Contents

1 All Macros

```
//#pragma GCC optimize("Ofast")
//#pragma GCC optimization ("O3")
//#pragma comment(linker, "/stack:200000000")
//#pragma GCC optimize("unroll-loops")
//#pragma GCC target("sse,sse2,sse3,ssse3,sse4,popcnt,abm
    ,mmx,avx,tune=native")

#include <ext/pb_ds/assoc_container.hpp>
#include <ext/pb_ds/tree_policy.hpp>
using namespace __gnu_pbds;
    //find_by_order(k) --> returns iterator to the kth
        largest element counting from 0
    //order_of_key(val) --> returns the number of items
        in a set that are strictly smaller than our item
template <typename DT>
using ordered_set = tree <DT, null_type, less<DT>,
    rb_tree_tag,tree_order_statistics_node_update>;

/*--- DEBUG TEMPLATE STARTS HERE ---*/
#ifdef LOCAL
void show(int x) {cerr << x;}
void show(long long x) {cerr << x;}
void show(double x) {cerr << x;}
void show(char x) {cerr << '\'' << x << '\'';}
void show(const string &x) {cerr << '\"' << x << '\"';}
void show(bool x) {cerr << (x ? "true" : "false");}

template<typename T, typename V>
void show(pair<T, V> x) { cerr << '{'; show(x.first);
    cerr << ", "; show(x.second); cerr << '}'; }
template<typename T>
void show(T x) {int f = 0; cerr << "{"; for (auto &i: x)
    cerr << (f++ ? ", " : ""), show(i); cerr << "}";}

void debug_out(string s) {
    cerr << '\n';
}
template <typename T, typename... V>
void debug_out(string s, T t, V... v) {
    s.erase(remove(s.begin(), s.end(), ' '), s.end());
    cerr << "      "; // 8 spaces
    cerr << s.substr(0, s.find(','));
    s = s.substr(s.find(',') + 1);
    cerr << " = ";
    show(t);
    cerr << endl;
    if(sizeof...(v)) debug_out(s, v...);
}

#define dbg(x...) cerr << "LINE: " << __LINE__ << endl;
    debug_out(#x, x); cerr << endl;
#else
#define dbg(x...)
#endif

const int RANDOM = chrono::high_resolution_clock::now().
    time_since_epoch().count();
unsigned hash_f(unsigned x) {
  x = ((x >> 16) ^ x) * 0x45d9f3b;
  x = ((x >> 16) ^ x) * 0x45d9f3b;
  return x = (x >> 16) ^ x;
}

unsigned hash_combine(unsigned a, unsigned b) { return a
    * 31 + b; }
struct chash {
  int operator()(int x) const { return hash_f(x); }
};
typedef gp_hash_table<int, int, chash> gp;
gp table;

mt19937_64 rng(RANDOM);

long long random(long long l, long long r) {
    uniform_int_distribution<long long> dist(l, r);
    return dist(rng);
}
```

2 Data Structure

2.1 Segment Tree

```
const int N = 1000006;
using DT = LL;
using LT = LL;
constexpr DT I = 0;
constexpr LT None = 0;
DT val[4 * N];
LT lazy[4 * N];
int L, R;
void pull(int s, int e, int u) {
  val[u] = val[u << 1] + val[u << 1 | 1];
}
void apply(const LT &uval, int s, int e, int u) {
  if (uval == None) return;
  val[u] += (e - s + 1) * uval;
  lazy[u] += uval;
}
void reset(int u) { lazy[u] = None; }
DT merge(const DT &a, const DT &b) { return a + b; }
DT get(int s, int e, int u) { return val[u]; }
void push(int s, int e, int u) {
  if (s == e) return;
  apply(lazy[u], s, s + e >> 1, u << 1);
  apply(lazy[u], s + e + 2 >> 1, e, u << 1 | 1);
  reset(u);
}
void build(int s, int e, vector<DT> &v, int u = 1) {
  reset(u);
  if (s == e) {
    val[u] = v[s];
    return;
  }
  int m = s + e >> 1;
  build(s, m, v, u<<1);
  build(m + 1, e, v, u<<1|1);
  pull(s, e, u);
}
void update(int l, int r, LT uval, int s = L, int e = R,
    int u = 1) {
  if (l > e or s > r) return;
  if (l <= s and e <= r) {
    apply(uval, s, e, u);
    return;
  }
  push(s, e, u);
  int m = s+e >> 1;
  update(l, r, uval, s, m, u<<1);
  update(l, r, uval, m+1, e, u<<1|1);
  pull(s, e, u);
}
DT query(int l, int r, int s = L, int e = R, int u = 1) {
  if (l > e or s > r) return I;
  if (l <= s and e <= r) return get(s, e, u);
  push(s, e, u);
  int m = s+e >> 1;
  DT ql = query(l, r, s, m, u<<1),
     qr = query(l, r, m+1, e, u<<1|1);
  return merge(ql, qr);
}
void init(int _L, int _R, vector<DT> &v) {
  L = _L, R = _R;
  build(L, R, v);
}
```

2.2 Persistent Segment Tree

```
struct Node {
    int l = 0, r = 0, val = 0;
} tr[20 * N];
int ptr = 0;
int build(int st, int en) {
    int u = ++ptr;
    if (st == en) return u;
    int mid = (st + en) / 2;
    auto& [l, r, val] = tr[u];
    l = build(st, mid);
    r = build(mid + 1, en);
    val = tr[l].val + tr[r].val;
    return u;
}

int update(int pre, int st, int en, int idx, int v) {
    int u = ++ptr;
    tr[u] = tr[pre];
    if (st == en) {
        tr[u].val += v;
        return u;
    }
    int mid = (st + en) / 2;
    auto& [l, r, val] = tr[u];
    if (idx <= mid) {
        r = tr[pre].r;
        l = update(tr[pre].l, st, mid, idx, v);
    } else {
        l = tr[pre].l;
        r = update(tr[pre].r, mid + 1, en, idx, v);
    }
    tr[u].val = tr[l].val + tr[r].val;
    return u;
}
// finding the kth elelment in a range
int query(int left, int right, int st, int en, int k) {
    if (st == en) return st;
    int cnt = tr[tr[right].l].val - tr[tr[left].l].val;
    int mid = (st + en) / 2;
    if (cnt >= k) return query(tr[left].l, tr[right].l,
        st, mid, k);
    else return query(tr[left].r, tr[right].r, mid + 1,
        en, k - cnt);
}
int V[N], root[N], a[N];
int main() {
    map<int, int> mp; int n, q;
    cin >> n >> q;
    for (int i = 1; i <= n; i++) cin >> a[i], mp[a[i]];
    int c = 0;
    for (auto x : mp) mp[x.first] = ++c, V[c] = x.first;
    root[0] = build(1, n);
    for (int i = 1; i <= n; i++) {
        root[i] = update(root[i - 1], 1, n, mp[a[i]], 1);
    }
    while (q--) {
        int l, r, k; cin >> l >> r >> k; l++, k++;
        cout << V[query(root[l - 1], root[r], 1, n, k)]
            << '\n';
    }
    return 0;
}
```

2.3 Lazy Persistent Segment Tree

```
struct node {
    int val;
    int lazy;
    int left, right;
} nodes[MAXN];
int sz = 0;
int a[MAXN];
int build(int s, int e) {
    int curr = sz;
    sz++;
    if(s == e) {
        nodes[curr].left = nodes[curr].right = -1;
        nodes[curr].val = a[s];
        nodes[curr].lazy = 0;
        return curr;
    }
    int m = (s + e) / 2;
    nodes[curr].left = build(s, m);
    nodes[curr].right = build(m + 1, e);
    nodes[curr].val = nodes[nodes[curr].left].val + nodes
        [nodes[curr].right].val;
    return curr;
}
int update(int prev, int s, int e, int l, int r, int val)
    {
    if(s > r or e < l) return prev;
    int curr = sz;
    sz++;
    if(s >= l and e <= r) {
        nodes[curr].left = nodes[prev].left;
        nodes[curr].right = nodes[prev].right;
        nodes[curr].val = nodes[prev].val + val*(e-s+1);
        nodes[curr].lazy = nodes[prev].lazy + val;
        return curr;
    }
    int m = (s + e) / 2;
    nodes[curr].left = update(nodes[prev].left, s, m, l,
        r, val);
    nodes[curr].right = update(nodes[prev].right, m+1, e,
        l, r, val);
    nodes[curr].lazy = nodes[prev].lazy;
    nodes[curr].val = nodes[nodes[curr].left].val + nodes
        [nodes[curr].right].val + nodes[curr].lazy*(e-s
        +1);
    return curr;
}
ll query(int nd, int s, int e, int l, int r, ll c) {
    if(s > r or e < l) return 0;
    if(s >= l and e <= r) return c*(e-s+1) + nodes[nd].
        val;
    int m = (s+e)/2;
    c += nodes[nd].lazy;
    return query(nodes[nd].left, s, m, l, r, c) + query(
        nodes[nd].right, m+1, e, l, r, c);
}
```

2.4 Implicit Segment Tree

```
struct node {
    ll val;
    ll lazy;
    int left, right;
};
node nodes[4*1000006];
int sz;
void reset(int nd) {
    nodes[nd].left = nodes[nd].right = -1;
    nodes[nd].val = nodes[nd].lazy = 0;
}
int getLeft(int nd) {
    if(nodes[nd].left == -1) {
        nodes[nd].left = sz++;
        reset(nodes[nd].left);
    }
    return nodes[nd].left;
}
int getRight(int nd) {
    if(nodes[nd].right == -1) {
        nodes[nd].right = sz++;
        reset(nodes[nd].right);
    }
    return nodes[nd].right;
}
```

```
void update(int nd, int s, int e, int l, int r, ll val) {
    if(e < l or s > r) return;
    if(s >= l and e <= r) {
        nodes[nd].val += val*(e-s + 1);
        nodes[nd].lazy += val;
        return;
    }
    int m = (s + e) / 2;
    update(getLeft(nd), s, m, l ,r, val);
    update(getRight(nd), m+1, e, l, r, val);
    nodes[nd].val = nodes[nodes[nd].left].val + nodes[
        nodes[nd].right].val + nodes[nd].lazy * (e-s+1);
}
ll query(int nd, int s, int e, int l, int r, ll c) {
    if(s > r or e < l) return 0;
    if(s >= l and e <= r) {
        return nodes[nd].val + c*(e-s+1);
    }
    int m = (s+e)/2;
    c += nodes[nd].lazy;
    return query(getLeft(nd), s, m, l, r, c) + query(
        getRight(nd), m+1, e, l, r, c);
}
```

2.5 DSU With Rollbacks

```
struct Rollback_DSU {
  int n;
  vector<int> par, sz;
  vector<pair<int, int>> op;
  Rollback_DSU(int n) : par(n), sz(n, 1) {
    iota(par.begin(), par.end(), 0);
    op.reserve(n);
  }
  int Anc(int node) {
    for (; node != par[node]; node = par[node])
      ; // no path compression
    return node;
  }
  void Unite(int x, int y) {
    if (sz[x = Anc(x)] < sz[y = Anc(y)]) swap(x, y);
    op.emplace_back(x, y);
    par[y] = x;
    sz[x] += sz[y];
  }
  void Undo(int t) {
    for (; op.size() > t; op.pop_back()) {
      par[op.back().second] = op.back().second;
      sz[op.back().first] -= sz[op.back().second];
    }
  }
};
```

2.6 BIT-2D

```
const int N = 1008;
int bit[N][N], n, m;
int a[N][N], q;
void update(int x, int y, int val) {
  for (; x < N; x += -x & x)
    for (int j = y; j < N; j += -j & j) bit[x][j] += val;
}
int get(int x, int y) {
  int ans = 0;
  for (; x; x -= x & -x)
    for (int j = y; j; j -= j & -j) ans += bit[x][j];
  return ans;
}
int get(int x1, int y1, int x2, int y2) {
  return get(x2, y2) - get(x1 - 1, y2) - get(x2, y1 - 1)
      + get(x1 - 1, y1 - 1);
}
```

2.7 Merge Sort Tree

```
vector<LL> Tree[4 * MAXN];
LL arr[MAXN];

vector<LL> merge(vector<LL> v1, vector<LL> v2) {
  LL i = 0, j = 0;
  vector<LL> ret;

  while (i < v1.size() || j < v2.size()) {
    if (i == v1.size()) {
      ret.push_back(v2[j]);
      j++;
    } else if (j == v2.size()) {
      ret.push_back(v1[i]);
      i++;
    } else {
      if (v1[i] < v2[j]) {
        ret.push_back(v1[i]);
        i++;
      } else {
        ret.push_back(v2[j]);
        j++;
      }
    }
  }

  return ret;
}

void Build(LL node, LL bg, LL ed) {
  if (bg == ed) {
    Tree[node].push_back(arr[bg]);
    return;
  }

  LL leftNode = 2 * node, rightNode = 2 * node + 1;
  LL mid = (bg + ed) / 2;

  Build(leftNode, bg, mid);
  Build(rightNode, mid + 1, ed);

  Tree[node] = merge(Tree[leftNode], Tree[rightNode]);
}

LL query(LL node, LL bg, LL ed, LL l, LL r, LL k) {
  if (ed < l || bg > r) return 0;

  if (l <= bg && ed <= r)
    return upper_bound(Tree[node].begin(), Tree[node].end
        (), k) -
          Tree[node].begin();

  LL leftNode = 2 * node, rightNode = 2 * node + 1;
  LL mid = (bg + ed) / 2;

  return query(leftNode, bg, mid, l, r, k) +
        query(rightNode, mid + 1, ed, l, r, k);
}
```

