Contents

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 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 $O(logn^2)$, query $O(logn^2)$

```
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);
  }
};
```

1.3 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) {
```

```cpp
        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]);
  }
};
```

1.4 DSU/UFDS

Uncomment the lines to reover which element belong to each set.
Time: $\approx O(1)$ for everything.

```cpp
struct DSU {
  vi ps;
  vi size;
  // vector<unordered_set<int>> sts;
  DSU(int N) : ps(N + 1), size(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]); }
  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];
    // sts[px].merge(sts[py]);
  }
};
```

1.5 Ordered Set

If you need an ordered **multi**set 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).

```cpp
#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>;
```

1.6 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 $O(1)$.

```cpp
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;
  }
};
```

1.7 SegTree Range Sum Query Range PA sum/set Update

Makes arithmetic progression updates in range and sum queries.
Considering $PA(A, R) = [A + R, A + 2R, A + 3R, ...]$

- **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 $O(logn)$

```cpp
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)) {}
```

```cpp
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); }
};
```

1.8 SegTree Point Update (dynamic function)

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

```cpp
#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]);
  }
};
```

1.9 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); }
};
```

1.10 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';
}
```

1.11 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; }
};
```

1.12 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 BUFFSZ(1.3e7);
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); }
};
```

1.13 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 + l; }
};
```

1.14 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; }
};
```

1.15 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 + l; }
};
```

1.16 Sparse Table

Answer the range query defined at the function **op**.
Build: O(NlogN), 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 a rray.

```
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 lenght 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;
/* 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 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 áest 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 cl) {
    comp[v] = cl;
    for (int u : adj_t[v]) {
      if (comp[u] == -1) dfs2(u, cl);
    }
  }

  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 totscc;
  vll2d adj, tadj;
  vll todo, comps, comp;
  vector<set<ll>> sccadj;
  vchar vis;
```

```
  SCC(ll _N)
    : N(_N), totscc(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);
        totscc++;
      }
  }

  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: $O(V \cdot E)$

```
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: $O(V * E)$

```
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 bfs(const ll n, int s, const vector<vll> &adj, vll &color) {
  queue<ll> q;
  q.push(s);
  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;
}

bool checkBipartite(int n, const vll2d &adj) {
  vll color(n, oo);
  for (int i = 0; i < n; i++) {
    if (color[i] != oo) {
      if (not bfs(n, adj, color)) 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

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};
}
```

4.10 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;
  }
};
```

4.11 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 {};
```

```cpp
  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;
}
```

4.12 Euler Path (undirected)

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

```cpp
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;
}
```

4.13 Find Articulation/Cut Points

Given an **undirected** graph find it's articulation points.
articulation point (or cut vertex): is defined as a vertex which, when removed along with associated edges, makes the graph disconnected.
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;
char vis[MAXN];
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);
  }
}
```

4.14 Find Bridges

Find every bridge in a **undirected** connected graph.
bridge: A bridge is defined as an edge which, when removed, makes the graph disconnected.
Time: $O(N + M)$

```
const int MAXN(50);
vi2d G(MAXN);
int tin[MAXN];
int low[MAXN];
char vis[MAXN];
int timer;
int N, M;
vector<pii> bridges;

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

  for (auto v : G[u]) {
    if (v == p) continue;
    if (vis[v]) {
      low[u] = min(low[u], tin[v]);
    } else {
      dfs(v, u);
      low[u] = min(low[u], low[v]);
      if (low[v] > tin[u]) {
        bridges.emplace_back(u, v);
      }
    }
  }
}
void getBridges() {
  timer = 0;

  memset(vis, 0, sizeof(vis));
  memset(tin, -1, sizeof(tin));
  memset(low, -1, sizeof(low));
  bridges.clear();

  for (int i = 0; i < N; i++) {
    if (not vis[i]) dfs(i);
  }
}
```

4.15 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;
}
```

4.16 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;
}
```

4.17 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;
  }
}
```

4.18 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;
}
```

4.19 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;
}
```

