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1 Funciones C++

#include <algorithm> #include <numeric>

Algo	Params	Funcion
sort, stable_sort	f, l	ordena el intervalo
nth_element	f, nth, l	void ordena el n-esimo, y particiona el resto
fill, fill_n	f, l / n, elem	void llena [f, l) o [f, f+n) con elem
lower_bound, upper_bound	f, l, elem	it al primer / ultimo donde se puede insertar elem para que quede ordenada
binary_search	f, l, elem	bool esta elem en [f, l)
copy	f, l, resul	hace resul+i=f+i $\forall i$
find, find_if, find_first_of	f, l, elem / pred / f2, l2	it encuentra i $\in [f, l)$ tq. i=elem, pred(i), $i \in [f2, l2)$
count, count_if	f, l, elem/pred	cuenta elem, pred(i)
search	f, l, f2, l2	busca [f2,l2) $\in [f, l)$
replace, replace_if	f, l, old / pred, new	cambia old / pred(i) por new
reverse	f, l	da vuelta
partition, stable_partition	f, l, pred	pred(i) ad, !pred(i) atras
min_element, max_element	f, l, [comp]	it min, max de [f,l]
lexicographical_compare	f1,l1,f2,l2	bool con [f1,l1];[f2,l2]
next/prev_permutation	f,l	deja en [f,l) la perm sig, ant
set_intersection, set_difference, set_union, set_symmetric_difference,	f1, l1, f2, l2, res	[res, ...) la op. de conj
push_heap, pop_heap, make_heap	f, l, e / e /	mete/saca e en heap [f,l), hace un heap de [f,l)
is_heap	f,l	bool es [f,l) un heap
accumulate	f,l,i,[op]	$T = \sum / \text{oper de } [f, l)$
inner_product	f1, l1, f2, i	$T = i + [f1, l1) \cdot [f2, \dots)$
partial_sum	f, l, r, [op]	$r+i = \sum / \text{oper de } [f, f+i) \forall i \in [f, l)$
__builtin_ffs	unsigned int	Pos. del primer 1 desde la derecha
__builtin_clz	unsigned int	Cant. de ceros desde la izquierda.
__builtin_ctz	unsigned int	Cant. de ceros desde la derecha.
__builtin_popcount	unsigned int	Cant. de 1's en x.
__builtin_parity	unsigned int	1 si x es par, 0 si es impar.
__builtin_XXXXXXll	unsigned ll	= pero para long long's.

Specifier	Output	Example
d or i	Signed decimal integer	392
u	Unsigned decimal integer	7235
o	Unsigned octal	610
x	Unsigned hexadecimal integer	7fa
X	Unsigned hexadecimal integer (uppercase)	7FA
f	Decimal floating point, lowercase	392.65
F	Decimal floating point, uppercase	392.65
e	Scientific notation (mantissa/exponent), lowercase	3.9265e+2
E	Scientific notation (mantissa/exponent), uppercase	3.9265E+2
g	Use the shortest representation: %e or %f	392.65
G	Use the shortest representation: %E or %F	392.65
a	Hexadecimal floating point, lowercase	-0xc.90fep-2
A	Hexadecimal floating point, uppercase	-0XC.90FEP-2
c	Character	a
s	String of characters	sample
p	Pointer address	b8000000
%	A % followed by another % will write a single %.	%

2 Compile

2.1 Compile

```
1 g++-13 nombre.cpp -o nombre (compilar)
2 ./nombre (ejecutar)
3 g++ -std=c++23 -Wall -Wshadow -g -fsanitize=undefined -fsanitize=address
  -D_GLIBCXX_DEBUG nombre.cpp -o nombre
```

2.2 Template

```
1 #include <bits/stdc++.h>
2 #pragma GCC optimize("O3,unroll-loops")
3 #pragma GCC target("avx2,bmi,bmi2,lzcnt,popcnt")
4 using namespace std;
5 #define pb push_back
6 #define ll long long
7 #define s second
8 #define f first
9 #define MOD 1000000007
10 #define INF 1000000000000000
11
12 void solve(){
13
```

```

14 }
15
16 int main() {
17     ios_base::sync_with_stdio(false); cin.tie(0); cout.tie(0);
18     int t;cin>>t;for(int T=0;T<t;T++)
19         solve();
20 }

```

## 3 Data Structures

### 3.1 BIT

```

1  /*
2   Binary Indexed Tree (Fenwick Tree) Fast Implementation
3   -----
4   Indexing: 1-based
5   Bounds: [1, MAXN)
6   Time Complexity:
7       - update(x, val): O(log n) -> adds val to index x
8       - get(x): O(log n) -> prefix sum from 1 to x
9   Space Complexity: O(n)
10  */
11
12  const int MAXN = 10000;
13  int bit[MAXN];
14
15  // Add 'val' to index 'x'
16  void update(int x, int val) {
17      for (; x < MAXN; x += x & -x) {
18          bit[x] += val;
19      }
20  }
21
22  // Get prefix sum from 1 to 'x'
23  int get(int x) {
24      int ans = 0;
25      for (; x > 0; x -= x & -x) {
26          ans += bit[x];
27      }
28      return ans;
29  }

```

### 3.2 Bitset

```

1  bitset<3001> b[3001];
2
3  //set() Set the bit value at the given index to 1.
4  //reset() Set the bit value at the given index to 0.
5  //flip() Toggle the bit value at the given index.
6  //test() Check if the bit value at the given index is 1 or 0.
7  //count() Count the number of set bits.
8  //any() Checks if any bit is set
9  //all() Check if all bit is set.
10 //none() Check if no bit is set.
11 //to_string() Convert the bitset to a string representation.
12
13 #pragma GCC target("popcnt")
14 (int) __builtin_popcount(x);
15 (int) __builtin_popcountll(x);
16 __builtin_clz(x); // count leading zeros
17
18 // declare bitset
19 bitset<64> b;

```

### 3.3 Bit Trie

```

1  /*
2   Bit Trie (Binary Trie for Integers)
3   -----
4   Indexing: 0-based
5   Bit Width: [0, MAX_BIT] inclusive (e.g., 31 for 32-bit integers)
6   Time Complexity:
7       - Insert: O(MAX_BIT)
8       - Query: O(MAX_BIT)
9   Space Complexity: O(N * MAX_BIT) nodes (in worst case, 1 per bit per
10                      number)
11  */
12
13  const int K = 2; // Each node has 2 branches (bit 0 or 1)
14  const int MAX_BIT = 30; // Max bit position (for 32-bit integers)
15
16  struct Vertex {
17      int next[K]; // next[0] = child for bit 0, next[1] = child for bit 1
18
19      Vertex() {
20          fill(begin(next), end(next), -1); // -1 means no child
21      }
22  }

```

```

21 };
22
23 vector<Vertex> trie; // Trie nodes
24
25 // Inserts a number into the binary trie
26 void insert(int num) {
27     int v = 0; // Start from root
28     for (int j = MAX_BIT; j >= 0; --j) {
29         int c = (num >> j) & 1; // Extract j-th bit (0 or 1)
30         if (trie[v].next[c] == -1) {
31             trie[v].next[c] = trie.size();
32             trie.emplace_back(); // Add new node
33         }
34         v = trie[v].next[c]; // Move to next node
35     }
36 }

```

### 3.4 CHMIN/CHMAX Rangesum GCD Queries

```

1 // Segment tree for chmin, chmax, add and query sum.
2 // Complexity is O (n (log n) ^ 2)
3
4 // Range chmin (l, r, v) -> a[l], ..., a[r] = min(a[i], v) call update
  with 1
5 // Range chmax (l, r, v) -> a[l], ..., a[r] = max(a[i], v) call update
  with 2
6 // Range set (l, r, v) -> a[l], ..., a[r] = v call update with 3 (this
  calls chmax and chmin on the interval)
7 // Range add (l, r, v) -> a[l], ..., a[r] += v call update with 4
8 // You can obtain sum, max, min, gcd in segment
9
10 typedef long long ll;
11
12 const ll inf = 1e17;
13
14 ll gcd(ll a, ll b){
15     a = abs(a);
16     b = abs(b);
17     if(a == 0) return b;
18     return gcd(b % a, a);
19 }
20
21 struct sum_t {

```

```

22 ll sum, mx, mx2, cnt_mx, mn, mn2, cnt_mn, gcd_no_max_no_min;
23 static const ll null_v = 0;
24 sum_t(): sum(null_v), mx(-inf), mx2(-inf), cnt_mx(0), mn(inf), mn2(inf),
  cnt_mn(0), gcd_no_max_no_min(0) {}
25 sum_t(ll v): sum(v), mx(v), mx2(-inf), cnt_mx(1), mn(v), mn2(inf),
  cnt_mn(1), gcd_no_max_no_min(0) {}
26 sum_t(ll _sum, ll _mx, ll _mx2, ll _cnt_mx, ll _mn, ll _mn2, ll
  _cnt_mn, ll _gcd_no_max_no_min):
27     sum(_sum), mx(_mx), mx2(_mx2), cnt_mx(_cnt_mx), mn(_mn), mn2(_mn2),
  cnt_mn(_cnt_mn), gcd_no_max_no_min(_gcd_no_max_no_min) {}
28 sum_t op(sum_t& other) {
29     sum_t res;
30     res.sum = sum + other.sum;
31     res.gcd_no_max_no_min = gcd(gcd_no_max_no_min, other.
  gcd_no_max_no_min);
32
33     if(mx == other.mx){
34         res.mx = mx;
35         res.cnt_mx = cnt_mx + other.cnt_mx;
36         res.mx2 = max(mx2, other.mx2);
37     }
38     else if(mx > other.mx){
39         res.mx = mx;
40         res.cnt_mx = cnt_mx;
41         res.mx2 = max(mx2, other.mx);
42     }
43     else{
44         res.mx = other.mx;
45         res.cnt_mx = other.cnt_mx;
46         res.mx2 = max(mx, other.mx2);
47     }
48
49     if(mn == other.mn){
50         res.mn = mn;
51         res.cnt_mn = cnt_mn + other.cnt_mn;
52         res.mn2 = min(mn2, other.mn2);
53     }
54     else if(mn < other.mn){
55         res.mn = mn;
56         res.cnt_mn = cnt_mn;
57         res.mn2 = min(mn2, other.mn);
58     }
59     else{

```

```

60     res.mn = other.mn;
61     res.cnt_mn = other.cnt_mn;
62     res.mn2 = min(mn, other.mn2);
63 }
64
65 if(mx2 != -inf && mx2 != mn && other.mx2 != -inf && other.mx2 !=
    other.mn){
66     res.gcd_no_max_no_min = gcd(res.gcd_no_max_no_min, mx2 - other.mx2
        );
67 }
68
69 ll any = -1;
70
71 if(mx2 != -inf && mx2 != mn) any = mx2;
72 if(other.mx2 != -inf && other.mx2 != other.mn) any = other.mx2;
73
74 vector<ll> diff_max_min = {mx, mn, other.mx, other.mn};
75 for(ll val: diff_max_min){
76     if(val != res.mn && val != res.mx){
77         if(any != -1) res.gcd_no_max_no_min = gcd(res.gcd_no_max_no_min,
            val - any);
78         else any = val;
79     }
80 }
81
82 return res;
83 }
84 };
85
86 template <typename num_t>
87 struct segtree {
88     int n;
89     vector<num_t> tree, lazy;
90
91     void init(int s, const vector<ll> &A) {
92         n = s;
93         tree.assign(4 * n, num_t());
94         lazy.assign(4 * n, num_t());
95         init(0, 0, n - 1, A);
96     }
97
98     num_t init(int i, int l, int r, const vector<ll> &A) {
99         if (l == r) return tree[i] = num_t(A[l]);

```

```

100
101     int mid = (l + r) / 2;
102     num_t left = init(2 * i + 1, l, mid, A);
103     num_t right = init(2 * i + 2, mid + 1, r, A);
104     return tree[i] = left.op(right);
105 }
106
107 // update 3 is setting values to v
108 void update(int l, int r, ll v, int op) {
109     if (l > r) return;
110     if(op == 1){
111         update_chmin(0, 0, n - 1, l, r, v);
112     }
113     if(op == 2){
114         update_chmax(0, 0, n - 1, l, r, v);
115     }
116     if(op == 3){
117         update_chmin(0, 0, n - 1, l, r, v);
118         update_chmax(0, 0, n - 1, l, r, v);
119     }
120     if(op == 4){
121         update_add(0, 0, n - 1, l, r, v);
122     }
123 }
124
125 num_t update_chmin(int i, int tl, int tr, int ql, int qr, ll v) {
126     eval_lazy(i, tl, tr);
127
128     if (tr < ql || qr < tl || tree[i].mx <= v) return tree[i];
129     if (ql <= tl && tr <= qr && tree[i].mx2 < v) {
130         push_min(i, v);
131         eval_lazy(i, tl, tr);
132         return tree[i];
133     }
134
135     int mid = (tl + tr) / 2;
136     num_t a = update_chmin(2 * i + 1, tl, mid, ql, qr, v);
137     num_t b = update_chmin(2 * i + 2, mid + 1, tr, ql, qr, v);
138     return tree[i] = a.op(b);
139 }
140
141 num_t update_chmax(int i, int tl, int tr, int ql, int qr, ll v) {
142     eval_lazy(i, tl, tr);

