Fortcoders Code Library

askd, yangster67, Nea1

April 29th 2022

Contents

Intro

Main template

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

#define FOR(x,n) for(int x=0;x<n;x++)
#define forn(i, n) for (int i = 0; i < int(n); i++)
#define all(v) v.begin(),v.end()
using ll = long long;
using ld = long double;
using pii = pair<int, int>;
const char nl = '\n';

int main() {
  cin.tie(nullptr)->sync_with_stdio(false);
  cout << fixed << setprecision(20);
  // mt19937
  ↪ rng(chrono::steady_clock::now().time_since_epoch().count());
}
```

Fast IO

```cpp
namespace io {
constexpr int SIZE = 1 << 16;
char buf[SIZE], *head, *tail;
char get_char() {
  if (head == tail) tail = (head = buf) + fread(buf, 1, SIZE,
  ↪  stdin);
  return *head++;
}
ll read() {
  ll x = 0, f = 1;
  char c = get_char();
  for (; !isdigit(c); c = get_char()) (c == '-') && (f = -1);
  for (; isdigit(c); c = get_char()) x = x * 10 + c - '0';
  return x * f;
}
string read_s() {
  string str;
  char c = get_char();
  while (c == ' ' || c == '\n' || c == '\r') c = get_char();
  while (c != ' ' && c != '\n' && c != '\r') str += c, c =
  ↪  get_char();
  return str;
}
void print(int x) {
  if (x > 9) print(x / 10);
  putchar(x % 10 | '0');
}
void println(int x) { print(x), putchar('\n'); }
struct Read {
  Read& operator>>(ll& x) { return x = read(), *this; }
  Read& operator>>(long double& x) { return x =
  ↪  stold(read_s()), *this; }
} in;
}  // namespace io
```

Pragmas (lol)

```cpp
#pragma GCC optimize(2)
#pragma GCC optimize(3)
#pragma GCC optimize("Ofast")
#pragma GCC optimize("inline")
#pragma GCC optimize("-fgcse")
#pragma GCC optimize("-fgcse-lm")
#pragma GCC optimize("-fipa-sra")
#pragma GCC optimize("-ftree-pre")
#pragma GCC optimize("-ftree-vrp")
#pragma GCC optimize("-fpeephole2")
#pragma GCC optimize("-ffast-math")
#pragma GCC optimize("-fsched-spec")
#pragma GCC optimize("unroll-loops")
#pragma GCC optimize("-falign-jumps")
#pragma GCC optimize("-falign-loops")
#pragma GCC optimize("-falign-labels")
#pragma GCC optimize("-fdevirtualize")
#pragma GCC optimize("-fcaller-saves")
#pragma GCC optimize("-fcrossjumping")
#pragma GCC optimize("-fthread-jumps")
#pragma GCC optimize("-funroll-loops")
#pragma GCC optimize("-fwhole-program")
#pragma GCC optimize("-freorder-blocks")
#pragma GCC optimize("-fschedule-insns")
#pragma GCC optimize("inline-functions")
#pragma GCC optimize("-ftree-tail-merge")
#pragma GCC optimize("-fschedule-insns2")
#pragma GCC optimize("-fstrict-aliasing")
#pragma GCC optimize("-fstrict-overflow")
#pragma GCC optimize("-falign-functions")
#pragma GCC optimize("-fcse-skip-blocks")
#pragma GCC optimize("-fcse-follow-jumps")
#pragma GCC optimize("-fsched-interblock")
#pragma GCC optimize("-fpartial-inlining")
#pragma GCC optimize("no-stack-protector")
#pragma GCC optimize("-freorder-functions")
#pragma GCC optimize("-findirect-inlining")
#pragma GCC optimize("-fhoist-adjacent-loads")
#pragma GCC optimize("-frerun-cse-after-loop")
#pragma GCC optimize("inline-small-functions")
#pragma GCC optimize("-finline-small-functions")
#pragma GCC optimize("-ftree-switch-conversion")
#pragma GCC optimize("-foptimize-sibling-calls")
#pragma GCC optimize("-fexpensive-optimizations")
#pragma GCC optimize("-funsafe-loop-optimizations")
#pragma GCC optimize("inline-functions-called-once")
#pragma GCC optimize("-fdelete-null-pointer-checks")
#pragma GCC
↪  target("sse,sse2,sse3,ssse3,sse4.1,sse4.2,avx,avx2,popcnt,tune=nat
```

Data Structures

Segment Tree

Recursive

- Implicit segment tree, range query + point update

```cpp
struct Node {
  int lc, rc, p;
};

struct SegTree {
  vector<Node> t = {{}};
  SegTree(int n) { t.reserve(n * 40); }
  int modify(int p, int l, int r, int x, int v) {
    int u = p;
    if (p == 0) {
      t.push_back(t[p]);
      u = (int)t.size() - 1;
    }
    if (r - l == 1) {
      t[u].p = t[p].p + v;
    } else {
      int m = (l + r) / 2;
      if (x < m) {
        t[u].lc = modify(t[p].lc, l, m, x, v);
      } else {
        t[u].rc = modify(t[p].rc, m, r, x, v);
      }
      t[u].p = t[t[u].lc].p + t[t[u].rc].p;
    }
    return u;
  }
  int query(int p, int l, int r, int x, int y) {
    if (x <= l && r <= y) return t[p].p;
    int m = (l + r) / 2, res = 0;
    if (x < m) res += query(t[p].lc, l, m, x, y);
    if (y > m) res += query(t[p].rc, m, r, x, y);
    return res;
  }
}
```

```
34    };
```

- Persistent implicit, range query + point update

```
1    struct Node {
2      int lc = 0, rc = 0, p = 0;
3    };
4
5    struct SegTree {
6      vector<Node> t = {{}};   // init all
7      SegTree() = default;
8      SegTree(int n) { t.reserve(n * 20); }
9      int modify(int p, int l, int r, int x, int v) {
10       // p: original node, update a[x] -> v
11       t.push_back(t[p]);
12       int u = (int)t.size() - 1;
13       if (r - l == 1) {
14         t[u].p = v;
15       } else {
16         int m = (l + r) / 2;
17         if (x < m) {
18           t[u].lc = modify(t[p].lc, l, m, x, v);
19           t[u].rc = t[p].rc;
20         } else {
21           t[u].lc = t[p].lc;
22           t[u].rc = modify(t[p].rc, m, r, x, v);
23         }
24         t[u].p = t[t[u].lc].p + t[t[u].rc].p;
25       }
26       return u;
27     }
28     int query(int p, int l, int r, int x, int y) {
29       // query sum a[x]...a[y-1] rooted at p
30       // t[p] holds the info of [l, r)
31       if (x <= l && r <= y) return t[p].p;
32       int m = (l + r) / 2, res = 0;
33       if (x < m) res += query(t[p].lc, l, m, x, y);
34       if (y > m) res += query(t[p].rc, m, r, x, y);
35       return res;
36     }
37   };
```

Iterating

- Iterating, range query + point update

```
1    struct Node {
2      ll v = 0, init = 0;
3    };
4
5    Node pull(const Node &a, const Node &b) {
6      if (!a.init) return b;
7      if (!b.init) return a;
8      Node c;
9      return c;
10   }
11
12   struct SegTree {
13     ll n;
14     vector<Node> t;
15     SegTree(ll _n) : n(_n), t(2 * n){};
16     void modify(ll p, const Node &v) {
17       t[p += n] = v;
18       for (p /= 2; p; p /= 2) t[p] = pull(t[p * 2], t[p * 2 +
↪    1]);
19     }
20     Node query(ll l, ll r) {
21       Node left, right;
22       for (l += n, r += n; l < r; l /= 2, r /= 2) {
23         if (l & 1) left = pull(left, t[l++]);
24         if (r & 1) right = pull(t[--r], right);
25       }
26       return pull(left, right);
27     }
28   };
```

- Iterating, range query + range update

```
1    struct Node {
2      ll v = 0;
3    };
4    struct Tag {
5      ll v = 0;
6    };
7    Node pull(const Node& a, const Node& b) { return {max(a.v,
↪    b.v)}; }
8    Tag pull(const Tag& a, const Tag& b) { return {a.v + b.v}; }
9    Node apply_tag(const Node& a, const Tag& b) { return {a.v +
↪    b.v}; }
10
11   struct SegTree {
12     ll n, h;
13     vector<Node> t;
14     vector<Tag> lazy;
15     SegTree(ll _n) : n(_n), h((ll)log2(n)), t(2 * _n), lazy(2 *
↪    _n) {}
16     void apply(ll x, const Tag& tag) {
17       t[x] = apply_tag(t[x], tag);
18       lazy[x] = pull(lazy[x], tag);
19     }
20     void build(ll l) {
21       for (l = (l + n) / 2; l > 0; l /= 2) {
22         if (!lazy[l].v) t[l] = pull(t[l * 2], t[2 * l + 1]);
23       }
24     }
25     void push(ll l) {
26       l += n;
27       for (ll s = h; s > 0; s--) {
28         ll i = l >> s;
29         if (lazy[i].v) {
30           apply(2 * i, lazy[i]);
31           apply(2 * i + 1, lazy[i]);
32         }
33         lazy[i] = Tag();
34       }
35     }
36     void modify(ll l, ll r, const Tag& v) {
37       push(l), push(r - 1);
38       ll l0 = l, r0 = r;
39       for (l += n, r += n; l < r; l /= 2, r /= 2) {
40         if (l & 1) apply(l++, v);
41         if (r & 1) apply(--r, v);
42       }
43       build(l0), build(r0 - 1);
44     }
45     Node query(ll l, ll r) {
46       push(l), push(r - 1);
47       Node left, right;
48       for (l += n, r += n; l < r; l /= 2, r /= 2) {
49         if (l & 1) left = pull(left, t[l++]);
50         if (r & 1) right = pull(t[--r], right);
51       }
52       return pull(left, right);
53     }
54   };
```

- AtCoder Segment Tree (recursive structure but iterative)

```
1    template <class T> struct PointSegmentTree {
2      int size = 1;
3      vector<T> tree;
4      PointSegmentTree(int n) : PointSegmentTree(vector<T>(n)) {}
5      PointSegmentTree(vector<T>& arr) {
6        while(size < (int)arr.size())
7          size <<= 1;
8        tree = vector<T>(size << 1);
9        for(int i = size + arr.size() - 1; i >= 1; i--)
10         if(i >= size) tree[i] = arr[i - size];
11         else consume(i);
12     }
13     void set(int i, T val) {
14       tree[i += size] = val;
15       for(i >>= 1; i >= 1; i >>= 1)
16         consume(i);
17     }
18     T get(int i) { return tree[i + size]; }
```

```cpp
19    T query(int l, int r) {
20      T resl, resr;
21      for(l += size, r += size + 1; l < r; l >>= 1, r >>= 1) {
22        if(l & 1) resl = resl * tree[l++];
23        if(r & 1) resr = tree[--r] * resr;
24      }
25      return resl * resr;
26    }
27    T query_all() { return tree[1]; }
28    void consume(int i) { tree[i] = tree[i << 1] * tree[i << 1 |
      1]; }
29  };
30
31
32  struct SegInfo {
33    ll v;
34    SegInfo() : SegInfo(0) {}
35    SegInfo(ll val) : v(val) {}
36    SegInfo operator*(SegInfo b) {
37      return SegInfo(v + b.v);
38    }
39  };
```

Union Find

```cpp
1  vector<int> p(n);
2  iota(p.begin(), p.end(), 0);
3  function<int(int)> find = [&](int x) { return p[x] == x ? x :
     (p[x] = find(p[x])); };
4  auto merge = [&](int x, int y) { p[find(x)] = find(y); };
```

- Persistent version

```cpp
1  struct Node {
2    int lc, rc, p;
3  };
4
5  struct SegTree {
6    vector<Node> t = {{0, 0, -1}};  // init all
7    SegTree() = default;
8    SegTree(int n) { t.reserve(n * 20); }
9    int modify(int p, int l, int r, int x, int v) {
10     // p: original node, update a[x] -> v
11     t.push_back(t[p]);
12     int u = (int)t.size() - 1;
13     if (r - l == 1) {
14       t[u].p = v;
15     } else {
16       int m = (l + r) / 2;
17       if (x < m) {
18         t[u].lc = modify(t[p].lc, l, m, x, v);
19         t[u].rc = t[p].rc;
20       } else {
21         t[u].lc = t[p].lc;
22         t[u].rc = modify(t[p].rc, m, r, x, v);
23       }
24       t[u].p = t[t[u].lc].p + t[t[u].rc].p;
25     }
26     return u;
27   }
28   int query(int p, int l, int r, int x, int y) {
29     // query sum a[x]...a[y-1] rooted at p
30     // t[p] holds the info of [l, r)
31     if (x <= l && r <= y) return t[p].p;
32     int m = (l + r) / 2, res = 0;
33     if (x < m) res += query(t[p].lc, l, m, x, y);
34     if (y > m) res += query(t[p].rc, m, r, x, y);
35     return res;
36   }
37 };
38
39 struct DSU {
40   int n;
41   SegTree seg;
42   DSU(int _n) : n(_n), seg(n) {}
43   int get(int p, int x) { return seg.query(p, 0, n, x, x + 1);
      }
```

```cpp
44    int set(int p, int x, int v) { return seg.modify(p, 0, n, x,
      v); }
45    int find(int p, int x) {
46      int parent = get(p, x);
47      if (parent < 0) return x;
48      return find(p, parent);
49    }
50    int is_same(int p, int x, int y) { return find(p, x) ==
      find(p, y); }
51    int merge(int p, int x, int y) {
52      int rx = find(p, x), ry = find(p, y);
53      if (rx == ry) return -1;
54      int rank_x = -get(p, rx), rank_y = -get(p, ry);
55      if (rank_x < rank_y) {
56        p = set(p, rx, ry);
57      } else if (rank_x > rank_y) {
58        p = set(p, ry, rx);
59      } else {
60        p = set(p, ry, rx);
61        p = set(p, rx, -rx - 1);
62      }
63      return p;
64    }
65  };
```

Fenwick Tree

