

Fortcoders Code Library

askd, yangster67, Nea1

April 29th 2022

Contents

Intro	2
Main template	2
Fast IO	2
Pragmas (lol)	2
Data Structures	2
Segment Tree	2
Recursive	2
Iterating	3
Union Find	4
Fenwick Tree	4
Fenwick2D Tree	4
PBDS	5
Treap	5
Implicit treap	6
Persistent implicit treap	6
2D Sparse Table	6
K-D Tree	7
Link/Cut Tree	7
Geometry	8
Basic stuff	8
Transformation	8
Relation	9
Area	10
Convex	10
Basic 3D	11
Miscellaneous	12
Graph Theory	12
Max Flow	12
PushRelabel Max-Flow (faster)	12
Min-Cost Max-Flow	13
Max Cost Feasible Flow	13
Heavy-Light Decomposition	14
General Unweight Graph Matching	14
Maximum Bipartite Matching	15
2-SAT and Strongly Connected Components	15
Enumerating Triangles	15
Tarjan	15
Kruskal reconstruct tree	16
Math	16
Inverse	16
Mod Class	16
Cancer mod class	17
NTT, FFT, FWT	17
Polynomial Class	18
Sieve	19
Gaussian Elimination	20
is_prime	20
Radix Sort	20
lucas	21
parity of n choose m	21
sosdp	21
String	21
AC Automaton	21
KMP	22

Z function	22
General Suffix Automaton	22
Manacher	22
Lyndon	22
minimal representation	23

Intro

Main template

```
1 #include <bits/stdc++.h>
2 using namespace std;
3
4 #define FOR(x,n) for(int x=0;x<n;x++)
5 #define forn(i, n) for (int i = 0; i < int(n); i++)
6 #define all(v) v.begin(),v.end()
7 using ll = long long;
8 using ld = long double;
9 using pii = pair<int, int>;
10 const char nl = '\n';
11
12 int main() {
13     cin.tie(nullptr)->sync_with_stdio(false);
14     cout << fixed << setprecision(20);
15     // mt19937
16     ↪ rng(chrono::steady_clock::now().time_since_epoch().count());
17 }
```

Fast IO

```
1 namespace io {
2 constexpr int SIZE = 1 << 16;
3 char buf[SIZE], *head, *tail;
4 char get_char() {
5     if (head == tail) tail = (head = buf) + fread(buf, 1, SIZE,
6     ↪ stdin);
7     return *head++;
8 }
9 ll read() {
10     ll x = 0, f = 1;
11     char c = get_char();
12     for (; !isdigit(c); c = get_char()) (c == '-') && (f = -1);
13     for (; isdigit(c); c = get_char()) x = x * 10 + c - '0';
14     return x * f;
15 }
16 string read_s() {
17     string str;
18     char c = get_char();
19     while (c == ' ' || c == '\n' || c == '\r') c = get_char();
20     while (c != ' ' && c != '\n' && c != '\r') str += c, c =
21     ↪ get_char();
22     return str;
23 }
24 void print(int x) {
25     if (x > 9) print(x / 10);
26     putchar(x % 10 | '0');
27 }
28 void println(int x) { print(x), putchar('\n'); }
29 struct Read {
30     Read& operator>>(ll& x) { return x = read(), *this; }
31     Read& operator>>(long double& x) { return x =
32     ↪ stold(read_s()), *this; }
33 } in;
34 } // namespace io
```

Pragmas (lol)

```
1 #pragma GCC optimize(2)
2 #pragma GCC optimize(3)
3 #pragma GCC optimize("Ofast")
4 #pragma GCC optimize("inline")
5 #pragma GCC optimize("-fgcse")
6 #pragma GCC optimize("-fgcse-lm")
7 #pragma GCC optimize("-fipa-sra")
8 #pragma GCC optimize("-ftree-pre")
9 #pragma GCC optimize("-ftree-vcnp")
10 #pragma GCC optimize("-fpeephole2")
11 #pragma GCC optimize("-ffast-math")
12 #pragma GCC optimize("-fsched-spec")
13 #pragma GCC optimize("unroll-loops")
14 #pragma GCC optimize("-falign-jumps")
15 #pragma GCC optimize("-falign-loops")
```

```
16 #pragma GCC optimize("-falign-labels")
17 #pragma GCC optimize("-fdevirtualize")
18 #pragma GCC optimize("-fcaller-saves")
19 #pragma GCC optimize("-fcrossjumping")
20 #pragma GCC optimize("-fthread-jumps")
21 #pragma GCC optimize("-funroll-loops")
22 #pragma GCC optimize("-fwhole-program")
23 #pragma GCC optimize("-freorder-blocks")
24 #pragma GCC optimize("-fschedule-insns")
25 #pragma GCC optimize("inline-functions")
26 #pragma GCC optimize("-ftree-tail-merge")
27 #pragma GCC optimize("-fschedule-insns2")
28 #pragma GCC optimize("-fstrict-aliasing")
29 #pragma GCC optimize("-fstrict-overflow")
30 #pragma GCC optimize("-falign-functions")
31 #pragma GCC optimize("-fcse-skip-blocks")
32 #pragma GCC optimize("-fcse-follow-jumps")
33 #pragma GCC optimize("-fsched-interblock")
34 #pragma GCC optimize("-fpartial-inlining")
35 #pragma GCC optimize("no-stack-protector")
36 #pragma GCC optimize("-freorder-functions")
37 #pragma GCC optimize("-findirect-inlining")
38 #pragma GCC optimize("-fhoist-adjacent-loads")
39 #pragma GCC optimize("-frerun-cse-after-loop")
40 #pragma GCC optimize("inline-small-functions")
41 #pragma GCC optimize("-finline-small-functions")
42 #pragma GCC optimize("-ftree-switch-conversion")
43 #pragma GCC optimize("-foptimize-sibling-calls")
44 #pragma GCC optimize("-fexpensive-optimizations")
45 #pragma GCC optimize("-funsafe-loop-optimizations")
46 #pragma GCC optimize("inline-functions-called-once")
47 #pragma GCC optimize("-fdelete-null-pointer-checks")
48 #pragma GCC
49     ↪ target("sse,sse2,sse3,ssse3,sse4.1,sse4.2,avx,avx2,popcnt,tune=na
```