2.8 MO with Update

```
const int N = 1e5 + 5, sz = 2700, bs = 25;
int arr[N], freq[2 * N], cnt[2 * N], id[N], ans[N];
struct query {
  int l, r, t, L, R;
  query(int l = 1, int r = 0, int t = 1, int id = -1)
      : l(l), r(r), t(t), L(l / sz), R(r / sz) {}
  bool operator<(const query &rhs) const {
    return (L < rhs.L) or (L == rhs.L and R < rhs.R) or
          (L == rhs.L and R == rhs.R and t < rhs.t);
  }
} Q[N];
struct update {
  int idx, val, last;
} Up[N];
int qi = 0, ui = 0;
int l = 1, r = 0, t = 0;
```

```
void add(int idx) {
  --cnt[freq[arr[idx]]];
  freq[arr[idx]]++;
  cnt[freq[arr[idx]]]++;
}
void remove(int idx) {
  --cnt[freq[arr[idx]]];
  freq[arr[idx]]--;
  cnt[freq[arr[idx]]]++;
}
void apply(int t) {
  const bool f = l <= Up[t].idx and Up[t].idx <= r;
  if (f) remove(Up[t].idx);
  arr[Up[t].idx] = Up[t].val;
  if (f) add(Up[t].idx);
}
void undo(int t) {
  const bool f = l <= Up[t].idx and Up[t].idx <= r;
  if (f) remove(Up[t].idx);
  arr[Up[t].idx] = Up[t].last;
  if (f) add(Up[t].idx);
}
int mex() {
  for (int i = 1; i <= N; i++)
    if (!cnt[i]) return i;
  assert(0);
}
int main() {
  int n, q;
  cin >> n >> q;
  int counter = 0;
  map<int, int> M;
  for (int i = 1; i <= n; i++) {
    cin >> arr[i];
    if (!M[arr[i]]) M[arr[i]] = ++counter;
    arr[i] = M[arr[i]];
  }
  iota(id, id + N, 0);
  while (q--) {
    int tp, x, y;
    cin >> tp >> x >> y;
    if (tp == 1)
      Q[++qi] = query(x, y, ui);
    else {
      if (!M[y]) M[y] = ++counter;
      y = M[y];
      Up[++ui] = {x, y, arr[x]};
      arr[x] = y;
    }
  }
  t = ui;
  cnt[0] = 3 * n;
  sort(id + 1, id + qi + 1, [&](int x, int y) { return Q[
      x] < Q[y]; });
  for (int i = 1; i <= qi; i++) {
    int x = id[i];
    while (Q[x].t > t) apply(++t);
    while (Q[x].t < t) undo(t--);
    while (Q[x].l < l) add(--l);
    while (Q[x].r > r) add(++r);
    while (Q[x].l > l) remove(l++);
    while (Q[x].r < r) remove(r--);
    ans[x] = mex();
  }
  for (int i = 1; i <= qi; i++) cout << ans[i] << '\n';
}
```

2.9 SparseTable (Rectangle Query)

```
#include <bits/stdc++.h>
using namespace std;

const int MAXN = 505;
const int LOGN = 9;

// O(n^2 (logn)^2
// Supports Rectangular Query
int A[MAXN][MAXN];
int M[MAXN][MAXN][LOGN][LOGN];

void Build2DSparse(int N) {
  for (int i = 1; i <= N; i++) {
    for (int j = 1; j <= N; j++) {
      M[i][j][0][0] = A[i][j];
    }
    for (int q = 1; (1 << q) <= N; q++) {
      int add = 1 << (q - 1);
      for (int j = 1; j + add <= N; j++) {
        M[i][j][0][q] = max(M[i][j][0][q - 1], M[i][j +
            add][0][q - 1]);
      }
    }
  }

  for (int p = 1; (1 << p) <= N; p++) {
    int add = 1 << (p - 1);
    for (int i = 1; i + add <= N; i++) {
      for (int q = 0; (1 << q) <= N; q++) {
        for (int j = 1; j <= N; j++) {
          M[i][j][p][q] = max(M[i][j][p - 1][q], M[i + add
              ][j][p - 1][q]);
        }
      }
    }
  }
}

// returns max of all A[i][j], where x1<=i<=x2 and y1<=j
    <=y2
int Query(int x1, int y1, int x2, int y2) {
  int kX = log2(x2 - x1 + 1);
  int kY = log2(y2 - y1 + 1);
  int addX = 1 << kX;
  int addY = 1 << kY;

  int ret1 = max(M[x1][y1][kX][kY], M[x1][y2 - addY + 1][
      kX][kY]);
  int ret2 = max(M[x2 - addX + 1][y1][kX][kY],
                 M[x2 - addX + 1][y2 - addY + 1][kX][kY]);
  return max(ret1, ret2);
}
```

2.10 Sparse Table

```
// 0-based indexing, query finds in range [first, last]
#define lg(x) (31 - __builtin_clz(x))
const int N = 1e5 + 1;
const int K = lg(N);
int a[N], tr[N][K + 1];
namespace sparse_table {
  int f(int p1, int p2) { return min(p1, p2); }
  void build() {
    for(int i = 0; i < n; i++)
      tr[i][0] = a[i];
    for(int j = 1; j <= K; j++) {
      for(int i = 0; i + (1<<j) <= n; i++)
        tr[i][j] = f(tr[i][j - 1], tr[i + (1<<(j - 1))][j
            - 1]);
    }
  }
  int query(int l, int r) {
    int d = lg(r - l + 1);
    return f(table[l][d], table[r - (1<<d) + 1][d]);
  }
}
```

3 DP

3.1 Convex Hull Trick

```
struct line {
  ll m, c;
  line() {}
  line(ll m, ll c) : m(m), c(c) {}
};
struct convex_hull_trick {
  vector<line> lines;
  int ptr = 0;
  convex_hull_trick() {}
  bool bad(line a, line b, line c) {
    return 1.0 * (c.c - a.c) * (a.m - b.m) < 1.0 * (b.c -
        a.c) * (a.m - c.m);
  }
  void add(line L) {
    int sz = lines.size();
    while (sz >= 2 && bad(lines[sz - 2], lines[sz - 1], L
        )) {
      lines.pop_back();
      sz--;
    }
    lines.pb(L);
  }
  ll get(int idx, int x) { return (1ll * lines[idx].m * x
      + lines[idx].c); }
  ll query(int x) {
    if (lines.empty()) return 0;
    if (ptr >= lines.size()) ptr = lines.size() - 1;
    while (ptr < lines.size() - 1 && get(ptr, x) > get(
        ptr + 1, x)) ptr++;
    return get(ptr, x);
  }
};
ll sum[MAX];
ll dp[MAX];
int arr[MAX];
int main() {
  fastio;
  int t;
  cin >> t;
  while (t--) {
    int n, a, b, c;
    cin >> n >> a >> b >> c;
    for (int i = 1; i <= n; i++) cin >> sum[i];
    for (int i = 1; i <= n; i++) dp[i] = 0, sum[i] += sum
        [i - 1];
    convex_hull_trick cht;
    cht.add(line(0, 0));
    for (int pos = 1; pos <= n; pos++) {
      dp[pos] = cht.query(sum[pos]) - 1ll * a * sqr(sum[
          pos]) - c;
      cht.add(line(2ll * a * sum[pos], dp[pos] - a * sqr(
          sum[pos])));
    }
    ll ans = (-1ll * dp[n]);
    ans += (1ll * sum[n] * b);
    cout << ans << "\n";
  }
}
```

3.2 Dynamic CHT

```
#include <bits/stdc++.h>

using namespace std;

typedef long long ll;

const ll IS_QUERY = -(1LL << 62);

struct line {
  ll m, b;
  mutable function <const line*()> succ;

  bool operator < (const line &rhs) const {
    if (rhs.b != IS_QUERY) return m < rhs.m;
    const line *s = succ();
    if (!s) return 0;
    ll x = rhs.m;
    return b - s -> b < (s -> m - m) * x;
  }
};

struct HullDynamic : public multiset <line> {
  bool bad (iterator y) {
    auto z = next(y);
    if (y == begin()) {
      if (z == end()) return 0;
      return y -> m == z -> m && y -> b <= z -> b;
    }
    auto x = prev(y);
    if (z == end()) return y -> m == x -> m && y -> b <=
        x -> b;
    return 1.0 * (x -> b - y -> b) * (z -> m - y -> m) >=
        1.0 * (y -> b - z -> b) * (y -> m - x -> m);
  }
  void insert_line (ll m, ll b) {
    auto y = insert({m, b});
    y -> succ = [=] {return next(y) == end() ? 0 : &*next
        (y);};
    if (bad(y)) {erase(y); return;}
    while (next(y) != end() && bad(next(y))) erase(next(y
        ));
    while (y != begin() && bad(prev(y))) erase(prev(y));
  }

  ll eval (ll x) {
    auto l = *lower_bound((line) {x, IS_QUERY});
    return l.m * x + l.b;
  }
};

int main() {
  HullDynamic hull;
  hull.insert_line(1, 1);
  hull.insert_line(-1, 1);
  cout << hull.eval(69) << endl;
  cout << hull.eval(420) << endl;
  return 0;
}
```

3.3 Li Chao Tree

```
struct line {
  LL m, c;
  line(LL m = 0, LL c = 0) : m(m), c(c) {}
};
LL calc(line L, LL x) { return 1LL * L.m * x + L.c; }
struct node {
  LL m, c;
  line L;
  node *lft, *rt;
  node(LL m = 0, LL c = 0, node *lft = NULL, node *rt =
      NULL)
      : L(line(m, c)), lft(lft), rt(rt) {}
};
struct LiChao {
  node *root;
  LiChao() { root = new node(); }
  void update(node *now, int L, int R, line newline) {
    int mid = L + (R - L) / 2;
    line lo = now->L, hi = newline;
    if (calc(lo, L) > calc(hi, L)) swap(lo, hi);
    if (calc(lo, R) <= calc(hi, R)) {
      now->L = hi;
      return;
```

```
    }
    if (calc(lo, mid) < calc(hi, mid)) {
      now->L = hi;
      if (now->rt == NULL) now->rt = new node();
      update(now->rt, mid + 1, R, lo);
    } else {
      now->L = lo;
      if (now->lft == NULL) now->lft = new node();
      update(now->lft, L, mid, hi);
    }
  }
  LL query(node *now, int L, int R, LL x) {
    if (now == NULL) return -inf;
    int mid = L + (R - L) / 2;
    if (x <= mid)
      return max(calc(now->L, x), query(now->lft, L, mid,
          x));
    else
      return max(calc(now->L, x), query(now->rt, mid + 1,
          R, x));
  }
};
```

4 Geometry

4.1 Point

```
typedef double Tf;
typedef double Ti; /// use long long for exactness
const Tf PI = acos(-1), EPS = 1e-9;
int dcmp(Tf x) { return abs(x) < EPS ? 0 : (x < 0 ? -1 :
    1); }

struct Point {
  Ti x, y;
  Point(Ti x = 0, Ti y = 0) : x(x), y(y) {}

  Point operator+(const Point& u) const { return Point(x
      + u.x, y + u.y); }
  Point operator-(const Point& u) const { return Point(x
      - u.x, y - u.y); }
  Point operator*(const LL u) const { return Point(x * u,
       y * u); }
  Point operator*(const Tf u) const { return Point(x * u,
       y * u); }
  Point operator/(const Tf u) const { return Point(x / u,
       y / u); }

  bool operator==(const Point& u) const {
    return dcmp(x - u.x) == 0 && dcmp(y - u.y) == 0;
  }
  bool operator!=(const Point& u) const { return !(*this
      == u); }
  bool operator<(const Point& u) const {
    return dcmp(x - u.x) < 0 || (dcmp(x - u.x) == 0 &&
        dcmp(y - u.y) < 0);
  }
};
Ti dot(Point a, Point b) { return a.x * b.x + a.y * b.y;
    }
Ti cross(Point a, Point b) { return a.x * b.y - a.y * b.x
    ; }
Tf length(Point a) { return sqrt(dot(a, a)); }
Ti sqLength(Point a) { return dot(a, a); }
Tf distance(Point a, Point b) { return length(a - b); }
Tf angle(Point u) { return atan2(u.y, u.x); }

// returns angle between oa, ob in (-PI, PI]
Tf angleBetween(Point a, Point b) {
  Tf ans = angle(b) - angle(a);
  return ans <= -PI ? ans + 2 * PI : (ans > PI ? ans - 2
      * PI : ans);
}
// Rotate a ccw by rad radians, Tf Ti same
Point rotate(Point a, Tf rad) {
  return Point(a.x * cos(rad) - a.y * sin(rad),
               a.x * sin(rad) + a.y * cos(rad));
}
// rotate a ccw by angle th with cos(th) = co && sin(th)
    = si, tf ti same
Point rotatePrecise(Point a, Tf co, Tf si) {
  return Point(a.x * co - a.y * si, a.y * co + a.x * si);
}
Point rotate90(Point a) { return Point(-a.y, a.x); }
// scales vector a by s such that length of a becomes s,
    Tf Ti same
Point scale(Point a, Tf s) { return a / length(a) * s; }
// returns an unit vector perpendicular to vector a, Tf
    Ti same
Point normal(Point a) {
  Tf l = length(a);
  return Point(-a.y / l, a.x / l);
}
// returns 1 if c is left of ab, 0 if on ab && -1 if
    right of ab
int orient(Point a, Point b, Point c) { return dcmp(cross
    (b - a, c - a)); }
/// Use as sort(v.begin(), v.end(), polarComp(O, dir))
/// Polar comparator around O starting at direction dir
struct polarComp {
  Point O, dir;
  polarComp(Point O = Point(0, 0), Point dir = Point(1,
      0)) : O(O), dir(dir) {}
  bool half(Point p) {
    return dcmp(cross(dir, p)) < 0 ||
           (dcmp(cross(dir, p)) == 0 && dcmp(dot(dir, p))
               > 0);
  }
  bool operator()(Point p, Point q) {
    return make_tuple(half(p), 0) < make_tuple(half(q),
        cross(p, q));
  }
};
struct Segment {
  Point a, b;
  Segment(Point aa, Point bb) : a(aa), b(bb) {}
};
typedef Segment Line;
struct Circle {
  Point o;
  Tf r;
  Circle(Point o = Point(0, 0), Tf r = 0) : o(o), r(r) {}
  // returns true if point p is in || on the circle
  bool contains(Point p) { return dcmp(sqLength(p - o) -
      r * r) <= 0; }
  // returns a point on the circle rad radians away from
      +X CCW
  Point point(Tf rad) {
    static_assert(is_same<Tf, Ti>::value);
    return Point(o.x + cos(rad) * r, o.y + sin(rad) * r);
  }
  // area of a circular sector with central angle rad
  Tf area(Tf rad = PI + PI) { return rad * r * r / 2; }
  // area of the circular sector cut by a chord with
      central angle alpha
  Tf sector(Tf alpha) { return r * r * 0.5 * (alpha - sin
      (alpha)); }
};
```