```cpp
1  template <typename T> struct FenwickTree {
2    int size = 1, high_bit = 1;
3    vector<T> tree;
4    FenwickTree(int _size) : size(_size) {
5      tree.resize(size + 1);
6      while((high_bit << 1) <= size) high_bit <<= 1;
7    }
8    FenwickTree(vector<T>& arr) : FenwickTree(arr.size()) {
9      for(int i = 0; i < size; i++) update(i, arr[i]);
10   }
11   int lower_bound(T x) {
12     int res = 0; T cur = 0;
13     for(int bit = high_bit; bit > 0; bit >>= 1) {
14       if((res|bit) <= size && cur + tree[res|bit] < x) {
15         res |= bit; cur += tree[res];
16       }
17     }
18     return res;
19   }
20   T prefix_sum(int i) {
21     T ret = 0;
22     for(i++; i > 0; i -= (i & -i)) ret += tree[i];
23     return ret;
24   }
25   T range_sum(int l, int r) { return (l > r) ? 0 :
      prefix_sum(r) - prefix_sum(l - 1); }
26   void update(int i, T delta) { for(i++; i <= size; i += (i &
      -i)) tree[i] += delta; }
27 };
```

Fenwick2D Tree

```cpp
1  struct Fenwick2D {
2    ll n, m;
3    vector<vector<ll>> a;
4    Fenwick2D(ll _n, ll _m) : n(_n), m(_m), a(n, vector<ll>(m))
      {}
5    void add(ll x, ll y, ll v) {
6      for (int i = x + 1; i <= n; i += i & -i) {
7        for (int j = y + 1; j <= m; j += j & -j) {
8          (a[i - 1][j - 1] += v) %= MOD;
9        }
10     }
11   }
12   void add(ll x1, ll x2, ll y1, ll y2, ll v) {
13     // [(x1, y1), (x2, y2))
14     add(x1, y1, v);
15     add(x1, y2, MOD - v), add(x2, y1, MOD - v);
16     add(x2, y2, v);
```

```
17       }
18       ll sum(ll x, ll y) {  // [(0, 0), (x, y))
19         ll ans = 0;
20         for (int i = x; i > 0; i -= i & -i) {
21           for (int j = y; j > 0; j -= j & -j) {
22             (ans += a[i - 1][j - 1]) %= MOD;
23           }
24         }
25         return ans;
26       }
27     };
```

PBDS

```
1    #include <bits/stdc++.h>
2    #include <ext/pb_ds/assoc_container.hpp>
3    using namespace std;
4    using namespace __gnu_pbds;
5    template<typename T>
6    using ordered_set = tree<T, null_type, less<T>, rb_tree_tag,
     ↪ tree_order_statistics_node_update>;
7    template<typename T, typename X>
8    using ordered_map = tree<T, X, less<T>, rb_tree_tag,
     ↪ tree_order_statistics_node_update>;
9    template<typename T, typename X>
10   using fast_map = cc_hash_table<T, X>;
11   template<typename T, typename X>
12   using ht = gp_hash_table<T, X>;
13   mt19937_64
     ↪ rng(chrono::steady_clock::now().time_since_epoch().count());
14
15   struct splitmix64 {
16       size_t operator()(size_t x) const {
17           static const size_t fixed =
     ↪ chrono::steady_clock::now().time_since_epoch().count();
18           x += 0x9e3779b97f4a7c15 + fixed;
19           x = (x ^ (x >> 30)) * 0xbf58476d1ce4e5b9;
20           x = (x ^ (x >> 27)) * 0x94d049bb133111eb;
21           return x ^ (x >> 31);
22       }
23   };
```

Treap

- (No rotation version)

```
1    struct Node {
2      Node *l, *r;
3      int s, sz;
4      // int t = 0, a = 0, g = 0; // for lazy propagation
5      ll w;
6
7      Node(int _s) : l(nullptr), r(nullptr), s(_s), sz(1),
     ↪ w(rng()) {}
8      void apply(int vt, int vg) {
9        // for lazy propagation
10       // s -= vt;
11       // t += vt, a += vg, g += vg;
12     }
13     void push() {
14       // for lazy propagation
15       // if (l != nullptr) l->apply(t, g);
16       // if (r != nullptr) r->apply(t, g);
17       // t = g = 0;
18     }
19     void pull() { sz = 1 + (l ? l->sz : 0) + (r ? r->sz : 0); }
20   };
21
22   std::pair<Node *, Node *> split(Node *t, int v) {
23     if (t == nullptr) return {nullptr, nullptr};
24     t->push();
25     if (t->s < v) {
26       auto [x, y] = split(t->r, v);
27       t->r = x;
28       t->pull();
29       return {t, y};
```

```
30     } else {
31       auto [x, y] = split(t->l, v);
32       t->l = y;
33       t->pull();
34       return {x, t};
35     }
36   }
37
38   Node *merge(Node *p, Node *q) {
39     if (p == nullptr) return q;
40     if (q == nullptr) return p;
41     if (p->w < q->w) swap(p, q);
42     auto [x, y] = split(q, p->s + rng() % 2);
43     p->push();
44     p->l = merge(p->l, x);
45     p->r = merge(p->r, y);
46     p->pull();
47     return p;
48   }
49
50   Node *insert(Node *t, int v) {
51     auto [x, y] = split(t, v);
52     return merge(merge(x, new Node(v)), y);
53   }
54
55   Node *erase(Node *t, int v) {
56     auto [x, y] = split(t, v);
57     auto [p, q] = split(y, v + 1);
58     return merge(merge(x, merge(p->l, p->r)), q);
59   }
60
61   int get_rank(Node *&t, int v) {
62     auto [x, y] = split(t, v);
63     int res = (x ? x->sz : 0) + 1;
64     t = merge(x, y);
65     return res;
66   }
67
68   Node *kth(Node *t, int k) {
69     k--;
70     while (true) {
71       int left_sz = t->l ? t->l->sz : 0;
72       if (k < left_sz) {
73         t = t->l;
74       } else if (k == left_sz) {
75         return t;
76       } else {
77         k -= left_sz + 1, t = t->r;
78       }
79     }
80   }
81
82   Node *get_prev(Node *&t, int v) {
83     auto [x, y] = split(t, v);
84     Node *res = kth(x, x->sz);
85     t = merge(x, y);
86     return res;
87   }
88
89   Node *get_next(Node *&t, int v) {
90     auto [x, y] = split(t, v + 1);
91     Node *res = kth(y, 1);
92     t = merge(x, y);
93     return res;
94   }
```

- USAGE

```
1    int main() {
2      cin.tie(nullptr)->sync_with_stdio(false);
3      int n;
4      cin >> n;
5      Node *t = nullptr;
6      for (int op, x; n--;) {
7        cin >> op >> x;
8        if (op == 1) {
9          t = insert(t, x);
10       } else if (op == 2) {
```

```
11          t = erase(t, x);
12        } else if (op == 3) {
13          cout << get_rank(t, x) << "\n";
14        } else if (op == 4) {
15          cout << kth(t, x)->s << "\n";
16        } else if (op == 5) {
17          cout << get_prev(t, x)->s << "\n";
18        } else {
19          cout << get_next(t, x)->s << "\n";
20        }
21      }
22    }
```

Implicit treap

- Split by size

```
1   struct Node {
2     Node *l, *r;
3     int s, sz;
4     // int lazy = 0;
5     ll w;
6
7     Node(int _s) : l(nullptr), r(nullptr), s(_s), sz(1),
    ↪  w(rnd()) {}
8     void apply() {
9       // for lazy propagation
10      // lazy ^= 1;
11    }
12    void push() {
13      // for lazy propagation
14      // if (lazy) {
15      //   swap(l, r);
16      //   if (l != nullptr) l->apply();
17      //   if (r != nullptr) r->apply();
18      //   lazy = 0;
19      // }
20    }
21    void pull() { sz = 1 + (l ? l->sz : 0) + (r ? r->sz : 0); }
22  };
23
24  std::pair<Node *, Node *> split(Node *t, int v) {
25    // first->sz == v
26    if (t == nullptr) return {nullptr, nullptr};
27    t->push();
28    int left_sz = t->l ? t->l->sz : 0;
29    if (left_sz < v) {
30      auto [x, y] = split(t->r, v - left_sz - 1);
31      t->r = x;
32      t->pull();
33      return {t, y};
34    } else {
35      auto [x, y] = split(t->l, v);
36      t->l = y;
37      t->pull();
38      return {x, t};
39    }
40  }
41
42  Node *merge(Node *p, Node *q) {
43    if (p == nullptr) return q;
44    if (q == nullptr) return p;
45    if (p->w < q->w) {
46      p->push();
47      p->r = merge(p->r, q);
48      p->pull();
49      return p;
50    } else {
51      q->push();
52      q->l = merge(p, q->l);
53      q->pull();
54      return q;
55    }
56  }
```

Persistent implicit treap

```
1   pair<Node *, Node *> split(Node *t, int v) {
2     // first->sz == v
3     if (t == nullptr) return {nullptr, nullptr};
4     t->push();
5     int left_sz = t->l ? t->l->sz : 0;
6     t = new Node(*t);
7     if (left_sz < v) {
8       auto [x, y] = split(t->r, v - left_sz - 1);
9       t->r = x;
10      t->pull();
11      return {t, y};
12    } else {
13      auto [x, y] = split(t->l, v);
14      t->l = y;
15      t->pull();
16      return {x, t};
17    }
18  }
19
20  Node *merge(Node *p, Node *q) {
21    if (p == nullptr) return new Node(*q);
22    if (q == nullptr) return new Node(*p);
23    if (p->w < q->w) {
24      p = new Node(*p);
25      p->push();
26      p->r = merge(p->r, q);
27      p->pull();
28      return p;
29    } else {
30      q = new Node(*q);
31      q->push();
32      q->l = merge(p, q->l);
33      q->pull();
34      return q;
35    }
36  }
```

2D Sparse Table

- Sorry that this sucks - askd

```
1   template <class T, class Compare = less<T>>
2   struct SparseTable2d {
3     int n = 0, m = 0;
4     T**** table;
5     int* log;
6     inline T choose(T x, T y) {
7       return Compare()(x, y) ? x : y;
8     }
9     SparseTable2d(vector<vector<T>>& grid) {
10      if(grid.empty() || grid[0].empty()) return;
11      n = grid.size(); m = grid[0].size();
12      log = new int[max(n, m) + 1];
13      log[1] = 0;
14      for(int i = 2; i <= max(n, m); i++)
15        log[i] = log[i - 1] + ((i ^ (i - 1)) > i);
16      table = new T***[n];
17      for(int i = n - 1; i >= 0; i--) {
18        table[i] = new T**[m];
19        for(int j = m - 1; j >= 0; j--) {
20          table[i][j] = new T*[log[n - i] + 1];
21          for(int k = 0; k <= log[n - i]; k++) {
22            table[i][j][k] = new T[log[m - j] + 1];
23            if(!k) table[i][j][k][0] = grid[i][j];
24            else table[i][j][k][0] = choose(table[i][j][k-1][0],
    ↪  table[i+(1<<(k-1))][j][k-1][0]);
25            for(int l = 1; l <= log[m - j]; l++)
26              table[i][j][k][l] = choose(table[i][j][k][l-1],
    ↪  table[i][j+(1<<(l-1))][k][l-1]);
27          }
28        }
29      }
30    }
31    T query(int r1, int r2, int c1, int c2) {
32      assert(r1 >= 0 && r2 < n && r1 <= r2);
```

```
33        assert(c1 >= 0 && c2 < m && c1 <= c2);
34        int r1 = log[r2 - r1 + 1], cl = log[c2 - c1 + 1];
35        T ca1 = choose(table[r1][c1][rl][cl],
   ↪    table[r2-(1<<rl)+1][c1][rl][cl]);
36        T ca2 = choose(table[r1][c2-(1<<cl)+1][rl][cl],
   ↪    table[r2-(1<<rl)+1][c2-(1<<cl)+1][rl][cl]);
37        return choose(ca1, ca2);
38      }
39  };
```

  ● USAGE

```
1  vector<vector<int>> test =  {
2    {1, 2, 3, 4}, {2, 3, 4, 5}, {9, 9, 9, 9}, {-1, -1, -1, -1}
3  };
4
5  SparseTable2d<int> st(test);                // Range min query
6  SparseTable2d<int,greater<int>> st2(test);  // Range max query
```

K-D Tree

```
1  struct Point {
2    int x, y;
3  };
4  struct Rectangle {
5    int lx, rx, ly, ry;
6  };
7
8  bool is_in(const Point &p, const Rectangle &rg) {
9    return (p.x >= rg.lx) && (p.x <= rg.rx) && (p.y >= rg.ly) &&
   ↪  (p.y <= rg.ry);
10  }
11
12  struct KDTree {
13    vector<Point> points;
14    struct Node {
15      int lc, rc;
16      Point point;
17      Rectangle range;
18      int num;
19    };
20    vector<Node> nodes;
21    int root = -1;
22    KDTree(const vector<Point> &points_) {
23      points = points_;
24      Rectangle range = {-1e9, 1e9, -1e9, 1e9};
25      root = tree_construct(0, (int)points.size(), range, 0);
26    }
27    int tree_construct(int l, int r, Rectangle range, int depth)
   ↪  {
28      if (l == r) return -1;
29      if (l > r) throw;
30      int mid = (l + r) / 2;
31      auto comp = (depth % 2) ? [](Point &a, Point &b) { return
   ↪  a.x < b.x; }
32                              : [](Point &a, Point &b) { return
   ↪  a.y < b.y; };
33      nth_element(points.begin() + l, points.begin() + mid,
   ↪  points.begin() + r, comp);
34      Rectangle l_range(range), r_range(range);
35      if (depth % 2) {
36        l_range.rx = points[mid].x;
37        r_range.lx = points[mid].x;
38      } else {
39        l_range.ry = points[mid].y;
40        r_range.ly = points[mid].y;
41      }
42      Node node = {tree_construct(l, mid, l_range, depth + 1),
43                   tree_construct(mid + 1, r, r_range, depth +
   ↪  1), points[mid], range, r - l};
44      nodes.push_back(node);
45      return (int)nodes.size() - 1;
46    }
47
48    int inner_query(int id, const Rectangle &rec, int depth) {
49      if (id == -1) return 0;
50      Rectangle rg = nodes[id].range;
```

```
51      if (rg.lx >= rec.lx && rg.rx <= rec.rx && rg.ly >= rec.ly
   ↪  && rg.ry <= rec.ry) {
52        return nodes[id].num;
53      }
54      int ans = 0;
55      if (depth % 2) { // pruning
56        if (rec.lx <= nodes[id].point.x) ans +=
   ↪  inner_query(nodes[id].lc, rec, depth + 1);
57        if (rec.rx >= nodes[id].point.x) ans +=
   ↪  inner_query(nodes[id].rc, rec, depth + 1);
58      } else {
59        if (rec.ly <= nodes[id].point.y) ans +=
   ↪  inner_query(nodes[id].lc, rec, depth + 1);
60        if (rec.ry >= nodes[id].point.y) ans +=
   ↪  inner_query(nodes[id].rc, rec, depth + 1);
61      }
62      if (is_in(nodes[id].point, rec)) ans += 1;
63      return ans;
64    }
65    int query(const Rectangle &rec) { return inner_query(root,
   ↪  rec, 0); }
66  };
```

Link/Cut Tree