Data Structures

Segment Tree

Recursive

- Implicit segment tree, range query + point update

```
1 struct Node {
2     int lc, rc, p;
3 };
4
5 struct SegTree {
6     vector<Node> t = {};
7     SegTree(int n) { t.reserve(n * 40); }
8     int modify(int p, int l, int r, int x, int v) {
9         int u = p;
10        if (p == 0) {
11            t.push_back(t[p]);
12            u = (int)t.size() - 1;
13        }
14        if (r - l == 1) {
15            t[u].p = t[p].p + v;
16        } else {
17            int m = (l + r) / 2;
18            if (x < m) {
19                t[u].lc = modify(t[p].lc, l, m, x, v);
20            } else {
21                t[u].rc = modify(t[p].rc, m, r, x, v);
22            }
23            t[u].p = t[t[u].lc].p + t[t[u].rc].p;
24        }
25        return u;
26    }
27    int query(int p, int l, int r, int x, int y) {
28        if (x <= l && r <= y) return t[p].p;
29        int m = (l + r) / 2, res = 0;
30        if (x < m) res += query(t[p].lc, l, m, x, y);
31        if (y > m) res += query(t[p].rc, m, r, x, y);
32        return res;
33    }
34 }
```

```
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 +
19         1]);
20     }
21     Node query(ll l, ll r) {
22         Node left, right;
23         for (l += n, r += n; l < r; l /= 2, r /= 2) {
24             if (l & 1) left = pull(left, t[l++]);
25             if (r & 1) right = pull(t[--r], right);
26         }
27         return pull(left, right);
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,
8     b.v)}; }
9 Tag pull(const Tag& a, const Tag& b) { return {a.v + b.v}; }
10 Node apply_tag(const Node& a, const Tag& b) { return {a.v +
11     b.v}; }
12
13 struct SegTree {
14     ll n, h;
15     vector<Node> t;
16     vector<Tag> lazy;
17     SegTree(ll _n) : n(_n), h((ll)log2(n)), t(2 * _n), lazy(2 *
18     _n) {}
19     void apply(ll x, const Tag& tag) {
20         t[x] = apply_tag(t[x], tag);
21         lazy[x] = pull(lazy[x], tag);
22     }
23     void build(ll l) {
24         for (l = (l + n) / 2; l > 0; l /= 2) {
25             if (!lazy[l].v) t[l] = pull(t[l * 2], t[2 * l + 1]);
26         }
27     }
28     void push(ll l) {
29         l += n;
30         for (ll s = h; s > 0; s--) {
31             ll i = l >> s;
32             if (lazy[i].v) {
33                 apply(2 * i, lazy[i]);
34                 apply(2 * i + 1, lazy[i]);
35             }
36             lazy[i] = Tag();
37         }
38     }
39     void modify(ll l, ll r, const Tag& v) {
40         push(l), push(r - 1);
41         ll l0 = l, r0 = r;
42         for (l += n, r += n; l < r; l /= 2, r /= 2) {
43             if (l & 1) apply(l++, v);
44             if (r & 1) apply(--r, v);
45         }
46         build(l0), build(r0 - 1);
47     }
48     Node query(ll l, ll r) {
49         push(l), push(r - 1);
50         Node left, right;
51         for (l += n, r += n; l < r; l /= 2, r /= 2) {
52             if (l & 1) left = pull(left, t[l++]);
53             if (r & 1) right = pull(t[--r], right);
54         }
55         return pull(left, right);
56     }
57 };
```

- 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]; }
```

```

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

```

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

```

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);
↪ }

```

```

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

```

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

```

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,
7  ↪ tree_order_statistics_node_update>;
8  template<typename T, typename X>
9  using ordered_map = tree<T, X, less<T>, rb_tree_tag,
10 ↪ tree_order_statistics_node_update>;
11 template<typename T, typename X>
12 using fast_map = cc_hash_table<T, X>;
13 template<typename T, typename X>
14 using ht = gp_hash_table<T, X>;
15 mt19937_64
16 ↪ rng(chrono::steady_clock::now().time_since_epoch().count());
17
18 struct splitmix64 {
19     size_t operator()(size_t x) const {
20         static const size_t fixed =
21         ↪ chrono::steady_clock::now().time_since_epoch().count();
22         x += 0x9e3779b97f4a7c15 + fixed;
23         x = (x ^ (x >> 30)) * 0xbf58476d1ce4e5b9;
24         x = (x ^ (x >> 27)) * 0x94d049bb133111eb;
25         return x ^ (x >> 31);
26     }
27 };

```

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),
8      ↪ w(rng()) {}
9      void apply(int vt, int vg) {
10         // for lazy propagation
11         // s -= vt;
12         // t += vt, a += vg, g += vg;
13     }
14     void push() {
15         // for lazy propagation
16         // if (l != nullptr) l->apply(t, g);
17         // if (r != nullptr) r->apply(t, g);
18         // t = g = 0;
19     }
20     void pull() { sz = 1 + (l ? l->sz : 0) + (r ? r->sz : 0); }
21 };
22
23 std::pair<Node *, Node *> split(Node *t, int v) {
24     if (t == nullptr) return {nullptr, nullptr};
25     t->push();
26     if (t->s < v) {
27         auto [x, y] = split(t->r, v);
28         t->r = x;
29         t->pull();
30         return {t, y};
31     }
32 }

```

```

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),
8     ↪ w(rnd()) {}
9     void apply() {
10         // for lazy propagation
11         // lazy ^= 1;
12     }
13     void push() {
14         // for lazy propagation
15         // if (lazy) {
16         //     swap(l, r);
17         //     if (l != nullptr) l->apply();
18         //     if (r != nullptr) r->apply();
19         //     lazy = 0;
20         // }
21     }
22     void pull() { sz = 1 + (l ? l->sz : 0) + (r ? r->sz : 0); }
23 };
24
25 std::pair<Node *, Node *> split(Node *t, int v) {
26     // first->sz == v
27     if (t == nullptr) return {nullptr, nullptr};
28     t->push();
29     int left_sz = t->l ? t->l->sz : 0;
30     if (left_sz < v) {
31         auto [x, y] = split(t->r, v - left_sz - 1);
32         t->r = x;
33         t->pull();
34         return {t, y};
35     } else {
36         auto [x, y] = split(t->l, v);
37         t->l = y;
38         t->pull();
39         return {x, t};
40     }
41 }
42
43 Node *merge(Node *p, Node *q) {
44     if (p == nullptr) return q;
45     if (q == nullptr) return p;
46     if (p->w < q->w) {
47         p->push();
48         p->r = merge(p->r, q);
49         p->pull();
50         return p;
51     } else {
52         q->push();
53         q->l = merge(p, q->l);
54         q->pull();
55         return q;
56     }
57 }