4.2 Linear

```
// **** LINE LINE INTERSECTION START ****
// returns true if point p is on segment s
bool onSegment(Point p, Segment s) {
  return dcmp(cross(s.a - p, s.b - p)) == 0 && dcmp(dot(s
      .a - p, s.b - p)) <= 0;
}
// returns true if segment p && q touch or intersect
bool segmentsIntersect(Segment p, Segment q) {
```

```
  if (onSegment(p.a, q) || onSegment(p.b, q)) return true
      ;
  if (onSegment(q.a, p) || onSegment(q.b, p)) return true
      ;

  Ti c1 = cross(p.b - p.a, q.a - p.a);
  Ti c2 = cross(p.b - p.a, q.b - p.a);
  Ti c3 = cross(q.b - q.a, p.a - q.a);
  Ti c4 = cross(q.b - q.a, p.b - q.a);
  return dcmp(c1) * dcmp(c2) < 0 && dcmp(c3) * dcmp(c4) <
      0;
}
bool linesParallel(Line p, Line q) {
  return dcmp(cross(p.b - p.a, q.b - q.a)) == 0;
}
// lines are represented as a ray from a point: (point,
    vector)
// returns false if two lines (p, v) && (q, w) are
    parallel or collinear
// true otherwise, intersection point is stored at o via
    reference, Tf Ti Same
bool lineLineIntersection(Point p, Point v, Point q,
    Point w, Point& o) {
  if (dcmp(cross(v, w)) == 0) return false;
  Point u = p - q;
  o = p + v * (cross(w, u) / cross(v, w));
  return true;
}
// returns false if two lines p && q are parallel or
    collinear
// true otherwise, intersection point is stored at o via
    reference
bool lineLineIntersection(Line p, Line q, Point& o) {
  return lineLineIntersection(p.a, p.b - p.a, q.a, q.b -
      q.a, o);
}
// returns the distance from point a to line l
// **** LINE LINE INTERSECTION FINISH ****
Tf distancePointLine(Point p, Line l) {
  return abs(cross(l.b - l.a, p - l.a) / length(l.b - l.a
      ));
}
// returns the shortest distance from point a to segment
    s
Tf distancePointSegment(Point p, Segment s) {
  if (s.a == s.b) return length(p - s.a);
  Point v1 = s.b - s.a, v2 = p - s.a, v3 = p - s.b;
  if (dcmp(dot(v1, v2)) < 0)
    return length(v2);
  else if (dcmp(dot(v1, v3)) > 0)
    return length(v3);
  else
    return abs(cross(v1, v2) / length(v1));
}
// returns the shortest distance from segment p to
    segment q
Tf distanceSegmentSegment(Segment p, Segment q) {
  if (segmentsIntersect(p, q)) return 0;
  Tf ans = distancePointSegment(p.a, q);
  ans = min(ans, distancePointSegment(p.b, q));
  ans = min(ans, distancePointSegment(q.a, p));
  ans = min(ans, distancePointSegment(q.b, p));
  return ans;
}
// returns the projection of point p on line l, Tf Ti
    Same
Point projectPointLine(Point p, Line l) {
  Point v = l.b - l.a;
  return l.a + v * ((Tf)dot(v, p - l.a) / dot(v, v));
}
```

4.3 Circular

```
// Extremely inaccurate for finding near touches
// compute intersection of line l with circle c
// The intersections are given in order of the ray (l.a,
    l.b), Tf Ti same
vector<Point> circleLineIntersection(Circle c, Line l) {
  vector<Point> ret;
  Point b = l.b - l.a, a = l.a - c.o;
  Tf A = dot(b, b), B = dot(a, b);
  Tf C = dot(a, a) - c.r * c.r, D = B * B - A * C;
  if (D < -EPS) return ret;
  ret.push_back(l.a + b * (-B - sqrt(D + EPS)) / A);
  if (D > EPS) ret.push_back(l.a + b * (-B + sqrt(D)) / A
      );
  return ret;
}
// signed area of intersection of circle(c.o, c.r) &&
// triangle(c.o, s.a, s.b) [cross(a-o, b-o)/2]
Tf circleTriangleIntersectionArea(Circle c, Segment s) {
  using Linear::distancePointSegment;
  Tf OA = length(c.o - s.a);
  Tf OB = length(c.o - s.b);
  // sector
  if (dcmp(distancePointSegment(c.o, s) - c.r) >= 0)
    return angleBetween(s.a - c.o, s.b - c.o) * (c.r * c.
        r) / 2.0;
  // triangle
  if (dcmp(OA - c.r) <= 0 && dcmp(OB - c.r) <= 0)
    return cross(c.o - s.b, s.a - s.b) / 2.0;
  // three part: (A, a) (a, b) (b, B)
  vector<Point> Sect = circleLineIntersection(c, s);
  return circleTriangleIntersectionArea(c, Segment(s.a,
      Sect[0])) +
        circleTriangleIntersectionArea(c, Segment(Sect
            [0], Sect[1])) +
        circleTriangleIntersectionArea(c, Segment(Sect
            [1], s.b));
}
// area of intersecion of circle(c.o, c.r) && simple
    polyson(p[])
Tf circlePolyIntersectionArea(Circle c, Polygon p) {
  Tf res = 0;
  int n = p.size();
  for (int i = 0; i < n; ++i)
    res += circleTriangleIntersectionArea(c, Segment(p[i
        ], p[(i + 1) % n]));
  return abs(res);
}
// locates circle c2 relative to c1
// interior           (d < R - r)       ----> -2
// interior tangents (d = R - r)     ----> -1
// concentric      (d = 0)
// secants           (R - r < d < R + r) ----> 0
// exterior tangents (d = R + r)     ----> 1
// exterior           (d > R + r)       ----> 2
int circleCirclePosition(Circle c1, Circle c2) {
  Tf d = length(c1.o - c2.o);
  int in = dcmp(d - abs(c1.r - c2.r)), ex = dcmp(d - (c1.
      r + c2.r));
  return in < 0 ? -2 : in == 0 ? -1 : ex == 0 ? 1 : ex >
      0 ? 2 : 0;
}
// compute the intersection points between two circles c1
    && c2, Tf Ti same
vector<Point> circleCircleIntersection(Circle c1, Circle
    c2) {
  vector<Point> ret;
  Tf d = length(c1.o - c2.o);
  if (dcmp(d) == 0) return ret;
  if (dcmp(c1.r + c2.r - d) < 0) return ret;
  if (dcmp(abs(c1.r - c2.r) - d) > 0) return ret;

  Point v = c2.o - c1.o;
  Tf co = (c1.r * c1.r + sqLength(v) - c2.r * c2.r) / (2
      * c1.r * length(v));
  Tf si = sqrt(abs(1.0 - co * co));
```

```
  Point p1 = scale(rotatePrecise(v, co, -si), c1.r) + c1.
      o;
  Point p2 = scale(rotatePrecise(v, co, si), c1.r) + c1.o
      ;

  ret.push_back(p1);
  if (p1 != p2) ret.push_back(p2);
  return ret;
}
// intersection area between two circles c1, c2
Tf circleCircleIntersectionArea(Circle c1, Circle c2) {
  Point AB = c2.o - c1.o;
  Tf d = length(AB);
  if (d >= c1.r + c2.r) return 0;
  if (d + c1.r <= c2.r) return PI * c1.r * c1.r;
  if (d + c2.r <= c1.r) return PI * c2.r * c2.r;

  Tf alpha1 = acos((c1.r * c1.r + d * d - c2.r * c2.r) /
      (2.0 * c1.r * d));
  Tf alpha2 = acos((c2.r * c2.r + d * d - c1.r * c1.r) /
      (2.0 * c2.r * d));
  return c1.sector(2 * alpha1) + c2.sector(2 * alpha2);
}
// returns tangents from a point p to circle c, Tf Ti
    same
vector<Point> pointCircleTangents(Point p, Circle c) {
  vector<Point> ret;
  Point u = c.o - p;
  Tf d = length(u);
  if (d < c.r)
    ;
  else if (dcmp(d - c.r) == 0) {
    ret = {rotate(u, PI / 2)};
  } else {
    Tf ang = asin(c.r / d);
    ret = {rotate(u, -ang), rotate(u, ang)};
  }
  return ret;
}
// returns the points on tangents that touches the circle
    , Tf Ti Same
vector<Point> pointCircleTangencyPoints(Point p, Circle c
    ) {
  Point u = p - c.o;
  Tf d = length(u);
  if (d < c.r)
    return {};
  else if (dcmp(d - c.r) == 0)
    return {c.o + u};
  else {
    Tf ang = acos(c.r / d);
    u = u / length(u) * c.r;
    return {c.o + rotate(u, -ang), c.o + rotate(u, ang)};
  }
}
// for two circles c1 && c2, returns two list of points a
    && b
// such that a[i] is on c1 && b[i] is c2 && for every i
// Line(a[i], b[i]) is a tangent to both circles
// CAUTION: a[i] = b[i] in case they touch | -1 for c1 =
    c2
int circleCircleTangencyPoints(Circle c1, Circle c2,
    vector<Point> &a,
                               vector<Point> &b) {
  a.clear(), b.clear();
  int cnt = 0;
  if (dcmp(c1.r - c2.r) < 0) {
    swap(c1, c2);
    swap(a, b);
  }
  Tf d2 = sqLength(c1.o - c2.o);
  Tf rdif = c1.r - c2.r, rsum = c1.r + c2.r;
  if (dcmp(d2 - rdif * rdif) < 0) return 0;
  if (dcmp(d2) == 0 && dcmp(c1.r - c2.r) == 0) return -1;

  Tf base = angle(c2.o - c1.o);
  if (dcmp(d2 - rdif * rdif) == 0) {
    a.push_back(c1.point(base));
    b.push_back(c2.point(base));
    cnt++;
    return cnt;
  }

  Tf ang = acos((c1.r - c2.r) / sqrt(d2));
  a.push_back(c1.point(base + ang));
  b.push_back(c2.point(base + ang));
  cnt++;
  a.push_back(c1.point(base - ang));
  b.push_back(c2.point(base - ang));
  cnt++;

  if (dcmp(d2 - rsum * rsum) == 0) {
    a.push_back(c1.point(base));
    b.push_back(c2.point(PI + base));
    cnt++;
  } else if (dcmp(d2 - rsum * rsum) > 0) {
    Tf ang = acos((c1.r + c2.r) / sqrt(d2));
    a.push_back(c1.point(base + ang));
    b.push_back(c2.point(PI + base + ang));
    cnt++;
    a.push_back(c1.point(base - ang));
    b.push_back(c2.point(PI + base - ang));
    cnt++;
  }
  return cnt;
}
```