```
1  struct Node {
2    Node *ch[2], *p;
3    int id;
4    bool rev;
5    Node(int id) : ch{nullptr, nullptr}, p(nullptr), id(id),
   ↪  rev(false) {}
6    friend void reverse(Node *p) {
7      if (p != nullptr) {
8        swap(p->ch[0], p->ch[1]);
9        p->rev ^= 1;
10      }
11    }
12    void push() {
13      if (rev) {
14        reverse(ch[0]);
15        reverse(ch[1]);
16        rev = false;
17      }
18    }
19    void pull() {}
20    bool is_root() { return p == nullptr || p->ch[0] != this &&
   ↪  p->ch[1] != this; }
21    bool pos() { return p->ch[1] == this; }
22    void rotate() {
23      Node *q = p;
24      bool x = !pos();
25      q->ch[!x] = ch[x];
26      if (ch[x] != nullptr) ch[x]->p = q;
27      p = q->p;
28      if (!q->is_root()) q->p->ch[q->pos()] = this;
29      ch[x] = q;
30      q->p = this;
31      pull();
32      q->pull();
33    }
34    void splay() {
35      vector<Node *> s;
36      for (Node *i = this; !i->is_root(); i = i->p)
   ↪  s.push_back(i->p);
37      while (!s.empty()) s.back()->push(), s.pop_back();
38      push();
39      while (!is_root()) {
40        if (!p->is_root()) {
41          if (pos() == p->pos()) {
42            p->rotate();
43          } else {
44            rotate();
45          }
46        }
47        rotate();
48      }
```

```
49        pull();
50      }
51    void access() {
52      for (Node *i = this, *q = nullptr; i != nullptr; q = i, i
   ↪ = i->p) {
53        i->splay();
54        i->ch[1] = q;
55        i->pull();
56      }
57      splay();
58    }
59    void makeroot() {
60      access();
61      reverse(this);
62    }
63  };
64  void link(Node *x, Node *y) {
65    x->makeroot();
66    x->p = y;
67  }
68  void split(Node *x, Node *y) {
69    x->makeroot();
70    y->access();
71  }
72  void cut(Node *x, Node *y) {
73    split(x, y);
74    x->p = y->ch[0] = nullptr;
75    y->pull();
76  }
77  bool connected(Node *p, Node *q) {
78      p->access();
79      q->access();
80      return p->p != nullptr;
81  }
```

Geometry

Basic stuff

```
1  using ll = long long;
2  using ld = long double;
3
4  constexpr auto eps = 1e-8;
5  const auto PI = acos(-1);
6  int sgn(ld x) { return (abs(x) <= eps) ? 0 : (x < 0 ? -1 : 1);
   ↪ }
7
8  struct Point {
9    ld x = 0, y = 0;
10   Point() = default;
11   Point(ld _x, ld _y) : x(_x), y(_y) {}
12   bool operator<(const Point &p) const { return !sgn(p.x - x)
   ↪ ? sgn(y - p.y) < 0 : x < p.x; }
13   bool operator==(const Point &p) const { return !sgn(p.x - x)
   ↪ && !sgn(p.y - y); }
14   Point operator+(const Point &p) const { return {x + p.x, y +
   ↪ p.y}; }
15   Point operator-(const Point &p) const { return {x - p.x, y -
   ↪ p.y}; }
16   Point operator*(ld a) const { return {x * a, y * a}; }
17   Point operator/(ld a) const { return {x / a, y / a}; }
18   auto operator*(const Point &p) const { return x * p.x + y *
   ↪ p.y; }  // dot
19   auto operator^(const Point &p) const { return x * p.y - y *
   ↪ p.x; }  // cross
20   friend auto &operator>>(istream &i, Point &p) { return i >>
   ↪ p.x >> p.y; }
21   friend auto &operator<<(ostream &o, Point p) { return o <<
   ↪ p.x << ' ' << p.y; }
22 };
23
24 struct Line {
25   Point s = {0, 0}, e = {0, 0};
26   Line() = default;
27   Line(Point _s, Point _e) : s(_s), e(_e) {}
```

```
28   friend auto &operator>>(istream &i, Line &l) { return i >>
   ↪ l.s >> l.e; }  // ((x1, y1), (x2, y2)
29 };
30
31 struct Segment : Line {
32   using Line::Line;
33 };
34
35 struct Circle {
36   Point o = {0, 0};
37   ld r = 0;
38   Circle() = default;
39   Circle(Point _o, ld _r) : o(_o), r(_r) {}
40 };
```

```
1  auto dist2(const Point &a) { return a * a; }
2  auto dist2(const Point &a, const Point &b) { return dist2(a -
   ↪ b); }
3  auto dist(const Point &a) { return sqrt(dist2(a)); }
4  auto dist(const Point &a, const Point &b) { return
   ↪ sqrt(dist2(a - b)); }
5  auto dist(const Point &a, const Line &l) { return abs((a -
   ↪ l.s) ^ (l.e - l.s)) / dist(l.s, l.e); }
6  auto dist(const Point &p, const Segment &l) {
7    if (l.s == l.e) return dist(p, l.s);
8    auto d = dist2(l.s, l.e), t = min(d, max((ld)0, (p - l.s) *
   ↪ (l.e - l.s)));
9    return dist((p - l.s) * d, (l.e - l.s) * t) / d;
10 }
11 /* Needs is_intersect
12 auto dist(const Segment &l1, const Segment &l2) {
13   if (is_intersect(l1, l2)) return (ld)0;
14   return min({dist(l1.s, l2), dist(l1.e, l2), dist(l2.s, l1),
   ↪ dist(l2.e, l1)});
15 } */
16
17 Point perp(const Point &p) { return Point(-p.y, p.x); }
18
19 auto rad(const Point &p) { return atan2(p.y, p.x); }
```

Transformation

```
1  Point project(const Point &p, const Line &l) {
2    return l.s + ((l.e - l.s) * ((l.e - l.s) * (p - l.s))) /
   ↪ dist2(l.e - l.s);
3  }
4
5  Point reflect(const Point &p, const Line &l) {
6    return project(p, l) * 2 - p;
7  }
8
9  Point dilate(const Point &p, ld scale_x = 1, ld scale_y = 1) {
   ↪ return Point(p.x * scale_x, p.y * scale_y); }
10 Line dilate(const Line &l, ld scale_x = 1, ld scale_y = 1) {
   ↪ return Line(dilate(l.s, scale_x, scale_y), dilate(l.e,
   ↪ scale_x, scale_y)); }
11 Segment dilate(const Segment &l, ld scale_x = 1, ld scale_y =
   ↪ 1) { return Segment(dilate(l.s, scale_x, scale_y),
   ↪ dilate(l.e, scale_x, scale_y)); }
12 vector<Point> dilate(const vector<Point> &p, ld scale_x = 1,
   ↪ ld scale_y = 1) {
13   int n = p.size();
14   vector<Point> res(n);
15   for (int i = 0; i < n; i++)
16     res[i] = dilate(p[i], scale_x, scale_y);
17   return res;
18 }
19
20 Point rotate(const Point &p, ld a) { return Point(p.x * cos(a)
   ↪ - p.y * sin(a), p.x * sin(a) + p.y * cos(a)); }
21 Line rotate(const Line &l, ld a) { return Line(rotate(l.s, a),
   ↪ rotate(l.e, a)); }
22 Segment rotate(const Segment &l, ld a) { return
   ↪ Segment(rotate(l.s, a), rotate(l.e, a)); }
23 Circle rotate(const Circle &c, ld a) { return
   ↪ Circle(rotate(c.o, a), c.r); }
24 vector<Point> rotate(const vector<Point> &p, ld a) {
```

```
25    int n = p.size();
26    vector<Point> res(n);
27    for (int i = 0; i < n; i++)
28      res[i] = rotate(p[i], a);
29    return res;
30  }
31
32  Point translate(const Point &p, ld dx = 0, ld dy = 0) { return
    ↪  Point(p.x + dx, p.y + dy); }
33  Line translate(const Line &l, ld dx = 0, ld dy = 0) { return
    ↪  Line(translate(l.s, dx, dy), translate(l.e, dx, dy)); }
34  Segment translate(const Segment &l, ld dx = 0, ld dy = 0) {
    ↪  return Segment(translate(l.s, dx, dy), translate(l.e, dx,
    ↪  dy)); }
35  Circle translate(const Circle &c, ld dx = 0, ld dy = 0) {
    ↪  return Circle(translate(c.o, dx, dy), c.r); }
36  vector<Point> translate(const vector<Point> &p, ld dx = 0, ld
    ↪  dy = 0) {
37    int n = p.size();
38    vector<Point> res(n);
39    for (int i = 0; i < n; i++)
40      res[i] = translate(p[i], dx, dy);
41    return res;
42  }
```

Relation

```
1   enum class Relation { SEPARATE, EX_TOUCH, OVERLAP, IN_TOUCH,
    ↪  INSIDE };
2   Relation get_relation(const Circle &a, const Circle &b) {
3     auto c1c2 = dist(a.o, b.o);
4     auto r1r2 = a.r + b.r, diff = abs(a.r - b.r);
5     if (sgn(c1c2 - r1r2) > 0) return Relation::SEPARATE;
6     if (sgn(c1c2 - r1r2) == 0) return Relation::EX_TOUCH;
7     if (sgn(c1c2 - diff) > 0) return Relation::OVERLAP;
8     if (sgn(c1c2 - diff) == 0) return Relation::IN_TOUCH;
9     return Relation::INSIDE;
10  }
11
12  auto get_cos_from_triangle(ld a, ld b, ld c) { return (a * a +
    ↪  b * b - c * c) / (2.0 * a * b); }
13
14  bool on_line(const Line &l, const Point &p) { return !sgn((l.s
    ↪  - p) ^ (l.e - p)); }
15
16  bool on_segment(const Segment &l, const Point &p) {
17    return !sgn((l.s - p) ^ (l.e - p)) && sgn((l.s - p) * (l.e -
    ↪  p)) <= 0;
18  }
19
20  bool on_segment2(const Segment &l, const Point &p) { // assume
    ↪  p on Line l
21    if (l.s == p || l.e == p) return true;
22    if (min(l.s, l.e) < p && p < max(l.s, l.e)) return true;
23    return false;
24  }
25
26  bool is_parallel(const Line &a, const Line &b) { return
    ↪  !sgn((a.s - a.e) ^ (b.s - b.e)); }
27  bool is_orthogonal(const Line &a, const Line &b) { return
    ↪  !sgn((a.s - a.e) * (b.s - b.e)); }
28
29  int is_intersect(const Segment &a, const Segment &b) {
30    auto d1 = sgn((a.e - a.s) ^ (b.s - a.s)), d2 = sgn((a.e -
    ↪  a.s) ^ (b.e - a.s));
31    auto d3 = sgn((b.e - b.s) ^ (a.s - b.s)), d4 = sgn((b.e -
    ↪  b.s) ^ (a.e - b.s));
32    if (d1 * d2 < 0 && d3 * d4 < 0) return 2;  // intersect at
    ↪  non-end point
33    return (d1 == 0 && sgn((b.s - a.s) * (b.s - a.e)) <= 0) ||
34           (d2 == 0 && sgn((b.e - a.s) * (b.e - a.e)) <= 0) ||
35           (d3 == 0 && sgn((a.s - b.s) * (a.s - b.e)) <= 0) ||
36           (d4 == 0 && sgn((a.e - b.s) * (a.e - b.e)) <= 0);
37  }
38
39  int is_intersect(const Line &a, const Segment &b) {
```

```
40    auto d1 = sgn((a.e - a.s) ^ (b.s - a.s)), d2 = sgn((a.e -
    ↪  a.s) ^ (b.e - a.s));
41    if (d1 * d2 < 0) return 2;  // intersect at non-end point
42    return d1 == 0 || d2 == 0;
43  }
44
45  Point intersect(const Line &a, const Line &b) {
46    auto u = a.e - a.s, v = b.e - b.s;
47    auto t = ((b.s - a.s) ^ v) / (u ^ v);
48    return a.s + u * t;
49  }
50
51  int is_intersect(const Circle &c, const Line &l) {
52    auto d = dist(c.o, l);
53    return sgn(d - c.r) < 0 ? 2 : !sgn(d - c.r);
54  }
55
56  vector<Point> intersect(const Circle &a, const Circle &b) {
57    auto relation = get_relation(a, b);
58    if (relation == Relation::INSIDE || relation ==
    ↪  Relation::SEPARATE) return {};
59    auto vec = b.o - a.o;
60    auto d2 = dist2(vec);
61    auto p = (d2 + a.r * a.r - b.r * b.r) / ((long double)2 *
    ↪  d2), h2 = a.r * a.r - p * p * d2;
62    auto mid = a.o + vec * p, per = perp(vec) * sqrt(max((long
    ↪  double)0, h2) / d2);
63    if (relation == Relation::OVERLAP)
64      return {mid + per, mid - per};
65    else
66      return {mid};
67  }
68
69  vector<Point> intersect(const Circle &c, const Line &l) {
70    if (!is_intersect(c, l)) return {};
71    auto v = l.e - l.s, t = v / dist(v);
72    Point a = l.s + t * ((c.o - l.s) * t);
73    auto d = sqrt(max((ld)0, c.r * c.r - dist2(c.o, a)));
74    if (!sgn(d)) return {a};
75    return {a - t * d, a + t * d};
76  }
77
78  int in_poly(const vector<Point> &p, const Point &a) {
79    int cnt = 0, n = (int)p.size();
80    for (int i = 0; i < n; i++) {
81      auto q = p[(i + 1) % n];
82      if (on_segment(Segment(p[i], q), a)) return 1;  // on the
    ↪  edge of the polygon
83      cnt ^= ((a.y < p[i].y) - (a.y < q.y)) * ((p[i] - a) ^ (q -
    ↪  a)) > 0;
84    }
85    return cnt ? 2 : 0;
86  }
87
88  int is_intersect(const vector<Point> &p, const Line &a) {
89    // 1: touching, >=2: intersect count
90    int cnt = 0, edge_cnt = 0, n = (int)p.size();
91    for (int i = 0; i < n; i++) {
92      auto q = p[(i + 1) % n];
93      if (on_line(a, p[i]) && on_line(a, q)) return -1;  //
    ↪  infinity
94      auto t = is_intersect(a, Segment(p[i], q));
95      (t == 1) && edge_cnt++, (t == 2) && cnt++;
96    }
97    return cnt + edge_cnt / 2;
98  }
99
100 vector<Point> tangent(const Circle &c, const Point &p) {
101   auto d = dist(c.o, p), l = c.r * c.r / d, h = sqrt(c.r * c.r
    ↪  - l * l);
102   auto v = (p - c.o) / d;
103   return {c.o + v * l + perp(v) * h, c.o + v * l - perp(v) *
    ↪  h};
104 }
105
106 Circle get_circumscribed(const Point &a, const Point &b, const
    ↪  Point &c) {
```