```

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 - asked

```

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],
25                     ↪ table[i+(1<<(k-1))][j][k-1][0]);
26                     for (int l = 1; l <= log[m - j]; l++)
27                         table[i][j][k][l] = choose(table[i][j][k][l-1],
28                     ↪ table[i+(1<<(l-1))][j][k][l-1]);
29                 }
30             }
31         }
32         T query(int r1, int r2, int c1, int c2) {
33             assert(r1 >= 0 && r2 < n && r1 <= r2);
34         }
35     }
36 };

```

```

33     assert(c1 >= 0 && c2 < m && c1 <= c2);
34     int r1 = log[r2 - r1 + 1], c1 = log[c2 - c1 + 1];
35     T ca1 = choose(table[r1][c1][r1][c1],
36     ↪ table[r2-(1<<r1)+1][c1][r1][c1]);
37     T ca2 = choose(table[r1][c2-(1<<c1)+1][r1][c1],
38     ↪ table[r2-(1<<r1)+1][c2-(1<<c1)+1][r1][c1]);
39     return choose(ca1, ca2);
40 }
41 };

```

• 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) &&
10    ↪ (p.y <= rg.ry));
11 }
12
13 struct KDTree {
14     vector<Point> points;
15     struct Node {
16         int lc, rc;
17         Point point;
18         Rectangle range;
19         int num;
20     };
21     vector<Node> nodes;
22     int root = -1;
23     KDTree(const vector<Point> &points_) {
24         points = points_;
25         Rectangle range = {-1e9, 1e9, -1e9, 1e9};
26         root = tree_construct(0, (int)points.size(), range, 0);
27     }
28     int tree_construct(int l, int r, Rectangle range, int depth)
29     ↪ {
30         if (l == r) return -1;
31         if (l > r) throw;
32         int mid = (l + r) / 2;
33         auto comp = (depth % 2) ? [](Point &a, Point &b) { return
34         ↪ a.x < b.x; }
35         : [](Point &a, Point &b) { return
36         ↪ a.y < b.y; };
37         nth_element(points.begin() + l, points.begin() + mid,
38         ↪ points.begin() + r, comp);
39         Rectangle l_range(range), r_range(range);
40         if (depth % 2) {
41             l_range.rx = points[mid].x;
42             r_range.lx = points[mid].x;
43         } else {
44             l_range.ry = points[mid].y;
45             r_range.ly = points[mid].y;
46         }
47         Node node = {tree_construct(l, mid, l_range, depth + 1),
48         ↪ tree_construct(mid + 1, r, r_range, depth +
49         ↪ 1), points[mid], range, r - l};
50         nodes.push_back(node);
51         return (int)nodes.size() - 1;
52     }
53
54     int inner_query(int id, const Rectangle &rec, int depth) {
55         if (id == -1) return 0;
56         Rectangle rg = nodes[id].range;

```

```

51         if (rg.lx >= rec.lx && rg.rx <= rec.rx && rg.ly >= rec.ly
52         ↪ && rg.ry <= rec.ry) {
53             return nodes[id].num;
54         }
55         int ans = 0;
56         if (depth % 2) { // pruning
57             if (rec.lx <= nodes[id].point.x) ans +=
58             ↪ inner_query(nodes[id].lc, rec, depth + 1);
59             if (rec.rx >= nodes[id].point.x) ans +=
60             ↪ inner_query(nodes[id].rc, rec, depth + 1);
61         } else {
62             if (rec.ly <= nodes[id].point.y) ans +=
63             ↪ inner_query(nodes[id].lc, rec, depth + 1);
64             if (rec.ry >= nodes[id].point.y) ans +=
65             ↪ inner_query(nodes[id].rc, rec, depth + 1);
66         }
67         if (is_in(nodes[id].point, rec)) ans += 1;
68         return ans;
69     }
70
71     int query(const Rectangle &rec) { return inner_query(root,
72     ↪ rec, 0); }
73 };

```

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),
6     ↪ rev(false) {}
7     friend void reverse(Node *p) {
8         if (p != nullptr) {
9             swap(p->ch[0], p->ch[1]);
10            p->rev ^= 1;
11        }
12    }
13    void push() {
14        if (rev) {
15            reverse(ch[0]);
16            reverse(ch[1]);
17            rev = false;
18        }
19    }
20    void pull() {}
21    bool is_root() { return p == nullptr || p->ch[0] != this &&
22    ↪ p->ch[1] != this; }
23    bool pos() { return p->ch[1] == this; }
24    void rotate() {
25        Node *q = p;
26        bool x = !pos();
27        q->ch[!x] = ch[x];
28        if (ch[x] != nullptr) ch[x]->p = q;
29        p = q->p;
30        if (!q->is_root()) q->p->ch[q->pos()] = this;
31        ch[x] = q;
32        q->p = this;
33        pull();
34        q->pull();
35    }
36    void splay() {
37        vector<Node *> s;
38        for (Node *i = this; !i->is_root(); i = i->p)
39        ↪ s.push_back(i->p);
40        while (!s.empty()) s.back()->push(), s.pop_back();
41        push();
42        while (!is_root()) {
43            if (pos() == p->pos()) {
44                p->rotate();
45            } else {
46                rotate();
47            }
48        }
49    }
50 };