4.4 Convex

```
/// minkowski sum of two polygons in O(n)
Polygon minkowskiSum(Polygon A, Polygon B) {
  int n = A.size(), m = B.size();
  rotate(A.begin(), min_element(A.begin(), A.end()), A.
      end());
  rotate(B.begin(), min_element(B.begin(), B.end()), B.
      end());

  A.push_back(A[0]);
  B.push_back(B[0]);
  for (int i = 0; i < n; i++) A[i] = A[i + 1] - A[i];
  for (int i = 0; i < m; i++) B[i] = B[i + 1] - B[i];

  Polygon C(n + m + 1);
  C[0] = A.back() + B.back();
  merge(A.begin(), A.end() - 1, B.begin(), B.end() - 1, C
      .begin() + 1,
        polarComp(Point(0, 0), Point(0, -1)));
  for (int i = 1; i < C.size(); i++) C[i] = C[i] + C[i -
      1];
  C.pop_back();
  return C;
}
// finds the rectangle with minimum area enclosing a
    convex polygon and
// the rectangle with minimum perimeter enclosing a
    convex polygon
// Tf Ti Same
pair<Tf, Tf> rotatingCalipersBoundingBox(const Polygon &p
    ) {
  using Linear::distancePointLine;
  int n = p.size();
  int l = 1, r = 1, j = 1;
  Tf area = 1e100;
  Tf perimeter = 1e100;
  for (int i = 0; i < n; i++) {
    Point v = (p[(i + 1) % n] - p[i]) / length(p[(i + 1)
        % n] - p[i]);
```

```
    while (dcmp(dot(v, p[r % n] - p[i]) - dot(v, p[(r +
        1) % n] - p[i])) < 0)
      r++;
    while (j < r || dcmp(cross(v, p[j % n] - p[i]) -
                         cross(v, p[(j + 1) % n] - p[i])) <
                             0)
      j++;
    while (l < j ||
           dcmp(dot(v, p[l % n] - p[i]) - dot(v, p[(l + 1)
                % n] - p[i])) > 0)
      l++;
    Tf w = dot(v, p[r % n] - p[i]) - dot(v, p[l % n] - p[
        i]);
    Tf h = distancePointLine(p[j % n], Line(p[i], p[(i +
        1) % n]));
    area = min(area, w * h);
    perimeter = min(perimeter, 2 * w + 2 * h);
  }
  return make_pair(area, perimeter);
}
// returns the left side of polygon u after cutting it by
     ray a->b
Polygon cutPolygon(Polygon u, Point a, Point b) {
  using Linear::lineLineIntersection;
  using Linear::onSegment;

  Polygon ret;
  int n = u.size();
  for (int i = 0; i < n; i++) {
    Point c = u[i], d = u[(i + 1) % n];
    if (dcmp(cross(b - a, c - a)) >= 0) ret.push_back(c);
    if (dcmp(cross(b - a, d - c)) != 0) {
      Point t;
      lineLineIntersection(a, b - a, c, d - c, t);
      if (onSegment(t, Segment(c, d))) ret.push_back(t);
    }
  }
  return ret;
}
// returns true if point p is in or on triangle abc
bool pointInTriangle(Point a, Point b, Point c, Point p)
    {
  return dcmp(cross(b - a, p - a)) >= 0 && dcmp(cross(c -
      b, p - b)) >= 0 &&
         dcmp(cross(a - c, p - c)) >= 0;
}
// pt must be in ccw order with no three collinear points
// returns inside = -1, on = 0, outside = 1
int pointInConvexPolygon(const Polygon &pt, Point p) {
  int n = pt.size();
  assert(n >= 3);

  int lo = 1, hi = n - 1;
  while (hi - lo > 1) {
    int mid = (lo + hi) / 2;
    if (dcmp(cross(pt[mid] - pt[0], p - pt[0])) > 0)
      lo = mid;
    else
      hi = mid;
  }

  bool in = pointInTriangle(pt[0], pt[lo], pt[hi], p);
  if (!in) return 1;

  if (dcmp(cross(pt[lo] - pt[lo - 1], p - pt[lo - 1])) ==
      0) return 0;
  if (dcmp(cross(pt[hi] - pt[lo], p - pt[lo])) == 0)
      return 0;
  if (dcmp(cross(pt[hi] - pt[(hi + 1) % n], p - pt[(hi +
      1) % n])) == 0)
    return 0;
  return -1;
}
// Extreme Point for a direction is the farthest point in
     that direction
// u is the direction for extremeness
int extremePoint(const Polygon &poly, Point u) {
  int n = (int)poly.size();
  int a = 0, b = n;
  while (b - a > 1) {
    int c = (a + b) / 2;
    if (dcmp(dot(poly[c] - poly[(c + 1) % n], u)) >= 0 &&
        dcmp(dot(poly[c] - poly[(c - 1 + n) % n], u)) >=
            0) {
      return c;
    }

    bool a_up = dcmp(dot(poly[(a + 1) % n] - poly[a], u))
        >= 0;
    bool c_up = dcmp(dot(poly[(c + 1) % n] - poly[c], u))
        >= 0;
    bool a_above_c = dcmp(dot(poly[a] - poly[c], u)) > 0;

    if (a_up && !c_up)
      b = c;
    else if (!a_up && c_up)
      a = c;
    else if (a_up && c_up) {
      if (a_above_c)
        b = c;
      else
        a = c;
    } else {
      if (!a_above_c)
        b = c;
      else
        a = c;
    }
  }

  if (dcmp(dot(poly[a] - poly[(a + 1) % n], u)) > 0 &&
      dcmp(dot(poly[a] - poly[(a - 1 + n) % n], u)) > 0)
    return a;
  return b % n;
}
// For a convex polygon p and a line l, returns a list of
     segments
// of p that touch or intersect line l.
// the i'th segment is considered (p[i], p[(i + 1) modulo
     |p|])
// #1 If a segment is collinear with the line, only that
    is returned
// #2 Else if l goes through i'th point, the i'th segment
     is added
// Complexity: O(lg |p|)
vector<int> lineConvexPolyIntersection(const Polygon &p,
    Line l) {
  assert((int)p.size() >= 3);
  assert(l.a != l.b);

  int n = p.size();
  vector<int> ret;

  Point v = l.b - l.a;
  int lf = extremePoint(p, rotate90(v));
  int rt = extremePoint(p, rotate90(v) * Ti(-1));
  int olf = orient(l.a, l.b, p[lf]);
  int ort = orient(l.a, l.b, p[rt]);

  if (!olf || !ort) {
    int idx = (!olf ? lf : rt);
    if (orient(l.a, l.b, p[(idx - 1 + n) % n]) == 0)
      ret.push_back((idx - 1 + n) % n);
    else
      ret.push_back(idx);
    return ret;
  }
```

```
  if (olf == ort) return ret;

  for (int i = 0; i < 2; ++i) {
    int lo = i ? rt : lf;
    int hi = i ? lf : rt;
    int olo = i ? ort : olf;

    while (true) {
      int gap = (hi - lo + n) % n;
      if (gap < 2) break;

      int mid = (lo + gap / 2) % n;
      int omid = orient(l.a, l.b, p[mid]);
      if (!omid) {
        lo = mid;
        break;
      }
      if (omid == olo)
        lo = mid;
      else
        hi = mid;
    }
    ret.push_back(lo);
  }
  return ret;
}
// Calculate [ACW, CW] tangent pair from an external
    point
constexpr int CW = -1, ACW = 1;
bool isGood(Point u, Point v, Point Q, int dir) {
  return orient(Q, u, v) != -dir;
}
Point better(Point u, Point v, Point Q, int dir) {
  return orient(Q, u, v) == dir ? u : v;
}
Point pointPolyTangent(const Polygon &pt, Point Q, int
    dir, int lo, int hi) {
  while (hi - lo > 1) {
    int mid = (lo + hi) / 2;
    bool pvs = isGood(pt[mid], pt[mid - 1], Q, dir);
    bool nxt = isGood(pt[mid], pt[mid + 1], Q, dir);

    if (pvs && nxt) return pt[mid];
    if (!(pvs || nxt)) {
      Point p1 = pointPolyTangent(pt, Q, dir, mid + 1, hi
          );
      Point p2 = pointPolyTangent(pt, Q, dir, lo, mid -
          1);
      return better(p1, p2, Q, dir);
    }

    if (!pvs) {
      if (orient(Q, pt[mid], pt[lo]) == dir)
        hi = mid - 1;
      else if (better(pt[lo], pt[hi], Q, dir) == pt[lo])
        hi = mid - 1;
      else
        lo = mid + 1;
    }
    if (!nxt) {
      if (orient(Q, pt[mid], pt[lo]) == dir)
        lo = mid + 1;
      else if (better(pt[lo], pt[hi], Q, dir) == pt[lo])
        hi = mid - 1;
      else
        lo = mid + 1;
    }
  }

  Point ret = pt[lo];
  for (int i = lo + 1; i <= hi; i++) ret = better(ret, pt
      [i], Q, dir);
  return ret;
}
// [ACW, CW] Tangent
pair<Point, Point> pointPolyTangents(const Polygon &pt,
    Point Q) {
  int n = pt.size();
  Point acw_tan = pointPolyTangent(pt, Q, ACW, 0, n - 1);
  Point cw_tan = pointPolyTangent(pt, Q, CW, 0, n - 1);
  return make_pair(acw_tan, cw_tan);
}
```

4.5 Polygon

```
typedef vector<Point> Polygon;
// removes redundant colinear points
// polygon can't be all colinear points
Polygon RemoveCollinear(const Polygon &poly) {
  Polygon ret;
  int n = poly.size();
  for (int i = 0; i < n; i++) {
    Point a = poly[i];
    Point b = poly[(i + 1) % n];
    Point c = poly[(i + 2) % n];
    if (dcmp(cross(b - a, c - b)) != 0 && (ret.empty() ||
        b != ret.back()))
      ret.push_back(b);
  }
  return ret;
}
// returns the signed area of polygon p of n vertices
Tf signedPolygonArea(const Polygon &p) {
  Tf ret = 0;
  for (int i = 0; i < (int)p.size() - 1; i++)
    ret += cross(p[i] - p[0], p[i + 1] - p[0]);
  return ret / 2;
}
// given a polygon p of n vertices, generates the convex
    hull in in CCW
// Tested on https://acm.timus.ru/problem.aspx?space=1&
    num=1185
// Caution: when all points are colinear AND
    removeRedundant == false
// output will be contain duplicate points (from upper
    hull) at back
Polygon convexHull(Polygon p, bool removeRedundant) {
  int check = removeRedundant ? 0 : -1;
  sort(p.begin(), p.end());
  p.erase(unique(p.begin(), p.end()), p.end());

  int n = p.size();
  Polygon ch(n + n);
  int m = 0; // preparing lower hull
  for (int i = 0; i < n; i++) {
    while (m > 1 &&
           dcmp(cross(ch[m - 1] - ch[m - 2], p[i] - ch[m -
               1])) <= check)
      m--;
    ch[m++] = p[i];
  }
  int k = m; // preparing upper hull
  for (int i = n - 2; i >= 0; i--) {
    while (m > k &&
           dcmp(cross(ch[m - 1] - ch[m - 2], p[i] - ch[m -
               2])) <= check)
      m--;
    ch[m++] = p[i];
  }
  if (n > 1) m--;
  ch.resize(m);
  return ch;
}
// returns inside = -1, on = 0, outside = 1
int pointInPolygon(const Polygon &p, Point o) {
  using Linear::onSegment;
  int wn = 0, n = p.size();
  for (int i = 0; i < n; i++) {
```

```
    int j = (i + 1) % n;
    if (onSegment(o, Segment(p[i], p[j])) || o == p[i])
        return 0;
    int k = dcmp(cross(p[j] - p[i], o - p[i]));
    int d1 = dcmp(p[i].y - o.y);
    int d2 = dcmp(p[j].y - o.y);
    if (k > 0 && d1 <= 0 && d2 > 0) wn++;
    if (k < 0 && d2 <= 0 && d1 > 0) wn--;
  }
  return wn ? -1 : 1;
}
// Given a simple polygon p, and a line l, returns (x, y)
// x = longest segment of l in p, y = total length of l
    in p.
pair<Tf, Tf> linePolygonIntersection(Line l, const
    Polygon &p) {
  using Linear::lineLineIntersection;
  int n = p.size();
  vector<pair<Tf, int>> ev;
  for (int i = 0; i < n; ++i) {
    Point a = p[i], b = p[(i + 1) % n], z = p[(i - 1 + n)
        % n];
    int ora = orient(l.a, l.b, a), orb = orient(l.a, l.b,
        b),
      orz = orient(l.a, l.b, z);
    if (!ora) {
      Tf d = dot(a - l.a, l.b - l.a);
      if (orz && orb) {
        if (orz != orb) ev.emplace_back(d, 0);
        // else // Point Touch
      } else if (orz)
        ev.emplace_back(d, orz);
      else if (orb)
        ev.emplace_back(d, orb);
    } else if (ora == -orb) {
      Point ins;
      lineLineIntersection(l, Line(a, b), ins);
      ev.emplace_back(dot(ins - l.a, l.b - l.a), 0);
    }
  }
  sort(ev.begin(), ev.end());

  Tf ans = 0, len = 0, last = 0, tot = 0;
  bool active = false;
  int sign = 0;
  for (auto &qq : ev) {
    int tp = qq.second;
    Tf d = qq.first; /// current Segment is (last, d)
    if (sign) {     /// On Border
      len += d - last;
      tot += d - last;
      ans = max(ans, len);
      if (tp != sign) active = !active;
      sign = 0;
    } else {
      if (active) { /// Strictly Inside
        len += d - last;
        tot += d - last;
        ans = max(ans, len);
      }
      if (tp == 0)
        active = !active;
      else
        sign = tp;
    }
    last = d;
    if (!active) len = 0;
  }
  ans /= length(l.b - l.a);
  tot /= length(l.b - l.a);
  return {ans, tot};
}
```

4.6 Point Redifined

```
namespace geo {
    #define x real()
    #define y imag()
    #define setx(i) real(i)
    #define sety(i) imag(i)
    typedef complex<double> point;
    typedef point vec2;

    double dist(point a, point b) { return abs(b-a); }
    double dot(vec2 a, vec2 b) { return (conj(a) * b).x;
        }
    double cross(vec2 a, vec2 b) { return (conj(a) * b).y
        ; }
    vec2 rotate90(vec2 a) { return point(-a.y, a.x); }
    double area(vec2 a, vec2 b) { return abs(cross(a,b));
         }
    // double area(point a, point b, point c) { return
        area( getVec2(a,b), getVec2(a,c) ); }
    vec2 unitVec2(vec2 a) { return a/abs(a); }
    vec2 getVec2(point a, point b) { return b-a; }
    double angleBetween(vec2 a, vec2 b) { return acos(dot
        (a,b)/(abs(a) * abs(b))); } // In radian
}
```

5 Graph

5.1 SCC

```
typedef long long LL;
const LL N = 1e6 + 7;

bool vis[N];
vector<int> adj[N], adjr[N];
vector<int> order, component;
// tp = 0 ,finding topo order, tp = 1 , reverse edge
    traversal

void dfs(int u, int tp = 0) {
  vis[u] = true;
  if (tp) component.push_back(u);
  auto& ad = (tp ? adjr : adj);
  for (int v : ad[u])
    if (!vis[v]) dfs(v, tp);
  if (!tp) order.push_back(u);
}
int main() {
  for (int i = 1; i <= n; i++) {
    if (!vis[i]) dfs(i);
  }
  memset(vis, 0, sizeof vis);
  reverse(order.begin(), order.end());
  for (int i : order) {
    if (!vis[i]) {
      // one component is found
      dfs(i, 1), component.clear();
    }
  }
}
```

5.2 Virtual tree

```
/*
 * - Use add_edge(u, v, w) to add edge
 * - At first implement LCA
 * - Call init_lca, dfs
 * - Call get_virtual_tree(nodes) -> vector<int>: nodes
     in virtual tree
 */
struct virtual_tree {
    vector<vector<PII>> g, vt;
    vector<int> in, val, out;
    LCA lca;
    int t;
    virtual_tree() {}
```

```
virtual_tree(int n) : g(n+1), vt(n+1), in(n+1), val(n
    +1), out(n+1), t(0) {}
void add_edge(int u, int v, int w = 1) {
    g[u].emplace_back(v, w);
    g[v].emplace_back(u, w);
}
void init_lca(int root) {
    vector<vector<int>> _g(g.size());
    for (int u = 0; u < g.size(); u++)
        for (auto [v, w]: g[u])
            _g[u].push_back(v);
    lca = LCA(_g, root, root);
}
void dfs(int u, int p = -1, int d = 0) {
    in[u] = ++t;
    val[u] = d;
    for (auto [v, w]: g[u])
        if (v xor p)
            dfs(v, u, d+w);
    out[u] = t;
}
bool is_anc(int u, int p) {
    return in[p] <= in[u] and out[u] <= out[p];
}
void clear(vector<int> nodes) {
    for (auto e: nodes)
        vt[e].clear();
}
vector<int> get_virtual_tree(vector<int> v) {
    sort(all(v), [&](int a, int b) { return in[a] <
        in[b]; });
    int n = v.size();
    for (int i = 1; i < n; i++)
        v.push_back(lca.lca(v[i], v[i-1]));
    sort(all(v), [&](int a, int b) { return in[a] <
        in[b]; });
    v.erase(unique(all(v)), v.end());
    stack<int> s;
    s.push(v[0]);
    for (int i = 1; i < v.size(); i++) {
        while (not is_anc(v[i], s.top())) s.pop();
        vt[s.top()].emplace_back(v[i], val[v[i]] - val
            [s.top()]);
        vt[v[i]].emplace_back(s.top(), val[v[i]] - val
            [s.top()]);
        s.push(v[i]);
    }
    return v;
}
};
```

5.3 Euler Tour on Edge

```
// for simplicity, G[idx] contains the adjacency list of
    a node
// while G(e) is a reference to the e-th edge.
const int N = 2e5 + 5;
int in[N], out[N], fwd[N], bck[N];
int t = 0;
void dfs(graph &G, int node, int par) {
  out[node] = t;
  for (int e : G[node]) {
    int v = G(e).to(node);
    if (v == par) continue;
    fwd[e] = t++;
    dfs(G, v, node);
    bck[e] = t++;
  }
  in[node] = t - 1;
}
void init(graph &G, int node) {
  t = 0;
  dfs(G, node, node);
}
```