```
107    Line u((a + b) / 2, ((a + b) / 2) + perp(b - a));
108    Line v((b + c) / 2, ((b + c) / 2) + perp(c - b));
109    auto o = intersect(u, v);
110    return Circle(o, dist(o, a));
111  }
112
113  Circle get_inscribed(const Point &a, const Point &b, const
    ↪  Point &c) {
114    auto l1 = dist(b - c), l2 = dist(c - a), l3 = dist(a - b);
115    Point o = (a * l1 + b * l2 + c * l3) / (l1 + l2 + l3);
116    return Circle(o, dist(o, Line(a, b)));
117  }
118
119  pair<ld, ld> get_centroid(const vector<Point> &p) {
120    int n = (int)p.size();
121    ld x = 0, y = 0, sum = 0;
122    auto a = p[0], b = p[1];
123    for (int i = 2; i < n; i++) {
124      auto c = p[i];
125      auto s = area({a, b, c});
126      sum += s;
127      x += s * (a.x + b.x + c.x);
128      y += s * (a.y + b.y + c.y);
129      swap(b, c);
130    }
131    return {x / (3 * sum), y / (3 * sum)};
132  }
```

Area

```
1   auto area(const vector<Point> &p) {
2     int n = (int)p.size();
3     long double area = 0;
4     for (int i = 0; i < n; i++) area += p[i] ^ p[(i + 1) % n];
5     return area / 2.0;
6   }
7
8   auto area(const Point &a, const Point &b, const Point &c) {
9     return ((long double)((b - a) ^ (c - a))) / 2.0;
10  }
11
12  auto area2(const Point &a, const Point &b, const Point &c) {
    ↪   return (b - a) ^ (c - a); }
13
14  auto area_intersect(const Circle &c, const vector<Point> &ps)
    ↪   {
15    int n = (int)ps.size();
16    auto arg = [&](const Point &p, const Point &q) { return
    ↪   atan2(p ^ q, p * q); };
17    auto tri = [&](const Point &p, const Point &q) {
18      auto r2 = c.r * c.r / (long double)2;
19      auto d = q - p;
20      auto a = d * p / dist2(d), b = (dist2(p) - c.r * c.r) /
    ↪   dist2(d);
21      long double det = a * a - b;
22      if (sgn(det) <= 0) return arg(p, q) * r2;
23      auto s = max((long double)0, -a - sqrt(det)), t =
    ↪   min((long double)1, -a + sqrt(det));
24      if (sgn(t) < 0 || sgn(1 - s) <= 0) return arg(p, q) * r2;
25      auto u = p + d * s, v = p + d * t;
26      return arg(p, u) * r2 + (u ^ v) / 2 + arg(v, q) * r2;
27    };
28    long double sum = 0;
29    for (int i = 0; i < n; i++) sum += tri(ps[i] - c.o, ps[(i +
    ↪   1) % n] - c.o);
30    return sum;
31  }
32
33  auto adaptive_simpson(ld _l, ld _r, function<ld(ld)> f) {
34    auto simpson = [&](ld l, ld r) { return (r - l) * (f(l) + 4
    ↪   * f((l + r) / 2) + f(r)) / 6; };
35    function<ld(ld, ld, ld)> asr = [&](ld l, ld r, ld s) {
36      auto mid = (l + r) / 2;
37      auto left = simpson(l, mid), right = simpson(mid, r);
38      if (!sgn(left + right - s)) return left + right;
39      return asr(l, mid, left) + asr(mid, r, right);
40    };
```

```
41    return asr(_l, _r, simpson(_l, _r));
42  }
43
44  vector<Point> half_plane_intersect(vector<Line> &L) {
45    int n = (int)L.size(), l = 0, r = 0;  // [left, right]
46    sort(L.begin(), L.end(),
47        [](const Line &a, const Line &b) { return rad(a.s -
    ↪   a.e) < rad(b.s - b.e); });
48    vector<Point> p(n), res;
49    vector<Line> q(n);
50    q[0] = L[0];
51    for (int i = 1; i < n; i++) {
52      while (l < r && sgn((L[i].e - L[i].s) ^ (p[r - 1] -
    ↪   L[i].s)) <= 0) r--;
53      while (l < r && sgn((L[i].e - L[i].s) ^ (p[l] - L[i].s))
    ↪   <= 0) l++;
54      q[++r] = L[i];
55      if (sgn((q[r].e - q[r].s) ^ (q[r - 1].e - q[r - 1].s)) ==
    ↪   0) {
56        r--;
57        if (sgn((q[r].e - q[r].s) ^ (L[i].s - q[r].s)) > 0) q[r]
    ↪   = L[i];
58      }
59      if (l < r) p[r - 1] = intersect(q[r - 1], q[r]);
60    }
61    while (l < r && sgn((q[l].e - q[l].s) ^ (p[r - 1] - q[l].s))
    ↪   <= 0) r--;
62    if (r - l <= 1) return {};
63    p[r] = intersect(q[r], q[l]);
64    return vector<Point>(p.begin() + l, p.begin() + r + 1);
65  }
```

Convex

```
1   vector<Point> get_convex(vector<Point> &points, bool
    ↪   allow_collinear = false) {
2     // strict, no repeat, two pass
3     sort(points.begin(), points.end());
4     points.erase(unique(points.begin(), points.end()),
    ↪   points.end());
5     vector<Point> L, U;
6     for (auto &t : points) {
7       for (ll sz = L.size(); sz > 1 && (sgn((t - L[sz - 2]) ^
    ↪   (L[sz - 1] - L[sz - 2])) >= 0);
8           L.pop_back(), sz = L.size()) {
9       }
10      L.push_back(t);
11    }
12    for (auto &t : points) {
13      for (ll sz = U.size(); sz > 1 && (sgn((t - U[sz - 2]) ^
    ↪   (U[sz - 1] - U[sz - 2])) <= 0);
14          U.pop_back(), sz = U.size()) {
15      }
16      U.push_back(t);
17    }
18    // contain repeats if all collinear, use a set to remove
    ↪   repeats
19    if (allow_collinear) {
20      for (int i = (int)U.size() - 2; i >= 1; i--)
    ↪   L.push_back(U[i]);
21    } else {
22      set<Point> st(L.begin(), L.end());
23      for (int i = (int)U.size() - 2; i >= 1; i--) {
24        if (st.count(U[i]) == 0) L.push_back(U[i]),
    ↪   st.insert(U[i]);
25      }
26    }
27    return L;
28  }
29
30  vector<Point> get_convex2(vector<Point> &points, bool
    ↪   allow_collinear = false) {  // strict, no repeat, one pass
31    nth_element(points.begin(), points.begin(), points.end());
32    sort(points.begin() + 1, points.end(), [&](const Point &a,
    ↪   const Point &b) {
33      int rad_diff = sgn((a - points[0]) ^ (b - points[0]));
```

10

```cpp
34        return !rad_diff ? (dist2(a - points[0]) < dist2(b -
   ↪  points[0])) : (rad_diff > 0);
35      });
36      if (allow_collinear) {
37        int i = (int)points.size() - 1;
38        while (i >= 0 && !sgn((points[i] - points[0]) ^ (points[i]
   ↪  - points.back()))) i--;
39        reverse(points.begin() + i + 1, points.end());
40      }
41      vector<Point> hull;
42      for (auto &t : points) {
43        for (ll sz = hull.size();
44             sz > 1 && (sgn((t - hull[sz - 2]) ^ (hull[sz - 1] -
   ↪  hull[sz - 2])) >= allow_collinear);
45             hull.pop_back(), sz = hull.size()) {
46        }
47        hull.push_back(t);
48      }
49      return hull;
50    }
51
52    vector<Point> get_convex_safe(vector<Point> points, bool
   ↪  allow_collinear = false) {
53      return get_convex(points, allow_collinear);
54    }
55
56    vector<Point> get_convex2_safe(vector<Point> points, bool
   ↪  allow_collinear = false) {
57      return get_convex2(points, allow_collinear);
58    }
59
60    bool is_convex(const vector<Point> &p, bool allow_collinear =
   ↪  false) {
61      int n = p.size();
62      int lo = 1, hi = -1;
63      for (int i = 0; i < n; i++) {
64        int cur = sgn((p[(i + 2) % n] - p[(i + 1) % n]) ^ (p[(i +
   ↪  1) % n] - p[i]));
65        lo = min(lo, cur); hi = max(hi, cur);
66      }
67      return allow_collinear ? (hi - lo) < 2 : (lo == hi && lo);
68    }
69
70    auto rotating_calipers(const vector<Point> &hull) {
71      // use get_convex2
72      int n = (int)hull.size();  // return the square of longest
   ↪  dist
73      assert(n > 1);
74      if (n <= 2) return dist2(hull[0], hull[1]);
75      ld res = 0;
76      for (int i = 0, j = 2; i < n; i++) {
77        auto d = hull[i], e = hull[(i + 1) % n];
78        while (area2(d, e, hull[j]) < area2(d, e, hull[(j + 1) %
   ↪  n])) j = (j + 1) % n;
79        res = max(res, max(dist2(d, hull[j]), dist2(e, hull[j])));
80      }
81      return res;
82    }
83
84    // Find polygon cut to the left of l
85    vector<Point> convex_cut(const vector<Point> &p, const Line
   ↪  &l) {
86      int n = p.size();
87      vector<Point> cut;
88      for (int i = 0; i < n; i++) {
89        auto a = p[i], b = p[(i + 1) % n];
90        if (sgn((l.e - l.s) ^ (a - l.s)) >= 0)
91          cut.push_back(a);
92        if (sgn((l.e - l.s) ^ (a - l.s)) * sgn((l.e - l.s) ^ (b -
   ↪  l.s)) == -1)
93          cut.push_back(intersect(Line(a, b), l));
94      }
95      return cut;
96    }
97
98    // Sort by angle in range [0, 2pi)
99    template <class RandomIt>
```

```cpp
100   void polar_sort(RandomIt first, RandomIt last, Point origin =
   ↪  Point(0, 0)) {
101     auto get_quad = [&](const Point& p) {
102       Point diff = p - origin;
103       if (diff.x > 0 && diff.y >= 0) return 1;
104       if (diff.x <= 0 && diff.y > 0) return 2;
105       if (diff.x < 0 && diff.y <= 0) return 3;
106       return 4;
107     };
108     auto polar_cmp = [&](const Point& p1, const Point& p2) {
109       int q1 = get_quad(p1), q2 = get_quad(p2);
110       if (q1 != q2) return q1 < q2;
111       return ((p1 - origin) ^ (p2 - origin)) > 0;
112     };
113     sort(first, last, polar_cmp);
114   }
```

Basic 3D

```cpp
1     using ll = long long;
2     using ld = long double;
3
4     constexpr auto eps = 1e-8;
5     const auto PI = acos(-1);
6     int sgn(ld x) { return (abs(x) <= eps) ? 0 : (x < 0 ? -1 : 1);
   ↪  }
7
8     struct Point3D {
9       ld x = 0, y = 0, z = 0;
10      Point3D() = default;
11      Point3D(ld _x, ld _y, ld _z) : x(_x), y(_y), z(_z) {}
12      bool operator<(const Point3D &p) const { return !sgn(p.x -
   ↪  x) ? (!sgn(p.y - y) ? sgn(p.z - z) < 0 : y < p.y) : x <
   ↪  p.x; }
13      bool operator==(const Point3D &p) const { return !sgn(p.x -
   ↪  x) && !sgn(p.y - y) && !sgn(p.z - z); }
14      Point3D operator+(const Point3D &p) const { return {x + p.x,
   ↪  y + p.y, z + p.z}; }
15      Point3D operator-(const Point3D &p) const { return {x - p.x,
   ↪  y - p.y, z - p.z}; }
16      Point3D operator*(ld a) const { return {x * a, y * a, z *
   ↪  a}; }
17      Point3D operator/(ld a) const { return {x / a, y / a, z /
   ↪  a}; }
18      auto operator*(const Point3D &p) const { return x * p.x + y
   ↪  * p.y + z * p.z; }  // dot
19      Point3D operator^(const Point3D &p) const { return {y * p.z
   ↪  - z * p.y, z * p.x - x * p.z, x * p.y - y * p.x}; }  //
   ↪  cross
20      friend auto &operator>>(istream &i, Point3D &p) { return i
   ↪  >> p.x >> p.y >> p.z; }
21    };
22
23    struct Line3D {
24      Point3D s = {0, 0, 0}, e = {0, 0, 0};
25      Line3D() = default;
26      Line3D(Point3D _s, Point3D _e) : s(_s), e(_e) {}
27    };
28
29    struct Segment3D : Line3D {
30      using Line3D::Line3D;
31    };
32
33    auto dist2(const Point3D &a) { return a * a; }
34    auto dist2(const Point3D &a, const Point3D &b) { return
   ↪  dist2(a - b); }
35    auto dist(const Point3D &a) { return sqrt(dist2(a)); }
36    auto dist(const Point3D &a, const Point3D &b) { return
   ↪  sqrt(dist2(a - b)); }
37    auto dist(const Point3D &a, const Line3D &l) { return dist((a
   ↪  - l.s) ^ (l.e - l.s)) / dist(l.s, l.e); }
38    auto dist(const Point3D &p, const Segment3D &l) {
39      if (l.s == l.e) return dist(p, l.s);
40      auto d = dist2(l.s, l.e), t = min(d, max((ld)0, (p - l.s) *
   ↪  (l.e - l.s)));
41      return dist((p - l.s) * d, (l.e - l.s) * t) / d;
42    }
```

Miscellaneous