```

```

143
144     if (tr < ql || qr < tl || tree[i].mn >= v) return tree[i];
145     if (ql <= tl && tr <= qr && tree[i].mn2 > v) {
146         push_max(i, v);
147         eval_lazy(i, tl, tr);
148         return tree[i];
149     }
150
151     int mid = (tl + tr) / 2;
152     num_t a = update_chmax(2 * i + 1, tl, mid, ql, qr, v);
153     num_t b = update_chmax(2 * i + 2, mid + 1, tr, ql, qr, v);
154     return tree[i] = a.op(b);
155 }
156
157 num_t update_add(int i, int tl, int tr, int ql, int qr, ll v) {
158     eval_lazy(i, tl, tr);
159
160     if (tr < ql || qr < tl) return tree[i];
161     if (ql <= tl && tr <= qr) {
162         push_add(i, tl, tr, v);
163         eval_lazy(i, tl, tr);
164         return tree[i];
165     }
166
167     int mid = (tl + tr) / 2;
168     num_t a = update_add(2 * i + 1, tl, mid, ql, qr, v);
169     num_t b = update_add(2 * i + 2, mid + 1, tr, ql, qr, v);
170     return tree[i] = a.op(b);
171 }
172
173 num_t query(int l, int r){
174     if (l > r) return num_t();
175     return query(0, 0, n - 1, l, r);
176 }
177
178 num_t query(int i, int tl, int tr, int ql, int qr) {
179     eval_lazy(i, tl, tr);
180
181     if (ql <= tl && tr <= qr) return tree[i];
182     if (tr < ql || qr < tl) return num_t();
183
184     int mid = (tl + tr) / 2;
185     num_t a = query(2 * i + 1, tl, mid, ql, qr);

```

```

186     num_t b = query(2 * i + 2, mid + 1, tr, ql, qr);
187     return a.op(b);
188 }
189
190 ll query_gcd(int l, int r){
191     if(l > r) return 0;
192     return query_gcd(0, 0, n - 1, l, r);
193 }
194
195 ll query_gcd(int i, int tl, int tr, int ql, int qr){
196     eval_lazy(i, tl, tr);
197
198     if (ql <= tl && tr <= qr){
199         ll res = gcd(tree[i].mx, tree[i].gcd_no_max_no_min);
200         if(tree[i].mn2 != inf) res = gcd(res, tree[i].mn2 - tree[i].mn);
201         if(tree[i].mx2 != -inf) res = gcd(res, tree[i].mx - tree[i].mx2);
202         return res;
203     }
204     if (tr < ql || qr < tl) return 0;
205
206     int mid = (tl + tr) / 2;
207     ll a = query_gcd(2 * i + 1, tl, mid, ql, qr);
208     ll b = query_gcd(2 * i + 2, mid + 1, tr, ql, qr);
209     return gcd(a, b);
210 }
211
212 void eval_lazy(int i, int l, int r) {
213     if (l != r) {
214         int mid = (l + r) / 2;
215
216         push_add(2 * i + 1, l, mid, lazy[i].sum);
217         push_add(2 * i + 2, mid + 1, r, lazy[i].sum);
218
219         push_min(2 * i + 1, tree[i].mx);
220         push_min(2 * i + 2, tree[i].mx);
221
222         push_max(2 * i + 1, tree[i].mn);
223         push_max(2 * i + 2, tree[i].mn);
224
225     }
226     lazy[i] = num_t();
227 }
228

```



```

229 void push_add(int i, int l, int r, ll v){
230     if(v == 0) return;
231     tree[i].mx += v;
232     tree[i].sum += v * (r - l + 1);
233     tree[i].mx2 += (tree[i].mx2 == -inf ? 0 : v);
234     tree[i].mn += v;
235     tree[i].mn2 += (tree[i].mn2 == inf ? 0 : v);
236     lazy[i].sum += v;
237 }
238
239 void push_min(int i, ll v){
240     if (tree[i].mx <= v) return;
241     if(tree[i].mn == tree[i].mx){
242         tree[i].mn = v;
243     }
244     else if(tree[i].mn2 == tree[i].mx){
245         tree[i].mn2 = v;
246     }
247     tree[i].sum -= tree[i].mx * tree[i].cnt_mx;
248     tree[i].mx = v;
249     tree[i].sum += tree[i].mx * tree[i].cnt_mx;
250 }
251
252 void push_max(int i, ll v){
253     if (tree[i].mn >= v) return;
254     if(tree[i].mx == tree[i].mn){
255         tree[i].mx = v;
256     }
257     else if(tree[i].mx2 == tree[i].mn){
258         tree[i].mx2 = v;
259     }
260     tree[i].sum -= tree[i].mn * tree[i].cnt_mn;
261     tree[i].mn = v;
262     tree[i].sum += tree[i].mn * tree[i].cnt_mn;
263 }
264 };
265
266 int main(){
267     ios_base::sync_with_stdio(false); cin.tie(NULL);
268     int n; cin >> n;
269     vector<ll> A(n);
270     for(int i = 0; i < n; i++) cin >> A[i];
271     segtree <sum_t> st;

```

```

272     st.init(n, A);
273     int q; cin >> q;
274     while(q--){
275         int t, l, r; cin >> t >> l >> r;
276         l--; r--;
277         if(t < 5){
278             ll x; cin >> x;
279             st.update(l, r, x, t);
280         }
281         else{
282             if(t == 8){
283                 cout << st.query_gcd(l, r) << endl;
284             }
285             else{
286                 auto ans = st.query(l, r);
287                 if(t == 5) cout << ans.sum << endl;
288                 else if (t == 6) cout << ans.mn << endl;
289                 else if(t == 7) cout << ans.mx << endl;
290             }
291         }
292     }
293 }

```

### 3.5 Disjoint Sparse Table

```

1 // queries are given weird because it is a lot of them but it is segment
  multiplication
2 #include<bits/stdc++.h>
3 using namespace std;
4
5 #define pii pair<int,int>
6 #define pll pair<ll,ll>
7 #define eb emplace_back
8 #define ll long long
9 #define nl '\n'
10 #define deb(x) cerr<<#x" = "<<x<<nl
11 #define in() ( { int a ; scanf("%d",&a); a; } )
12
13 const int N = 3e5 + 9;
14 int mod = 1e9 + 7;
15
16 struct DST {
17     vector<vector<int>> left, right;

```

```

18 int k, n;
19 DST(vector<int> & a) {
20     n = (int)a.size();
21     k = log2(n) + 2;
22     left.assign(k + 1, vector<int>(n));
23     right.assign(k + 1, vector<int>(n));
24     for(int j = 0; (1 << j) <= n; ++j) {
25         int mask = (1 << j) - 1;
26         int nw = 1; //neutral
27         for(int i = 0; i < n; ++i) {
28             nw = 1LL * nw * a[i] % mod; //prefix value
29             left[j][i] = nw;
30             if((i & mask) == mask) nw = 1; //neutral
31         }
32         nw = 1; //neutral
33         for(int i = n - 1; i >= 0; --i) {
34             nw = 1LL * nw * a[i] % mod; //prefix value
35             right[j][i] = nw;
36             if((i & mask) == 0) nw = 1; //neutral
37         }
38     }
39 }
40 int query(int l, int r) {
41     if(l == r) return left[0][l];
42     int i = 31 - __builtin_clz(l ^ r);
43     int uno = left[i][r];
44     int dos = right[i][l];
45     return 1LL * uno * dos % mod;
46 }
47 };
48
49 int32_t main() {
50     int tc = in();
51     while(tc--) {
52         int n = in(), p = in(), q = in();
53         mod = p;
54         vector<int> a(n);
55         for(int i = 0; i < n; i++) a[i] = in();
56         DST t(a);
57         vector<int> b((q >> 6) + 2);
58         for(int i = 0; i < (int)b.size(); i++) b[i] = in();
59         int x = 0, l = 1, r = 1;
60         for(int i = 0; i < q; i++) {

```

```

61             if(i % 64 == 0) {
62                 l = (b[i / 64] + x) % n;
63                 r = (b[(i / 64) + 1] + x) % n;
64             } else {
65                 l = (l + x) % n;
66                 r = (r + x) % n;
67             }
68             if(l > r) swap(l, r);
69             int ans = t.query(l, r);
70             x = ans;
71             x++;
72             x %= mod;
73         }
74         printf("%d\n", x);
75     }
76     return 0;
77 }

```

### 3.6 Disjoint Set Union Bipartite

```

1  /*
2  DSU with Parity - Bipartite Checker
3  -----
4  Indexing: 0-based
5  Node Bounds: [0, n-1] inclusive
6
7  Features:
8  - Tracks parity (even/odd length) of paths in each component
9  - Can be used to detect odd-length cycles (non-bipartite components)
10 - Supports dynamic edge additions
11
12 Functions:
13 - make_set(v): initializes singleton component
14 - find_set(v): returns root of v and its parity relative to root
15 - add_edge(a, b): merges two components and checks for bipartite
   violation
16 - is_bipartite(v): returns whether component containing v is
   bipartite
17 */
18
19 const int MAXN = 100005; // Set according to constraints
20
21 pair<int, int> parent[MAXN]; // parent[v] = {root, parity_from_root_to_v

```

```

    }
22 int rank[MAXN];           // Union by rank
23 bool bipartite[MAXN];     // bipartite[root] = true if component is
    bipartite
24
25 // Create a new set for node v
26 void make_set(int v) {
27     parent[v] = {v, 0};   // Self-rooted, even parity to self
28     rank[v] = 0;
29     bipartite[v] = true;
30 }
31
32 // Find the root of v and track parity along the path (0 = even, 1 = odd
    )
33 pair<int, int> find_set(int v) {
34     if (v != parent[v].first) {
35         auto [par, parity] = parent[v];
36         auto root = find_set(par);
37         parent[v] = {root.first, parity ^ root.second}; // Path compression
            with parity update
38     }
39     return parent[v];
40 }
41
42 // Adds an edge between a and b, merges components and checks for odd
    cycles
43 void add_edge(int a, int b) {
44     auto [ra, pa] = find_set(a); // ra = root of a, pa = parity from root
        to a
45     auto [rb, pb] = find_set(b); // rb = root of b, pb = parity from root
        to b
46
47     if (ra == rb) {
48         // Same component: edge (a, b) adds a cycle -> check parity
49         if ((pa ^ pb) == 0) {
50             bipartite[ra] = false; // Found odd-length cycle
51         }
52     } else {
53         // Merge smaller rank under larger
54         if (rank[ra] < rank[rb]) swap(ra, rb), swap(pa, pb);
55
56         // Make rb child of ra; update parity of root
57         parent[rb] = {ra, pa ^ pb ^ 1};

```

```

58
59     bipartite[ra] &= bipartite[rb]; // Component is only bipartite if
        both were
60     if (rank[ra] == rank[rb]) rank[ra]++;
61 }
62 }
63
64 // Check if the component containing v is bipartite
65 bool is_bipartite(int v) {
66     return bipartite[find_set(v).first];
67 }

```

### 3.7 Disjoint Set Union

```

1  /*
2  Disjoint Set Union (Union-Find) with Rollback
3  -----
4  Indexing: 0-based
5  Node Bounds: [0, N-1]
6
7  Features:
8      - Path compression + union by size
9      - Optional rollback to previous state
10     - Supports dynamic connectivity in offline algorithms (e.g., divide
        & conquer)
11
12  Functions:
13      - get(x): find root of x
14      - connected(a, b): check if a and b are in same component
15      - size(x): size of component containing x
16      - unite(x, y): union x and y, returns true if merged
17      - time(): current rollback timestamp
18      - rollback(t): revert to state at timestamp t
19  */
20
21 struct DSU {
22     vector<int> e;           // e[x] < 0 -> root; size = -e[x]; e
        [x] >= 0 -> parent
23     vector<pair<int, int>> st; // rollback stack: stores (index, old
        value)
24
25     DSU(int N) : e(N, -1) {}
26

```

```

27 // Find with path compression
28 int get(int x) {
29     return e[x] < 0 ? x : get(e[x]);
30 }
31
32 // Check if x and y belong to the same component
33 bool connected(int a, int b) {
34     return get(a) == get(b);
35 }
36
37 // Return size of component containing x
38 int size(int x) {
39     return -e[get(x)];
40 }
41
42 // Union by size, returns true if union happened
43 bool unite(int x, int y) {
44     x = get(x), y = get(y);
45     if (x == y) return false;
46     if (e[x] > e[y]) swap(x, y); // Ensure x has larger size (more
47                                 // negative)
48     st.push_back({x, e[x]});
49     st.push_back({y, e[y]});
50     e[x] += e[y];
51     e[y] = x;
52     return true;
53 }
54
55 // Return current rollback timestamp
56 int time() {
57     return (int)st.size();
58 }
59
60 // Roll back to previous state at time t
61 void rollback(int t) {
62     for (int i = time(); i-- > t;) {
63         e[st[i].first] = st[i].second;
64     }
65     st.resize(t);
66 };

```

### 3.8 Disjoint Set Union Queue Like Rollback

```

1 #include <bits/stdc++.h>
2 #define finish(x) return cout << x << endl, 0
3 typedef long long ll;
4 typedef long double ldb;
5 const int md = 1e9 + 7;
6 const ll inf = 2e18;
7 const int OO = 1;
8 const int OOO = 1;
9 using namespace std;
10
11 // used in the original data structure to represent a change in
12 // memory cell
13 struct change {
14     int t, value;
15     int *cell;
16     change() {}
17     change(int _time, int _value, int *_cell) {
18         t = _time;
19         value = _value;
20         cell = _cell;
21     }
22     void undo() {
23         *cell = value;
24     }
25 };
26
27 // dsu with normal undo, allows to query bipartite-ness.
28 struct dsu {
29     int n;
30     vector<int> p, r;
31     vector<int> up;
32     int nxtupd;
33     vector<change> stack;
34     int first_violate;
35     dsu() {}
36     dsu(int sz) {
37         n = sz;
38         p.resize(n);
39         r.resize(n, 0);
40         up.resize(n, 0);
41         nxtupd = 0;