```



```

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 };
41
42 auto dist2(const Point &a) { return a * a; }
43 auto dist2(const Point &a, const Point &b) { return dist2(a -
↪ b); }
44 auto dist(const Point &a) { return sqrt(dist2(a)); }
45 auto dist(const Point &a, const Point &b) { return
↪ sqrt(dist2(a - b)); }
46 auto dist(const Point &a, const Line &l) { return abs((a -
↪ l.s) ^ (l.e - l.s)) / dist(l.s, l.e); }
47 auto dist(const Point &p, const Segment &l) {
48     if (l.s == l.e) return dist(p, l.s);
49     auto d = dist2(l.s, l.e), t = min(d, max((ld)0, (p - l.s) *
↪ (l.e - l.s)));
50     return dist((p - l.s) * d, (l.e - l.s) * t) / d;
51 }
52 /* Needs is_intersect
53 auto dist(const Segment &l1, const Segment &l2) {
54     if (is_intersect(l1, l2)) return (ld)0;
55     return min({dist(l1.s, l2), dist(l1.e, l2), dist(l2.s, l1),
↪ dist(l2.e, l1)});
56 } */
57
58 Point perp(const Point &p) { return Point(-p.y, p.x); }
59
60 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) {
10     return Point(p.x * scale_x, p.y * scale_y); }
11 Line dilate(const Line &l, ld scale_x = 1, ld scale_y = 1) {
12     return Line(dilate(l.s, scale_x, scale_y), dilate(l.e,
↪ scale_x, scale_y)); }
13 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)); }
14 vector<Point> dilate(const vector<Point> &p, ld scale_x = 1,
↪ ld scale_y = 1) {
15     int n = p.size();
16     vector<Point> res(n);
17     for (int i = 0; i < n; i++)
18         res[i] = dilate(p[i], scale_x, scale_y);
19     return res;
20 }
21
22 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)); }
23 Line rotate(const Line &l, ld a) { return Line(rotate(l.s, a),
↪ rotate(l.e, a)); }
24 Segment rotate(const Segment &l, ld a) { return
↪ Segment(rotate(l.s, a), rotate(l.e, a)); }
25 Circle rotate(const Circle &c, ld a) { return
↪ Circle(rotate(c.o, a), c.r); }
26 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) {
13     ↪ return (b - a) ^ (c - a); }
14
15 auto area_intersect(const Circle &c, const vector<Point> &ps)
16     ↪ {
17     int n = (int)ps.size();
18     auto arg = [&](const Point &p, const Point &q) { return
19     ↪ atan2(p ^ q, p * q); };
20     auto tri = [&](const Point &p, const Point &q) {
21         auto r2 = c.r * c.r / (long double)2;
22         auto d = q - p;
23         auto a = d * p / dist2(d), b = (dist2(p) - c.r * c.r) /
24         ↪ dist2(d);
25         long double det = a * a - b;
26         if (sgn(det) <= 0) return arg(p, q) * r2;
27         auto s = max((long double)0, -a + sqrt(det)), t =
28         ↪ min((long double)1, -a + sqrt(det));
29         if (sgn(t) < 0 || sgn(1 - s) <= 0) return arg(p, q) * r2;
30         auto u = p + d * s, v = p + d * t;
31         return arg(p, u) * r2 + (u ^ v) / 2 + arg(v, q) * r2;
32     };
33     long double sum = 0;
34     for (int i = 0; i < n; i++) sum += tri(ps[i] - c.o, ps[(i +
35     ↪ 1) % n] - c.o);
36     return sum;
37 }
38
39 auto adaptive_simpson(ld _l, ld _r, function<ld(ld)> f) {
40     auto simpson = [&](ld l, ld r) { return (r - l) * (f(l) + 4
41     ↪ * f((l + r) / 2) + f(r)) / 6; };
42     function<ld(ld, ld, ld)> asr = [&](ld l, ld r, ld s) {
43         auto mid = (l + r) / 2;
44         auto left = simpson(l, mid), right = simpson(mid, r);
45         if (!sgn(left + right - s)) return left + right;
46         return asr(l, mid, left) + asr(mid, r, right);
47     };

```

```

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 -
48     ↪ a.e) < rad(b.s - b.e); });
49     vector<Point> p(n), res;
50     vector<Line> q(n);
51     q[0] = L[0];
52     for (int i = 1; i < n; i++) {
53         while (1 < r && sgn((L[i].e - L[i].s) ^ (p[r - 1] -
54     ↪ L[i].s)) <= 0) r--;
55         while (1 < r && sgn((L[i].e - L[i].s) ^ (p[l] - L[i].s))
56     ↪ <= 0) l++;
57         q[++r] = L[i];
58         if (sgn((q[r].e - q[r].s) ^ (q[r - 1].e - q[r - 1].s)) ==
59     ↪ 0) {
60             r--;
61             if (sgn((q[r].e - q[r].s) ^ (L[i].s - q[r].s)) > 0) q[r]
62     ↪ = L[i];
63             if (1 < r) p[r - 1] = intersect(q[r - 1], q[r]);
64         }
65         while (1 < r && sgn((q[l].e - q[l].s) ^ (p[r - 1] - q[l].s))
66     ↪ <= 0) l--;
67         if (r - l <= 1) return {};
68         p[r] = intersect(q[r], q[l]);
69         return vector<Point>(p.begin() + l, p.begin() + r + 1);
70     }

```

Convex

```

1 vector<Point> get_convex(vector<Point> &points, bool
2     ↪ allow_collinear = false) {
3     // strict, no repeat, two pass
4     sort(points.begin(), points.end());
5     points.erase(unique(points.begin(), points.end()),
6     ↪ points.end());
7     vector<Point> L, U;
8     for (auto &t : points) {
9         for (ll sz = L.size(); sz > 1 && (sgn((t - L[sz - 2]) ^
10     ↪ (L[sz - 1] - L[sz - 2])) >= 0);
11             L.pop_back(), sz = L.size()) {
12         }
13         L.push_back(t);
14     }
15     for (auto &t : points) {
16         for (ll sz = U.size(); sz > 1 && (sgn((t - U[sz - 2]) ^
17     ↪ (U[sz - 1] - U[sz - 2])) <= 0);
18             U.pop_back(), sz = U.size()) {
19         }
20         U.push_back(t);
21     }
22     // contain repeats if all collinear, use a set to remove
23     ↪ repeats
24     if (allow_collinear) {
25         for (int i = (int)U.size() - 2; i >= 1; i--)
26     ↪ L.push_back(U[i]);
27     } else {
28         set<Point> st(L.begin(), L.end());
29         for (int i = (int)U.size() - 2; i >= 1; i--) {
30             if (st.count(U[i]) == 0) L.push_back(U[i]),
31     ↪ st.insert(U[i]);
32         }
33     }
34     return L;
35 }
36
37 vector<Point> get_convex2(vector<Point> &points, bool
38     ↪ allow_collinear = false) { // strict, no repeat, one pass
39     nth_element(points.begin(), points.begin(), points.end());
40     sort(points.begin() + 1, points.end(), [&](const Point &a,
41     ↪ const Point &b) {
42         int rad_diff = sgn((a - points[0]) ^ (b - points[0]));