```cpp
1  tuple<int,int,ld> closest_pair(vector<Point> &p) {
2    using Pt = pair<Point,int>;
3    int n = p.size();
4    assert(n > 1);
5    vector<Pt> pts(n), buf;
6    for (int i = 0; i < n; i++) pts[i] = {p[i], i};
7    sort(pts.begin(), pts.end());
8    buf.reserve(n);
9    auto cmp_y = [](const Pt& p1, const Pt& p2) { return
   ↪ p1.first.y < p2.first.y; };
10   function<tuple<int,int,ld>(int, int)> recurse = [&](int l,
   ↪ int r) -> tuple<int,int,ld> {
11     int i = pts[l].second, j = pts[l + 1].second;
12     ld d = dist(pts[l].first, pts[l + 1].first);
13     if (r - l < 5) {
14       for (int a = l; a < r; a++) for (int b = a + 1; b < r;
   ↪ b++) {
15         ld cur = dist(pts[a].first, pts[b].first);
16         if (cur < d) { i = pts[a].second; j = pts[b].second; d
   ↪ = cur; }
17       }
18       sort(pts.begin() + l, pts.begin() + r, cmp_y);
19     }
20     else {
21       int mid = (l + r)/2;
22       ld x = pts[mid].first.x;
23       auto [li, lj, ldist] = recurse(l, mid);
24       auto [ri, rj, rdist] = recurse(mid, r);
25       if (ldist < rdist) { i = li; j = lj; d = ldist; }
26       else { i = ri; j = rj; d = rdist; }
27       inplace_merge(pts.begin() + l, pts.begin() + mid,
   ↪ pts.begin() + r, cmp_y);
28       buf.clear();
29       for (int a = l; a < r; a++) {
30         if (abs(x - pts[a].first.x) >= d) continue;
31         for (int b = buf.size() - 1; b >= 0; b--) {
32           if (pts[a].first.y - buf[b].first.y >= d) break;
33           ld cur = dist(pts[a].first, buf[b].first);
34           if (cur < d) { i = pts[a].second; j = buf[b].second;
   ↪ d = cur; }
35         }
36         buf.push_back(pts[a]);
37       }
38     }
39     return {i, j, d};
40   };
41   return recurse(0, n);
42 }
43
44 Line abc_to_line(ld a, ld b, ld c) {
45   assert(!sgn(a) || !sgn(b));
46   if(a == 0) return Line(Point(0, -c/b), Point(1, -c/b));
47   if(b == 0) return Line(Point(-c/a, 0), Point(-c/a, 1));
48   Point s(0, -c/b), e(1, (-c - a)/b), diff = e - s;
49   return Line(s, s + diff/dist(diff));
50 }
51
52 tuple<ld,ld,ld> line_to_abc(const Line& l) {
53   Point diff = l.e - l.s;
54   return {-diff.y, diff.x, -(diff ^ l.s)};
55 }
```

Graph Theory

Max Flow

```cpp
1  struct Edge {
2    int from, to, cap, remain;
3  };
4
5  struct Dinic {
6    int n;
7    vector<Edge> e;
8    vector<vector<int>> g;
9    vector<int> d, cur;
10   Dinic(int _n) : n(_n), g(n), d(n), cur(n) {}
11   void add_edge(int u, int v, int c) {
12     g[u].push_back((int)e.size());
13     e.push_back({u, v, c, c});
14     g[v].push_back((int)e.size());
15     e.push_back({v, u, 0, 0});
16   }
17   ll max_flow(int s, int t) {
18     int inf = 1e9;
19     auto bfs = [&]() {
20       fill(d.begin(), d.end(), inf), fill(cur.begin(),
   ↪ cur.end(), 0);
21       d[s] = 0;
22       vector<int> q{s}, nq;
23       for (int step = 1; q.size(); swap(q, nq), nq.clear(),
   ↪ step++) {
24         for (auto& node : q) {
25           for (auto& edge : g[node]) {
26             int ne = e[edge].to;
27             if (!e[edge].remain || d[ne] <= step) continue;
28             d[ne] = step, nq.push_back(ne);
29             if (ne == t) return true;
30           }
31         }
32       }
33       return false;
34     };
35     function<int(int, int)> find = [&](int node, int limit) {
36       if (node == t || !limit) return limit;
37       int flow = 0;
38       for (int i = cur[node]; i < g[node].size(); i++) {
39         cur[node] = i;
40         int edge = g[node][i], oe = edge ^ 1, ne = e[edge].to;
41         if (!e[edge].remain || d[ne] != d[node] + 1) continue;
42         if (int temp = find(ne, min(limit - flow,
   ↪ e[edge].remain))) {
43           e[edge].remain -= temp, e[oe].remain += temp, flow
   ↪ += temp;
44         } else {
45           d[ne] = -1;
46         }
47         if (flow == limit) break;
48       }
49       return flow;
50     };
51     ll res = 0;
52     while (bfs())
53       while (int flow = find(s, inf)) res += flow;
54     return res;
55   }
56 };
```

- USAGE

```cpp
1  int main() {
2    int n, m, s, t;
3    cin >> n >> m >> s >> t;
4    Dinic dinic(n);
5    for (int i = 0, u, v, c; i < m; i++) {
6      cin >> u >> v >> c;
7      dinic.add_edge(u - 1, v - 1, c);
8    }
9    cout << dinic.max_flow(s - 1, t - 1) << '\n';
10 }
```

PushRelabel Max-Flow (faster)

```cpp
1  //
   ↪ https://github.com/kth-competitive-programming/kactl/blob/main/con
2  #define rep(i, a, b) for (int i = a; i < (b); ++i)
3  #define all(x) begin(x), end(x)
4  #define sz(x) (int)(x).size()
5  typedef long long ll;
6  typedef pair<int, int> pii;
7  typedef vector<int> vi;
8
```

```
9   struct PushRelabel {
10    struct Edge {
11      int dest, back;
12      ll f, c;
13    };
14    vector<vector<Edge>> g;
15    vector<ll> ec;
16    vector<Edge*> cur;
17    vector<vi> hs;
18    vi H;
19    PushRelabel(int n) : g(n), ec(n), cur(n), hs(2 * n), H(n) {}
20
21    void addEdge(int s, int t, ll cap, ll rcap = 0) {
22      if (s == t) return;
23      g[s].push_back({t, sz(g[t]), 0, cap});
24      g[t].push_back({s, sz(g[s]) - 1, 0, rcap});
25    }
26
27    void addFlow(Edge& e, ll f) {
28      Edge& back = g[e.dest][e.back];
29      if (!ec[e.dest] && f) hs[H[e.dest]].push_back(e.dest);
30      e.f += f;
31      e.c -= f;
32      ec[e.dest] += f;
33      back.f -= f;
34      back.c += f;
35      ec[back.dest] -= f;
36    }
37    ll calc(int s, int t) {
38      int v = sz(g);
39      H[s] = v;
40      ec[t] = 1;
41      vi co(2 * v);
42      co[0] = v - 1;
43      rep(i, 0, v) cur[i] = g[i].data();
44      for (Edge& e : g[s]) addFlow(e, e.c);
45
46      for (int hi = 0;;) {
47        while (hs[hi].empty())
48          if (!hi--) return -ec[s];
49        int u = hs[hi].back();
50        hs[hi].pop_back();
51        while (ec[u] > 0)  // discharge u
52          if (cur[u] == g[u].data() + sz(g[u])) {
53            H[u] = 1e9;
54            for (Edge& e : g[u])
55              if (e.c && H[u] > H[e.dest] + 1) H[u] = H[e.dest]
↪  + 1, cur[u] = &e;
56            if (++co[H[u]], !--co[hi] && hi < v)
57              rep(i, 0, v) if (hi < H[i] && H[i] < v)--
↪  co[H[i]], H[i] = v + 1;
58            hi = H[u];
59          } else if (cur[u]->c && H[u] == H[cur[u]->dest] + 1)
60            addFlow(*cur[u], min(ec[u], cur[u]->c));
61          else
62            ++cur[u];
63      }
64    }
65    bool leftOfMinCut(int a) { return H[a] >= sz(g); }
66  };
```

Min-Cost Max-Flow

```
1   class MCMF {
2   public:
3    static constexpr int INF = 1e9;
4    const int n;
5    vector<tuple<int, int, int>> e;
6    vector<vector<int>> g;
7    vector<int> h, dis, pre;
8    bool dijkstra(int s, int t) {
9      dis.assign(n, INF);
10      pre.assign(n, -1);
11      priority_queue<pair<int, int>, vector<pair<int, int>>,
↪  greater<>> que;
12      dis[s] = 0;
13      que.emplace(0, s);
```

```
14      while (!que.empty()) {
15        auto [d, u] = que.top();
16        que.pop();
17        if (dis[u] != d) continue;
18        for (int i : g[u]) {
19          auto [v, f, c] = e[i];
20          if (c > 0 && dis[v] > d + h[u] - h[v] + f) {
21            dis[v] = d + h[u] - h[v] + f;
22            pre[v] = i;
23            que.emplace(dis[v], v);
24          }
25        }
26      }
27      return dis[t] != INF;
28    }
29    MCMF(int n) : n(n), g(n) {}
30    void add_edge(int u, int v, int fee, int c) {
31      g[u].push_back(e.size());
32      e.emplace_back(v, fee, c);
33      g[v].push_back(e.size());
34      e.emplace_back(u, -fee, 0);
35    }
36    pair<ll, ll> max_flow(const int s, const int t) {
37      int flow = 0, cost = 0;
38      h.assign(n, 0);
39      while (dijkstra(s, t)) {
40        for (int i = 0; i < n; ++i) h[i] += dis[i];
41        for (int i = t; i != s; i = get<0>(e[pre[i] ^ 1])) {
42          --get<2>(e[pre[i]]);
43          ++get<2>(e[pre[i] ^ 1]);
44        }
45        ++flow;
46        cost += h[t];
47      }
48      return {flow, cost};
49    }
50  };
```

Max Cost Feasible Flow

```
1   struct Edge {
2    int from, to, cap, remain, cost;
3   };
4
5   struct MCMF {
6    int n;
7    vector<Edge> e;
8    vector<vector<int>> g;
9    vector<ll> d, pre;
10    MCMF(int _n) : n(_n), g(n), d(n), pre(n) {}
11    void add_edge(int u, int v, int c, int w) {
12      g[u].push_back((int)e.size());
13      e.push_back({u, v, c, c, w});
14      g[v].push_back((int)e.size());
15      e.push_back({v, u, 0, 0, -w});
16    }
17    pair<ll, ll> max_flow(int s, int t) {
18      ll inf = 1e18;
19      auto spfa = [&]() {
20        fill(d.begin(), d.end(), -inf); // important!
21        vector<int> f(n), seen(n);
22        d[s] = 0, f[s] = 1e9;
23        vector<int> q{s}, nq;
24        for (; q.size(); swap(q, nq), nq.clear()) {
25          for (auto& node : q) {
26            seen[node] = false;
27            for (auto& edge : g[node]) {
28              int ne = e[edge].to, cost = e[edge].cost;
29              if (!e[edge].remain || d[ne] >= d[node] + cost)
↪  continue;
30              d[ne] = d[node] + cost, pre[ne] = edge;
31              f[ne] = min(e[edge].remain, f[node]);
32              if (!seen[ne]) seen[ne] = true, nq.push_back(ne);
33            }
34          }
35        }
36        return f[t];
```

```
37      };
38      ll flow = 0, cost = 0;
39      while (int temp = spfa()) {
40        if (d[t] < 0) break; // important!
41        flow += temp, cost += temp * d[t];
42        for (ll i = t; i != s; i = e[pre[i]].from) {
43          e[pre[i]].remain -= temp, e[pre[i] ^ 1].remain +=
↪  temp;
44        }
45      }
46      return {flow, cost};
47    }
48  };
```

Heavy-Light Decomposition

```
1   int root = 0, cur = 0;
2   vector<int> parent(n), deep(n), hson(n, -1), top(n), sz(n),
↪  dfn(n, -1);
3   function<int(int, int, int)> dfs = [&](int node, int fa, int
↪  dep) {
4     deep[node] = dep, sz[node] = 1, parent[node] = fa;
5     for (auto &ne : g[node]) {
6       if (ne == fa) continue;
7       sz[node] += dfs(ne, node, dep + 1);
8       if (hson[node] == -1|| sz[ne] > sz[hson[node]]) hson[node]
↪  = ne;
9     }
10    return sz[node];
11  };
12  function<void(int, int)> dfs2 = [&](int node, int t) {
13    top[node] = t, dfn[node] = cur++;
14    if (hson[node] == -1) return;
15    dfs2(hson[node], t);
16    for (auto &ne : g[node]) {
17      if (ne == parent[node] || ne == hson[node]) continue;
18      dfs2(ne, ne);
19    }
20  };
21  // read in graph as vector<vector<int>> g(n)
22  dfs(root, -1, 0), dfs2(root, root);
```

- USAGE: get LCA

```
1   function<int(int, int)> lca = [&](int x, int y) {
2     while (top[x] != top[y]) {
3       if (deep[top[x]] < deep[top[y]]) swap(x, y);
4       x = parent[top[x]];
5     }
6     return deep[x] < deep[y] ? x : y;
7   };
```

```
1   vector<ll> light(n);
2   SegTree heavy(n), form_parent(n);
3   // cin >> x >> y, x--, y--;
4   int z = lca(x, y);
5   while (x != z) {
6     if (dfn[top[x]] <= dfn[top[z]]) {
7       // [dfn[z], dfn[x]), from heavy
8       heavy.modify(dfn[z], dfn[x], 1);
9       break;
10    }
11    // x -> top[x];
12    heavy.modify(dfn[top[x]], dfn[x], 1);
13    light[parent[top[x]]] += a[top[x]];
14    x = parent[top[x]];
15  }
16  while (y != z) {
17    if (dfn[top[y]] <= dfn[top[z]]) {
18      // (dfn[z], dfn[y]], from heavy
19      form_parent.modify(dfn[z] + 1, dfn[y] + 1, 1);
20      break;
21    }
22    // y -> top[y];
23    form_parent.modify(dfn[top[y]], dfn[y] + 1, 1);
24    y = parent[top[y]];
25  }
```

General Unweight Graph Matching

- Complexity: $O(n^3)$ (?)