4.20 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.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)]];
  }
};
```

4.21 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;
}
```

4.22 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 capacity;
  vi parent;

  maxflow(int _n) : n(_n), g(n), capacity(n, vll(n)), parent(n) {}

  void add(int u, int v, ll c, bool set = true) {
    g[u].emplace_back(v);
    g[v].emplace_back(u);
    if (set)
      capacity[u][v] = c;
    else
      capacity[u][v] += c;
  }

  ll bfs(int s, int t) {
    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 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 = parent[cur];
        capacity[prev][cur] -= new_flow;
```

```
        capacity[cur][prev] += new_flow;
        cur = prev;
      }
    }

    return flow;
  }
};
```

4.23 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 = oo) {
    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);
  }
};
```

4.24 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({oo, 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 0ll;
  }

  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;
  }
};
```

4.25 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_childs;
  vector<int> sizes, values, ans;
  set<int> cnt;

  SmallToLarge(vector<vector<int>> &&g, vector<int> &&v)
    : tree(g), vis_childs(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;
    }

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

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

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

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

    update_ans(u);

    if (!keep) {
      for (auto x : vis_childs[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];
      }
    }
  }
};
```

4.26 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;
}
```

4.27 Topological Sorting

Assumes that :

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

$O(V)$

```cpp
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;
}
```

4.28 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 .

```cpp
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);      // O(V)
  auto [node2, dist2] = mostDistantFrom(adj, n, node1);  // O(V)
  auto diameter = twoNodesDist(adj, n, node1, node2);    // O(V)
  return diameter;
}
```

5 Math

5.1 GCD (with factorization)

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

```cpp
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

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

5.3 LCM (with factorization)

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

```cpp
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 vctor 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)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 /= 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 Fourrier 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 : 1ll)) % 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;
```

```cpp
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

$O(\sqrt{N})$

```cpp
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 $O(\sqrt{N})$

```cpp
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 $K^0 + K^1 + ... + K^n$

```cpp
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 $O(MAXN)$ in memory.

```cpp
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 $T_n >= 2 \cdot T_{n-1} + 1$, 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;
```

```cpp
  if (n == 1) return a;
  ll x = fpow(a, n / 2, mod) % mod;
  return ((x * x) % mod * (n & 1 ? a : 1ll)) % 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 Double Hash Range Query

```cpp
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 - l + 1] % MOD : 0));
    ll hash2 = (hi2[l] - (r + 1 < n ? hi2[r + 1] * p2[r - l + 1] % MOD2 : 0));
    return {(hash < 0 ? hash + MOD : hash), (hash2 < 0 ? hash2 + MOD2 : hash2)
    };
  }
};
```

8.3 Hash Range Query

```cpp
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;
  }
};
```

8.4 K-th digit in digit string

Find the k-th digit in a *digit string*, only works for $1 <= k <= 10^{18}$!
Time: precompute $O(1)$, query $O(1)$

```cpp
using vull = vector<ull>;
vull 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';
}
```

8.5 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(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;
}
```

8.6 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;
}
```

8.7 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];
  }
}
```

8.8 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 occurences
    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 occurences of a given string t
  int countOccurences(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 firstOccurence(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 everyOccurence(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);
}
};
```

8.9 Z-function get occurence positions

$O(len(s) + len(p))$

```
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 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);
```

```cpp
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)
```

9.3 .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
```

9.4 .bashrc

```bash
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
}
```

9.5 macro.cpp

```
#include <bits/stdc++.h>
using namespace std;
#ifdef LOCAL
#include "debug.cpp"
#endif
#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 pb(___x) push_back(___x)
#define mp(___a, ___b) make_pair(___a, ___b)
#define eb(___x) emplace_back(___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;

auto solve() {}
int32_t main(void) {
#ifndef LOCAL
  fastio;
#endif

  int t;
  t = 1;
  // cin >> t;
  for (int i = 1; i <= t; i++) {
    solve();
  }
}
```