos];
    for (int i = mpos - k; i <= mpos + k; i++) {
        if (s2[i] != '#') {
            ans += s2[i];
        }
    }
    return ans;
}

void run() {
    string s;
    cin >> s;
    auto ans = longest_palindrome(s);
    cout << ans << endl;
}

```

8.5 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;
}

```

8.6 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];
    }
}

```

8.7 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;
getEveryOccurence(cur, len(t), ans);
return ans;
}

void getEveryOccurence(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) getEveryOccurence(u, P_length, ans);
}
};

```

8.8 Z-function get occurence 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 - l], 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;
}

```

9 Settings and macros

9.1 short-macro.cpp

```

#include <bits/stdc++.h>
using namespace std;
#define endl '\n'
#define fastio \
    ios_base::sync_with_stdio(false); \
    cin.tie(0); \
    cout.tie(0);
#define len(__x) (int) __x.size()
using ll = long long;
using pii = pair<int, int>;
#define all(a) a.begin(), a.end()

```

```

void run() {}
int32_t main(void) {
    fastio;
    int t;
    t = 1;
    // cin >> t;
    while (t--) run();
}

```

9.2 .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

```

9.3 degug.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)

```

9.4 .bashrc

```

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() {
    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
}

```

9.5 macro.cpp

```

#include <bits/stdc++.h>
using namespace std;
#define endl '\n'
#define fastio \
    ios_base::sync_with_stdio(false); \
    cin.tie(0); \
    cout.tie(0);
#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 snd second
#define fst first
#define pb(____x) push_back(____x)
#define mp(____a, ____b) make_pair(____a, ____b)
#define eb(____x) emplace_back(____x)

```

```

const ll oo = 1e18;

void run() {}
int32_t main(void) {
    fastio;
    int t;
    t = 1;
    // cin >> t;
    while (t--) run();
}

```