5.4 LCA In O(1)

```
/* LCA in O(1)
 * depth calculates weighted distance
 * level calculates distance by number of edges
 * Preprocessing in NlongN */
LL depth[N];
int level[N];

int st[N], en[N], LOG[N], par[N];
int a[N], id[N], table[L][N];

vector<PII> adj[N];
int n, root, Time, cur;

void init(int nodes, int root_) {
  n = nodes, root = root_, LOG[0] = LOG[1] = 0;
  for (int i = 2; i <= n; i++) LOG[i] = LOG[i >> 1] + 1;
  for (int i = 0; i <= n; i++) adj[i].clear();
}

void addEdge(int u, int v, int w) {
  adj[u].push_back(PII(v, w));
  adj[v].push_back(PII(u, w));
}

int lca(int u, int v) {
  if (en[u] > en[v]) swap(u, v);
  if (st[v] <= st[u] && en[u] <= en[v]) return v;

  int l = LOG[id[v] - id[u] + 1];
  int p1 = id[u], p2 = id[v] - (1 << l) + 1;
  int d1 = level[table[l][p1]], d2 = level[table[l][p2]];

  if (d1 < d2)
    return par[table[l][p1]];
  else
    return par[table[l][p2]];
}

LL dist(int u, int v) {
  int l = lca(u, v);
  return (depth[u] + depth[v] - (depth[l] * 2));
}

/* Euler tour */
void dfs(int u, int p) {
  st[u] = ++Time, par[u] = p;

  for (auto [v, w] : adj[u]) {
    if (v == p) continue;
    depth[v] = depth[u] + w;
    level[v] = level[u] + 1;
    dfs(v, u);
  }

  en[u] = ++Time;
  a[++cur] = u, id[u] = cur;
}

/* RMQ */
void pre() {
  cur = Time = 0, dfs(root, root);
  for (int i = 1; i <= n; i++) table[0][i] = a[i];

  for (int l = 0; l < L - 1; l++) {
    for (int i = 1; i <= n; i++) {
      table[l + 1][i] = table[l][i];

      bool C1 = (1 << l) + i <= n;
      bool C2 = level[table[l][i + (1 << l)]] < level[
          table[l][i]];
```

```
    if (C1 && C2) table[l + 1][i] = table[l][i + (1 << l)];
  }
 }
}
```

5.5 LCA in O(n) memory

```
struct LCA {
    int n;
    vector<int> lvl, par, jmp;
    LCA(vector<vector<int>> const& g, int u, int p) : n(g.size()), lvl(n, -1), par(n, -1), jmp(n, p) {
        lvl[u] = 0, par[u] = p;
        queue<int> q;
        for (q.push(u); q.size(); q.pop()) {
            int u = q.front();
            for (int v: g[u]) if (lvl[v] < 0) {
                q.push(v);
                lvl[v] = lvl[u] + 1, par[v] = u;
                if (lvl[jmp[u]] << 1 == lvl[u] + lvl[jmp[jmp[u]]]) jmp[v] = jmp[jmp[u]];
                else jmp[v] = u;
            }
        }
    }
    int getAnc(int u, int d) {
        d = max(0, lvl[u] - d);
        while (lvl[u] > d) {
            if (lvl[jmp[u]] < d) u = par[u];
            else u = jmp[u];
        }
        return u;
    }
    int lca(int u, int v) {
        if (lvl[u] < lvl[v]) swap(u, v);
        u = getAnc(u, lvl[u] - lvl[v]);
        while (u != v) {
            if (jmp[u] == jmp[v]) u = par[u], v = par[v];
            else u = jmp[u], v = jmp[v];
        }
        return u;
    }
    int dist(int u, int v) { return lvl[u] + lvl[v] - 2*lvl[lca(u, v)]; }
};
```

5.6 HLD

```
const int N = 1e6 + 7;
template <typename DT>
struct Segtree {
  // write lazy segtree here
};
Segtree<int> tree(N);
vector<int> adj[N];
int depth[N], par[N], pos[N];
int head[N], heavy[N], cnt;

int dfs(int u, int p) {
  int SZ = 1, mxsz = 0, heavyc;
  depth[u] = depth[p] + 1;

  for (auto v : adj[u]) {
    if (v == p) continue;
    par[v] = u;
    int subsz = dfs(v, u);
    if (subsz > mxsz) heavy[u] = v, mxsz = subsz;
    SZ += subsz;
  }
  return SZ;
}
void decompose(int u, int h) {
  head[u] = h, pos[u] = ++cnt;
  if (heavy[u] != -1) decompose(heavy[u], h);

  for (int v : adj[u]) {
    if (v == par[u]) continue;
    if (v != heavy[u]) decompose(v, v);
  }
}
int query(int a, int b) {
  int ret = 0;
  for (; head[a] != head[b]; b = par[head[b]]) {
    if (depth[head[a]] > depth[head[b]]) swap(a, b);
    ret += tree.query(1, 0, cnt, pos[head[b]], pos[b]);
  }

  if (depth[a] > depth[b]) swap(a, b);
  ret += tree.query(1, 0, cnt, pos[a], pos[b]);
  return ret;
}
```

5.7 Centroid tree

```
namespace centroid {
 const int N = 2e5;
 int sz[N+1];
 bitset<N> vis;
 vector<int> adj[N+1];
 void dfs_size(int u = 1, int p = 0) {
  sz[u] = 1;
  for (auto v : adj[u])
   if (v != p) {
    dfs_size(v, u);
    sz[u] += sz[v];
   }
 }
 int find_centroid(int u, int p) {
  int total = sz[u];
  for (auto v : adj[u])
   if (v != p and not vis[v] and 2 * sz[v] > total) {
    sz[u] = total - sz[v];
    sz[v] = total;
    return find_centroid(v, u);
   }
  return u;
 }
 int query(int u) {
  int ans = 1e6;
  for (int i = u; i; i = par[i])
   ans = min(ans, minD[i] + lca::dist(i, u));
  return ans;
 }
 void update(int u) {
  for (int i = u; i; i = par[i])
   minD[i] = min(minD[i], lca::dist(i, u));
 }
 int decompose(int u, int p) {
  u = find_centroid(u, p);
  vis[u] = 1;
  for (auto v : adj[u])
   if (not vis[v])
    par[decompose(v, u)] = u;
  return u;
 }
}
```

5.8 Dinic Max Flow

```
/**
Implementation of Dinic's algorithm with optional scaling
Source: Chilli (https://codeforces.com/blog/entry/66006)

Complexity: O(ans*E) or O(V^2E) without scaling, O(VE log(U)) with scaling,
Scaling performs much better in worst case, but has much higher constant factor
To enable scaling, call maxFlow(true)
Everything 0-indexed
*/
```

```
namespace Dinic {
    typedef long long LL;
    const int N = 5005, K = 60; /// N > no of nodes, K >=
         max bits in capacity
    const LL INF = 1e18;
    struct Edge { int frm, to; LL cap, flow; };
    int s, t, n;
    int level[N], ptr[N];
    vector<Edge> edges;
    vector<int> adj[N];
    void init(int nodes) {
        n = nodes;
        for (int i=0; i<n; i++) adj[i].clear();
        edges.clear();
    }
    /// For adding undirected Edge (u, v, c) call addEdge
         (u, v, c, c);
    int addEdge(int a, int b, LL cap, LL revcap = 0) {
        edges.push_back({a, b, cap, 0});
        edges.push_back({b, a, revcap, 0});
        adj[a].push_back(edges.size()-2);
        adj[b].push_back(edges.size()-1);
        return edges.size()-2;
    }
    bool bfs(LL lim) {
        fill(level, level+n, -1);
        level[s] = 0;
        queue<int> q;
        q.push(s);

        while (!q.empty() && level[t] == -1) {
            int v = q.front();
            q.pop();
            for (int id: adj[v]) {
                Edge e = edges[id];
                if (level[e.to] == -1 && e.cap - e.flow >=
                     lim) {
                    q.push(e.to);
                    level[e.to] = level[v] + 1;
                }
            }
        }
        return level[t] != -1;
    }
    LL dfs(int v, LL flow) {
        if (v == t || !flow)     return flow;
        for (; ptr[v] < adj[v].size(); ptr[v]++) {
            int eid = adj[v][ptr[v]];
            Edge &e = edges[eid];
            if (level[e.to] != level[v] + 1) continue;
            if (LL pushed = dfs(e.to, min(flow, e.cap - e.
                 flow))) {
                e.flow += pushed;
                edges[eid^1].flow -= pushed;
                return pushed;
            }
        }
        return 0;
    }
    LL maxFlow(int source, int sink, bool SCALING = false
         ) {
        s = source, t = sink;

        long long flow = 0;
        for (LL lim = SCALING ? (1LL << K) : 1; lim > 0;
             lim >>= 1) {
            while (bfs(lim)) {
                fill(ptr, ptr+n, 0);
                while (LL pushed = dfs(s, INF)) flow +=
                     pushed;
            }
        }
        return flow;
    }
    bool leftOfMinCut(int x) {return level[x] != -1;}
    /// Only works for undirected graph, Make sure to add
         UNDIRECTED edges. (u, v, c, c)
    /// returns n by n matrix flow, st flow[i][j] =
         maxFlow
    /// tree holds the edges of a gomory-hu tree of the
         graph
    vector<vector<LL>> allPairMaxFlow(vector<Edge> &tree)
         {
        tree.clear();
        vector<vector<LL>> flow(n, vector<LL> (n, INF));
        vector<int> par(n);
        for (int i=1; i<n; i++) {
            for (auto &e: edges)  e.flow = 0;
            LL f = maxFlow(i, par[i]);
            tree.push_back({i, par[i], f});

            for (int j=i+1; j<n; j++)
                if (par[j] == par[i] && leftOfMinCut(j))
                    par[j] = i;

            flow[i][par[i]] = flow[par[i]][i] = f;
            for (int j=0; j<i; j++)
                if (j != par[i])  flow[i][j] = flow[j][i]
                    = min(f, flow[par[i]][j]);
        }
        return flow;
    }
}
```

5.9 Min Cost Max Flow

```
mt19937 rnd(chrono::steady_clock::now().time_since_epoch
    ().count());
const LL inf = 1e9;
struct edge {
  int v, rev;
  LL cap, cost, flow;
  edge() {}
  edge(int v, int rev, LL cap, LL cost)
      : v(v), rev(rev), cap(cap), cost(cost), flow(0) {}
};
struct mcmf {
  int src, sink, n;
  vector<int> par, idx, Q;
  vector<bool> inq;
  vector<LL> dis;
  vector<vector<edge>> g;
  mcmf() {}
  mcmf(int src, int sink, int n)
      : src(src),
        sink(sink),
        n(n),
        par(n),
        idx(n),
        inq(n),
        dis(n),
        g(n),
        Q(10000005) {} // use Q(n) if not using random
  void add_edge(int u, int v, LL cap, LL cost, bool
      directed = true) {
    edge _u = edge(v, g[v].size(), cap, cost);
    edge _v = edge(u, g[u].size(), 0, -cost);
    g[u].pb(_u);
    g[v].pb(_v);
    if (!directed) add_edge(v, u, cap, cost, true);
  }
  bool spfa() {
    for (int i = 0; i < n; i++) {
      dis[i] = inf, inq[i] = false;
    }
    int f = 0, l = 0;
```

```
    dis[src] = 0, par[src] = -1, Q[l++] = src, inq[src] =
        true;
    while (f < l) {
      int u = Q[f++];
      for (int i = 0; i < g[u].size(); i++) {
        edge &e = g[u][i];
        if (e.cap <= e.flow) continue;
        if (dis[e.v] > dis[u] + e.cost) {
          dis[e.v] = dis[u] + e.cost;
          par[e.v] = u, idx[e.v] = i;
          if (!inq[e.v]) inq[e.v] = true, Q[l++] = e.v;
          // if (!inq[e.v]) {
          //   inq[e.v] = true;
          //   if (f && rnd() & 7) Q[--f] = e.v;
          //   else Q[l++] = e.v;
          // }
        }
      }
      inq[u] = false;
    }
    return (dis[sink] != inf);
  }
  pair<LL, LL> solve() {
    LL mincost = 0, maxflow = 0;
    while (spfa()) {
      LL bottleneck = inf;
      for (int u = par[sink], v = idx[sink]; u != -1; v =
          idx[u], u = par[u]) {
        edge &e = g[u][v];
        bottleneck = min(bottleneck, e.cap - e.flow);
      }
      for (int u = par[sink], v = idx[sink]; u != -1; v =
          idx[u], u = par[u]) {
        edge &e = g[u][v];
        e.flow += bottleneck;
        g[e.v][e.rev].flow -= bottleneck;
      }
      mincost += bottleneck * dis[sink], maxflow +=
          bottleneck;
    }
    return make_pair(mincost, maxflow);
  }
};
// want to minimize cost and don't care about flow
// add edge from sink to dummy sink (cap = inf, cost = 0)
// add edge from source to sink (cap = inf, cost = 0)
// run mcmf, cost returned is the minimum cost
```

5.10 Bridge Tree

```
const int N = 1e5 + 1;
vector<int> g[N], tree[N];
int in[N], low[N], ptr, compId[N];
void go(int u, int p = -1) {
    in[u] = low[u] = ++ptr;
    for (int v: g[u]) {
        if (in[v]) {
            if (v == p) p = -1;
            else low[u] = min(low[u], in[v]);
        } else {
            go(v, u);
            low[u] = min(low[u], low[v]);
        }
    }
}
void shrink(int u, int id) {
    compId[u] = id;
    for (int v: g[u]) if (not compId[v]) {
        if (low[v] > in[u]) {
            tree[id].emplace_back(++ptr);
            tree[ptr].emplace_back(id);
            shrink(v, ptr);
        } else
            shrink(v, id);
    }
}
int main() {
  for (int i = 1; i <= n; ++i) if (!in[i]) go(i);
  vector <int> roots; ptr = 0;
  for (int i = 1; i <= n; ++i) if (!compId[i]) {
    roots.emplace_back(++ptr);
    shrink(i, ptr);
  }
}
```

5.11 Block-cut tree

```
const int N = 4e5 + 1;
bitset <N> art;
vector <int> g[N], tree[N], st, comp[N];
int n, ptr, cur, in[N], low[N], id[N];
void memclear() {
    for (int i = 1; i <= n; i++) {
        g[i].clear();
        in[i] = low[i] = art[i] = 0;
    }
    for (int i = 1; i <= ptr; i++) {
        tree[i].clear(); comp[i].clear();
    }
    st.clear();
    ptr = cur = 0;
}
void dfs (int u, int from = -1) {
    in[u] = low[u] = ++ptr;
    st.emplace_back(u);
    for (int v : g[u]) if (v ^ from) {
        if (!in[v]) {
            dfs(v, u);
            low[u] = min(low[u], low[v]);
            if (low[v] >= in[u]) {
                art[u] = ~from or in[v] > in[u] + 1;
                comp[++cur].emplace_back(u);
                while (comp[cur].back() ^ v) {
                    comp[cur].emplace_back(st.back());
                    st.pop_back();
                }
            }
        } else
            low[u] = min(low[u], in[v]);
    }
}
void build_tree() {
    ptr = 0;
    for (int i = 1; i <= n; ++i)
        if (art[i]) id[i] = ++ptr;
    for (int i = 1; i <= cur; ++i) {
        int x = ++ptr;
        for (int u : comp[i]) {
            if (art[u]) {
                tree[x].emplace_back(id[u]);
                tree[id[u]].emplace_back(x);
            } else
                id[u] = x;
        }
    }
}
```