```
1   struct BlossomMatch {
2     int n;
3     vector<vector<int>> e;
4     BlossomMatch(int _n) : n(_n), e(_n) {}
5     void add_edge(int u, int v) { e[u].push_back(v),
↪  e[v].push_back(u); }
6     vector<int> find_matching() {
7       vector<int> match(n, -1), vis(n), link(n), f(n), dep(n);
8       function<int(int)> find = [&](int x) { return f[x] == x ?
↪  x : (f[x] = find(f[x])); };
9       auto lca = [&](int u, int v) {
10        u = find(u), v = find(v);
11        while (u != v) {
12          if (dep[u] < dep[v]) swap(u, v);
13          u = find(link[match[u]]);
14        }
15        return u;
16      };
17      queue<int> que;
18      auto blossom = [&](int u, int v, int p) {
19        while (find(u) != p) {
20          link[u] = v, v = match[u];
21          if (vis[v] == 0) vis[v] = 1, que.push(v);
22          f[u] = f[v] = p, u = link[v];
23        }
24      };
25      // find an augmenting path starting from u and augment (if
↪  exist)
26      auto augment = [&](int node) {
27        while (!que.empty()) que.pop();
28        iota(f.begin(), f.end(), 0);
29        // vis = 0 corresponds to inner vertices, vis = 1
↪  corresponds to outer vertices
30        fill(vis.begin(), vis.end(), -1);
31        que.push(node);
32        vis[node] = 1, dep[node] = 0;
33        while (!que.empty()) {
34          int u = que.front();
35          que.pop();
36          for (auto v : e[u]) {
37            if (vis[v] == -1) {
38              vis[v] = 0, link[v] = u, dep[v] = dep[u] + 1;
39              // found an augmenting path
40              if (match[v] == -1) {
41                for (int x = v, y = u, temp; y != -1; x = temp,
↪  y = x == -1 ? -1 : link[x]) {
42                  temp = match[y], match[x] = y, match[y] = x;
43                }
44                return;
45              }
46              vis[match[v]] = 1, dep[match[v]] = dep[u] + 2;
47              que.push(match[v]);
48            } else if (vis[v] == 1 && find(v) != find(u)) {
49              // found a blossom
50              int p = lca(u, v);
51              blossom(u, v, p), blossom(v, u, p);
52            }
53          }
54        }
55      };
56      // find a maximal matching greedily (decrease constant)
57      auto greedy = [&]() {
58        for (int u = 0; u < n; ++u) {
59          if (match[u] != -1) continue;
60          for (auto v : e[u]) {
61            if (match[v] == -1) {
62              match[u] = v, match[v] = u;
63              break;
64            }
65          }
66        }
67      };
68      greedy();
69      for (int u = 0; u < n; ++u)
```

```
70        if (match[u] == -1) augment(u);
71      return match;
72    }
73  };
```

Maximum Bipartite Matching

- Needs dinic, complexity $\approx O(n + m\sqrt{n})$

```
1   struct BipartiteMatch {
2     int l, r;
3     Dinic dinic = Dinic(0);
4     BipartiteMatch(int _l, int _r) : l(_l), r(_r) {
5       dinic = Dinic(l + r + 2);
6       for (int i = 1; i <= l; i++) dinic.add_edge(0, i, 1);
7       for (int i = 1; i <= r; i++) dinic.add_edge(l + i, l + r +
↪   1, 1);
8     }
9     void add_edge(int u, int v) { dinic.add_edge(u + 1, l + v +
↪   1, 1); }
10    ll max_matching() { return dinic.max_flow(0, l + r + 1); }
11  };
```

2-SAT and Strongly Connected Components

```
1   void scc(vector<vector<int>>& g, int* idx) {
2     int n = g.size(), ct = 0;
3     int out[n];
4     vector<int> ginv[n];
5     memset(out, -1, sizeof out);
6     memset(idx, -1, n * sizeof(int));
7     function<void(int)> dfs = [&](int cur) {
8       out[cur] = INT_MAX;
9       for(int v : g[cur]) {
10        ginv[v].push_back(cur);
11        if(out[v] == -1) dfs(v);
12      }
13      ct++; out[cur] = ct;
14    };
15    vector<int> order;
16    for(int i = 0; i < n; i++) {
17      order.push_back(i);
18      if(out[i] == -1) dfs(i);
19    }
20    sort(order.begin(), order.end(), [&](int& u, int& v) {
21      return out[u] > out[v];
22    });
23    ct = 0;
24    stack<int> s;
25    auto dfs2 = [&](int start) {
26      s.push(start);
27      while(!s.empty()) {
28        int cur = s.top();
29        s.pop();
30        idx[cur] = ct;
31        for(int v : ginv[cur])
32          if(idx[v] == -1) s.push(v);
33      }
34    };
35    for(int v : order) {
36      if(idx[v] == -1) {
37        dfs2(v);
38        ct++;
39      }
40    }
41  }
42
43  // 0 => impossible, 1 => possible
44  pair<int,vector<int>> sat2(int n, vector<pair<int,int>>&
↪   clauses) {
45    vector<int> ans(n);
46    vector<vector<int>> g(2*n + 1);
47    for(auto [x, y] : clauses) {
48      x = x < 0 ? -x + n : x;
49      y = y < 0 ? -y + n : y;
50      int nx = x <= n ? x + n : x - n;
```

```
51      int ny = y <= n ? y + n : y - n;
52      g[nx].push_back(y);
53      g[ny].push_back(x);
54    }
55    int idx[2*n + 1];
56    scc(g, idx);
57    for(int i = 1; i <= n; i++) {
58      if(idx[i] == idx[i + n]) return {0, {}};
59      ans[i - 1] = idx[i + n] < idx[i];
60    }
61    return {1, ans};
62  }
```

Enumerating Triangles

- Complexity: $O(n + m\sqrt{m})$

```
1   void enumerate_triangles(vector<pair<int,int>>& edges,
↪   function<void(int,int,int)> f) {
2     int n = 0;
3     for(auto [u, v] : edges) n = max({n, u + 1, v + 1});
4     vector<int> deg(n);
5     vector<int> g[n];
6     for(auto [u, v] : edges) {
7       deg[u]++;
8       deg[v]++;
9     }
10    for(auto [u, v] : edges) {
11      if(u == v) continue;
12      if(deg[u] > deg[v] || (deg[u] == deg[v] && u > v))
13        swap(u, v);
14      g[u].push_back(v);
15    }
16    vector<int> flag(n);
17    for(int i = 0; i < n; i++) {
18      for(int v : g[i]) flag[v] = 1;
19      for(int v : g[i]) for(int u : g[v]) {
20        if(flag[u]) f(i, v, u);
21      }
22      for(int v : g[i]) flag[v] = 0;
23    }
24  }
```

Tarjan

- shrink all circles into points (2-edge-connected-component)

```
1   int cnt = 0, now = 0;
2   vector<ll> dfn(n, -1), low(n), belong(n, -1), stk;
3   function<void(ll, ll)> tarjan = [&](ll node, ll fa) {
4     dfn[node] = low[node] = now++, stk.push_back(node);
5     for (auto& ne : g[node]) {
6       if (ne == fa) continue;
7       if (dfn[ne] == -1) {
8         tarjan(ne, node);
9         low[node] = min(low[node], low[ne]);
10      } else if (belong[ne] == -1) {
11        low[node] = min(low[node], dfn[ne]);
12      }
13    }
14    if (dfn[node] == low[node]) {
15      while (true) {
16        auto v = stk.back();
17        belong[v] = cnt;
18        stk.pop_back();
19        if (v == node) break;
20      }
21      ++cnt;
22    }
23  };
```

- 2-vertex-connected-component / Block forest

```
1   int cnt = 0, now = 0;
2   vector<vector<ll>> e1(n);
```

```
3    vector<ll> dfn(n, -1), low(n), stk;
4    function<void(ll)> tarjan = [&](ll node) {
5      dfn[node] = low[node] = now++, stk.push_back(node);
6      for (auto& ne : g[node]) {
7        if (dfn[ne] == -1) {
8          tarjan(ne);
9          low[node] = min(low[node], low[ne]);
10         if (low[ne] == dfn[node]) {
11           e1.push_back({});
12           while (true) {
13             auto x = stk.back();
14             stk.pop_back();
15             e1[n + cnt].push_back(x);
16             // e1[x].push_back(n + cnt); // undirected
17             if (x == ne) break;
18           }
19           e1[node].push_back(n + cnt);
20           // e1[n + cnt].push_back(node); // undirected
21           cnt++;
22         }
23       } else {
24         low[node] = min(low[node], dfn[ne]);
25       }
26     }
27   };
```

Kruskal reconstruct tree

```
1    int _n, m;
2    cin >> _n >> m; // _n: # of node, m: # of edge
3    int n = 2 * _n - 1; // root: n-1
4    vector<array<int, 3>> edges(m);
5    for (auto& [w, u, v] : edges) {
6      cin >> u >> v >> w, u--, v--;
7    }
8    sort(edges.begin(), edges.end());
9    vector<int> p(n);
10   iota(p.begin(), p.end(), 0);
11   function<int(int)> find = [&](int x) { return p[x] == x ? x :
     ↪  (p[x] = find(p[x])); };
12   auto merge = [&](int x, int y) { p[find(x)] = find(y); };
13   vector<vector<int>> g(n);
14   vector<int> val(m);
15   val.reserve(n);
16   for (auto [w, u, v] : edges) {
17     u = find(u), v = find(v);
18     if (u == v) continue;
19     val.push_back(w);
20     int node = (int)val.size() - 1;
21     g[node].push_back(u), g[node].push_back(v);
22     merge(u, node), merge(v, node);
23   }
```

Math

Inverse

```
1    ll inv(ll a, ll m) { return a == 1 ? 1 : ((m - m / a) * inv(m
     ↪  % a, m) % m); }
2    // or
3    power(a, MOD - 2)
```

- USAGE: get factorial

```
1    vector<Z> f(MAX_N, 1), rf(MAX_N, 1);
2    for (int i = 2; i < MAX_N; i++) f[i] = f[i - 1] * i % MOD;
3    rf[MAX_N - 1] = power(f[MAX_N - 1], MOD - 2);
4    for (int i = MAX_N - 2; i > 1; i--) rf[i] = rf[i + 1] * (i +
     ↪  1) % MOD;
5    auto binom = [&](ll n, ll r) -> Z {
6    if (n < 0 || r < 0 || n < r) return 0;
7      return f[n] * rf[n - r] * rf[r];
8    };
```

Mod Class

```
1    constexpr ll norm(ll x) { return (x % MOD + MOD) % MOD; }
2    template <typename T>
3    constexpr T power(T a, ll b, T res = 1) {
4      for (; b; b /= 2, (a *= a) %= MOD)
5        if (b & 1) (res *= a) %= MOD;
6      return res;
7    }
8    struct Z {
9      ll x;
10     constexpr Z(ll _x = 0) : x(norm(_x)) {}
11     // auto operator<=>(const Z &) const = default; // cpp20
     ↪  only
12     Z operator-() const { return Z(norm(MOD - x)); }
13     Z inv() const { return power(*this, MOD - 2); }
14     Z &operator*=(const Z &rhs) { return x = x * rhs.x % MOD,
     ↪  *this; }
15     Z &operator+=(const Z &rhs) { return x = norm(x + rhs.x),
     ↪  *this; }
16     Z &operator-=(const Z &rhs) { return x = norm(x - rhs.x),
     ↪  *this; }
17     Z &operator/=(const Z &rhs) { return *this *= rhs.inv(); }
18     Z &operator%=(const ll &rhs) { return x %= rhs, *this; }
19     friend Z operator*(Z lhs, const Z &rhs) { return lhs *= rhs;
     ↪  }
20     friend Z operator+(Z lhs, const Z &rhs) { return lhs += rhs;
     ↪  }
21     friend Z operator-(Z lhs, const Z &rhs) { return lhs -= rhs;
     ↪  }
22     friend Z operator/(Z lhs, const Z &rhs) { return lhs /= rhs;
     ↪  }
23     friend Z operator%(Z lhs, const ll &rhs) { return lhs %=
     ↪  rhs; }
24     friend auto &operator>>(istream &i, Z &z) { return i >> z.x;
     ↪  }
25     friend auto &operator<<(ostream &o, const Z &z) { return o
     ↪  << z.x; }
26   };
```

- large mod (for NTT to do FFT in ll range without modulo)

```
1    using ll = long long;
2    using i128 = __int128;
3    constexpr i128 MOD = 9223372036737335297;
4
5    constexpr i128 norm(i128 x) { return x < 0 ? (x + MOD) % MOD :
     ↪  x % MOD; }
6    template <typename T>
7    constexpr T power(T a, i128 b, T res = 1) {
8      for (; b; b /= 2, (a *= a) %= MOD)
9        if (b & 1) (res *= a) %= MOD;
10     return res;
11   }
12   struct Z {
13     i128 x;
14     constexpr Z(i128 _x = 0) : x(norm(_x)) {}
15     Z operator-() const { return Z(norm(MOD - x)); }
16     Z inv() const { return power(*this, MOD - 2); }
17     // auto operator<=>(const Z&) const = default;
18     Z &operator*=(const Z &rhs) { return x = x * rhs.x % MOD,
     ↪  *this; }
19     Z &operator+=(const Z &rhs) { return x = norm(x + rhs.x),
     ↪  *this; }
20     Z &operator-=(const Z &rhs) { return x = norm(x - rhs.x),
     ↪  *this; }
21     Z &operator/=(const Z &rhs) { return *this *= rhs.inv(); }
22     Z &operator%=(const i128 &rhs) { return x %= rhs, *this; }
23     friend Z operator*(Z lhs, const Z &rhs) { return lhs *= rhs;
     ↪  }
24     friend Z operator+(Z lhs, const Z &rhs) { return lhs += rhs;
     ↪  }
25     friend Z operator-(Z lhs, const Z &rhs) { return lhs -= rhs;
     ↪  }
26     friend Z operator/(Z lhs, const Z &rhs) { return lhs /= rhs;
     ↪  }
```

```
27    friend Z operator%(Z lhs, const i128 &rhs) { return lhs %=
   ↪ rhs; }
28  };
```

- fastest mod class! be careful with overflow, only use when the time limit is tight