```

```

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>

```

```

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

```

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

```
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
10     ↪ p1.first.y < p2.first.y; };
11     function<tuple<int,int,ld>(int, int)> recurse = [&](int l,
12     ↪ int r) -> tuple<int,int,ld> {
13         int i = pts[l].second, j = pts[l + 1].second;
14         ld d = dist(pts[l].first, pts[l + 1].first);
15         if (r - l < 5) {
16             for (int a = l; a < r; a++) for (int b = a + 1; b < r;
17             ↪ b++) {
18                 ld cur = dist(pts[a].first, pts[b].first);
19                 if (cur < d) { i = pts[a].second; j = pts[b].second; d
20                 ↪ = cur; }
21             }
22             sort(pts.begin() + l, pts.begin() + r, cmp_y);
23         }
24         else {
25             int mid = (l + r)/2;
26             ld x = pts[mid].first.x;
27             auto [li, lj, ldist] = recurse(l, mid);
28             auto [ri, rj, rdist] = recurse(mid, r);
29             if (ldist < rdist) { i = li; j = lj; d = ldist; }
30             else { i = ri; j = rj; d = rdist; }
31             inplace_merge(pts.begin() + l, pts.begin() + mid,
32             ↪ pts.begin() + r, cmp_y);
33             buf.clear();
34             for (int a = l; a < r; a++) {
35                 if (abs(x - pts[a].first.x) >= d) continue;
36                 for (int b = buf.size() - 1; b >= 0; b--) {
37                     if (pts[a].first.y - buf[b].first.y >= d) break;
38                     ld cur = dist(pts[a].first, buf[b].first);
39                     if (cur < d) { i = pts[a].second; j = buf[b].second;
40                     ↪ d = cur; }
41                 }
42                 buf.push_back(pts[a]);
43             }
44             return {i, j, d};
45         }
46     };
47     return recurse(0, n);
48 }
49
50 Line abc_to_line(ld a, ld b, ld c) {
51     assert(!sgn(a) || !sgn(b));
52     if (a == 0) return Line(Point(0, -c/b), Point(1, -c/b));
53     if (b == 0) return Line(Point(-c/a, 0), Point(-c/a, 1));
54     Point s(0, -c/b), e(1, (-c - a)/b), diff = e - s;
55     return Line(s, s + diff/dist(diff));
56 }
57
58 tuple<ld,ld,ld> line_to_abc(const Line& l) {
59     Point diff = l.e - l.s;
60     return {-diff.y, diff.x, -(diff ^ l.s)};
61 }
```

Graph Theory

Max Flow

```
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(),
21             ↪ cur.end(), 0);
22             d[s] = 0;
23             vector<int> q{s}, nq;
24             for (int step = 1; q.size(); swap(q, nq), nq.clear(),
25             ↪ step++) {
26                 for (auto& node : q) {
27                     for (auto& edge : g[node]) {
28                         int ne = e[edge].to;
29                         if (!e[edge].remain || d[ne] <= step) continue;
30                         d[ne] = step, nq.push_back(ne);
31                         if (ne == t) return true;
32                     }
33                 }
34             }
35             return false;
36         };
37         function<int(int, int)> find = [&](int node, int limit) {
38             if (node == t || !limit) return limit;
39             int flow = 0;
40             for (int i = cur[node]; i < g[node].size(); i++) {
41                 cur[node] = i;
42                 int edge = g[node][i], oe = edge ^ 1, ne = e[edge].to;
43                 if (!e[edge].remain || d[ne] != d[node] + 1) continue;
44                 if (int temp = find(ne, min(limit - flow,
45                 ↪ e[edge].remain))) {
46                     e[edge].remain -= temp, e[oe].remain += temp, flow
47                     ↪ += temp;
48                 } else {
49                     d[ne] = -1;
50                 }
51                 if (flow == limit) break;
52             }
53             return flow;
54         };
55         ll res = 0;
56         while (bfs())
57             while (int flow = find(s, inf)) res += flow;
58         return res;
59     }
60 }
```

• USAGE

```
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)

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



```

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]
56 + 1, cur[u] = &e;
57                     if (++co[H[u]], !--co[hi] && hi < v)
58                         rep(i, 0, v) if (hi < H[i] && H[i] < v)--
59 + co[H[i]], H[i] = v + 1;
60                     hi = H[u];
61                 } else if (cur[u]->c && H[u] == H[cur[u]->dest] + 1)
62                     addFlow(*cur[u], min(ec[u], cur[u]->c));
63                 else
64                     ++cur[u];
65             }
66         }
67         bool leftOfMinCut(int a) { return H[a] >= sz(g); }
68     };

```

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>>,
12 + greater<>> que;
13        dis[s] = 0;
14        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)
30 + continue;
31                        d[ne] = d[node] + cost, pre[ne] = edge;
32                        f[ne] = min(e[edge].remain, f[node]);
33                        if (!seen[ne]) seen[ne] = true, nq.push_back(ne);
34                    }
35                }
36            }
37            return f[t];
38        };

```

```

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 };
8
9 vector<ll> light(n);
10 SegTree heavy(n), form_parent(n);
11 // cin >> x >> y, x--, y--;
12 int z = lca(x, y);
13 while (x != z) {
14     if (dfn[top[x]] <= dfn[top[z]]) {
15         // [dfn[z], dfn[x]], from heavy
16         heavy.modify(dfn[z], dfn[x], 1);
17         break;
18     }
19     // x -> top[x];
20     heavy.modify(dfn[top[x]], dfn[x], 1);
21     light[parent[top[x]]] += a[top[x]];
22     x = parent[top[x]];
23 }
24 while (y != z) {
25     if (dfn[top[y]] <= dfn[top[z]]) {
26         // [dfn[z], dfn[y]], from heavy
27         form_parent.modify(dfn[z] + 1, dfn[y] + 1, 1);
28         break;
29     }
30     // y -> top[y];
31     form_parent.modify(dfn[top[y]], dfn[y] + 1, 1);
32     y = parent[top[y]];
33 }

```

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 :
12     ↪ (p[x] = find(p[x])); };
13 auto merge = [&](int x, int y) { p[find(x)] = find(y); };
14 vector<vector<int>> g(n);
15 vector<int> val(m);
16 val.reserve(n);
17 for (auto [w, u, v] : edges) {
18     u = find(u), v = find(v);
19     if (u == v) continue;
20     val.push_back(w);
21     int node = (int)val.size() - 1;
22     g[node].push_back(u), g[node].push_back(v);
23     merge(u, node), merge(v, node);
24 }

```

Math

Inverse