```

```

41     first_violate = -1;
42     for (int i = 0; i < n; i++) p[i] = i;
43 }
44 void upd(int *cell, int value) {
45     stack.push_back(change(nxtupd, *cell, cell));
46     *cell = value;
47 }
48 pair<int, int> find(int x) {
49     if (x == p[x]) return{ x, 0 };
50     pair<int, int> tmp = find(p[x]);
51     tmp.second ^= up[x];
52     return tmp;
53 }
54 bool is_bipartite() {
55     return first_violate == -1; // no violation
56 }
57 void unite(int x, int y) {
58     nxtupd++;
59     int col = 1;
60     pair<int, int> tmp = find(x);
61     x = tmp.first, col ^= tmp.second;
62     tmp = find(y);
63     y = tmp.first, col ^= tmp.second;
64     if (x == y) {
65         if (col == 1 && first_violate == -1) first_violate = nxtupd;
66         upd(&p[0], p[0]); // mark this update's existence.
67         return;
68     }
69     if (r[x] < r[y]) {
70         upd(&p[x], y);
71         upd(&up[x], col);
72     }
73     else {
74         upd(&p[y], x);
75         upd(&up[y], col);
76         if (r[x] == r[y]) {
77             upd(&r[x], r[x] + 1);
78         }
79     }
80     return;
81 }
82 void undo() {
83     if (!stack.size()) return;

```

```

84     int t = stack.back().t;
85     if (first_violate == t) first_violate = -1;
86     while (stack.size() && stack.back().t == t) {
87         stack.back().undo();
88         stack.pop_back();
89     }
90 }
91 };
92
93 // I'd want this 'struct update' to be more generic, and support
94 // maintaining different kinds of updates...
95 // but for now I'm not sure how. So this is a specific impl for this
96 // problem ('update' only relates to 'unite').
97 struct update {
98     char type; // 'A' or 'B'
99     int x, y;
100     update() {}
101     update(int xx, int yy) {
102         x = xx;
103         y = yy;
104         type = 'B';
105     }
106 };
107
108 struct dsuqueue {
109     dsu D;
110     vector<update> S;
111     int bottom; // bottom of the stack: S[0..bottom-1] is entirely B's
112     .
113     dsuqueue() {}
114     dsuqueue(int sz) {
115         D = dsu(sz);
116         bottom = 0;
117     }
118     // utility:
119     void advance_bottom() {
120         while (bottom < S.size() && S[bottom].type == 'B') bottom++;
121     }
122     void fix() {
123         if (!S.size() || S.back().type == 'A') return;
124         advance_bottom();
125         vector<update> saveB, saveA;
126         saveB.push_back(S.back());

```

```

124     S.pop_back(), D.undo();
125     while (saveA.size() != saveB.size() && S.size() > bottom) {
126         if (S.back().type == 'A')
127             saveA.push_back(S.back());
128         else
129             saveB.push_back(S.back());
130         S.pop_back(), D.undo();
131     }
132     // reverse saveA and saveB so their relative order is maintained
133     reverse(saveA.begin(), saveA.end());
134     reverse(saveB.begin(), saveB.end());
135     for (const update &u : saveB) {
136         S.push_back(u);
137         D.unite(u.x, u.y);
138     }
139     for (const update &u : saveA) {
140         S.push_back(u);
141         D.unite(u.x, u.y);
142     }
143     advance_bottom();
144 }
145 void reverse_updates() {
146     for (int i = 0; i < S.size(); i++)
147         D.undo();
148     for (int i = (int)S.size() - 1; i >= 0; i--) {
149         D.unite(S[i].x, S[i].y);
150         S[i].type = 'A';
151     }
152     reverse(S.begin(), S.end());
153     bottom = 0;
154 }
155 void undo() {
156     advance_bottom();
157     if (bottom == S.size()) {
158         // no more A's, let's reverse and begin again.
159         reverse_updates();
160     }
161     fix();
162     D.undo();
163     S.pop_back();
164 }
165
166 // begin copying all functions from the original dsu.

```

```

167 bool is_bipartite() {
168     return D.is_bipartite();
169 }
170 void unite(int x, int y) {
171     D.unite(x, y);
172     S.push_back(update(x, y));
173 }
174 };
175
176 int n, m, q;
177 vector<pair<int, int>> e;
178 vector<int> R; // for each i, R[i] would be the minimum such that
179                // query (i, R[i]) is answered with NO (the graph is bipartite)
180
181 int main() {
182     ios::sync_with_stdio(0), cin.tie(0);
183     cin >> n >> m >> q;
184     dsuqueue D(n);
185     e.resize(m);
186     for (auto &i : e) {
187         cin >> i.first >> i.second;
188         --i.first, --i.second;
189     }
190
191     R.resize(m);
192     for (int i = 0; i < m; i++)
193         D.unite(e[i].first, e[i].second);
194     int nxt = 0;
195     for (int i = 0; i < m; i++) {
196         while (!D.is_bipartite() && nxt < m) {
197             D.undo();
198             nxt++;
199         }
200         if (D.is_bipartite())
201             R[i] = nxt - 1;
202         else
203             R[i] = md;
204
205         D.unite(e[i].first, e[i].second);
206     }
207
208     while (q--) {
209         int l, r;

```

```

209     cin >> l >> r;
210     --l, --r;
211     if (R[l] <= r) cout << "NO\n";
212     else cout << "YES\n";
213 }
214 }

```

### 3.9 Dynamic Connectivity

```

1  /*
2  Offline Dynamic Connectivity - Segment Tree + Rollback DSU
3  -----
4  Indexing: 0-based
5  Node Bounds: [0, n-1]
6
7  Features:
8  - Handles dynamic edge insertions and deletions over time
9  - Answers queries of type: "how many connected components at time t
10   ?"
11  - All operations are processed offline
12
13  Components:
14  - DSU with rollback (stores a stack of previous states)
15  - Segment tree over time to store active edge intervals
16  */
17 // Rollbackable Disjoint Set Union (Union-Find)
18 struct DSU {
19     vector<int> e; // e[x] < 0 means x is a root, and size is -e[x]
20     vector<pair<int, int>> st; // Stack for rollback (stores changed
21         values)
22     int cnt; // Current number of connected components
23
24     DSU() {}
25     DSU(int N) : e(N, -1), cnt(N) {}
26
27     // Find root of x with path compression
28     int get(int x) {
29         return e[x] < 0 ? x : get(e[x]);
30     }
31
32     // Check if x and y are connected
33     bool connected(int a, int b) {

```

```

33         return get(a) == get(b);
34     }
35
36     // Size of component containing x
37     int size(int x) {
38         return -e[get(x)];
39     }
40
41     // Union two components; record state for rollback
42     bool unite(int x, int y) {
43         x = get(x), y = get(y);
44         if (x == y) return false; // Already connected
45
46         if (e[x] > e[y]) swap(x, y); // Union by size: ensure x is larger
47
48         // Save state for rollback
49         st.push_back({x, e[x]});
50         st.push_back({y, e[y]});
51
52         e[x] += e[y]; // Merge y into x
53         e[y] = x;
54         cnt--; // One fewer component
55         return true;
56     }
57
58     // Undo last union
59     void rollback() {
60         auto [x1, y1] = st.back(); st.pop_back();
61         e[x1] = y1;
62         auto [x2, y2] = st.back(); st.pop_back();
63         e[x2] = y2;
64         cnt++;
65     }
66 };
67
68 // Represents a single union operation (on edge u-v)
69 struct query {
70     int v, u;
71     bool united;
72     query(int _v, int _u) : v(_v), u(_u), united(false) {}
73 };
74
75 // Segment Tree for storing edge intervals [l, r]

```

```

76 struct QueryTree {
77     vector<vector<query>> t; // Each node stores queries that are active
78         in that time segment
79     DSU dsu;
80     int T; // Number of total operations (time steps)
81
82     QueryTree() {}
83     QueryTree(int _T, int n) : T(_T) {
84         dsu = DSU(n);
85         t.resize(4 * T + 4);
86     }
87
88     // Internal segment tree add function
89     void add(int v, int l, int r, int ul, int ur, query& q) {
90         if (ul > ur) return;
91         if (l == ul && r == ur) {
92             t[v].push_back(q);
93             return;
94         }
95         int mid = (l + r) / 2;
96         add(2 * v, l, mid, ul, min(ur, mid), q);
97         add(2 * v + 1, mid + 1, r, max(ul, mid + 1), ur, q);
98     }
99
100     // Public wrapper: add a query in interval [l, r]
101     void add_query(query q, int l, int r) {
102         add(1, 0, T - 1, l, r, q);
103     }
104
105     // Traverse the segment tree and simulate unions with rollback
106     void dfs(int v, int l, int r, vector<int>& ans) {
107         // Apply all union operations in this segment node
108         for (query& q : t[v]) {
109             q.united = dsu.unite(q.v, q.u);
110         }
111
112         if (l == r) {
113             ans[l] = dsu.cnt; // Save answer for time l
114         } else {
115             int mid = (l + r) / 2;
116             dfs(2 * v, l, mid, ans);
117             dfs(2 * v + 1, mid + 1, r, ans);
118         }
119     }

```

```

118
119     // Rollback all operations applied in this node
120     for (query& q : t[v]) {
121         if (q.united)
122             dsu.rollback();
123     }
124 }
125 };
126
127 int main() {
128     int n, k;
129     cin >> n >> k; // n nodes, k operations
130     if (k == 0) return 0;
131     QueryTree st(k, n);
132     map<pair<int, int>, int> mp; // Edge -> start time
133     vector<int> ans(k); // Answers for '?' queries
134     vector<int> qmarks; // Indices of '?' queries
135     // Parse all k operations
136     for (int i = 0; i < k; i++) {
137         char c;
138         cin >> c;
139         if (c == '?') {
140             qmarks.push_back(i); // Save query index
141             continue;
142         }
143         int u, v;
144         cin >> u >> v;
145         u--; v--;
146         if (u > v) swap(u, v); // Normalize edge direction
147
148         if (c == '+') {
149             mp[{u, v}] = i; // Mark time edge is added
150         } else {
151             // Edge removed: store active interval
152             st.add_query(query(u, v), mp[{u, v}], i);
153             mp[{u, v}] = -1;
154         }
155     }
156
157     // Any edge still active is added until end of timeline
158     for (auto [edge, start] : mp) {
159         if (start != -1) {
160             st.add_query(query(edge.first, edge.second), start, k - 1);
161         }
162     }

```



```

161 }
162 // Process the tree to compute all '?'-query answers
163 st.dfs(1, 0, k - 1, ans);
164 // Output results of all '?'
165 for (int x : qmarks) {
166     cout << ans[x] << '\n';
167 }
168 }

```

### 3.10 Fenwick Tree

```

1  /*
2  Fenwick Tree (Binary Indexed Tree)
3  -----
4  Indexing: 0-based
5  Bounds: [0, n-1] inclusive
6  Time Complexity:
7      - add(x, v): O(log n)
8      - sum(x): O(log n) -> prefix sum over [0, x)
9      - rangeSum(l, r): O(log n) -> sum over [l, r)
10     - select(k): O(log n) -> smallest x such that prefix sum >= k (works
11       for monotonic cumulative sums)
12
13     Space Complexity: O(n)
14 */
15 template <typename T>
16 struct Fenwick {
17     int n;
18     std::vector<T> a;
19
20     Fenwick(int n_ = 0) {
21         init(n_);
22     }
23
24     // Initialize BIT of size n
25     void init(int n_) {
26         n = n_;
27         a.assign(n, T{});
28     }
29
30     // Add value 'v' to position 'x'
31     void add(int x, const T &v) {

```

```

32     for (int i = x + 1; i <= n; i += i & -i) {
33         a[i - 1] = a[i - 1] + v;
34     }
35 }
36
37 // Compute prefix sum on range [0, x)
38 T sum(int x) const {
39     T ans{};
40     for (int i = x; i > 0; i -= i & -i) {
41         ans = ans + a[i - 1];
42     }
43     return ans;
44 }
45
46 // Compute sum over range [l, r)
47 T rangeSum(int l, int r) const {
48     return sum(r) - sum(l);
49 }
50
51 // Find the smallest x such that sum[0, x) > k (if exists), or returns
52 // n
53 int select(const T &k) const {
54     int x = 0;
55     T cur{};
56     for (int i = 1 << std::lg(n); i; i >>= 1) {
57         if (x + i <= n && cur + a[x + i - 1] <= k) {
58             cur = cur + a[x + i - 1];
59             x += i;
60         }
61     }
62     return x;
63 };
64 // Fenwick<int> bit(n);

```

### 3.11 Fenwick Tree 2D

```

1  /*
2  2D Fenwick Tree (Binary Indexed Tree)
3  -----
4  Indexing: 1-based
5  Bounds: [1, n] inclusive
6  Time Complexity:

```

```

7   -update(x, y, v):  $O(\log^2 n)$ 
8   -get(x, y): sum of rectangle [1,1] to [x,y]
9   -get1(x1, y1, x2, y2): sum over rectangle [x1,y1] to [x2,y2]
10  Space Complexity:  $O(n^2)$ 
11
12  -Can be adapted for rectangular grids by using n, m separately
13  */
14
15  struct Fenwick2D {
16      vector<vector<ll>> b; // 2D BIT array
17      int n;                // Grid size (1-based)
18
19      Fenwick2D(int _n) : b(_n + 5, vector<ll>(_n + 5, 0)), n(_n) {}
20
21      // Add 'val' to cell (x, y)
22      void update(int x, int y, int val) {
23          for (; x <= n; x += (x & -x)) {
24              for (int j = y; j <= n; j += (j & -j)) {
25                  b[x][j] += val;
26              }
27          }
28      }
29
30      // Get sum of rectangle [(1,1) to (x,y)]
31      ll get(int x, int y) {
32          ll ans = 0;
33          for (; x > 0; x -= x & -x) {
34              for (int j = y; j > 0; j -= j & -j) {
35                  ans += b[x][j];
36              }
37          }
38          return ans;
39      }
40
41      // Get sum over subrectangle [(x1,y1) to (x2,y2)]
42      ll get1(int x1, int y1, int x2, int y2) {
43          return get(x2, y2) - get(x1-1, y2) - get(x2, y1-1) + get(x1-1, y1-1);
44      }
45  };
46  // Usage example:
47  Fenwick2D fw(n);
48  fw.update(3, 4, 5);                // add 5 to (3, 4)
49  ll sum = fw.get(3, 4);              // sum from (1,1) to (3,4)

```

```

50  ll range = fw.get1(2, 2, 5, 5);    // sum in rectangle [(2,2)-(5,5)]

```

### 3.12 Li Chao Tree

```

1  // min of  $a * x^3 + b * x^2 + c * x + d$ 
2
3  #include <bits/stdc++.h>
4  using namespace std;
5  typedef long long ll;
6
7  const int N = (int)1e5 + 5;
8  const int C = (int)1e5 + 5;
9  const int T = 10;
10 const int M = 350; // sqrt(10^5)
11 const ll inf = (ll)1e19;
12
13 namespace segtree {
14     struct Poly {
15         ll a, b, c, d = inf;
16         ll operator()(ll x) { return a * x * x * x + b * x * x + c * x + d; }
17     } a[T][C * 4];
18     int t = -1;
19
20     void insert(int l, int r, Poly poly, int o=0) {
21         if(l + 1 == r) {
22             if(poly(l) < a[t][o](l)) a[t][o] = poly;
23             return;
24         }
25         int mid = (l + r) >> 1, lson = o * 2 + 1, rson = o * 2 + 2;
26         bool b1 = poly(mid) < a[t][o](mid), b2 = poly(l) < a[t][o](l);
27         if(b1) swap(poly, a[t][o]);
28         if(b1 != b2) insert(l, mid, poly, lson);
29         else insert(mid, r, poly, rson);
30     }
31
32     ll query(int l, int r, int x, int o=0) {
33         if(l + 1 == r) return a[t][o](x);
34         int mid = (l + r) >> 1, lson = o * 2 + 1, rson = o * 2 + 2;
35         if(x < mid) return min(a[t][o](x), query(l, mid, x, lson));
36         else return min(a[t][o](x), query(mid, r, x, rson));
37     }
38 }

```

```

39 ll ans[M];
40
41 void init() {
42     int n; cin >> n;
43     fill(ans, ans + M, inf);
44     segtree::t++;
45     while(n--) {
46         int a, b, c, d; cin >> d >> c >> b >> a;
47         segtree::Poly p = {a, b, c, d};
48         segtree::insert(M, C, p);
49         for(int i = 0 ; i < M ; ++i) ans[i] = min(ans[i], p(i));
50     }
51 }
52 void solve() {
53     int q; cin >> q;
54     while(q--) {
55         int x; cin >> x;
56         if(x < M) cout << ans[x] << '\n';
57         else cout << segtree::query(M, C, x) << '\n';
58     }
59 }
60
61 int main() {
62     ios_base::sync_with_stdio(0), cin.tie(0);
63     int t; cin >> t;
64     while(t--) {
65         init();
66         solve();
67     }
68 }

```

### 3.13 Linked List

```

1  /*
2   Linked list
3   -----
4   Time Complexity:
5       -insert: O(1)
6   Space Complexity: O(n)
7
8   -Can be adapted for rectangular grids by using n, m separately
9  */
10 // === Constructors and Destructor ===

```

```

11 // list()           // Default constructor, creates an empty list.
12 // list(n, val)      // Creates a list with 'n' elements, all
                       // initialized to 'val'.
13 // list(first, last) // Creates a list from another range (e.g.,
                       // another list or array).
14 // list(const list& other) // Copy constructor.
15 // list(list&& other)    // Move constructor.
16 // ~list()             // Destructor, destroys the list.
17
18 // === Iterators ===
19 // begin()             // Returns an iterator to the first element of
                       // the list.
20 // end()               // Returns an iterator to the position just
                       // past the last element.
21 // rbegin()            // Returns a reverse iterator to the last
                       // element.
22 // rend()             // Returns a reverse iterator to the position
                       // just before the first element.
23 // insert(it, val)     // Inserts 'val' before the position of the
                       // iterator 'it'.
24 // erase(it)           // Removes the element at the position of the
                       // iterator 'it'.
25 // erase(first, last)  // Removes a range of elements from 'first' to
                       // 'last'.
26 // push_back(val)      // Adds 'val' to the end of the list.
27 // push_front(val)     // Adds 'val' to the front of the list.
28 // pop_back()          // Removes the last element of the list.
29 // pop_front()         // Removes the first element of the list.
30 // clear()             // Removes all elements from the list.
31
32 // === Capacity ===
33 // empty()             // Returns true if the list is empty, otherwise
                       // false.
34 // size()              // Returns the number of elements in the list.
35 // max_size()          // Returns the maximum number of elements the
                       // list can hold.
36
37 // === Modifiers ===
38 // insert(it, n, val)  // Inserts 'n' copies of 'val' before the
                       // position of 'it'.
39 // insert(it, first, last) // Inserts a range of elements before the
                       // position of 'it'.
40 // remove(val)         // Removes all occurrences of 'val' from the

```

```

    list.
41 // remove_if(pred)      // Removes all elements that satisfy the
    predicate 'pred'.
42 // unique()             // Removes consecutive duplicate elements from
    the list.
43 // merge(other)         // Merges two sorted lists into one sorted
    list.
44 // merge(other, pred)   // Merges two sorted lists into one sorted
    list using custom comparison 'pred'.
45 // splice(it, other)    // Transfers elements from another list 'other'
    to the list at position 'it'.
46 // splice(it, other, it2) // Transfers an element from another list '
    other' at position 'it2' to the list at position 'it'.
47 // splice(it, other, first, last) // Transfers a range from another list
    'other' from 'first' to 'last' to the list at position 'it'.
48 // reverse()           // Reverses the order of elements in the list.
49 // sort()               // Sorts the elements in the list in ascending
    order.
50 // sort(comp)           // Sorts the elements in the list using custom
    comparison 'comp'.
51 // swap(other)          // Swaps the content of the list with another
    list 'other'.
52
53 // === Element Access ===
54 // front()              // Returns a reference to the first element in
    the list.
55 // back()               // Returns a reference to the last element in
    the list.
56
57 // === Search ===
58 // find(val)             // Returns an iterator to the first occurrence
    of 'val'.
59 // find_if(pred)         // Returns an iterator to the first element
    satisfying the predicate 'pred'.
60 // count(val)            // Returns the number of occurrences of 'val'
    in the list.
61 // count_if(pred)        // Returns the number of elements satisfying
    the predicate 'pred'.
62 // equal_range(val)      // Returns a pair of iterators representing the
    range of elements equal to 'val'.
63
64 // === Other Functions ===
65 // swap(other)           // Swaps the contents of the list with another

```

```

    list 'other'.
66 // emplace(it, args...) // Constructs and inserts an element at the
    position 'it' using 'args...' (perfect forwarding).
67 // emplace_front(args...) // Constructs and inserts an element at the
    front using 'args...' (perfect forwarding).
68 // emplace_back(args...) // Constructs and inserts an element at the
    back using 'args...' (perfect forwarding).

```

### 3.14 Merge Sort Tree

```

1  /*
2  Merge Sort Tree (Segment Tree of Sorted Arrays)
3  -----
4  Indexing: 0-based
5  Node Bounds: [0, n-1] inclusive
6  Time Complexity:
7      - build(): O(n log n)
8      - q(l, r, x): O(log^2 n) -> number of elements <= x in [l, r)
9  Space Complexity: O(n log n)
10
11 Features:
12     - Supports frequency/count queries: "how many values <= x in range [
        l, r)?"
13     - Static array (no point updates unless rebuilt)
14 */
15
16 const int MAXN = 100005;      // size of original array
17 const int MAXT = 2 * MAXN;    // size of segment tree (2n)
18
19 vector<int> t[MAXT];          // Segment tree: each node holds sorted vector
20 int a[MAXN];                  // Original array
21 int n;                         // Size of array
22
23 // Build merge sort tree (bottom-up)
24 void build() {
25     // Fill leaves
26     for (int i = 0; i < n; i++) {
27         t[i + n].push_back(a[i]);
28     }
29
30     // Merge children into parent
31     for (int i = n - 1; i > 0; i--) {
32         auto &left = t[2 * i], &right = t[2 * i + 1];

```

```

33     merge(left.begin(), left.end(), right.begin(), right.end(),
34           back_inserter(t[i]));
35 }
36 }
37 // Query how many elements <= 'x' in range [l, r)
38 int q(int l, int r, int x) {
39     int res = 0;
40     for (l += n, r += n; l < r; l >>= 1, r >>= 1) {
41         if (l & 1) {
42             res += upper_bound(t[l].begin(), t[l].end(), x) - t[l].begin();
43             l++;
44         }
45         if (r & 1) {
46             r--;
47             res += upper_bound(t[r].begin(), t[r].end(), x) - t[r].begin();
48         }
49     }
50     return res;
51 }
52 // Read n and array a, then call build()

```

### 3.15 Minimum Cartesian Tree

```

1  /*
2  Min Cartesian Tree
3  -----
4  Indexing: 0-based
5  Time Complexity: O(n)
6  Space Complexity: O(n)
7  Tree Properties:
8      - Binary tree where in-order traversal = original array
9      - Tree satisfies min-heap property: parent <= children
10     - 'par[i]': parent of node i
11     - 'sons[i][0]': left child, 'sons[i][1]': right child
12     - 'root': index of root node
13
14  Use cases:
15     - RMQ construction
16     - LCA over RMQ via Cartesian Tree
17  */
18
19 struct min_cartesian_tree {

```

```

20     vector<int> par;           // parent for each node
21     vector<vector<int>> sons;  // left and right children
22     int root;
23
24     void init(int n, const vector<int> &arr) {
25         par.assign(n, -1);
26         sons.assign(n, vector<int>(2, -1)); // 0 = left, 1 = right
27         stack<int> st;
28
29         for (int i = 0; i < n; i++) {
30             int last = -1;
31
32             // Maintain increasing stack -> build min Cartesian Tree
33             // Change > to < for max Cartesian Tree
34             while (!st.empty() && arr[st.top()] > arr[i]) {
35                 last = st.top();
36                 st.pop();
37             }
38
39             if (!st.empty()) {
40                 par[i] = st.top();
41                 sons[st.top()][1] = i;
42             }
43             if (last != -1) {
44                 par[last] = i;
45                 sons[i][0] = last;
46             }
47
48             st.push(i);
49         }
50
51         for (int i = 0; i < n; i++) {
52             if (par[i] == -1) {
53                 root = i;
54             }
55         }
56     }
57 };
58 // Example usage:
59 vector<int> a = {4, 2, 6, 1, 3};
60 min_cartesian_tree ct;
61 ct.init(a.size(), a);
62 cout << "Root index: " << ct.root << '\n';

```

### 3.16 Multi Ordered Set

```

1 #include <ext/pb_ds/assoc_container.hpp>
2 #include <ext/pb_ds/tree_policy.hpp>
3 using namespace __gnu_pbds;
4 template <typename T> using oset = __gnu_pbds::tree<
5     T, __gnu_pbds::null_type, less<T>, __gnu_pbds::rb_tree_tag,
6     __gnu_pbds::tree_order_statistics_node_update
7 >;
8
9 //en main
10
11 oset<pair<int,int>> name;
12 map<int,int> cuenta;
13 function<void(int)> meter = [&] (int val) {
14     name.insert({val,++cuenta[val]});
15 };
16 auto quitar = [&] (int val) {
17     name.erase({val,cuenta[val]--});
18 };
19
20 meter(x);
21 quitar(y);
22 multiset.order_of_key({y+1,-1})-multiset.order_of_key({x,0})

```

### 3.17 Ordered Set

```

1 #include <ext/pb_ds/assoc_container.hpp>
2 #include <ext/pb_ds/tree_policy.hpp>
3 using namespace __gnu_pbds;
4 template <typename T> using oset = __gnu_pbds::tree<
5     T, __gnu_pbds::null_type, less<T>, __gnu_pbds::rb_tree_tag,
6     __gnu_pbds::tree_order_statistics_node_update
7 >;
8 // order_of_key() primero mayor o igual;
9 // find_by_order() apuntador al elemento k;
10 // oset<pair<int,int>> os;
11 // os.insert({1,2});
12 // os.insert({2,3});
13 // os.insert({5,6});
14 // ll k=os.order_of_key({2,0});
15 // cout<<k<<endl; // 1
16 // pair<int,int> p=os.find_by_order(k);