5.12 Tree Isomorphism

```
// Define random(l, r) function
typedef pair<long long, long long> PLL;
namespace TreeHash {
    PLL operator + (PLL a, PLL b) { return {a.first+b.
        first, a.second+b.second}; }
    PLL operator * (PLL a, PLL b) { return {a.first*b.
        first, a.second*b.second}; }
    PLL operator % (PLL a, int b) { return {a.first%b, a.
        second%b}; }
    using Tree = vector<vector<int>>;
```

```
    constexpr int N = 1e5, MAX = 1e9, MOD = 1e9 + 7;
    PLL val[N+1]{{1, 1}};
    void init() {
        set<PLL> s;
        for (int i = 1; i <= N; i++) {
            PLL v{random(1, MAX), random(1, MAX)};
            while (s.count(v)) v = {random(1, MAX), random
                (1, MAX)};
            val[i] = v;
        }
    }
    int hash(Tree const& g, vector<PII>& hashList, int u,
         int p = -1) {
        int h = 0;
        vector<PII> hashes;
        for (auto v: g[u]) if (v xor p) {
            h = max(h, hash(g, hashList, v, u));
            hashes.emplace_back(hashList[v]);
        }
        hashList[u] = {1, 1};
        for (auto e: hashes)
            hashList[u] = hashList[u] * (val[h] + e) % MOD
                ;
        return h + 1;
    }
    vector<PII> hashList(Tree const& g, int root) {
        vector<PII> hashList(g.size());
        hash(g, hashList, root);
        return hashList;
    }
    bool is_isomorphic(Tree g1, Tree g2) {
        auto c1 = Diameter::find_center(g1), c2 =
            Diameter::find_center(g2);
        assert(max(c1.size(), c2.size()) < 3);
        for (auto e: c2) {
            auto h1 = hashList(g1, c1[0]),
                 h2 = hashList(g2, e);
            if (h1[c1[0]] == h2[e]) return true;
        }
        return false;
    }
}
```

5.13 Tree diameter

```
namespace Diameter {
    using Tree = vector<vector<int>>;
    vector<int> bfs(const Tree& g, int root) {
        queue<int> q;
        q.push(root);
        vector<int> lvl(g.size());
        lvl[root] = 1;
        while (q.size()) {
            int u = q.front(); q.pop();
            for (auto v: g[u]) if (not lvl[v]) {
                lvl[v] = lvl[u] + 1;
                q.push(v);
            }
        }
        return lvl;
    }
    bool dfs(vector<int>& ans, const Tree& g, int u, int
         d, int p = -1) {
        ans.push_back(u);
        if (u == d) return true;
        for (auto v: g[u]) if (v xor p)
            if (dfs(ans, g, v, d, u))
                return true;
        ans.pop_back();
        return false;
    }
    vector<int> find_diameter(const Tree &g) {
        auto d = bfs(g, 1);
        int u = max_element(all(d)) - d.begin();
        d = bfs(g, u);
        int v = max_element(all(d)) - d.begin();
        vector<int> ret;
        dfs(ret, g, u, v);
        return ret;
    }
    vector<int> find_center(const Tree& g) {
        auto v = find_diameter(g);
        int l = 0, r = v.size() - 1;
        for (; r-l+1 > 2; l++, r--);
        if (l == r) return {v[l]};
        return {v[l], v[r]};
    }
}
```

5.14 Grundy

```
/*
single pile game-> greedy or game dp
multiple pile game and disjunctive(before playing, choose
     1 pile) -> NIM game
else-> Grundy(converts n any game piles to n NIM piles)
-----------------------------------------------------------

grundy(x)->the smallest nonreachable grundy value
there are n pile of games and k type of moves.
if XOR(grundy(games)) == 0: losing state
else winning state
*/
vector<int> moves, dp;
int mex(vector<int> &a) {
    set<int> b(a.begin(), a.end());
    for (int i = 0; ; ++i)
        if (!b.count(i))
            return i;
}
int grundy(int x) {
 if (dp[x] != -1) return dp[x];
 vector<int> reachable;
 for (auto m : moves) {
  if (x - m < 0) continue;
  int val = grundy(x - m);
  reachable.push_back(val);
 }
 return dp[x] = mex(reachable);
}
```

6 Math

6.1 Linear Sieve

```
const int N = 10000000;
vector<int> lp(N+1);
vector<int> pr;

for (int i=2; i <= N; ++i) {
    if (lp[i] == 0) {
        lp[i] = i;
        pr.push_back(i);
    }
    for (int j = 0; i * pr[j] <= N; ++j) {
        lp[i * pr[j]] = pr[j];
        if (pr[j] == lp[i]) {
            break;
        }
    }
}
```

6.2 Pollard Rho

```
LL mul(LL a, LL b, LL mod) {
  return (__int128)a * b % mod;
  // LL ans = a * b - mod * (LL) (1.L / mod * a * b);
```

```
  // return ans + mod * (ans < 0) - mod * (ans >= (LL)
      mod);
}
LL bigmod(LL num, LL pow, LL mod) {
  LL ans = 1;
  for (; pow > 0; pow >>= 1, num = mul(num, num, mod))
    if (pow & 1) ans = mul(ans, num, mod);
  return ans;
}
bool is_prime(LL n) {
  if (n < 2 or n % 6 % 4 != 1) return (n | 1) == 3;
  LL a[] = {2, 325, 9375, 28178, 450775, 9780504,
      1795265022};
  LL s = __builtin_ctzll(n - 1), d = n >> s;
  for (LL x : a) {
    LL p = bigmod(x % n, d, n), i = s;
    for (; p != 1 and p != n - 1 and x % n and i--; p =
        mul(p, p, n))
      ;
    if (p != n - 1 and i != s) return false;
  }
  return true;
}
LL get_factor(LL n) {
  auto f = [&](LL x) { return mul(x, x, n) + 1; };
  LL x = 0, y = 0, t = 0, prod = 2, i = 2, q;
  for (; t++ % 40 or gcd(prod, n) == 1; x = f(x), y = f(f
      (y))) {
    (x == y) ? x = i++, y = f(x) : 0;
    prod = (q = mul(prod, max(x, y) - min(x, y), n)) ? q
        : prod;
  }
  return gcd(prod, n);
}
map<LL, int> factorize(LL n) {
  map<LL, int> res;
  if (n < 2) return res;
  LL small_primes[] = {2, 3, 5, 7, 11, 13, 17, 19, 23,
      29, 31, 37, 41,
                       43, 47, 53, 59, 61, 67, 71, 73, 79,
                           83, 89, 97};
  for (LL p : small_primes)
    for (; n % p == 0; n /= p, res[p]++)
      ;

  auto _factor = [&](LL n, auto &_factor) {
    if (n == 1) return;
    if (is_prime(n))
      res[n]++;
    else {
      LL x = get_factor(n);
      _factor(x, _factor);
      _factor(n / x, _factor);
    }
  };
  _factor(n, _factor);
  return res;
}
```

6.3 Chinese Remainder Theorem

```
// given a, b will find solutions for
// ax + by = 1
tuple<LL, LL, LL> EGCD(LL a, LL b) {
  if (b == 0)
    return {1, 0, a};
  else {
    auto [x, y, g] = EGCD(b, a % b);
    return {y, x - a / b * y, g};
  }
}
// given modulo equations, will apply CRT
PLL CRT(vector<PLL> &v) {
  LL V = 0, M = 1;
  for (auto &[v, m] : v) { // value % mod
    auto [x, y, g] = EGCD(M, m);
    if ((v - V) % g != 0) return {-1, 0};
    V += x * (v - V) / g % (m / g) * M, M *= m / g;
    V = (V % M + M) % M;
  }
  return make_pair(V, M);
}
```

6.4 Mobius Function

```
const int N = 1e6 + 5;
int mob[N];
void mobius() {
  memset(mob, -1, sizeof mob);
  mob[1] = 1;
  for (int i = 2; i < N; i++)
    if (mob[i]) {
      for (int j = i + i; j < N; j += i) mob[j] -= mob[i
          ];
    }
}
```

6.5 FFT

```
using CD = complex<double>;
typedef long long LL;
const double PI = acos(-1.0L);

int N;
vector<int> perm;
vector<CD> wp[2];
void precalculate(int n) {
  assert((n & (n - 1)) == 0), N = n;
  perm = vector<int>(N, 0);
  for (int k = 1; k < N; k <<= 1) {
    for (int i = 0; i < k; i++) {
      perm[i] <<= 1;
      perm[i + k] = 1 + perm[i];
    }
  }
  wp[0] = wp[1] = vector<CD>(N);
  for (int i = 0; i < N; i++) {
    wp[0][i] = CD(cos(2 * PI * i / N), sin(2 * PI * i / N
        ));
    wp[1][i] = CD(cos(2 * PI * i / N), -sin(2 * PI * i /
        N));
  }
}
void fft(vector<CD> &v, bool invert = false) {
  if (v.size() != perm.size()) precalculate(v.size());
  for (int i = 0; i < N; i++)
    if (i < perm[i]) swap(v[i], v[perm[i]]);
  for (int len = 2; len <= N; len *= 2) {
    for (int i = 0, d = N / len; i < N; i += len) {
      for (int j = 0, idx = 0; j < len / 2; j++, idx += d
          ) {
        CD x = v[i + j];
        CD y = wp[invert][idx] * v[i + j + len / 2];
        v[i + j] = x + y;
        v[i + j + len / 2] = x - y;
      }
    }
  }
  if (invert) {
    for (int i = 0; i < N; i++) v[i] /= N;
  }
}
void pairfft(vector<CD> &a, vector<CD> &b, bool invert =
    false) {
  int N = a.size();
  vector<CD> p(N);
  for (int i = 0; i < N; i++) p[i] = a[i] + b[i] * CD(0,
      1);
  fft(p, invert);
  p.push_back(p[0]);
```

```
  for (int i = 0; i < N; i++) {
    if (invert) {
      a[i] = CD(p[i].real(), 0);
      b[i] = CD(p[i].imag(), 0);
    } else {
      a[i] = (p[i] + conj(p[N - i])) * CD(0.5, 0);
      b[i] = (p[i] - conj(p[N - i])) * CD(0, -0.5);
    }
  }
}
vector<LL> multiply(const vector<LL> &a, const vector<LL>
    &b) {
  int n = 1;
  while (n < a.size() + b.size()) n <<= 1;
  vector<CD> fa(a.begin(), a.end()), fb(b.begin(), b.end
      ());
  fa.resize(n);
  fb.resize(n);
  //       fft(fa); fft(fb);
  pairfft(fa, fb);
  for (int i = 0; i < n; i++) fa[i] = fa[i] * fb[i];
  fft(fa, true);
  vector<LL> ans(n);
  for (int i = 0; i < n; i++) ans[i] = round(fa[i].real()
      );
  return ans;
}
const int M = 1e9 + 7, B = sqrt(M) + 1;
vector<LL> anyMod(const vector<LL> &a, const vector<LL> &
    b) {
  int n = 1;
  while (n < a.size() + b.size()) n <<= 1;
  vector<CD> al(n), ar(n), bl(n), br(n);
  for (int i = 0; i < a.size(); i++) al[i] = a[i] % M / B
      , ar[i] = a[i] % M % B;
  for (int i = 0; i < b.size(); i++) bl[i] = b[i] % M / B
      , br[i] = b[i] % M % B;
  pairfft(al, ar);
  pairfft(bl, br);
  //       fft(al); fft(ar); fft(bl); fft(br);
  for (int i = 0; i < n; i++) {
    CD ll = (al[i] * bl[i]), lr = (al[i] * br[i]);
    CD rl = (ar[i] * bl[i]), rr = (ar[i] * br[i]);
    al[i] = ll;
    ar[i] = lr;
    bl[i] = rl;
    br[i] = rr;
  }
  pairfft(al, ar, true);
  pairfft(bl, br, true);
  //       fft(al, true); fft(ar, true); fft(bl, true);
      fft(br, true);
  vector<LL> ans(n);
  for (int i = 0; i < n; i++) {
    LL right = round(br[i].real()), left = round(al[i].
        real());
    ;
    LL mid = round(round(bl[i].real()) + round(ar[i].real
        ()));
    ans[i] = ((left % M) * B * B + (mid % M) * B + right)
        % M;
  }
  return ans;
}
```

6.6 NTT

```
const LL N = 1 << 18;
const LL MOD = 786433;

vector<LL> P[N];
LL rev[N], w[N | 1], a[N], b[N], inv_n, g;
LL Pow(LL b, LL p) {
  LL ret = 1;
  while (p) {
    if (p & 1) ret = (ret * b) % MOD;
    b = (b * b) % MOD;
    p >>= 1;
  }
  return ret;
}
LL primitive_root(LL p) {
  vector<LL> factor;
  LL phi = p - 1, n = phi;
  for (LL i = 2; i * i <= n; i++) {
    if (n % i) continue;
    factor.emplace_back(i);
    while (n % i == 0) n /= i;
  }
  if (n > 1) factor.emplace_back(n);
  for (LL res = 2; res <= p; res++) {
    bool ok = true;
    for (LL i = 0; i < factor.size() && ok; i++)
      ok &= Pow(res, phi / factor[i]) != 1;
    if (ok) return res;
  }
  return -1;
}
void prepare(LL n) {
  LL sz = abs(31 - __builtin_clz(n));
  LL r = Pow(g, (MOD - 1) / n);
  inv_n = Pow(n, MOD - 2);
  w[0] = w[n] = 1;
  for (LL i = 1; i < n; i++) w[i] = (w[i - 1] * r) % MOD;
  for (LL i = 1; i < n; i++)
    rev[i] = (rev[i >> 1] >> 1) | ((i & 1) << (sz - 1));
}
void NTT(LL *a, LL n, LL dir = 0) {
  for (LL i = 1; i < n - 1; i++)
    if (i < rev[i]) swap(a[i], a[rev[i]]);
  for (LL m = 2; m <= n; m <<= 1) {
    for (LL i = 0; i < n; i += m) {
      for (LL j = 0; j < (m >> 1); j++) {
        LL &u = a[i + j], &v = a[i + j + (m >> 1)];
        LL t = v * w[dir ? n - n / m * j : n / m * j] %
            MOD;
        v = u - t < 0 ? u - t + MOD : u - t;
        u = u + t >= MOD ? u + t - MOD : u + t;
      }
    }
  }
  if (dir)
    for (LL i = 0; i < n; i++) a[i] = (inv_n * a[i]) %
        MOD;
}
vector<LL> mul(vector<LL> p, vector<LL> q) {
  LL n = p.size(), m = q.size();
  LL t = n + m - 1, sz = 1;
  while (sz < t) sz <<= 1;
  prepare(sz);

  for (LL i = 0; i < n; i++) a[i] = p[i];
  for (LL i = 0; i < m; i++) b[i] = q[i];
  for (LL i = n; i < sz; i++) a[i] = 0;
  for (LL i = m; i < sz; i++) b[i] = 0;

  NTT(a, sz);
  NTT(b, sz);
  for (LL i = 0; i < sz; i++) a[i] = (a[i] * b[i]) % MOD;
  NTT(a, sz, 1);

  vector<LL> c(a, a + sz);
  while (c.size() && c.back() == 0) c.pop_back();
  return c;
}
```