```

1 ll inv(ll a, ll m) { return a == 1 ? 1 : ((m - m / a) * inv(m
2     ↪ % a, m) % m); }
3 // or
4 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 +
5     ↪ 1) % MOD;
6 auto binom = [&](ll n, ll r) -> Z {
7     if (n < 0 || r < 0 || n < r) return 0;
8     return f[n] * rf[n - r] * rf[r];
9 };

```

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
12    ↪ only
13    Z operator-() const { return Z(norm(MOD - x)); }
14    Z inv() const { return power(*this, MOD - 2); }
15    Z &operator*=(const Z &rhs) { return x = x * rhs.x % MOD,
16    ↪ *this; }
17    Z &operator+=(const Z &rhs) { return x = norm(x + rhs.x),
18    ↪ *this; }
19    Z &operator-=(const Z &rhs) { return x = norm(x - rhs.x),
20    ↪ *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    ↪ }
25    friend Z operator+(Z lhs, const Z &rhs) { return lhs += rhs;
26    ↪ }
27    friend Z operator-(Z lhs, const Z &rhs) { return lhs -= rhs;
28    ↪ }
29    friend Z operator/(Z lhs, const Z &rhs) { return lhs /= rhs;
30    ↪ }
31    friend Z operator%(Z lhs, const ll &rhs) { return lhs %=
32    ↪ rhs; }
33    friend auto &operator>>(istream &i, Z &z) { return i >> z.x;
34    ↪ }
35    friend auto &operator<<(ostream &o, const Z &z) { return o
36    ↪ << z.x; }
37 };

```

- 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 :
6     ↪ x % MOD; }
7 template <typename T>
8 constexpr T power(T a, i128 b, T res = 1) {
9     for (; b; b /= 2, (a *= a) %= MOD)
10         if (b & 1) (res *= a) %= MOD;
11     return res;
12 }
13 struct Z {
14     i128 x;
15     constexpr Z(i128 _x = 0) : x(norm(_x)) {}
16     Z operator-() const { return Z(norm(MOD - x)); }
17     Z inv() const { return power(*this, MOD - 2); }
18     // auto operator<=>(const Z&) const = default;
19     Z &operator*=(const Z &rhs) { return x = x * rhs.x % MOD,
20     ↪ *this; }
21     Z &operator+=(const Z &rhs) { return x = norm(x + rhs.x),
22     ↪ *this; }
23     Z &operator-=(const Z &rhs) { return x = norm(x - rhs.x),
24     ↪ *this; }
25     Z &operator/=(const Z &rhs) { return *this *= rhs.inv(); }
26     Z &operator%=(const i128 &rhs) { return x %= rhs, *this; }
27     friend Z operator*(Z lhs, const Z &rhs) { return lhs * rhs;
28     ↪ }
29     friend Z operator+(Z lhs, const Z &rhs) { return lhs += rhs;
30     ↪ }
31     friend Z operator-(Z lhs, const Z &rhs) { return lhs -= rhs;
32     ↪ }
33     friend Z operator/(Z lhs, const Z &rhs) { return lhs /= rhs;
34     ↪ }
35 };

```

```

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 $p\hat{x} * y$, 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(ll(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, 0), ntt(b, 0);
93         for (int i = 0; i < n; i++) a[i] *= b[i];
94         ntt(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     }

```

```

115 Poly integr() const {
116     vector<Z> res(size() + 1);
117     for (int i = 0; i < size(); ++i) res[i + 1] = a[i] / (i +
↪ 1);
118     return Poly(res);
119 }
120 Poly inv(int m) const {
121     Poly x({a[0].inv()});
122     int k = 1;
123     while (k < m) {
124         k *= 2;
125         x = (x * (Poly({2}) - modxx(k) * x)).modxx(k);
126     }
127     return x.modxx(m);
128 }
129 Poly log(int m) const { return (deriv() *
↪ inv(m)).integr().modxx(m); }
130 Poly exp(int m) const {
131     Poly x({1});
132     int k = 1;
133     while (k < m) {
134         k *= 2;
135         x = (x * (Poly({1}) - x.log(k) + modxx(k))).modxx(k);
136     }
137     return x.modxx(m);
138 }
139 Poly pow(int k, int m) const {
140     int i = 0;
141     while (i < size() && a[i].x == 0) i++;
142     if (i == size() || 1LL * i * k >= m) {
143         return Poly(vector<Z>(m));
144     }
145     Z v = a[i];
146     auto f = divxx(i) * v.inv();
147     return (f.log(m - i * k) * k).exp(m - i * k).mulxx(i * k)
↪ * power(v, k);
148 }
149 Poly sqrt(int m) const {
150     Poly x({1});
151     int k = 1;
152     while (k < m) {
153         k *= 2;
154         x = (x + (modxx(k) * x.inv(k)).modxx(k)) * ((MOD + 1) /
↪ 2);
155     }
156     return x.modxx(m);
157 }
158 Poly mult(Poly b) const {
159     if (b.size() == 0) return Poly();
160     int n = b.size();
161     reverse(b.a.begin(), b.a.end());
162     return ((*this) * b).divxx(n - 1);
163 }
164 Poly divmod(Poly b) const {
165     auto n = size(), m = b.size();
166     auto t = *this;
167     reverse(t.a.begin(), t.a.end());
168     reverse(b.a.begin(), b.a.end());
169     Poly res = (t * b.inv(n)).modxx(n - m + 1);
170     reverse(res.a.begin(), res.a.end());
171     return res;
172 }
173 vector<Z> eval(vector<Z> x) const {
174     if (size() == 0) return vector<Z>(x.size(), 0);
175     const int n = max(int(x.size()), size());
176     vector<Poly> q(4 * n);
177     vector<Z> ans(x.size());
178     x.resize(n);
179     function<void(int, int, int)> build = [&](int p, int l,
↪ int r) {
180         if (r - l == 1) {
181             q[p] = Poly({1, -x[l]});
182         } else {
183             int m = (l + r) / 2;
184             build(2 * p, l, m), build(2 * p + 1, m, r);
185             q[p] = q[2 * p] * q[2 * p + 1];
186         }

```