```

```

17 // cout<<p.f<<" "<<p.s<<endl; // 2 3
18 // os.erase(p);
19 // p=os.find_by_order(k);
20 // cout<<p.f<<" "<<p.s<<endl; // 5 6
21
22
23 // check if upperbound or lowerbound does what you want
24 // because they give better time.
25
26 // to allow repetitions
27 #define ordered_set tree<int, null_type,less_equal<int>, rb_tree_tag,
28     tree_order_statistics_node_update>
29
30 // to not allow repetitions
31 #define ordered_set tree<int, null_type,less<int>, rb_tree_tag,
32     tree_order_statistics_node_update>
33
34 //order_of_key(x): number of items are strictly smaller than x
35
36 //find_by_order(k) iterator to the kth element

```

### 3.18 Palindromic Tree

```

1 /*
2 Palindromic Tree (Eertree)
3 -----
4 Indexing: 0-based
5 Time Complexity:
6     - extend(i): O(1) amortized
7     - calc_occurrences(): O(n)
8 Space Complexity: O(n)
9
10 Features:
11     - Each node represents a unique palindromic substring
12     - Efficient online construction
13     - 'oc': how many times this palindrome occurs as suffix
14     - 'cnt': number of palindromic suffixes in its subtree
15     - 'link': suffix link to longest proper palindromic suffix
16 */
17
18 const int N = 3e5 + 9;
19
20 struct PalindromicTree {

```

```

21 struct node {
22     int nxt[26];    // transitions by character
23     int len;        // length of palindrome
24     int st, en;     // start and end indices in string
25     int link;       // suffix link
26     int cnt = 0;    // number of palindromic suffixes
27     int oc = 0;     // occurrences of the palindrome
28 };
29
30 string s;
31 vector<node> t;
32 int sz, last;
33
34 PalindromicTree() {}
35 PalindromicTree(const string &s) {
36     s = _s;
37     int n = s.size();
38     t.clear();
39     t.resize(n + 5); // up to n + 2 distinct palindromes
40     sz = 2;
41     last = 2;
42     // Root 1: imaginary (-1 length), simplifies links
43     t[1].len = -1;
44     t[1].link = 1;
45     // Root 2: length 0, link to root 1
46     t[2].len = 0;
47     t[2].link = 1;
48 }
49
50 // Extend tree with s[pos], returns 1 if a new node is created
51 int extend(int pos) {
52     int cur = last;
53     int ch = s[pos] - 'a';
54     // Find longest suffix palindrome that can be extended
55     while (true) {
56         int curlen = t[cur].len;
57         if (pos - 1 - curlen >= 0 && s[pos - 1 - curlen] == s[pos]) break;
58         cur = t[cur].link;
59     }
60
61     if (t[cur].nxt[ch]) {
62         // Already exists
63         last = t[cur].nxt[ch];

```

```

64         t[last].oc++;
65         return 0;
66     }
67     // Create new node
68     sz++;
69     last = sz;
70     t[sz].oc = 1;
71     t[sz].len = t[cur].len + 2;
72     t[cur].nxt[ch] = sz;
73     t[sz].en = pos;
74     t[sz].st = pos - t[sz].len + 1;
75
76     if (t[sz].len == 1) {
77         t[sz].link = 2;
78         t[sz].cnt = 1;
79         return 1;
80     }
81     // Compute suffix link
82     while (true) {
83         cur = t[cur].link;
84         int curlen = t[cur].len;
85         if (pos - 1 - curlen >= 0 && s[pos - 1 - curlen] == s[pos]) {
86             t[sz].link = t[cur].nxt[ch];
87             break;
88         }
89     }
90     t[sz].cnt = 1 + t[t[sz].link].cnt;
91     return 1;
92 }
93 // Accumulate total occurrences for each palindrome node
94 void calc_occurrences() {
95     for (int i = sz; i >= 3; i--) {
96         t[t[i].link].oc += t[i].oc;
97     }
98 }
99 };
100
101 int main() {
102     string s;
103     cin >> s;
104     PalindromicTree t(s);
105     for (int i = 0; i < s.size(); i++) {
106         t.extend(i);

```

```

107 }
108 t.calc_occurrences();
109 long long total = 0;
110 for (int i = 3; i <= t.sz; i++) {
111     total += t.t[i].oc;
112 }
113 cout << total << '\n'; // Total palindromic substrings
114 return 0;
115 }

```

### 3.19 Persistent Array

```

1  /*
2   Persistent Array (via Persistent Segment Tree)
3   -----
4   Indexing: 0-based
5   Bounds: [0, n-1]
6   Time Complexity:
7       - point update: O(log n)
8       - point query: O(log n)
9   Space Complexity: O(log n) per update/version
10
11  Features:
12      - Supports point updates with full version history
13      - Allows querying any version at any index
14  */
15
16  struct Node {
17      int val;
18      Node *l, *r;
19
20      // Leaf node with value
21      Node(int x) : val(x), l(nullptr), r(nullptr) {}
22
23      // Internal node with children (value is not used)
24      Node(Node *ll, Node *rr) : val(0), l(ll), r(rr) {}
25  };
26
27  int n;
28  int a[100001]; // Initial array
29  Node *roots[100001]; // Roots of all versions (0-based)
30
31  // Build version 0 from initial array

```

```

32 Node *build(int l = 0, int r = n - 1) {
33     if (l == r) return new Node(a[l]);
34     int mid = (l + r) / 2;
35     return new Node(build(l, mid), build(mid + 1, r));
36 }
37
38 // Create new version with a[pos] = val
39 Node *update(Node *node, int pos, int val, int l = 0, int r = n - 1) {
40     if (l == r) return new Node(val);
41     int mid = (l + r) / 2;
42     if (pos <= mid)
43         return new Node(update(node->l, pos, val, l, mid), node->r);
44     else
45         return new Node(node->l, update(node->r, pos, val, mid + 1, r));
46 }
47
48 // Query value at position 'pos' in a given version (node)
49 int query(Node *node, int pos, int l = 0, int r = n - 1) {
50     if (l == r) return node->val;
51     int mid = (l + r) / 2;
52     if (pos <= mid) return query(node->l, pos, l, mid);
53     else return query(node->r, pos, mid + 1, r);
54 }
55
56 // External helper: get value at index in version
57 int get_item(int index, int version) {
58     return query(roots[version], index);
59 }
60
61 // External helper: make new version based on 'prev_version', updating
62 // one index
63 void update_item(int index, int value, int prev_version, int new_version) {
64     roots[new_version] = update(roots[prev_version], index, value);
65 }
66
67 // Initializes version 0 from given array
68 void init_arr(int nn, int *init) {
69     n = nn;
70     for (int i = 0; i < n; i++) a[i] = init[i];
71     roots[0] = build();
72 }

```



## 3.20 Persistent Segment Tree

```

1  /*
2  Persistent Segment Tree (Point Updates, Range Queries)
3  -----
4  Indexing: 1-based
5  Bounds: [1, n]
6  Time Complexity:
7      - Build: O(n)
8      - Point update: O(log n) -> returns new version
9      - Range query: O(log n)
10     - Copy version: O(1)
11
12  Features:
13     - Each update creates a new tree version with shared unchanged nodes
14     - Supports querying over any version
15     - Useful in rollback problems, version history, and functional
16       programming
17  */
18  struct Node {
19      ll val;      // segment sum
20      Node *l, *r;
21
22      // Leaf node
23      Node(ll x) : val(x), l(nullptr), r(nullptr) {}
24
25      // Internal node with children
26      Node(Node *_l, Node *_r) {
27          l = _l;
28          r = _r;
29          val = 0;
30          if (l) val += l->val;
31          if (r) val += r->val;
32      }
33
34      // Version clone (used when copying tree version directly)
35      Node(Node *cp) : val(cp->val), l(cp->l), r(cp->r) {}
36  };
37
38  int n, sz = 1;
39  ll a[200001];      // Input array (1-indexed)
40  Node *t[200001];    // Roots of different versions (t[version_id])

```

```

41
42  // Build initial segment tree from array a[1..n]
43  Node *build(int l = 1, int r = n) {
44      if (l == r) return new Node(a[l]);
45      int mid = (l + r) / 2;
46      return new Node(build(l, mid), build(mid + 1, r));
47  }
48
49  // Update position 'pos' with 'val' in given 'node' version
50  Node *update(Node *node, int pos, int val, int l = 1, int r = n) {
51      if (l == r) return new Node(val); // replace leaf
52      int mid = (l + r) / 2;
53      if (pos <= mid)
54          return new Node(update(node->l, pos, val, l, mid), node->r);
55      else
56          return new Node(node->l, update(node->r, pos, val, mid + 1, r));
57  }
58
59  // Query sum over range [a, b] in given version
60  ll query(Node *node, int a, int b, int l = 1, int r = n) {
61      if (r < a || l > b) return 0;      // No overlap
62      if (l >= a && r <= b) return node->val; // Total overlap
63      int mid = (l + r) / 2;
64      return query(node->l, a, b, l, mid) + query(node->r, a, b, mid + 1, r)
65          ;
66  }
67
68  int main() {
69      ios_base::sync_with_stdio(false); cin.tie(NULL);
70
71      int q;
72      cin >> n >> q;
73      for (int i = 1; i <= n; i++) {
74          cin >> a[i];
75      }
76
77      // Build version 0
78      t[0] = build();
79      sz = 1;
80
81      while (q--) {
82          int ty;
83          cin >> ty;

```

```

83
84     if (ty == 1) {
85         // Point update: create new version from t[k] with a[pos] = x
86         int k, pos, x;
87         cin >> k >> pos >> x;
88         t[k] = update(t[k], pos, x);
89
90     } else if (ty == 2) {
91         // Range query on version k over [l, r]
92         int k, l, r;
93         cin >> k >> l >> r;
94         cout << query(t[k], l, r) << '\n';
95
96     } else if (ty == 3) {
97         // Clone version k into new version
98         int k;
99         cin >> k;
100         t[sz++] = new Node(t[k]);
101     }
102 }
103 return 0;
104 }

```

### 3.21 Polynomial Queries

```

1 // adds d * (i - l + 1) + a to range [l, r]
2 // d * (i - l + 1) = d*(1-l) + d*i
3 // Sum = A x segment_length + B x sum_of_indices_in_segment
4
5 struct sum_t {
6     ll val;
7     static const ll null_v = 0;
8     sum_t(): val(null_v) {}
9     sum_t(ll v): val(v) {}
10    sum_t op(sum_t& other) {
11        return sum_t(val + other.val);
12    }
13    sum_t lazy_op(sum_t& v, int size) {
14        return val + v.val * size;
15    }
16    sum_t lazy_op(sum_t& v, ll l, ll r) {
17        return val + v.val * ((l + r) * (r - l + 1)) / 2;
18    }

```

```

19 };
20
21 template <typename num_t>
22 struct segtree {
23     int n;
24     vector<num_t> tree, lazy, lazy1;
25
26     void init(int s) {
27         n = s;
28         tree.assign(4 * n, num_t(0));
29         lazy.assign(4 * n, num_t(0));
30         lazy1.assign(4 * n, num_t(0));
31         init(0, 0, n - 1);
32     }
33
34     num_t init(int i, int l, int r) {
35         if (l == r) return tree[i] = num_t(0);
36
37         int mid = (l + r) / 2;
38         num_t left = init(2 * i + 1, l, mid);
39         num_t right = init(2 * i + 2, mid + 1, r);
40         return tree[i] = left.op(right);
41     }
42
43     // do -l if you want it to add 0 to l. adds d * (i - l + 1) + a to
44     // range [l, r]
45     void update(int l, int r, ll d, ll a) {
46         if (l > r) return;
47         ll dd = d;
48         d = (1 - l) * d + a;
49         a = dd;
50         update(0, 0, n - 1, l, r, d, a);
51     }
52
53     num_t update(int i, int tl, int tr, int ql, int qr, ll D, ll A) {
54         eval_lazy(i, tl, tr);
55
56         if (tr < ql || qr < tl) return tree[i];
57         if (ql <= tl && tr <= qr) {
58             lazy[i].val += D;
59             lazy1[i].val += A;
60             eval_lazy(i, tl, tr);
61             return tree[i];

```

```

61     }
62
63     int mid = (tl + tr) / 2;
64     num_t a = update(2 * i + 1, tl, mid, ql, qr, D, A);
65     num_t b = update(2 * i + 2, mid + 1, tr, ql, qr, D, A);
66     return tree[i] = a.op(b);
67 }
68
69 num_t query(int l, int r) {
70     if (l > r) return num_t::null_v;
71     return query(0, 0, n - 1, l, r);
72 }
73
74 num_t query(int i, int tl, int tr, int ql, int qr) {
75     eval_lazy(i, tl, tr);
76
77     if (ql <= tl && tr <= qr) return tree[i];
78     if (tr < ql || qr < tl) return num_t::null_v;
79
80     int mid = (tl + tr) / 2;
81     num_t a = query(2 * i + 1, tl, mid, ql, qr);
82     num_t b = query(2 * i + 2, mid + 1, tr, ql, qr);
83     return a.op(b);
84 }
85
86 void eval_lazy(int i, int l, int r) {
87     tree[i] = tree[i].lazy_op(lazy1[i], l, r);
88     tree[i] = tree[i].lazy_op(lazy1[i], r - l + 1);
89     if (l != r) {
90         lazy[2 * i + 1].val += lazy[i].val;
91         lazy[2 * i + 2].val += lazy[i].val;
92         lazy1[2 * i + 1].val += lazy1[i].val;
93         lazy1[2 * i + 2].val += lazy1[i].val;
94     }
95     lazy[i] = lazy1[i] = num_t(0);
96 }
97 };
98
99 int main(){
100     ios_base::sync_with_stdio(false); cin.tie(NULL);
101     int n, q; cin >> n >> q;
102     segtree <sum_t> st;
103     st.init(n);