6.7 XOR Basis

```
int basis[21] = {}, sz = 0;
```

```
auto insert = [&](int x) {
  while (x) {
    int i = __builtin_ctz(x & -x);
    if (not basis[i]) {
      basis[i] = x;
      sz++;
      return x;
    }
    x ^= basis[i];
  }
  return 0;
};
```

7 String

7.1 Aho Corasick

```
const int N = 2000, L = 105;
struct AhoCorasick {
  int N, P;
  const int A = 256;
  vector<vector<int>> next;
  vector<int> link, out_link, end_in_pattern;
  vector<vector<int>> out;
  AhoCorasick() : N(0), P(0) { node(); }
  int node() {
    next.emplace_back(A, 0);
    link.emplace_back(0);
    out_link.emplace_back(0);
    out.emplace_back(0);
    end_in_pattern.emplace_back(0);
    return N++;
  }
  inline int get(char c) { return c; }
  int addPattern(const string T) {
    int u = 0;
    for (auto c : T) {
      if (!next[u][get(c)]) next[u][get(c)] = node();
      u = next[u][get(c)];
    }
    out[u].push_back(P);
    end_in_pattern[u] = 1;
    return P++;
  }
  void pushLinks() {
    queue<int> q;
    for (q.push(0); !q.empty();) {
      int u = q.front();
      q.pop();
      for (int c = 0; c < A; ++c) {
        int v = next[u][c];
        if (!v) next[u][c] = next[link[u]][c];
        else {
          link[v] = u ? next[link[u]][c] : 0;
          out_link[v] = out[link[v]].empty() ? out_link[
              link[v]] : link[v];
          q.push(v);
        }
        end_in_pattern[v] |= end_in_pattern[out_link[v]];
      }
    }
  }
  int advance(int u, char c) {
    while (u && !next[u][get(c)]) u = link[u];
    u = next[u][get(c)];
    return u;
  }
};
```

7.2 Double hash

```
// define +, -, * for (PLL, LL) and (PLL, PLL), % for (
    PLL, PLL);
PLL base(1949313259, 1997293877);
namespace Hashing {
    using LL = long long;
    using PLL = pair<LL,LL>;
    #define ff first
    #define ss second
    const PLL M = {2091573227, 2117566807};   ///Should
        be large primes
    const LL base = 1259;             ///Should be larger
        than alphabet size
    const int N = 1e6+7;              ///Highest length of
         string
    PLL operator+ (const PLL& a, LL x) {return {a.ff + x,
         a.ss + x};}
    PLL operator- (const PLL& a, LL x) {return {a.ff - x,
         a.ss - x};}
    PLL operator* (const PLL& a, LL x) {return {a.ff * x,
         a.ss * x};}
    PLL operator+ (const PLL& a, PLL x) {return {a.ff + x
        .ff, a.ss + x.ss};}
    PLL operator- (const PLL& a, PLL x) {return {a.ff - x
        .ff, a.ss - x.ss};}
    PLL operator* (const PLL& a, PLL x) {return {a.ff * x
        .ff, a.ss * x.ss};}
    PLL operator% (const PLL& a, PLL m) {return {a.ff % m
        .ff, a.ss % m.ss};}
    ostream& operator<<(ostream& os, PLL hash) {
        return os<<"("<<hash.ff<<", "<<hash.ss<<")";
    }
    PLL pb[N];     ///powers of base mod M
    ///Call pre before everything
    void hashPre() {
        pb[0] = {1,1};
        for (int i=1; i<N; i++)  pb[i] = (pb[i-1] * base)
            %M;
    }
    ///Calculates hashes of all prefixes of s including
         empty prefix
    vector<PLL> hashList(string s) {
        int n = s.size();
        vector<PLL> ans(n+1);
        ans[0] = {0,0};
        for (int i=1; i<=n; i++) ans[i] = (ans[i-1] *
            base + s[i-1])%M;
        return ans;
    }
    ///Calculates hash of substring s[l..r] (1 indexed)
    PLL substringHash(const vector<PLL> &hashlist, int l,
         int r) {
        return (hashlist[r]+(M-hashlist[l-1])*pb[r-l+1])%
            M;
    }
    ///Calculates Hash of a string
    PLL Hash (string s) {
        PLL ans = {0,0};
        for (int i=0; i<s.size(); i++) ans=(ans*base + s[
            i])%M;
        return ans;
    }
    ///Tested on https://toph.co/p/palindromist
    ///appends c to string
    PLL append(PLL cur, char c) {
        return (cur*base + c)%M;
    }
    ///Tested on https://toph.co/p/palindromist
    ///prepends c to string with size k
    PLL prepend(PLL cur, int k, char c) {
        return (pb[k]*c + cur)%M;
    }
    ///Tested on https://toph.co/p/chikongunia
    ///replaces the i-th (0-indexed) character from right
         from a to b;
    PLL replace(PLL cur, int i, char a, char b) {
        return cur + pb[i] * (M+b-a)%M;
    }
```

```
    ///Erases c from front of the string with size len
    PLL pop_front(PLL hash, int len, char c) {
        return (hash + pb[len-1]*(M-c))%M;
    }
    ///Tested on https://toph.co/p/palindromist
    ///concatenates two strings where length of the right
         is k
    PLL concat(PLL left, PLL right, int k) {
        return (left*pb[k] + right)%M;
    }
    PLL power (const PLL& a, LL p) {
        if (p==0)  return {1,1};
        PLL ans = power(a, p/2);
        ans = (ans * ans)%M;
        if (p%2)   ans = (ans*a)%M;
        return ans;
    }
    PLL inverse(PLL a) {
        if (M.ss == 1) return power(a, M.ff-2);
        return power(a, (M.ff-1)*(M.ss-1)-1);
    }
    ///Erases c from the back of the string
    PLL invb = inverse({base, base});
    PLL pop_back(PLL hash, char c) {
        return ((hash-c+M)*invb)%M;
    }
    ///Tested on https://toph.co/p/palindromist
    ///Calculates hash of string with size len repeated
         cnt times
    ///This is O(log n). For O(1), pre-calculate inverses
    PLL repeat(PLL hash, int len, LL cnt) {
        PLL mul = ((pb[len*cnt]-1+M) * inverse(pb[len]-1+
            M))%M;
        PLL ans = (hash*mul);
        if (pb[len].ff == 1)  ans.ff = hash.ff*cnt;
        if (pb[len].ss == 1)  ans.ss = hash.ss*cnt;
        return ans%M;
    }
    struct pair_hash {
        inline std::size_t operator()(const std::pair<LL,
            LL> & v) const {
            return v.first*31+v.second;
        }
    };
}
```

7.3 KMP

```
vector<int> prefix_function(string s) {
  int n = (int)s.length();
  vector<int> pi(n);
  for (int i = 1; i < n; i++) {
    int j = pi[i-1];
    while (j > 0 && s[i] != s[j])
      j = pi[j-1];
    if (s[i] == s[j])
      j++;
    pi[i] = j;
  }
  return pi;
}
```

7.4 Manacher's

```
vector<int> d1(n);
// d[i] = number of palindromes taking s[i] as center
for (int i = 0, l = 0, r = -1; i < n; i++) {
  int k = (i > r) ? 1 : min(d1[l + r - i], r - i + 1);
  while (0 <= i - k && i + k < n && s[i - k] == s[i + k])
       k++;
  d1[i] = k--;
  if (i + k > r) l = i - k, r = i + k;
}
vector<int> d2(n);
// d[i] = number of palindromes taking s[i-1] and s[i] as
     center
for (int i = 0, l = 0, r = -1; i < n; i++) {
  int k = (i > r) ? 0 : min(d2[l + r - i + 1], r - i + 1)
       ;
  while (0 <= i - k - 1 && i + k < n && s[i - k - 1] == s
      [i + k]) k++;
  d2[i] = k--;
  if (i + k > r) l = i - k - 1, r = i + k;
}
```

7.5 String Match FFT

```
//find occurrences of t in s where '?'s are automatically
     matched with any character
//res[i + m - 1] = sum_j=0 to m - 1_{s[i + j] * t[j] * (s
    [i + j] - t[j])
vector<int> string_matching(string &s, string &t) {
  int n = s.size(), m = t.size();
  vector<int> s1(n), s2(n), s3(n);
  for(int i = 0; i < n; i++) s1[i] = s[i] == '?' ? 0 : s[
      i] - 'a' + 1; //assign any non zero number for non
      '?'s
  for(int i = 0; i < n; i++) s2[i] = s1[i] * s1[i];
  for(int i = 0; i < n; i++) s3[i] = s1[i] * s2[i];
  vector<int> t1(m), t2(m), t3(m);
  for(int i = 0; i < m; i++) t1[i] = t[i] == '?' ? 0 : t[
      i] - 'a' + 1;
  for(int i = 0; i < m; i++) t2[i] = t1[i] * t1[i];
  for(int i = 0; i < m; i++) t3[i] = t1[i] * t2[i];
  reverse(t1.begin(), t1.end());
  reverse(t2.begin(), t2.end());
  reverse(t3.begin(), t3.end());
  vector<int> s1t3 = multiply(s1, t3);
  vector<int> s2t2 = multiply(s2, t2);
  vector<int> s3t1 = multiply(s3, t1);
  vector<int> res(n);
  for(int i = 0; i < n; i++) res[i] = s1t3[i] - s2t2[i] *
       2 + s3t1[i];
  vector<int> oc;
  for(int i = m - 1; i < n; i++) if(res[i] == 0) oc.
      push_back(i - m + 1);
  return oc;
}
```

7.6 Suffix Array

```
#include <bits/stdc++.h>

using namespace std;

/*
  O(|S| + |alphabet|) Suffix Array
  LIM := max{s[i]} + 2
*/

void inducedSort (const vector <int> &vec, int val_range,
     vector <int> &SA, const vector <int> &sl, const
    vector <int> &lms_idx) {
  vector <int> l(val_range, 0), r(val_range, 0);
  for (int c : vec) {
    ++r[c]; if (c + 1 < val_range) ++l[c + 1];
  }
  partial_sum(l.begin(), l.end(), l.begin());
  partial_sum(r.begin(), r.end(), r.begin());
  fill(SA.begin(), SA.end(), -1);
  for (int i = lms_idx.size() - 1; i >= 0; --i) SA[--r[
      vec[lms_idx[i]]]] = lms_idx[i];
  for (int i : SA) if (i > 0 and sl[i - 1]) SA[l[vec[i -
      1]]++] = i - 1;
  fill(r.begin(), r.end(), 0);
  for (int c : vec) ++r[c];
  partial_sum(r.begin(), r.end(), r.begin());
  for (int k = SA.size() - 1, i = SA[k]; k; --k, i = SA[k
      ]) {
    if (i and !sl[i - 1]) SA[--r[vec[i - 1]]] = i - 1;
```

```
  }
}

vector <int> suffixArray (const vector <int> &vec, int
    val_range) {
  const int n = vec.size();
  vector <int> sl(n), SA(n), lms_idx;
  for (int i = n - 2; i >= 0; --i) {
    sl[i] = vec[i] > vec[i + 1] or (vec[i] == vec[i + 1]
        and sl[i + 1]);
    if (sl[i] and !sl[i + 1]) lms_idx.emplace_back(i + 1)
        ;
  }
  reverse(lms_idx.begin(), lms_idx.end());
  inducedSort(vec, val_range, SA, sl, lms_idx);
  vector <int> new_lms_idx(lms_idx.size()), lms_vec(
      lms_idx.size());
  for (int i = 0, k = 0; i < n; ++i) {
    if (SA[i] > 0 and !sl[SA[i]] and sl[SA[i] - 1])
        new_lms_idx[k++] = SA[i];
  }
  int cur = 0; SA[n - 1] = 0;
  for (int k = 1; k < new_lms_idx.size(); ++k) {
    int i = new_lms_idx[k - 1], j = new_lms_idx[k];
    if (vec[i] ^ vec[j]) {
      SA[j] = ++cur; continue;
    }
    bool flag = 0;
    for (int a = i + 1, b = j + 1; ; ++a, ++b) {
      if (vec[a] ^ vec[b]) {
        flag = 1; break;
      }
      if ((!sl[a] and sl[a - 1]) or (!sl[b] and sl[b -
          1])) {
        flag = !(!sl[a] and sl[a - 1] and !sl[b] and sl[b
            - 1]); break;
      }
    }
    SA[j] = flag ? ++cur : cur;
  }
  for (int i = 0; i < lms_idx.size(); ++i) lms_vec[i] =
      SA[lms_idx[i]];
  if (cur + 1 < lms_idx.size()) {
    auto lms_SA = suffixArray(lms_vec, cur + 1);
    for (int i = 0; i < lms_idx.size(); ++i) new_lms_idx[
        i] = lms_idx[lms_SA[i]];
  }
  inducedSort(vec, val_range, SA, sl, new_lms_idx);
    return SA;
}

vector <int> getSuffixArray (const string &s, const int
    LIM = 128) {
  vector <int> vec(s.size() + 1);
  copy(begin(s), end(s), begin(vec)); vec.back() = '$';
  auto ret = suffixArray(vec, LIM);
  ret.erase(ret.begin()); return ret;
}

// build RMQ on it to get LCP of any two suffix
vector <int> getLCParray (const string &s, const vector <
    int> &SA) {
  int n = s.size(), k = 0;
  vector <int> lcp(n), rank(n);
  for (int i = 0; i < n; ++i) rank[SA[i]] = i;
  for (int i = 0; i < n; ++i, k ? --k : 0) {
    if (rank[i] == n - 1) {
      k = 0; continue;
    }
    int j = SA[rank[i] + 1];
    while (i + k < n and j + k < n and s[i + k] == s[j +
        k]) ++k;
    lcp[rank[i]] = k;
  }
  lcp[n - 1] = 0; return lcp;
}

int main() {
  string s; cin >> s;
  for (const int i : getSuffixArray(s)) printf("%d ", i);
  puts("");
  return 0;
}
```