```

187     };
188     build(1, 0, n);
189     auto work = [&](auto self, int p, int l, int r, const Poly
↪ &num) -> void {
190         if (r - l == 1) {
191             if (l < int(ans.size())) ans[l] = num[0];
192         } else {
193             int m = (l + r) / 2;
194             self(self, 2 * p, l, m, num.mult(q[2 * p + 1]).modxx(m
↪ - l));
195             self(self, 2 * p + 1, m, r, num.mult(q[2 * p]).modxx(r
↪ - m));
196         }
197     };
198     work(work, 1, 0, n, mult(q[1].inv(n)));
199     return ans;
200 }
201 };

```

Sieve

• linear sieve

```

1 vector<int> min_primes(MAX_N), primes;
2 primes.reserve(1e5);
3 for (int i = 2; i < MAX_N; i++) {
4     if (!min_primes[i]) min_primes[i] = i, primes.push_back(i);
5     for (auto& p : primes) {
6         if (p * i >= MAX_N) break;
7         min_primes[p * i] = p;
8         if (i % p == 0) break;
9     }
10 }

```

• mobius function

```

1 vector<int> min_p(MAX_N), mu(MAX_N), primes;
2 mu[1] = 1, primes.reserve(1e5);
3 for (int i = 2; i < MAX_N; i++) {
4     if (!min_p[i]) {
5         min_p[i] = i;
6         primes.push_back(i);
7         mu[i] = -1;
8     }
9     for (auto p : primes) {
10         if (i * p >= MAX_N) break;
11         min_p[i * p] = p;
12         if (i % p == 0) {
13             mu[i * p] = 0;
14             break;
15         }
16         mu[i * p] = -mu[i];
17     }
18 }

```

• Euler's totient function

```

1 vector<int> min_p(MAX_N), phi(MAX_N), primes;
2 phi[1] = 1, primes.reserve(1e5);
3 for (int i = 2; i < MAX_N; i++) {
4     if (!min_p[i]) {
5         min_p[i] = i;
6         primes.push_back(i);
7         phi[i] = i - 1;
8     }
9     for (auto p : primes) {
10         if (i * p >= MAX_N) break;
11         min_p[i * p] = p;
12         if (i % p == 0) {
13             phi[i * p] = phi[i] * p;
14             break;
15         }
16         phi[i * p] = phi[i] * phi[p];
17     }
18 }

```

Gaussian Elimination

```
1 bool is_0(Z v) { return v.x == 0; }
2 Z abs(Z v) { return v; }
3 bool is_0(double v) { return abs(v) < 1e-9; }
4
5 // 1 => unique solution, 0 => no solution, -1 => multiple
   ↪ solutions
6 template <typename T>
7 int gaussian_elimination(vector<vector<T>> &a, int limit) {
8     if (a.empty() || a[0].empty()) return -1;
9     int h = (int)a.size(), w = (int)a[0].size(), r = 0;
10    for (int c = 0; c < limit; c++) {
11        int id = -1;
12        for (int i = r; i < h; i++) {
13            if (!is_0(a[i][c]) && (id == -1 || abs(a[id][c]) <
   ↪ abs(a[i][c]))) {
14                id = i;
15            }
16        }
17        if (id == -1) continue;
18        if (id > r) {
19            swap(a[r], a[id]);
20            for (int j = c; j < w; j++) a[id][j] = -a[id][j];
21        }
22        vector<int> nonzero;
23        for (int j = c; j < w; j++) {
24            if (!is_0(a[r][j])) nonzero.push_back(j);
25        }
26        T inv_a = 1 / a[r][c];
27        for (int i = r + 1; i < h; i++) {
28            if (is_0(a[i][c])) continue;
29            T coeff = -a[i][c] * inv_a;
30            for (int j : nonzero) a[i][j] += coeff * a[r][j];
31        }
32        ++r;
33    }
34    for (int row = h - 1; row >= 0; row--) {
35        for (int c = 0; c < limit; c++) {
36            if (!is_0(a[row][c])) {
37                T inv_a = 1 / a[row][c];
38                for (int i = row - 1; i >= 0; i--) {
39                    if (is_0(a[i][c])) continue;
40                    T coeff = -a[i][c] * inv_a;
41                    for (int j = c; j < w; j++) a[i][j] += coeff *
   ↪ a[row][j];
42                }
43                break;
44            }
45        }
46    } // not-free variables: only it on its line
47    for (int i = r; i < h; i++) if (!is_0(a[i][limit])) return 0;
48    return (r == limit) ? 1 : -1;
49 }
50
51 template <typename T>
52 pair<int, vector<T>> solve_linear(vector<vector<T>> a, const
   ↪ vector<T> &b, int w) {
53    int h = (int)a.size();
54    for (int i = 0; i < h; i++) a[i].push_back(b[i]);
55    int sol = gaussian_elimination(a, w);
56    if (!sol) return {0, vector<T>()};
57    vector<T> x(w, 0);
58    for (int i = 0; i < h; i++) {
59        for (int j = 0; j < w; j++) {
60            if (!is_0(a[i][j])) {
61                x[j] = a[i][w] / a[i][j];
62                break;
63            }
64        }
65    }
66    return {sol, x};
67 }
```

is_prime

- (Miller–Rabin primality test)

```
1 i128 power(i128 a, i128 b, i128 MOD = 1, i128 res = 1) {
2     for (; b; b /= 2, (a *= a) %= MOD)
3         if (b & 1) (res *= a) %= MOD;
4     return res;
5 }
6
7 bool is_prime(ll n) {
8     if (n < 2) return false;
9     static constexpr int A[] = {2, 3, 5, 7, 11, 13, 17, 19, 23};
10    int s = __builtin_ctzll(n - 1);
11    ll d = (n - 1) >> s;
12    for (auto a : A) {
13        if (a == n) return true;
14        ll x = (ll)power(a, d, n);
15        if (x == 1 || x == n - 1) continue;
16        bool ok = false;
17        for (int i = 0; i < s - 1; ++i) {
18            x = ll((i128)x * x % n); // potential overflow!
19            if (x == n - 1) {
20                ok = true;
21                break;
22            }
23        }
24        if (!ok) return false;
25    }
26    return true;
27 }
28
29 ll pollard_rho(ll x) {
30     ll s = 0, t = 0, c = rng() % (x - 1) + 1;
31     ll stp = 0, goal = 1, val = 1;
32     for (goal = 1;; goal *= 2, s = t, val = 1) {
33         for (stp = 1; stp <= goal; ++stp) {
34             t = ll(((i128)t * t + c) % x);
35             val = ll(((i128)val * abs(t - s) % x);
36             if ((stp % 127) == 0) {
37                 ll d = gcd(val, x);
38                 if (d > 1) return d;
39             }
40         }
41         ll d = gcd(val, x);
42         if (d > 1) return d;
43     }
44 }
45
46 ll get_max_factor(ll _x) {
47     ll max_factor = 0;
48     function<void(ll)> fac = [&](ll x) {
49         if (x <= max_factor || x < 2) return;
50         if (is_prime(x)) {
51             max_factor = max_factor > x ? max_factor : x;
52             return;
53         }
54         ll p = x;
55         while (p >= x) p = pollard_rho(x);
56         while ((x % p) == 0) x /= p;
57         fac(x), fac(p);
58     };
59     fac(_x);
60     return max_factor;
61 }
```

Radix Sort