```

```

104 while(q--){
105     int t; cin >> t;
106     if(t == 1){
107         int l, r, a, d; cin >> l >> r >> a >> d;
108         l--; r--;
109         st.update(l, r, d, a);
110     }
111     else{
112         int l; cin >> l;
113         l--;
114         cout << st.query(l, l).val << endl;
115     }
116 }
117 }

```

### 3.22 Segment Tree

```

1  /*
2  Segment Tree (Iterative, Range Minimum Query)
3  -----
4  Indexing: 0-based
5  Bounds: [0, n-1] inclusive
6  Time Complexity:
7      - update(pos, val): O(log n)
8      - get(l, r): O(log n) -> query min in range [l, r)
9  Space Complexity: O(2n)
10 */
11 struct SegmentTree {
12     vector<ll> a; // segment tree array
13     int n;       // number of elements in original array
14
15     SegmentTree(int _n) : a(2 * _n, 1e18), n(_n) {}
16     // Update position 'pos' to value 'val'
17     void update(int pos, ll val) {
18         pos += n; // move to leaf
19         a[pos] = val; // set value
20         for (pos /= 2; pos > 0; pos /= 2) {
21             a[pos] = min(a[2 * pos], a[2 * pos + 1]); // update parent
22         }
23     }
24     // Get minimum value in range [l, r)
25     ll get(int l, int r) {
26         ll res = 1e18;

```

```

27     for (l += n, r += n; l < r; l >>= 1, r >>= 1) {
28         if (l & 1) res = min(res, a[l++]); // if l is right child
29         if (r & 1) res = min(res, a[--r]); // if r is left child
30     }
31     return res;
32 }
33 };

```

### 3.23 Segment Tree 2D

```

1  /*
2  2D Segment Tree (Sum over Rectangles)
3  -----
4  Indexing: 0-based
5  Grid Size: n * m
6  Time Complexity:
7      - build: O(nm log n log m)
8      - point update: O(log n log m)
9      - range query [x1..x2][y1..y2]: O(log n log m)
10 Space Complexity: O(4n x 4m)
11 */
12
13 const int MAXN = 505;
14 int n, m; // grid dimensions
15 int a[MAXN][MAXN]; // input grid
16 int t[4 * MAXN][4 * MAXN]; // segment tree
17
18 // Build the tree along y-axis (internal to each x-interval)
19 void build_y(int vx, int lx, int rx, int vy, int ly, int ry) {
20     if (ly == ry) {
21         if (lx == rx)
22             t[vx][vy] = a[lx][ly];
23         else
24             t[vx][vy] = t[vx * 2][vy] + t[vx * 2 + 1][vy];
25     } else {
26         int my = (ly + ry) / 2;
27         build_y(vx, lx, rx, vy * 2, ly, my);
28         build_y(vx, lx, rx, vy * 2 + 1, my + 1, ry);
29         t[vx][vy] = t[vx][vy * 2] + t[vx][vy * 2 + 1];
30     }
31 }
32
33 // Build the tree along x-axis and call build_y for each

```

```

34 void build_x(int vx, int lx, int rx) {
35     if (lx != rx) {
36         int mx = (lx + rx) / 2;
37         build_x(vx * 2, lx, mx);
38         build_x(vx * 2 + 1, mx + 1, rx);
39     }
40     build_y(vx, lx, rx, 1, 0, m - 1);
41 }
42
43 // Query along y-axis in a fixed x-node
44 int sum_y(int vx, int vy, int tly, int try_, int ly, int ry) {
45     if (ly > ry) return 0;
46     if (ly == tly && ry == try_) return t[vx][vy];
47     int tmy = (tly + try_) / 2;
48     return sum_y(vx, vy * 2, tly, tmy, ly, min(ry, tmy))
49         + sum_y(vx, vy * 2 + 1, tmy + 1, try_, max(ly, tmy + 1), ry);
50 }
51
52 // Query sum in rectangle [lx..rx][ly..ry]
53 int sum_x(int vx, int tlx, int trx, int lx, int rx, int ly, int ry) {
54     if (lx > rx) return 0;
55     if (lx == tlx && trx == rx)
56         return sum_y(vx, 1, 0, m - 1, ly, ry);
57     int tmx = (tlx + trx) / 2;
58     return sum_x(vx * 2, tlx, tmx, lx, min(rx, tmx), ly, ry)
59         + sum_x(vx * 2 + 1, tmx + 1, trx, max(lx, tmx + 1), rx, ly, ry);
60 }
61
62 // Update along y-axis for fixed x-node
63 void update_y(int vx, int lx, int rx, int vy, int ly, int ry, int x, int
64     y, int new_val) {
65     if (ly == ry) {
66         if (lx == rx)
67             t[vx][vy] = new_val;
68         else
69             t[vx][vy] = t[vx * 2][vy] + t[vx * 2 + 1][vy];
70     } else {
71         int my = (ly + ry) / 2;
72         if (y <= my)
73             update_y(vx, lx, rx, vy * 2, ly, my, x, y, new_val);
74         else
75             update_y(vx, lx, rx, vy * 2 + 1, my + 1, ry, x, y, new_val);
76         t[vx][vy] = t[vx][vy * 2] + t[vx][vy * 2 + 1];
77     }
78 }

```

```

76     }
77 }
78
79 // Update point (x, y) to new_val
80 void update_x(int vx, int lx, int rx, int x, int y, int new_val) {
81     if (lx != rx) {
82         int mx = (lx + rx) / 2;
83         if (x <= mx)
84             update_x(vx * 2, lx, mx, x, y, new_val);
85         else
86             update_x(vx * 2 + 1, mx + 1, rx, x, y, new_val);
87     }
88     update_y(vx, lx, rx, 1, 0, m - 1, x, y, new_val);
89 }

```

### 3.24 Segment Tree Dynamic

```

1  /*
2  Dynamic Segment Tree (Point Add, Range Sum)
3  -----
4  Indexing: [0, INF) or any large bounded range
5  Time Complexity:
6      - add(k, x): O(log U)
7      - get_sum(l, r): O(log U)
8        where U = range size (e.g., 1e9 if implicit bounds)
9
10 Space Complexity: O(nodes visited or created) -> worst O(log U) per
11 operation
12 */
13 struct Vertex {
14     int left, right;        // interval [left, right)
15     int sum = 0;            // sum of elements in this interval
16     Vertex *left_child = nullptr, *right_child = nullptr;
17
18     Vertex(int lb, int rb) {
19         left = lb;
20         right = rb;
21     }
22
23     // Create children lazily only when needed
24     void extend() {
25         if (!left_child && left + 1 < right) {

```

```

26         int mid = (left + right) / 2;
27         left_child = new Vertex(left, mid);
28         right_child = new Vertex(mid, right);
29     }
30 }
31
32 // Add 'x' to position 'k'
33 void add(int k, int x) {
34     extend();
35     sum += x;
36     if (left_child) {
37         if (k < left_child->right)
38             left_child->add(k, x);
39         else
40             right_child->add(k, x);
41     }
42 }
43
44 // Get sum over interval [lq, rq)
45 int get_sum(int lq, int rq) {
46     if (lq <= left && right <= rq)
47         return sum;
48     if (rq <= left || right <= lq)
49         return 0;
50     extend();
51     return left_child->get_sum(lq, rq) + right_child->get_sum(lq, rq);
52 }
53 };
54
55 Vertex *root = new Vertex(0, 1e9); // Range [0, 1e9)
56 root->add(5, 10); // a[5] += 10
57 root->add(1000, 20); // a[1000] += 20
58 cout << root->get_sum(0, 10) << '\n'; // sum of [0, 10) = 10
59 cout << root->get_sum(0, 2000) << '\n'; // sum of [0, 2000) = 30

```

### 3.25 Segment Tree Lazy Types

```

1 struct max_t {
2     ll val;
3     static const ll null_v = -1LL << 61;
4     max_t(): val(0) {}
5     max_t(ll v): val(v) {}
6     max_t op(max_t& other) {

```

```

7     return max_t(max(val, other.val));
8 }
9 max_t lazy_op(max_t& v, int size) {
10     return max_t(val + v.val);
11 }
12 };
13
14 struct min_t {
15     ll val;
16     static const ll null_v = 1LL << 61;
17     min_t(): val(0) {}
18     min_t(ll v): val(v) {}
19     min_t op(min_t& other) {
20         return min_t(min(val, other.val));
21     }
22     min_t lazy_op(min_t& v, int size) {
23         return min_t(val + v.val);
24     }
25 };
26
27 struct sum_t {
28     ll val;
29     static const ll null_v = 0;
30     sum_t(): val(0) {}
31     sum_t(ll v): val(v) {}
32     sum_t op(sum_t& other) {
33         return sum_t(val + other.val);
34     }
35     sum_t lazy_op(sum_t& v, int size) {
36         return sum_t(val + v.val * size);
37     }
38 };

```

### 3.26 Segment Tree Lazy

```

1  /*
2  Lazy Segment Tree (Range Update, Range Query)
3  -----
4  Indexing: 0-based
5  Bounds: [0, n-1]
6  Time Complexity:
7      - build: O(n)
8      - update(l, r, v): O(log n)

```

```

9      - query(l, r): O(log n)
10     Space Complexity: O(4n)
11 */
12
13 // See SegTreeLazy_types for num_t structs
14
15 const num_t num_t::null_v = num_t(0);
16
17
18 template <typename num_t>
19 struct segtree {
20     int n;
21     vector<num_t> tree, lazy;
22
23     // Initialize segment tree with array of size s
24     void init(int s, long long* arr) {
25         n = s;
26         tree.assign(4 * n, num_t());
27         lazy.assign(4 * n, num_t());
28         init(0, 0, n - 1, arr);
29     }
30
31     // Build segment tree from array
32     num_t init(int i, int l, int r, long long* arr) {
33         if (l == r) return tree[i] = num_t(arr[l]);
34
35         int mid = (l + r) / 2;
36         num_t left = init(2 * i + 1, l, mid, arr);
37         num_t right = init(2 * i + 2, mid + 1, r, arr);
38         return tree[i] = left.op(right);
39     }
40
41     // Public wrapper: update range [l, r] with value v
42     void update(int l, int r, num_t v) {
43         if (l > r) return;
44         update(0, 0, n - 1, l, r, v);
45     }
46
47     // Internal recursive update
48     num_t update(int i, int tl, int tr, int ql, int qr, num_t v) {
49         eval_lazy(i, tl, tr);
50
51         if (tr < ql || qr < tl) return tree[i]; // no overlap

```

```

52 if (ql <= tl && tr <= qr) {
53     lazy[i].val += v.val;
54     eval_lazy(i, tl, tr);
55     return tree[i];
56 }
57
58 int mid = (tl + tr) / 2;
59 num_t a = update(2 * i + 1, tl, mid, ql, qr, v);
60 num_t b = update(2 * i + 2, mid + 1, tr, ql, qr, v);
61 return tree[i] = a.op(b);
62 }
63
64 // Public wrapper: query sum in range [l, r]
65 num_t query(int l, int r) {
66     if (l > r) return num_t::null_v;
67     return query(0, 0, n - 1, l, r);
68 }
69
70 // Internal recursive query
71 num_t query(int i, int tl, int tr, int ql, int qr) {
72     eval_lazy(i, tl, tr);
73
74     if (ql <= tl && tr <= qr) return tree[i]; // total overlap
75     if (tr < ql || qr < tl) return num_t::null_v; // no overlap
76
77     int mid = (tl + tr) / 2;
78     num_t a = query(2 * i + 1, tl, mid, ql, qr);
79     num_t b = query(2 * i + 2, mid + 1, tr, ql, qr);
80     return a.op(b);
81 }
82
83 // Push down pending lazy updates to children
84 void eval_lazy(int i, int l, int r) {
85     tree[i] = tree[i].lazy_op(lazy[i], r - l + 1);
86     if (l != r) {
87         lazy[2 * i + 1].val += lazy[i].val;
88         lazy[2 * i + 2].val += lazy[i].val;
89     }
90     lazy[i] = num_t(); // reset lazy at this node
91 }
92 };