```
1  constexpr int MOD = 998244353;
2
3  constexpr int norm(int x) {
4    if (x < 0) x += MOD;
5    if (x >= MOD) x -= MOD;
6    return x;
7  }
8  template <typename T>
9  constexpr T power(T a, int b, T res = 1) {
10    for (; b; b /= 2, (a *= a) %= MOD)
11      if (b & 1) (res *= a) %= MOD;
12    return res;
13  }
14  struct Z {
15    int x;
16    constexpr Z(int _x = 0) : x(norm(_x)) {}
17    // constexpr auto operator<=>(const Z &) const = default; //
   ↪ cpp20 only
18    constexpr Z operator-() const { return Z(norm(MOD - x)); }
19    constexpr Z inv() const { return power(*this, MOD - 2); }
20    constexpr Z &operator*=(const Z &rhs) { return x = ll(x) *
   ↪ rhs.x % MOD, *this; }
21    constexpr Z &operator+=(const Z &rhs) { return x = norm(x +
   ↪ rhs.x), *this; }
22    constexpr Z &operator-=(const Z &rhs) { return x = norm(x -
   ↪ rhs.x), *this; }
23    constexpr Z &operator/=(const Z &rhs) { return *this *=
   ↪ rhs.inv(); }
24    constexpr Z &operator%=(const ll &rhs) { return x %= rhs,
   ↪ *this; }
25    constexpr friend Z operator*(Z lhs, const Z &rhs) { return
   ↪ lhs *= rhs; }
26    constexpr friend Z operator+(Z lhs, const Z &rhs) { return
   ↪ lhs += rhs; }
27    constexpr friend Z operator-(Z lhs, const Z &rhs) { return
   ↪ lhs -= rhs; }
28    constexpr friend Z operator/(Z lhs, const Z &rhs) { return
   ↪ lhs /= rhs; }
29    constexpr friend Z operator%(Z lhs, const ll &rhs) { return
   ↪ lhs %= rhs; }
30    friend auto &operator>>(istream &i, Z &z) { return i >> z.x;
   ↪ }
31    friend auto &operator<<(ostream &o, const Z &z) { return o
   ↪ << z.x; }
32  };
```

Cancer mod class

- Explanation: for some prime modulo p, maintains numbers of form p^x * y, where y is a nonzero remainder mod p
- Be careful with calling Cancer(x, y), it doesn't fix the input if y > p

```
1  struct Cancer {
2    ll x; ll y;
3    Cancer() : Cancer(0, 1) {}
4    Cancer(ll _y) {
5      x = 0, y = _y;
6      while(y % MOD == 0) {
7        y /= MOD;
8        x++;
9      }
10   }
11   Cancer(ll _x, ll _y) : x(_x), y(_y) {}
12   Cancer inv() { return Cancer(-x, power(y, MOD - 2)); }
13   Cancer operator*(const Cancer &c) { return Cancer(x + c.x,
   ↪ (y * c.y) % MOD); }
```

```
14   Cancer operator*(ll m) {
15     ll p = 0;
16     while(m % MOD == 0) {
17       m /= MOD;
18       p++;
19     }
20     return Cancer(x + p, (m * y) % MOD);
21   }
22   friend auto &operator<<(ostream &o, Cancer c) { return o <<
   ↪ c.x << ' ' << c.y; }
23  };
```

NTT, FFT, FWT

- ntt

```
1  void ntt(vector<Z>& a, int f) {
2    int n = int(a.size());
3    vector<Z> w(n);
4    vector<int> rev(n);
5    for (int i = 0; i < n; i++) rev[i] = (rev[i / 2] / 2) | ((i
   ↪ & 1) * (n / 2));
6    for (int i = 0; i < n; i++) {
7      if (i < rev[i]) swap(a[i], a[rev[i]]);
8    }
9    Z wn = power(f ? (MOD + 1) / 3 : 3, (MOD - 1) / n);
10   w[0] = 1;
11   for (int i = 1; i < n; i++) w[i] = w[i - 1] * wn;
12   for (int mid = 1; mid < n; mid *= 2) {
13     for (int i = 0; i < n; i += 2 * mid) {
14       for (int j = 0; j < mid; j++) {
15         Z x = a[i + j], y = a[i + j + mid] * w[n / (2 * mid) *
   ↪ j];
16         a[i + j] = x + y, a[i + j + mid] = x - y;
17       }
18     }
19   }
20   if (f) {
21     Z iv = power(Z(n), MOD - 2);
22     for (auto& x : a) x *= iv;
23   }
24  }
```

- USAGE: Polynomial multiplication

```
1  vector<Z> mul(vector<Z> a, vector<Z> b) {
2    int n = 1, m = (int)a.size() + (int)b.size() - 1;
3    while (n < m) n *= 2;
4    a.resize(n), b.resize(n);
5    ntt(a, 0), ntt(b, 0);
6    for (int i = 0; i < n; i++) a[i] *= b[i];
7    ntt(a, 1);
8    a.resize(m);
9    return a;
10  }
```

- FFT (should prefer NTT, only use this when input is not integer)

```
1  const double PI = acos(-1);
2  auto mul = [&](const vector<double>& aa, const vector<double>&
   ↪ bb) {
3    int n = (int)aa.size(), m = (int)bb.size(), bit = 1;
4    while ((1 << bit) < n + m - 1) bit++;
5    int len = 1 << bit;
6    vector<complex<double>> a(len), b(len);
7    vector<int> rev(len);
8    for (int i = 0; i < n; i++) a[i].real(aa[i]);
9    for (int i = 0; i < m; i++) b[i].real(bb[i]);
10   for (int i = 0; i < len; i++) rev[i] = (rev[i >> 1] >> 1) |
   ↪ ((i & 1) << (bit - 1));
11   auto fft = [&](vector<complex<double>>& p, int inv) {
12     for (int i = 0; i < len; i++)
13       if (i < rev[i]) swap(p[i], p[rev[i]]);
14     for (int mid = 1; mid < len; mid *= 2) {
15       auto w1 = complex<double>(cos(PI / mid), (inv ? -1 : 1)
   ↪ * sin(PI / mid));
```

```
16      for (int i = 0; i < len; i += mid * 2) {
17        auto wk = complex<double>(1, 0);
18        for (int j = 0; j < mid; j++, wk = wk * w1) {
19          auto x = p[i + j], y = wk * p[i + j + mid];
20          p[i + j] = x + y, p[i + j + mid] = x - y;
21        }
22      }
23    }
24    if (inv == 1) {
25      for (int i = 0; i < len; i++) p[i].real(p[i].real() /
   len);
26    }
27  };
28  fft(a, 0), fft(b, 0);
29  for (int i = 0; i < len; i++) a[i] = a[i] * b[i];
30  fft(a, 1);
31  a.resize(n + m - 1);
32  vector<double> res(n + m - 1);
33  for (int i = 0; i < n + m - 1; i++) res[i] = a[i].real();
34  return res;
35 };
```

Polynomial Class

```
1  using ll = long long;
2  constexpr ll MOD = 998244353;
3
4  ll norm(ll x) { return (x % MOD + MOD) % MOD; }
5  template <class T>
6  T power(T a, ll b, T res = 1) {
7    for (; b; b /= 2, (a *= a) %= MOD)
8      if (b & 1) (res *= a) %= MOD;
9    return res;
10 }
11
12 struct Z {
13   ll x;
14   Z(ll _x = 0) : x(norm(_x)) {}
15   // auto operator<=>(const Z &) const = default;
16   Z operator-() const { return Z(norm(MOD - x)); }
17   Z inv() const { return power(*this, MOD - 2); }
18   Z &operator*=(const Z &rhs) { return x = x * rhs.x % MOD,
      *this; }
19   Z &operator+=(const Z &rhs) { return x = norm(x + rhs.x),
      *this; }
20   Z &operator-=(const Z &rhs) { return x = norm(x - rhs.x),
      *this; }
21   Z &operator/=(const Z &rhs) { return *this *= rhs.inv(); }
22   Z &operator%=(const ll &rhs) { return x %= rhs, *this; }
23   friend Z operator*(Z lhs, const Z &rhs) { return lhs *= rhs;
      }
24   friend Z operator+(Z lhs, const Z &rhs) { return lhs += rhs;
      }
25   friend Z operator-(Z lhs, const Z &rhs) { return lhs -= rhs;
      }
26   friend Z operator/(Z lhs, const Z &rhs) { return lhs /= rhs;
      }
27   friend Z operator%(Z lhs, const ll &rhs) { return lhs %=
      rhs; }
28   friend auto &operator>>(istream &i, Z &z) { return i >> z.x;
      }
29   friend auto &operator<<(ostream &o, const Z &z) { return o
      << z.x; }
30 };
31
32 void ntt(vector<Z> &a, int f) {
33   int n = (int)a.size();
34   vector<Z> w(n);
35   vector<int> rev(n);
36   for (int i = 0; i < n; i++) rev[i] = (rev[i / 2] / 2) | ((i
      & 1) * (n / 2));
37   for (int i = 0; i < n; i++)
38     if (i < rev[i]) swap(a[i], a[rev[i]]);
39   Z wn = power(f ? (MOD + 1) / 3 : 3, (MOD - 1) / n);
40   w[0] = 1;
41   for (int i = 1; i < n; i++) w[i] = w[i - 1] * wn;
42   for (int mid = 1; mid < n; mid *= 2) {
```

```
43      for (int i = 0; i < n; i += 2 * mid) {
44        for (int j = 0; j < mid; j++) {
45          Z x = a[i + j], y = a[i + j + mid] * w[n / (2 * mid) *
      j];
46          a[i + j] = x + y, a[i + j + mid] = x - y;
47        }
48      }
49    }
50    if (f) {
51      Z iv = power(Z(n), MOD - 2);
52      for (int i = 0; i < n; i++) a[i] *= iv;
53    }
54 }
55
56 struct Poly {
57   vector<Z> a;
58   Poly() {}
59   Poly(const vector<Z> &_a) : a(_a) {}
60   int size() const { return (int)a.size(); }
61   void resize(int n) { a.resize(n); }
62   Z operator[](int idx) const {
63     if (idx < 0 || idx >= size()) return 0;
64     return a[idx];
65   }
66   Z &operator[](int idx) { return a[idx]; }
67   Poly mulxk(int k) const {
68     auto b = a;
69     b.insert(b.begin(), k, 0);
70     return Poly(b);
71   }
72   Poly modxk(int k) const { return Poly(vector<Z>(a.begin(),
      a.begin() + min(k, size()))); }
73   Poly divxk(int k) const {
74     if (size() <= k) return Poly();
75     return Poly(vector<Z>(a.begin() + k, a.end()));
76   }
77   friend Poly operator+(const Poly &a, const Poly &b) {
78     vector<Z> res(max(a.size(), b.size()));
79     for (int i = 0; i < (int)res.size(); i++) res[i] = a[i] +
      b[i];
80     return Poly(res);
81   }
82   friend Poly operator-(const Poly &a, const Poly &b) {
83     vector<Z> res(max(a.size(), b.size()));
84     for (int i = 0; i < (int)res.size(); i++) res[i] = a[i] -
      b[i];
85     return Poly(res);
86   }
87   friend Poly operator*(Poly a, Poly b) {
88     if (a.size() == 0 || b.size() == 0) return Poly();
89     int n = 1, m = (int)a.size() + (int)b.size() - 1;
90     while (n < m) n *= 2;
91     a.resize(n), b.resize(n);
92     ntt(a.a, 0), ntt(b.a, 0);
93     for (int i = 0; i < n; i++) a[i] *= b[i];
94     ntt(a.a, 1);
95     a.resize(m);
96     return a;
97   }
98   friend Poly operator*(Z a, Poly b) {
99     for (int i = 0; i < (int)b.size(); i++) b[i] *= a;
100    return b;
101  }
102  friend Poly operator*(Poly a, Z b) {
103    for (int i = 0; i < (int)a.size(); i++) a[i] *= b;
104    return a;
105  }
106  Poly &operator+=(Poly b) { return (*this) = (*this) + b; }
107  Poly &operator-=(Poly b) { return (*this) = (*this) - b; }
108  Poly &operator*=(Poly b) { return (*this) = (*this) * b; }
109  Poly deriv() const {
110    if (a.empty()) return Poly();
111    vector<Z> res(size() - 1);
112    for (int i = 0; i < size() - 1; ++i) res[i] = (i + 1) *
      a[i + 1];
113    return Poly(res);
114  }
```

```cpp
      Poly integr() const {
        vector<Z> res(size() + 1);
        for (int i = 0; i < size(); ++i) res[i + 1] = a[i] / (i +
   1);
        return Poly(res);
      }
      Poly inv(int m) const {
        Poly x({a[0].inv()});
        int k = 1;
        while (k < m) {
          k *= 2;
          x = (x * (Poly({2}) - modxk(k) * x)).modxk(k);
        }
        return x.modxk(m);
      }
      Poly log(int m) const { return (deriv() *
   inv(m)).integr().modxk(m); }
      Poly exp(int m) const {
        Poly x({1});
        int k = 1;
        while (k < m) {
          k *= 2;
          x = (x * (Poly({1}) - x.log(k) + modxk(k))).modxk(k);
        }
        return x.modxk(m);
      }
      Poly pow(int k, int m) const {
        int i = 0;
        while (i < size() && a[i].x == 0) i++;
        if (i == size() || 1LL * i * k >= m) {
          return Poly(vector<Z>(m));
        }
        Z v = a[i];
        auto f = divxk(i) * v.inv();
        return (f.log(m - i * k) * k).exp(m - i * k).mulxk(i * k)
   * power(v, k);
      }
      Poly sqrt(int m) const {
        Poly x({1});
        int k = 1;
        while (k < m) {
          k *= 2;
          x = (x + (modxk(k) * x.inv(k)).modxk(k)) * ((MOD + 1) /
   2);
        }
        return x.modxk(m);
      }
      Poly mulT(Poly b) const {
        if (b.size() == 0) return Poly();
        int n = b.size();
        reverse(b.a.begin(), b.a.end());
        return ((*this) * b).divxk(n - 1);
      }
      Poly divmod(Poly b) const {
        auto n = size(), m = b.size();
        auto t = *this;
        reverse(t.a.begin(), t.a.end());
        reverse(b.a.begin(), b.a.end());
        Poly res = (t * b.inv(n)).modxk(n - m + 1);
        reverse(res.a.begin(), res.a.end());
        return res;
      }
      vector<Z> eval(vector<Z> x) const {
        if (size() == 0) return vector<Z>(x.size(), 0);
        const int n = max(int(x.size()), size());
        vector<Poly> q(4 * n);
        vector<Z> ans(x.size());
        x.resize(n);
        function<void(int, int, int)> build = [&](int p, int l,
   int r) {
          if (r - l == 1) {
            q[p] = Poly({1, -x[l]});
          } else {
            int m = (l + r) / 2;
            build(2 * p, l, m), build(2 * p + 1, m, r);
            q[p] = q[2 * p] * q[2 * p + 1];
          }
        };
        build(1, 0, n);
        auto work = [&](auto self, int p, int l, int r, const Poly
   &num) -> void {
          if (r - l == 1) {
            if (l < int(ans.size())) ans[l] = num[0];
          } else {
            int m = (l + r) / 2;
            self(self, 2 * p, l, m, num.mulT(q[2 * p + 1]).modxk(m
   - l));
            self(self, 2 * p + 1, m, r, num.mulT(q[2 * p]).modxk(r
   - m));
          }
        };
        work(work, 1, 0, n, mulT(q[1].inv(n)));
        return ans;
      }
    };
```

Sieve

- linear sieve