7.7 Trie

```
template<int sz>
struct Trie {
  Trie() : id(1) {
    memset(endMark, 0, sizeof endMark);
    for_each(all(trie), [](vector<int> &v) { v.assign(sz,
        0); });
  }

  void insert(const string &s) {
    int cur = 0;
    for (auto c : s) {
      int val = c - 'a';
      if (not trie[cur][val])
        trie[cur][val] = id++;
      cur = trie[cur][val];
    }
    endMark[cur] = true;
  }

  bool search(const string &s) {
    int cur = 0;
    for (auto c : s) {
      int val = c - 'a';
      if (not trie[cur][val])
        return false;
      cur = trie[cur][val];
    }
    return endMark[cur];
  }
private:
  int id, endMark[100005];
  vector<int> trie[100005];
};
```

7.8 Z Algo

```
vector<int> calcz(string s) {
  int n = s.size();
  vector<int> z(n);
  int l = 0, r = 0;
  for (int i = 1; i < n; i++) {
    if (i > r) {
      l = r = i;
      while (r < n && s[r] == s[r - l]) r++;
      z[i] = r - l, r--;
    } else {
      int k = i - l;
      if (z[k] < r - i + 1) z[i] = z[k];
      else {
        l = i;
        while (r < n && s[r] == s[r - l]) r++;
        z[i] = r - l, r--;
      }
    }
  }
  return z;
}
```

8 Extra

8.1 Stress Tester

```
g++ -O2 -std=c++17 "$1".cpp -o $1
g++ -O2 -std=c++17 "$2".cpp -o $2
```

```
g++ -O2 -std=c++17 "$3".cpp -o $3
# $1 is actual code
# $2 is good code
# $3 is generator
for ((i = 1;; i++)); do
  echo 'Test #'$i
  timeout 1s ./$3 $RANDOM > in
  timeout 1s ./$1 < in > out
  timeout 1s ./$2 < in > ans
  diff -i ans out > diff.out
  if [ $? -ne 0 ]; then
    cat in
    cat diff.out
    break
  fi
done
```

8.2 Sublime Build

```
{
  "shell_cmd": "g++ -O2 -std=c++17 -g -DLOCAL -Wall -
      Wextra -Wpedantic -Wfloat-equal -Wshift-overflow=2
      -fsanitize=address -fsanitize=undefined -fno-
      sanitize-recover $file_name -o $file_base_name &&
      timeout 5s ./$file_base_name < in > out",
  "working_dir": "$file_path",
  "selector": "source.cpp"
}
```

8.3 vimrc

```
" Auto import & Compile
:autocmd BufNewFile *.cpp 0r ~/template.cpp
nnoremap <F4> :!xclip -o -sel clip > ~/cp/in <CR><CR>
inoremap <F4> <ESC>:!xclip -o -sel clip > ~/cp/in <CR><CR
    >
nnoremap <F6> :!xclip -sel clip % <CR><CR>
inoremap <F6> <ESC>:!xclip -sel clip % <CR><CR>
autocmd filetype cpp nnoremap <F9>   :wa \| !g++ -O2 -std
    =c++17 % -o %:r && timeout 5s ./%:r < ~/cp/in> ~/cp/
    out<CR>
autocmd filetype cpp inoremap <F9> <ESC>:wa \| !g++ -O2 -
    std=c++17 % -o %:r && timeout 5s ./%:r < ~/cp/in> ~/
    cp/out<CR>
autocmd filetype cpp nnoremap <F10>  :wa \| !make %:r D=1
     && ./%:r < ~/cp/in> ~/cp/out<CR>
autocmd filetype cpp inoremap <F10> <ESC>:wa \| !make
    clean && make %:r D=1 && ./%:r < ~/cp/in > ~/cp/out<
    CR>
" Auto Completion
inoremap ( ()<left>
inoremap <expr> ) strpart(getline('.'), col('.')-1, 1) ==
     ")" ? "\<Right>" : ")"
inoremap { {}<left>
inoremap <expr> } strpart(getline('.'), col('.')-1, 1) ==
     "}" ? "\<Right>" : "}"
inoremap [ []<left>
inoremap <expr> ] strpart(getline('.'), col('.')-1, 1) ==
     "]" ? "\<Right>" : "]"
inoremap <expr> " strpart(getline('.'), col('.')-1, 1) ==
     "\"" ? "\<Right>" : "\"\"\<left>"
inoremap <expr> ' strpart(getline('.'), col('.')-1, 1) ==
     "\'" ? "\<Right>" : "\'\'\<left>"
inoremap <expr> <CR> <sid>insert_newline()
function s:insert_newline() abort
  let pair = strpart(getline('.'), col('.')-2, 2)
  return stridx('(){}[]', pair) % 2 == 0 && strlen(pair)
      == 2 ? "\<CR>\<ESC>\O" : "\<CR>"
endfunction
inoremap <expr> <space> <sid>insert_space()
function s:insert_space() abort
  let pair = strpart(getline('.'), col('.')-2, 2)
  return stridx('(){}[]', pair) % 2 == 0 && strlen(pair)
      == 2 ? "\<space>\<space>\<left>" : "\<space>"
endfunction
inoremap <expr> <bs> <sid>rm_pair()
function s:rm_pair() abort
 let pair = strpart(getline('.'), col('.')-2, 2)
 return stridx('(){}[]''''""', pair) % 2 == 0 && strlen(
     pair) == 2 ? "\<del>\<bs>" : "\<bs>"
endfunction
set nocompatible            " be iMproved, required
filetype on                 " required
filetype plugin on
filetype plugin indent on
syntax on
set splitright splitbelow
set mouse=a
set number
set relativenumber
set tabstop=2
set shiftwidth=2
set expandtab
set softtabstop=2
set smartindent
set smarttab
set autoindent
set cindent
set noerrorbells
set ruler
set guifont=*
set backspace=indent,eol,start
" set ignorecase
set incsearch
set nowrap
set hlsearch
" set termguicolors
set foldmethod=indent
set nofoldenable
" set cursorline
set laststatus=2
set showcmd
set wildmenu
" colorscheme torte
if !has('nvim')
  set clipboard=unnamedplus
endif
if !has('nvim')
  set ttymouse=xterm2
endif
nnoremap <S-j> :m .+1<CR>==
nnoremap <S-k> :m .-2<CR>==
vnoremap <S-j> :m '>+1<CR>gv==gv
vnoremap <S-k> :m '<-2<CR>gv==gv
nnoremap <A-h> <C-w>h
nnoremap <A-j> <C-w>j
nnoremap <A-k> <C-w>k
nnoremap <A-l> <C-w>l
let mapleader = ','
map <leader>cp :50 vsplit in<CR>:split out<CR><C-w>h
```

9 Equations and Formulas

9.1 Catalan Numbers

$C_n = \frac{1}{n+1}\binom{2n}{n}$ $C_0 = 1, C_1 = 1$ and $C_n = \sum_{k=0}^{n-1} C_k C_{n-1-k}$

The number of ways to completely parenthesize n+1 factors.

The number of triangulations of a convex polygon with n+2 sides (i.e. the number of partitions of polygon into disjoint triangles by using the diagonals).

The number of ways to connect the $2n$ points on a circle to form n disjoint i.e. non-intersecting chords.

The number of rooted full binary trees with n+1 leaves (vertices are not numbered). A rooted binary tree is full if every vertex has either two children or no children.

Number of permutations of $1, \ldots, n$ that avoid the pattern 123 (or any of the other patterns of length 3); that is, the number of permutations with no three-term increasing sub-sequence. For $n = 3$, these permutations are 132, 213, 231, 312 and 321.

9.2 Stirling Numbers First Kind

The Stirling numbers of the first kind count permutations according to their number of cycles (counting fixed points as cycles of length one).

$S(n,k)$ counts the number of permutations of n elements with k disjoint cycles.

$S(n,k) = (n-1)\cdot S(n-1,k) + S(n-1,k-1)$, *where*, $S(0,0) = 1, S(n,0) = S(0,n) = 0$ $\sum_{k=0}^{n} S(n,k) = n!$

The unsigned Stirling numbers may also be defined algebraically, as the coefficient of the rising factorial:

$$x^{\bar{n}} = x(x+1)...(x+n-1) = \sum_{k=0}^{n} S(n,k)x^k$$

Lets $[n,k]$ be the stirling number of the first kind, then

$$\left[{n \atop k}\right] = \sum_{0 \le i_1 < i_2 < i_k < n} i_1 i_2 .... i_k.$$

9.3 Stirling Numbers Second Kind

Stirling number of the second kind is the number of ways to partition a set of n objects into k non-empty subsets.

$S(n,k) = k \cdot S(n-1,k) + S(n-1,k-1)$, *where* $S(0,0) = 1, S(n,0) = S(0,n) = 0$ $S(n,2) = 2^{n-1} - 1$ $S(n,k)\cdot k!$ = number of ways to color n nodes using colors from 1 to k such that each color is used at least once.

An r-associated Stirling number of the second kind is the number of ways to partition a set of n objects into k subsets, with each subset containing at least r elements. It is denoted by $S_r(n,k)$ and obeys the recurrence relation. $S_r(n+1,k) = kS_r(n,k) + \binom{n}{r-1} S_r(n-r+1, k-1)$

Denote the n objects to partition by the integers $1, 2, \ldots, n$. Define the reduced Stirling numbers of the second kind, denoted $S^d(n,k)$, to be the number of ways to partition the integers $1, 2, \ldots, n$ into k nonempty subsets such that all elements in each subset have pairwise distance at least d. That is, for any integers i and j in a given subset, it is required that $|i-j| \ge d$. It has been shown that these numbers satisfy, $S^d(n,k) = S(n-d+1, k-d+1), n \ge k \ge d$

9.4 Other Combinatorial Identities

$\binom{n}{k} = \frac{n}{k}\binom{n-1}{k-1}$

$\sum_{i=0}^{k} \binom{n+i}{i} = \sum_{i=0}^{k} \binom{n+i}{n} = \binom{n+k+1}{k}$

$n, r \in N, n > r, \sum_{i=r}^{n} \binom{i}{r} = \binom{n+1}{r+1}$

If $P(n) = \sum_{k=0}^{n} \binom{n}{k} \cdot Q(k)$, then,

$$Q(n) = \sum_{k=0}^{n} (-1)^{n-k} \binom{n}{k} \cdot P(k)$$

If $P(n) = \sum_{k=0}^{n} (-1)^k \binom{n}{k} \cdot Q(k)$, then,

$$Q(n) = \sum_{k=0}^{n} (-1)^k \binom{n}{k} \cdot P(k)$$

9.5 Different Math Formulas

Picks Theorem : $A = i + b/2 - 1$

Deragements : $d(i) = (i-1) \times (d(i-1) + d(i-2))$

$$\frac{n}{ab} \quad - \quad \left\{\frac{b\prime n}{a}\right\} \quad - \quad \left\{\frac{a\prime n}{b}\right\} \quad + \quad 1$$

9.6 GCD and LCM

if m is any integer, then $\gcd(a + m\cdot b, b) = \gcd(a,b)$

The gcd is a multiplicative function in the following sense: if a_1 and a_2 are relatively prime, then $\gcd(a_1 \cdot a_2, b) = \gcd(a_1, b) \cdot \gcd(a_2, b)$.

$\gcd(a, \operatorname{lcm}(b,c)) = \operatorname{lcm}(\gcd(a,b), \gcd(a,c))$.

$\operatorname{lcm}(a, \gcd(b,c)) = \gcd(\operatorname{lcm}(a,b), \operatorname{lcm}(a,c))$.

For non-negative integers a and b, where a and b are not both zero, $\gcd(n^a - 1, n^b - 1) = n^{\gcd(a,b)} - 1$

$\gcd(a,b) = \sum_{k \mid a \text{ and } k \mid b} \phi(k)$

$\sum_{i=1}^{n} [\gcd(i,n) = k] = \phi\left(\frac{n}{k}\right)$

$\sum_{k=1}^{n} \gcd(k,n) = \sum_{d \mid n} d \cdot \phi\left(\frac{n}{d}\right)$

$\sum_{k=1}^{n} x^{\gcd(k,n)} = \sum_{d \mid n} x^d \cdot \phi\left(\frac{n}{d}\right)$

$\sum_{k=1}^{n} \frac{1}{\gcd(k,n)} = \sum_{d \mid n} \frac{1}{d} \cdot \phi\left(\frac{n}{d}\right) = \frac{1}{n} \sum_{d \mid n} d \cdot \phi(d)$

$\sum_{k=1}^{n} \frac{k}{\gcd(k,n)} = \frac{n}{2} \cdot \sum_{d \mid n} \frac{1}{d} \cdot \phi\left(\frac{n}{d}\right) = \frac{n}{2} \cdot \frac{1}{n} \cdot \sum_{d \mid n} d \cdot \phi(d)$

$\sum_{k=1}^{n} \frac{n}{\gcd(k,n)} = 2 * \sum_{k=1}^{n} \frac{k}{\gcd(k,n)} - 1$, for $n > 1$

$\sum_{i=1}^{n} \sum_{j=1}^{n} [\gcd(i,j) = 1] = \sum_{d=1}^{n} \mu(d) \lfloor \frac{n}{d} \rfloor^2$

$\sum_{i=1}^{n} \sum_{j=1}^{n} \gcd(i,j) = \sum_{d=1}^{n} \phi(d) \lfloor \frac{n}{d} \rfloor^2$

$\sum_{i=1}^{n} \sum_{j=1}^{n} i \cdot j [\gcd(i,j) = 1] = \sum_{i=1}^{n} \phi(i) i^2$

$F(n) = \sum_{i=1}^{n} \sum_{j=1}^{n} \operatorname{lcm}(i,j) = \sum_{l=1}^{n} \left(\frac{\left(1 + \lfloor \frac{n}{l} \rfloor\right)\left(\lfloor \frac{n}{l} \rfloor\right)}{2} \right)^2 \sum_{d \mid l} \mu(d) l d$