```

### 3.27 Segment Tree Lazy Range Set

```

1  /*
2   Lazy Segment Tree (Range Set + Range Add + Range Sum)
3   -----
4   Indexing: 0-based
5   Bounds: [0, N-1]
6
7   Features:
8   - Supports range set (assign value), range add (increment), and
9     range sum queries
10  - Properly prioritizes lazy set > lazy add
11 */
12 const int maxN = 1e5 + 5;
13 int N, Q;
14 int a[maxN];
15
16 struct node {
17     ll val = 0; // range sum
18     ll lzAdd = 0; // pending addition
19     ll lzSet = 0; // pending set (non-zero means active)
20 };
21
22 node tree[maxN << 2];
23
24 #define lc (p << 1)
25 #define rc ((p << 1) | 1)
26
27 // Update current node based on its children
28 inline void pushup(int p) {
29     tree[p].val = tree[lc].val + tree[rc].val;
30 }
31
32 // Push lazy values down to children
33 void pushdown(int p, int l, int mid, int r) {
34     // Range set overrides any pending add
35     if (tree[p].lzSet != 0) {
36         tree[lc].lzSet = tree[rc].lzSet = tree[p].lzSet;
37         tree[lc].val = (mid - l + 1) * tree[p].lzSet;
38         tree[rc].val = (r - mid) * tree[p].lzSet;
39         tree[lc].lzAdd = tree[rc].lzAdd = 0;
40         tree[p].lzSet = 0;

```

```

41 }
42 // Otherwise propagate add
43 else if (tree[p].lzAdd != 0) {
44     if (tree[lc].lzSet == 0) tree[lc].lzAdd += tree[p].lzAdd;
45     else {
46         tree[lc].lzSet += tree[p].lzAdd;
47         tree[lc].lzAdd = 0;
48     }
49     if (tree[rc].lzSet == 0) tree[rc].lzAdd += tree[p].lzAdd;
50     else {
51         tree[rc].lzSet += tree[p].lzAdd;
52         tree[rc].lzAdd = 0;
53     }
54     tree[lc].val += (mid - l + 1) * tree[p].lzAdd;
55     tree[rc].val += (r - mid) * tree[p].lzAdd;
56     tree[p].lzAdd = 0;
57 }
58 }
59
60 // Build tree from array a[0..N-1]
61 void build(int p, int l, int r) {
62     tree[p].lzAdd = tree[p].lzSet = 0;
63     if (l == r) {
64         tree[p].val = a[l];
65         return;
66     }
67     int mid = (l + r) >> 1;
68     build(lc, l, mid);
69     build(rc, mid + 1, r);
70     pushup(p);
71 }
72
73 // Add 'val' to all elements in [a, b]
74 void add(int p, int l, int r, int a, int b, ll val) {
75     if (a > r || b < l) return;
76     if (a <= l && r <= b) {
77         tree[p].val += (r - l + 1) * val;
78         if (tree[p].lzSet == 0) tree[p].lzAdd += val;
79         else tree[p].lzSet += val;
80         return;
81     }
82     int mid = (l + r) >> 1;
83     pushdown(p, l, mid, r);

```

```

84     add(lc, l, mid, a, b, val);
85     add(rc, mid + 1, r, a, b, val);
86     pushup(p);
87 }
88
89 // Set all elements in [a, b] to 'val'
90 void set(int p, int l, int r, int a, int b, ll val) {
91     if (a > r || b < l) return;
92     if (a <= l && r <= b) {
93         tree[p].val = (r - l + 1) * val;
94         tree[p].lzAdd = 0;
95         tree[p].lzSet = val;
96         return;
97     }
98     int mid = (l + r) >> 1;
99     pushdown(p, l, mid, r);
100     set(lc, l, mid, a, b, val);
101     set(rc, mid + 1, r, a, b, val);
102     pushup(p);
103 }
104
105 // Query sum over [a, b]
106 ll query(int p, int l, int r, int a, int b) {
107     if (a > r || b < l) return 0;
108     if (a <= l && r <= b) return tree[p].val;
109     int mid = (l + r) >> 1;
110     pushdown(p, l, mid, r);
111     return query(lc, l, mid, a, b) + query(rc, mid + 1, r, a, b);
112 }
113
114 // Example usage
115 N = 5;
116 a[0] = 2, a[1] = 4, a[2] = 3, a[3] = 1, a[4] = 5;
117 build(1, 0, N - 1);
118 set(1, 0, N - 1, 1, 3, 7); // a[1..3] = 7
119 add(1, 0, N - 1, 2, 4, 2); // a[2..4] += 2
120 cout << query(1, 0, N - 1, 0, 4) << '\n'; // total sum

```

### 3.28 Segment Tree Lazy Range Set 2

```

1 #include <bits/stdc++.h>
2 using namespace std;
3
4 typedef long long ll;

```



```

5
6 struct sum_t {
7     ll val;
8     static const ll null_v = 0;
9     sum_t(): val(null_v) {}
10    sum_t(ll v): val(v) {}
11    sum_t op(sum_t& other) {
12        return sum_t(val + other.val);
13    }
14    sum_t lazy_op(sum_t& v, int size) {
15        return v.val * size;
16    }
17    sum_t lazy_op1(sum_t& v, int size) {
18        return val + v.val * size;
19    }
20 };
21
22 template <typename num_t>
23 struct segtree {
24     int n;
25     vector<num_t> tree, lazy, lazy1;
26
27     void init(int s) {
28         n = s;
29         tree.assign(4 * n, num_t(0));
30         lazy.assign(4 * n, num_t(-1));
31         lazy1.assign(4 * n, num_t(0));
32         init(0, 0, n - 1);
33     }
34
35     num_t init(int i, int l, int r) {
36         if (l == r) return tree[i] = num_t(0);
37
38         int mid = (l + r) / 2;
39         num_t left = init(2 * i + 1, l, mid);
40         num_t right = init(2 * i + 2, mid + 1, r);
41         return tree[i] = left.op(right);
42     }
43
44     void update(int l, int r, num_t v) {
45         if (l > r) return;
46         update(0, 0, n - 1, l, r, v);
47     }

```

```

48
49 num_t update(int i, int tl, int tr, int ql, int qr, num_t v) {
50     eval_lazy(i, tl, tr);
51
52     if (tr < ql || qr < tl) return tree[i];
53     if (ql <= tl && tr <= qr) {
54         lazy[i].val = v.val;
55         lazy1[i].val = 0;
56         eval_lazy(i, tl, tr);
57         return tree[i];
58     }
59
60     int mid = (tl + tr) / 2;
61     num_t a = update(2 * i + 1, tl, mid, ql, qr, v);
62     num_t b = update(2 * i + 2, mid + 1, tr, ql, qr, v);
63     return tree[i] = a.op(b);
64 }
65
66 void update1(int l, int r, num_t v) {
67     if (l > r) return;
68     update1(0, 0, n - 1, l, r, v);
69 }
70
71 num_t update1(int i, int tl, int tr, int ql, int qr, num_t v) {
72
73     if (tr < ql || qr < tl){
74         eval_lazy(i, tl, tr);
75         return tree[i];
76     }
77     if (ql <= tl && tr <= qr) {
78         lazy1[i].val += v.val;
79         if(lazy[i].val != -1){
80             lazy[i].val += lazy1[i].val;
81             lazy1[i].val = 0;
82         }
83         eval_lazy(i, tl, tr);
84         return tree[i];
85     }
86
87     eval_lazy(i, tl, tr);
88     int mid = (tl + tr) / 2;
89     num_t a = update1(2 * i + 1, tl, mid, ql, qr, v);
90     num_t b = update1(2 * i + 2, mid + 1, tr, ql, qr, v);

```

```

91     return tree[i] = a.op(b);
92 }
93
94 num_t query(int l, int r) {
95     if (l > r) return num_t::null_v;
96     return query(0, 0, n - 1, l, r);
97 }
98
99 num_t query(int i, int tl, int tr, int ql, int qr) {
100     eval_lazy(i, tl, tr);
101
102     if (ql <= tl && tr <= qr) return tree[i];
103     if (tr < ql || qr < tl) return num_t::null_v;
104
105     int mid = (tl + tr) / 2;
106     num_t a = query(2 * i + 1, tl, mid, ql, qr);
107     num_t b = query(2 * i + 2, mid + 1, tr, ql, qr);
108     return a.op(b);
109 }
110
111 void eval_lazy(int i, int l, int r) {
112     if(lazy[i].val != -1){
113         tree[i] = tree[i].lazy_op(lazy[i], r - l + 1);
114         if (l != r) {
115             lazy[2 * i + 1].val = lazy[i].val;
116             lazy[2 * i + 2].val = lazy[i].val;
117             lazy1[2 * i + 1].val = lazy1[2 * i + 2].val = 0;
118         }
119         lazy[i] = num_t(-1);
120         lazy1[i] = num_t(0);
121     }
122     else{
123         tree[i] = tree[i].lazy_op1(lazy1[i], r - l + 1);
124         if(l != r){
125             if(lazy[2 * i + 1].val == -1) lazy1[2 * i + 1].val += lazy1[i].
                val;
126             else{
127                 lazy[2 * i + 1].val += lazy1[i].val + lazy1[2 * i + 1].val;
128                 lazy1[2 * i + 1].val = 0;
129             }
130             if(lazy[2 * i + 2].val == -1) lazy1[2 * i + 2].val += lazy1[i].
                val;
131             else{

```

```

132         lazy[2 * i + 2].val += lazy1[i].val + lazy1[2 * i + 2].val;
133         lazy1[2 * i + 2].val = 0;
134     }
135 }
136 lazy1[i] = num_t(0);
137 }
138 }
139 };
140
141 int main(){
142     ios_base::sync_with_stdio(false); cin.tie(NULL);
143     int n, q; cin >> n >> q;
144     segtree <sum_t> st;
145     st.init(n);
146     while(q--){
147         int t; cin >> t;
148         if(t == 1){
149             int l, r, x; cin >> l >> r >> x;
150             r--;
151             st.update(l, r, x);
152         }
153         else if(t == 2){
154             int l, r, x; cin >> l >> r >> x;
155             r--;
156             st.update1(l, r, x);
157         }
158         else{
159             int l, r; cin >> l >> r;
160             r--;
161             cout << st.query(l, r).val << endl;
162         }
163     }
164 }

```

### 3.29 Segment Tree Max Subarray Sum

```

1 const ll inf=1e18;
2
3 struct Node {
4     ll maxi, l_max, r_max, sum;
5     Node(ll _maxi, ll _l_max, ll _r_max, ll _sum){
6         maxi=_maxi;
7         l_max=_l_max;

```

```

8   r_max=_r_max;
9   sum=_sum;
10  }
11  Node operator+(Node b) {
12      return {max(max(maxi, b.maxi), r_max + b.l_max),
13              max(l_max, sum + b.l_max), max(b.r_max, r_max + b.sum),
14              sum + b.sum};
15  }
16
17 };
18
19 struct SegmentTreeMaxSubSum{
20     int n;
21     vector<Node> t;
22     SegmentTreeMaxSubSum(int _n) : n(_n), t(2 * _n, Node(-inf, -inf, -inf,
23     -inf)) {}
24     void update(int pos, ll val) {
25         t[pos += n] = Node(val, val, val, val);
26         for (pos>>=1; pos ; pos >>= 1) {
27             t[pos] = t[2*pos]+t[2*pos+1];
28         }
29     }
30     Node query(int l, int r) {
31         Node node_l = Node(-inf, -inf, -inf, -inf);
32         Node node_r = Node(-inf, -inf, -inf, -inf);
33         for (l += n, r += n; l < r; l >>= 1, r >>= 1) {
34             if (l & 1) {
35                 node_l=node_l+t[l++];
36             }
37             if (r & 1) {
38                 node_r=t[--r]+node_r;
39             }
40         }
41         return node_l+node_r;
42     }
43 };

```

### 3.30 Segment Tree Range Update

```

1  /*
2  Segment Tree (Range Min Update, Point Query)
3  -----
4  Indexing: 0-based

```

```

5  Bounds: [0, n-1]
6  Time Complexity:
7      - update(l, r, val): O(log n) -> applies min(val) over [l, r)
8      - get(pos): O(log n) -> minimum affecting position pos
9  Space Complexity: O(2n)
10 */
11
12 struct SegmentTree {
13     vector<ll> a; // a[i] = min value affecting segment i
14     int n;
15
16     SegmentTree(int _n) : a(2 * _n, 1e18), n(_n) {}
17
18     // Get the effective minimum at position 'pos'
19     ll get(int pos) {
20         ll res = 1e18;
21         for (pos += n; pos > 0; pos >>= 1) {
22             res = min(res, a[pos]);
23         }
24         return res;
25     }
26
27     // Apply min(val) to all positions in [l, r)
28     void update(int l, int r, ll val) {
29         for (l += n, r += n; l < r; l >>= 1, r >>= 1) {
30             if (l & 1) {
31                 a[l] = min(a[l], val);
32                 l++;
33             }
34             if (r & 1) {
35                 --r;
36                 a[r] = min(a[r], val);
37             }
38         }
39     }
40 };

```

### 3.31 Segment Tree Struct Types

```

1  // Sum segment tree
2  struct sum_t{
3      ll val;
4      static const long long null_v = 0;

```

```

5
6  sum_t(): val(null_v) {}
7  sum_t(long long v): val(v) {}
8
9  sum_t operator + (const sum_t &a) const {
10     sum_t ans;
11     ans.val = val + a.val;
12     return ans;
13 }
14 };
15 // Min segment tree
16 struct min_t{
17     ll val;
18     static const long long null_v = 1e18;
19
20     min_t(): val(null_v) {}
21     min_t(long long v): val(v) {}
22
23     min_t operator + (const min_t &a) const {
24         min_t ans;
25         ans.val = min(val, a.val);
26         return ans;
27     }
28 };
29 // Max segment tree
30 struct max_t{
31     ll val;
32     static const long long null_v = -1e18;
33
34     max_t(): val(null_v) {}
35     max_t(long long v): val(v) {}
36
37     max_t operator + (const max_t &a) const {
38         max_t ans;
39         ans.val = max(val, a.val);
40         return ans;
41     }
42 };
43 // GCD segment tree
44 struct gcd_t{
45     ll val;
46     static const long long null_v = 0;
47