```cpp
vector<int> min_primes(MAX_N), primes;
primes.reserve(1e5);
for (int i = 2; i < MAX_N; i++) {
  if (!min_primes[i]) min_primes[i] = i, primes.push_back(i);
  for (auto& p : primes) {
    if (p * i >= MAX_N) break;
    min_primes[p * i] = p;
    if (i % p == 0) break;
  }
}
```

- mobius function

```cpp
vector<int> min_p(MAX_N), mu(MAX_N), primes;
mu[1] = 1, primes.reserve(1e5);
for (int i = 2; I < MAX_N; i++) {
  if (min_p[i] == 0) {
    min_p[i] = i;
    primes.push_back(i);
    mu[i] = -1;
  }
  for (auto p : primes) {
    if (i * p >= MAX_N) break;
    min_p[i * p] = p;
    if (i % p == 0) {
      mu[i * p] = 0;
      break;
    }
    mu[i * p] = -mu[i];
  }
}
```

- Euler's totient function

```cpp
vector<int> min_p(MAX_N), phi(MAX_N), primes;
phi[1] = 1, primes.reserve(1e5);
for (int i = 2; i < MAX_N; i++) {
  if (min_p[i] == 0) {
    min_p[i] = i;
    primes.push_back(i);
    phi[i] = i - 1;
  }
  for (auto p : primes) {
    if (i * p >= MAX_N) break;
    min_p[i * p] = p;
    if (i % p == 0) {
      phi[i * p] = phi[i] * p;
      break;
    }
    phi[i * p] = phi[i] * phi[p];
  }
}
```

Gaussian Elimination

```cpp
bool is_0(Z v) { return v.x == 0; }
Z abs(Z v) { return v; }
bool is_0(double v) { return abs(v) < 1e-9; }

// 1 => unique solution, 0 => no solution, -1 => multiple
//     solutions
template <typename T>
int gaussian_elimination(vector<vector<T>> &a, int limit) {
    if (a.empty() || a[0].empty()) return -1;
  int h = (int)a.size(), w = (int)a[0].size(), r = 0;
  for (int c = 0; c < limit; c++) {
    int id = -1;
    for (int i = r; i < h; i++) {
      if (!is_0(a[i][c]) && (id == -1 || abs(a[id][c]) <
        abs(a[i][c]))) {
        id = i;
      }
    }
    if (id == -1) continue;
    if (id > r) {
      swap(a[r], a[id]);
      for (int j = c; j < w; j++) a[id][j] = -a[id][j];
    }
    vector<int> nonzero;
    for (int j = c; j < w; j++) {
      if (!is_0(a[r][j])) nonzero.push_back(j);
    }
    T inv_a = 1 / a[r][c];
    for (int i = r + 1; i < h; i++) {
      if (is_0(a[i][c])) continue;
      T coeff = -a[i][c] * inv_a;
      for (int j : nonzero) a[i][j] += coeff * a[r][j];
    }
    ++r;
  }
  for (int row = h - 1; row >= 0; row--) {
    for (int c = 0; c < limit; c++) {
      if (!is_0(a[row][c])) {
        T inv_a = 1 / a[row][c];
        for (int i = row - 1; i >= 0; i--) {
          if (is_0(a[i][c])) continue;
          T coeff = -a[i][c] * inv_a;
          for (int j = c; j < w; j++) a[i][j] += coeff *
        a[row][j];
        }
        break;
      }
    }
  } // not-free variables: only it on its line
  for(int i = r; i < h; i++) if(!is_0(a[i][limit])) return 0;
  return (r == limit) ? 1 : -1;
}

template <typename T>
pair<int,vector<T>> solve_linear(vector<vector<T>> a, const
    vector<T> &b, int w) {
  int h = (int)a.size();
  for (int i = 0; i < h; i++) a[i].push_back(b[i]);
  int sol = gaussian_elimination(a, w);
  if(!sol) return {0, vector<T>()};
  vector<T> x(w, 0);
  for (int i = 0; i < h; i++) {
    for (int j = 0; j < w; j++) {
      if (!is_0(a[i][j])) {
        x[j] = a[i][w] / a[i][j];
        break;
      }
    }
  }
  return {sol, x};
}
```

is__prime

- (Miller–Rabin primality test)

```cpp
i128 power(i128 a, i128 b, i128 MOD = 1, i128 res = 1) {
  for (; b; b /= 2, (a *= a) %= MOD)
    if (b & 1) (res *= a) %= MOD;
  return res;
}

bool is_prime(ll n) {
  if (n < 2) return false;
  static constexpr int A[] = {2, 3, 5, 7, 11, 13, 17, 19, 23};
  int s = __builtin_ctzll(n - 1);
  ll d = (n - 1) >> s;
  for (auto a : A) {
    if (a == n) return true;
    ll x = (ll)power(a, d, n);
    if (x == 1 || x == n - 1) continue;
    bool ok = false;
    for (int i = 0; i < s - 1; ++i) {
      x = ll((i128)x * x % n);  // potential overflow!
      if (x == n - 1) {
        ok = true;
        break;
      }
    }
    if (!ok) return false;
  }
  return true;
}

ll pollard_rho(ll x) {
  ll s = 0, t = 0, c = rng() % (x - 1) + 1;
  ll stp = 0, goal = 1, val = 1;
  for (goal = 1;; goal *= 2, s = t, val = 1) {
    for (stp = 1; stp <= goal; ++stp) {
      t = ll(((i128)t * t + c) % x);
      val = ll((i128)val * abs(t - s) % x);
      if ((stp % 127) == 0) {
        ll d = gcd(val, x);
        if (d > 1) return d;
      }
    }
    ll d = gcd(val, x);
    if (d > 1) return d;
  }
}

ll get_max_factor(ll _x) {
  ll max_factor = 0;
  function<void(ll)> fac = [&](ll x) {
    if (x <= max_factor || x < 2) return;
    if (is_prime(x)) {
      max_factor = max_factor > x ? max_factor : x;
      return;
    }
    ll p = x;
    while (p >= x) p = pollard_rho(x);
    while ((x % p) == 0) x /= p;
    fac(x), fac(p);
  };
  fac(_x);
  return max_factor;
}
```

Radix Sort

```cpp
struct identity {
    template<typename T>
    T operator()(const T &x) const {
        return x;
    }
};

// A stable sort that sorts in passes of `bits_per_pass` bits
//     at a time.
template<typename T, typename T_extract_key = identity>
void radix_sort(vector<T> &data, int bits_per_pass = 10, const
    T_extract_key &extract_key = identity()) {
```

```
11      if (int64_t(data.size()) * (64 -
↪  __builtin_clzll(data.size())) < 2 * (1 << bits_per_pass))
↪  {
12          stable_sort(data.begin(), data.end(), [&](const T &a,
↪  const T &b) {
13              return extract_key(a) < extract_key(b);
14          });
15          return;
16      }
17
18      using T_key = decltype(extract_key(data.front()));
19      T_key minimum = numeric_limits<T_key>::max();
20
21      for (T &x : data)
22          minimum = min(minimum, extract_key(x));
23
24      int max_bits = 0;
25
26      for (T &x : data) {
27          T_key key = extract_key(x);
28          max_bits = max(max_bits, key == minimum ? 0 : 64 -
↪  __builtin_clzll(key - minimum));
29      }
30
31      int passes = max((max_bits + bits_per_pass / 2) /
↪  bits_per_pass, 1);
32
33      if (64 - __builtin_clzll(data.size()) <= 1.5 * passes) {
34          stable_sort(data.begin(), data.end(), [&](const T &a,
↪  const T &b) {
35              return extract_key(a) < extract_key(b);
36          });
37          return;
38      }
39
40      vector<T> buffer(data.size());
41      vector<int> counts;
42      int bits_so_far = 0;
43
44      for (int p = 0; p < passes; p++) {
45          int bits = (max_bits + p) / passes;
46          counts.assign(1 << bits, 0);
47
48          for (T &x : data) {
49              T_key key = T_key(extract_key(x) - minimum);
50              counts[(key >> bits_so_far) & ((1 << bits) -
↪  1)]++;
51          }
52
53          int count_sum = 0;
54
55          for (int &count : counts) {
56              int current = count;
57              count = count_sum;
58              count_sum += current;
59          }
60
61          for (T &x : data) {
62              T_key key = T_key(extract_key(x) - minimum);
63              int key_section = int((key >> bits_so_far) & ((1
↪  << bits) - 1));
64              buffer[counts[key_section]++] = x;
65          }
66
67          swap(data, buffer);
68          bits_so_far += bits;
69      }
70  }
```

- USAGE

```
1  radix_sort(edges, 10, [&](const edge &e) -> int { return
↪  abs(e.weight - x); });
```

String

AC Automaton

```
1  struct AC_automaton {
2    int sz = 26;
3    vector<vector<int>> e = {vector<int>(sz)};  // vector is
↪  faster than unordered_map
4    vector<int> fail = {0}, end = {0};
5    vector<int> fast = {0};  // closest end
6
7    int insert(string& s) {
8      int p = 0;
9      for (auto c : s) {
10        c -= 'a';
11        if (!e[p][c]) {
12          e.emplace_back(sz);
13          fail.emplace_back();
14          end.emplace_back();
15          fast.emplace_back();
16          e[p][c] = (int)e.size() - 1;
17        }
18        p = e[p][c];
19      }
20      end[p] += 1;
21      return p;
22    }
23
24    void build() {
25      queue<int> q;
26      for (int i = 0; i < sz; i++)
27        if (e[0][i]) q.push(e[0][i]);
28      while (!q.empty()) {
29        int p = q.front();
30        q.pop();
31        fast[p] = end[p] ? p : fast[fail[p]];
32        for (int i = 0; i < sz; i++) {
33          if (e[p][i]) {
34            fail[e[p][i]] = e[fail[p]][i];
35            q.push(e[p][i]);
36          } else {
37            e[p][i] = e[fail[p]][i];
38          }
39        }
40      }
41    }
42  };
```

KMP

- nex[i]: length of longest common prefix & suffix for pat[0..i]

```
1  vector<int> get_next(vector<int> &pat) {
2    int m = (int)pat.size();
3    vector<int> nex(m);
4    for (int i = 1, j = 0; i < m; i++) {
5      while (j && pat[j] != pat[i]) j = nex[j - 1];
6      if (pat[j] == pat[i]) j++;
7      nex[i] = j;
8    }
9    return nex;
10  }
```

- kmp match for txt and pat

```
1  auto nex = get_next(pat);
2  for (int i = 0, j = 0; i < n; i++) {
3    while (j && pat[j] != txt[i]) j = nex[j - 1];
4    if (pat[j] == txt[i]) j++;
5    if (j == m) {
6      // do what you want with the match
7      // start index is `i - m + 1`
8      j = nex[j - 1];
9    }
10  }
```

Z function

- z[i]: length of longest common prefix of s and s[i:]

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

General Suffix Automaton

```cpp
constexpr int SZ = 26;

struct GSAM {
  vector<vector<int>> e = {vector<int>(SZ)};  // the labeled
  ↪  edges from node i
  vector<int> parent = {-1};                   // the parent of
  ↪  i
  vector<int> length = {0};                    // the length of
  ↪  the longest string

  GSAM(int n) { e.reserve(2 * n), parent.reserve(2 * n),
  ↪  length.reserve(2 * n); };
  int extend(int c, int p) {  // character, last
    bool f = true;            // if already exist
    int r = 0;                // potential new node
    if (!e[p][c]) {           // only extend when not exist
      f = false;
      e.push_back(vector<int>(SZ));
      parent.push_back(0);
      length.push_back(length[p] + 1);
      r = (int)e.size() - 1;
      for (; ~p && !e[p][c]; p = parent[p]) e[p][c] = r;  //
  ↪  update parents
    }
    if (f || ~p) {
      int q = e[p][c];
      if (length[q] == length[p] + 1) {
        if (f) return q;
        parent[r] = q;
      } else {
        e.push_back(e[q]);
        parent.push_back(parent[q]);
        length.push_back(length[p] + 1);
        int qq = parent[q] = (int)e.size() - 1;
        for (; ~p && e[p][c] == q; p = parent[p]) e[p][c] =
  ↪  qq;
        if (f) return qq;
        parent[r] = qq;
      }
    }
    return r;
  }
};
```

- Topo sort on GSAM

```cpp
ll sz = gsam.e.size();
vector<int> c(sz + 1);
vector<int> order(sz);
for (int i = 1; i < sz; i++) c[gsam.length[i]]++;
for (int i = 1; i < sz; i++) c[i] += c[i - 1];
for (int i = 1; i < sz; i++) order[c[gsam.length[i]]--] = i;
reverse(order.begin(), order.end()); // reverse so that large
↪  len to small
```

- can be used as an ordinary SAM
- USAGE (the number of distinct substring)

```cpp
int main() {
  int n, last = 0;
  string s;
```

```cpp
  cin >> n;
  auto a = GSAM();
  for (int i = 0; i < n; i++) {
    cin >> s;
    last = 0;   // reset last
    for (auto&& c : s) last = a.extend(c, last);
  }
  ll ans = 0;
  for (int i = 1; i < a.e.size(); i++) {
    ans += a.length[i] - a.length[a.parent[i]];
  }
  cout << ans << endl;
  return 0;
}
```

Manacher

```cpp
string longest_palindrome(string& s) {
  // init "abc" -> "^$a#b#c$"
  vector<char> t{'^', '#'};
  for (char c : s) t.push_back(c), t.push_back('#');
  t.push_back('$');
  // manacher
  int n = t.size(), r = 0, c = 0;
  vector<int> p(n, 0);
  for (int i = 1; i < n - 1; i++) {
    if (i < r + c) p[i] = min(p[2 * c - i], r + c - i);
    while (t[i + p[i] + 1] == t[i - p[i] - 1]) p[i]++;
    if (i + p[i] > r + c) r = p[i], c = i;
  }
  // s[i] -> p[2 * i + 2] (even), p[2 * i + 2] (odd)
  // output answer
  int index = 0;
  for (int i = 0; i < n; i++)
    if (p[index] < p[i]) index = i;
  return s.substr((index - p[index]) / 2, p[index]);
}
```

Lyndon

- def: suf(s) > s

```cpp
void duval(const string &s) {
  int n = (int)s.size();
  for (int i = 0; i < n;) {
    int j = i, k = i + 1;
    for (; j < n && s[j] <= s[k]; j++, k++)
      if (s[j] < s[k]) j = i - 1;

    while (i <= j) {
      // cout << s.substr(i, k - j) << '\n';
      i += k - j;
    }
  }
}

int main() {
  string s;
  cin >> s;
  duval(s);
}
```