```
1 struct identity {
2     template<typename T>
3     T operator()(const T &x) const {
4         return x;
5     }
6 };
7
8 // A stable sort that sorts in passes of `bits_per_pass` bits
   ↪ at a time.
9 template<typename T, typename T_extract_key = identity>
10 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     {
13         stable_sort(data.begin(), data.end(), [&](const T &a,
↳ const T &b) {
14             return extract_key(a) < extract_key(b);
15         });
16         return;
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); });

```

lucas

```

1 ll lucas(ll n, ll m, ll p) {
2     if (m == 0) return 1;
3     return (binom(n % p, m % p, p) * lucas(n / p, m / p, p)) %
↳ p;
4 }

```

parity of n choose m

```

1 (n & m) == m <=> odd

```

sosdp

subset sum

```

1 auto f = a;
2 for (int i = 0; i < SZ; i++) {
3     for (int mask = 0; mask < (1 << SZ); mask++) {
4         if (mask & (1 << i)) f[mask] += f[mask ^ (1 << i)];
5     }
6 }

```

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:]`

```
1 vector<int> z_function(string s) {
2     int n = (int)s.size();
3     vector<int> z(n);
4     for (int i = 1, l = 0, r = 0; i < n; ++i) {
5         if (i <= r) z[i] = min(r - i + 1, z[i - l]);
6         while (i + z[i] < n && s[z[i]] == s[i + z[i]]) ++z[i];
7         if (i + z[i] - 1 > r) l = i, r = i + z[i] - 1;
8     }
9     return z;
10 }
```

General Suffix Automaton

```
1 constexpr int SZ = 26;
2
3 struct GSAM {
4     vector<vector<int>> e = {vector<int>(SZ)}; // the labeled
5     // edges from node i
6     vector<int> parent = {-1}; // the parent of
7     // i
8     vector<int> length = {0}; // the length of
9     // the longest string
10
11     GSAM(int n) { e.reserve(2 * n), parent.reserve(2 * n),
12     // length.reserve(2 * n); };
13     int extend(int c, int p) { // character, last
14         bool f = true; // if already exist
15         int r = 0; // potential new node
16         if (!e[p][c]) { // only extend when not exist
17             f = false;
18             e.push_back(vector<int>(SZ));
19             parent.push_back(0);
20             length.push_back(length[p] + 1);
21             r = (int)e.size() - 1;
22             for (; ~p && !e[p][c]; p = parent[p]) e[p][c] = r; //
23             // update parents
24         }
25         if (f || ~p) {
26             int q = e[p][c];
27             if (length[q] == length[p] + 1) {
28                 if (f) return q;
29                 parent[r] = q;
30             } else {
31                 e.push_back(e[q]);
32             }
33         }
34     }
35 }
```

```
27     parent.push_back(parent[q]);
28     length.push_back(length[p] + 1);
29     int qq = parent[q] = (int)e.size() - 1;
30     for (; ~p && e[p][c] == q; p = parent[p]) e[p][c] =
31     // qq;
32     if (f) return qq;
33     parent[r] = qq;
34 }
35 return r;
36 }
37 };
```

- Topo sort on GSAM

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

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

```
1 int main() {
2     int n, last = 0;
3     string s;
4     cin >> n;
5     auto a = GSAM();
6     for (int i = 0; i < n; i++) {
7         cin >> s;
8         last = 0; // reset last
9         for (auto&& c : s) last = a.extend(c, last);
10    }
11    ll ans = 0;
12    for (int i = 1; i < a.e.size(); i++) {
13        ans += a.length[i] - a.length[a.parent[i]];
14    }
15    cout << ans << endl;
16    return 0;
17 }
```

Manacher

```
1 string longest_palindrome(string& s) {
2     // init "abc" -> "~$a#b#c$"
3     vector<char> t{'^', '#'};
4     for (char c : s) t.push_back(c), t.push_back('#');
5     t.push_back('$');
6     // manacher
7     int n = t.size(), r = 0, c = 0;
8     vector<int> p(n, 0);
9     for (int i = 1; i < n - 1; i++) {
10        if (i < r + c) p[i] = min(p[2 * c - i], r + c - i);
11        while (t[i + p[i] + 1] == t[i - p[i] - 1]) p[i]++;
12        if (i + p[i] > r + c) r = p[i], c = i;
13    }
14    // s[i] -> p[2 * i + 2] (even), p[2 * i + 2] (odd)
15    // output answer
16    int index = 0;
17    for (int i = 0; i < n; i++)
18        if (p[index] < p[i]) index = i;
19    return s.substr((index - p[index]) / 2, p[index]);
20 }
```

Lyndon

- def: $\text{suf}(s) > s$

```
1 void duval(const string &s) {
2     int n = (int)s.size();
3     for (int i = 0; i < n; i++) {
4         int j = i, k = i + 1;
5         for (; j < n && s[j] <= s[k]; j++, k++)
```

```

6         if (s[j] < s[k]) j = i - 1;
7
8     while (i <= j) {
9         // cout << s.substr(i, k - j) << '\n';
10        i += k - j;
11    }
12 }
13 }

```

minimal representation

```

1  int k = 0, i = 0, j = 1;
2  while (k < n && i < n && j < n) {
3      if (s[(i + k) % n] == s[(j + k) % n]) {
4          k++;
5      } else {
6          s[(i + k) % n] > s[(j + k) % n] ? i = i + k + 1 : j = j +
↵      k + 1;
7          if (i == j) i++;
8          k = 0;
9      }
10 }
11 i = min(i, j); // from 0

```