```

```

48     gcd_t(): val(null_v) {}
49     gcd_t(long long v): val(v) {}
50
51     gcd_t operator + (const gcd_t &a) const {
52         gcd_t ans;
53         ans.val = gcd(val, a.val);
54         return ans;
55     }
56 };

```

### 3.32 Segment Tree Struct

```

1 // works as a 0-indexed segtree (not lazy)
2 template <typename num_t>
3 struct segtree
4 {
5     int n, k;
6     vector<num_t> tree;
7     void init(int s, vector<ll> arr)
8     {
9         n = s;
10        k = 0;
11        while ((1 << k) < n)
12            k++;
13        tree = vector<num_t>(2 * (1 << k) + 1);
14        for (int i = 0; i < n; i++)
15        {
16            tree[(1 << k) + i] = arr[i];
17        }
18        for (int i = (1 << k) - 1; i > 0; i--)
19        {
20            tree[i] = tree[i * 2] + tree[i * 2 + 1];
21        }
22    }
23    void update(int a, ll b)
24    {
25        a += (1 << k);
26        tree[a] = b;
27        for (a /= 2; a >= 1; a /= 2)
28        {
29            tree[a] = tree[a * 2] + tree[a * 2 + 1];
30        }
31    }

```

```

32 num_t find(int a, int b)
33 {
34     a += (1 << k);
35     b += (1 << k);
36     num_t s;
37     while (a <= b)
38     {
39         if (a % 2 == 1)
40             s = s + tree[a++];
41         if (b % 2 == 0)
42             s = s + tree[b--];
43         a /= 2;
44         b /= 2;
45     }
46     return s;
47 }
48 };

```

### 3.33 Segment Tree Walk

```

1  /*
2  Segment Tree Walk - Find First Position >= val
3  -----
4  Indexing: 0-based
5  Bounds: [0, n-1]
6  Time Complexity:
7      - build: O(n)
8      - update(pos, val): O(log n)
9      - get(L, R): O(log n) -> min value in [L, R]
10     - query(L, R, val): O(log n) -> find first index in [L, R] where a[i]
11       ] >= val
12
13 Features:
14     - Stores original value array in segment tree form
15     - Maps original indices to tree positions for fast updates
16     - Allows efficient walk to find constrained elements (e.g. lower
17       bound >= val)
18 */
19
20 struct SegmentTreeWalk {
21     vector<ll> a;           // segment tree values
22     vector<int> final_pos;  // maps index i to position in tree (leaf)
23     int n;

```

```

22 SegmentTreeWalk(int _n) : a(4 * _n, 1e18), final_pos(_n), n(_n) {}
23
24 // Build segment tree from array 'vals[0..n-1]', start with node=1, l
25 // =0, r=n-1
26 void build(int l, int r, int node, const vector<ll> &vals) {
27     if (l == r) {
28         final_pos[l] = node;
29         a[node] = vals[l];
30     } else {
31         int mid = (l + r) / 2;
32         build(l, mid, node * 2, vals);
33         build(mid + 1, r, node * 2 + 1, vals);
34         a[node] = min(a[node * 2], a[node * 2 + 1]);
35     }
36 }
37
38 // Update value at original index 'pos' to 'val'
39 void update(int pos, ll val) {
40     pos = final_pos[pos]; // leaf position
41     a[pos] = val;
42     for (pos /= 2; pos > 0; pos /= 2)
43         a[pos] = min(a[pos * 2], a[pos * 2 + 1]);
44 }
45
46 // Get min value in [L, R], with current node interval [l, r] and root
47 // 'node'
48 ll get(int l, int r, int L, int R, int node) {
49     if (L > R) return 1e18;
50     if (l == L && r == R) return a[node];
51     int mid = (l + r) / 2;
52     return min(
53         get(l, mid, L, min(R, mid), node * 2),
54         get(mid + 1, r, max(L, mid + 1), R, node * 2 + 1)
55     );
56 }
57
58 // Find first position in [L, R] with a[i] >= val, starting from node
59 // interval [l, r]
60 pair<ll, ll> query(int l, int r, int L, int R, int node, int val) {
61     if (l > R || r < L) return {-1, 0}; // out of query
62     bounds
63     if (a[node] < val) return {-1, 0}; // all values < val

```

```

61     if (l == r) return {a[node], 1};           // leaf node that
        satisfies
62
63     int mid = (l + r) / 2;
64     auto left = query(l, mid, L, R, node * 2, val);
65     if (left.first != -1) return left;
66     return query(mid + 1, r, L, R, node * 2 + 1, val);
67 }
68 };
69 // Example usage:
70 int n = 8;
71 vector<ll> vals = {4, 2, 7, 1, 9, 5, 6, 3};
72 SegmentTreeWalk st(n);
73 st.build(0, n - 1, 1, vals);

```

### 3.34 Sparse Table

```

1  /*
2  Sparse Table (Range Minimum Query)
3  -----
4  Indexing: 0-based
5  Bounds: [0, n-1]
6  Time Complexity:
7   - Build: O(n log n)
8   - Query: O(1)
9  Space Complexity: O(n log n)
10
11 Features:
12  - Immutable RMQ (no updates)
13  - Works for idempotent operations like min, max, gcd
14 */
15
16 const int MAXN = 100005;
17 const int K = 30; // floor(log2(MAXN))
18 int lg[MAXN + 1]; // log base 2 of each i
19 int st[K + 1][MAXN]; // st[k][i] = min in [i, i + 2^k - 1]
20
21 vector<int> a; // input array
22 int n;
23
24 // Returns min in range [L, R]
25 int mini(int L, int R) {
26     int len = R - L + 1;

```

```

27     int i = lg[len];
28     return min(st[i][L], st[i][R - (1 << i) + 1]);
29 }
30
31 int main() {
32     cin >> n;
33     a.resize(n);
34     for (int i = 0; i < n; i++) cin >> a[i];
35     // Precompute binary logs
36     lg[1] = 0;
37     for (int i = 2; i <= n; i++) {
38         lg[i] = lg[i / 2] + 1;
39     }
40     // Initialize 2^0 intervals
41     for (int i = 0; i < n; i++) {
42         st[0][i] = a[i];
43     }
44     // Build sparse table
45     for (int k = 1; k <= K; k++) {
46         for (int i = 0; i + (1 << k) <= n; i++) {
47             st[k][i] = min(st[k - 1][i], st[k - 1][i + (1 << (k - 1))]);
48         }
49     }
50     // Example usage
51     int q; cin >> q;
52     while (q--) {
53         int l, r;
54         cin >> l >> r;
55         cout << mini(l, r) << '\n';
56     }
57     return 0;
58 }

```

### 3.35 Sparse Table 2D

```

1  #include<bits/stdc++.h>
2  using namespace std;
3
4  const int N = 505, LG = 10;
5
6  int st[N][N][LG][LG];
7  int a[N][N], lg2[N];
8

```

```

9  int yo(int x1, int y1, int x2, int y2) {
10     x2++;
11     y2++;
12     int a = lg2[x2 - x1], b = lg2[y2 - y1];
13     return max(
14         max(st[x1][y1][a][b], st[x2 - (1 << a)][y1][a][b]),
15         max(st[x1][y2 - (1 << b)][a][b], st[x2 - (1 << a)][y2 - (1 << b)
16             ][a][b])
17     );
18 }
19 void build(int n, int m) { // 0 indexed
20     for (int i = 2; i < N; i++) lg2[i] = lg2[i >> 1] + 1;
21     for (int i = 0; i < n; i++) {
22         for (int j = 0; j < m; j++) {
23             st[i][j][0][0] = a[i][j];
24         }
25     }
26     for (int a = 0; a < LG; a++) {
27         for (int b = 0; b < LG; b++) {
28             if (a + b == 0) continue;
29             for (int i = 0; i + (1 << a) <= n; i++) {
30                 for (int j = 0; j + (1 << b) <= m; j++) {
31                     if (!a) {
32                         st[i][j][a][b] = max(st[i][j][a][b - 1], st[i][j + (1 << (b
33                             - 1))][a][b - 1]);
34                     } else {
35                         st[i][j][a][b] = max(st[i][j][a - 1][b], st[i + (1 << (a -
36                             1))][j][a - 1][b]);
37                     }
38                 }
39             }
40         }
41     }
42     string s[N];
43     int l[N][N], u[N][N];
44     int32_t main() {
45         ios_base::sync_with_stdio(0);
46         cin.tie(0);
47     }
48 }

```

```

49  int n, m;
50  cin >> n >> m;
51  for (int i = 0; i < n; i++) {
52      cin >> s[i];
53  }
54  for (int i = 0; i < n; i++) {
55      for (int j = 0; j < m; j++) {
56          if (!j) l[i][j] = 1;
57          else l[i][j] = 1 + (s[i][j - 1] <= s[i][j] ? l[i][j - 1] : 0);
58      }
59  }
60  for (int j = 0; j < m; j++) {
61      for (int i = 0; i < n; i++) {
62          if (!i) u[i][j] = 1;
63          else u[i][j] = 1 + (s[i - 1][j] <= s[i][j] ? u[i - 1][j] : 0);
64      }
65  }
66  for (int i = 0; i < n; i++) {
67      for (int j = 0; j < m; j++) {
68          int nw = 1, mnx = u[i][j], mny = l[i][j];
69          for (int len = 1; len <= min(i, j); len++) {
70              mnx = min(mnx, u[i][j - len]);
71              mny = min(mny, l[i - len][j]);
72              if (min(mnx, mny) >= len + 1) nw++;
73              else break;
74          }
75          a[i][j] = nw;
76      }
77  }
78  build(n, m);
79  int q;
80  cin >> q;
81  while (q--) {
82      int x1, y1, x2, y2;
83      cin >> x1 >> y1 >> x2 >> y2;
84      x1--, y1--;
85      x2--;
86      y2--;
87      int l = 1, r = min(x2 - x1 + 1, y2 - y1 + 1), ans = 0;
88      while (l <= r) {
89          int mid = l + r >> 1;
90          if (yo(x1 + mid - 1, y1 + mid - 1, x2, y2) >= mid) ans = mid, l =
mid + 1;

```

```

91     else r = mid - 1;
92     }
93     cout << ans << '\n';
94     }
95     return 0;
96 }
97 // https://www.codechef.com/problems/CENS20B

```

### 3.36 Square Root Decomposition

```

1  /*
2  Sqrt Decomposition (String Block Cut and Move)
3  -----
4  Operation:
5      - Supports moving substrings using block cut logic
6      - Rebuilds when too many blocks (for performance)
7
8  Indexing: 0-based
9  String Bounds: [0, n)
10 Time Complexity:
11     - cut(a, b): O(sqrt(n))
12     - rebuildDecomp(): O(n)
13 When to rebuild: after too many block splits
14
15 Use case: performing multiple cut/paste operations efficiently on
16           large strings
17 */
18 const int MAXI = 350; // = sqrt(n), for n up to 1e5
19
20 int n, numBlocks;
21 string s;
22
23 struct Block {
24     int l, r; // indices into string s
25     int sz() const { return r - l; }
26 };
27
28 Block blocks[2 * MAXI]; // current block array
29 Block newBlocks[2 * MAXI]; // used temporarily during cutting
30
31 // Rebuilds the entire decomposition into 1 block (or balanced ones)
32 void rebuildDecomp() {

```

```

33     string newS = s;
34     int k = 0;
35     // Flatten string using current block structure
36     for (int i = 0; i < numBlocks; i++) {
37         for (int j = blocks[i].l; j < blocks[i].r; j++) {
38             newS[k++] = s[j];
39         }
40     }
41     // Reset to one big block
42     numBlocks = 1;
43     blocks[0] = {0, n};
44     s = newS;
45 }
46
47 // Cut [a, b) into a separate region and reorder it to the end
48 void cut(int a, int b) {
49     int pos = 0, curBlock = 0;
50     // Pass 1: Split blocks to isolate [a, b)
51     for (int i = 0; i < numBlocks; i++) {
52         Block B = blocks[i];
53         bool containsA = (pos < a && pos + B.sz() > a);
54         bool containsB = (pos < b && pos + B.sz() > b);
55         int cutA = B.l + a - pos;
56         int cutB = B.l + b - pos;
57
58         if (containsA && containsB) {
59             newBlocks[curBlock++] = {B.l, cutA};
60             newBlocks[curBlock++] = {cutA, cutB};
61             newBlocks[curBlock++] = {cutB, B.r};
62         } else if (containsA) {
63             newBlocks[curBlock++] = {B.l, cutA};
64             newBlocks[curBlock++] = {cutA, B.r};
65         } else if (containsB) {
66             newBlocks[curBlock++] = {B.l, cutB};
67             newBlocks[curBlock++] = {cutB, B.r};
68         } else {
69             newBlocks[curBlock++] = B;
70         }
71
72         pos += B.sz();
73     }
74
75     // Pass 2: Reorder - move [a, b) to the end

```



```

76 pos = 0;
77 numBlocks = 0;
78
79 // First add all blocks not in [a, b)
80 for (int i = 0; i < curBlock; i++) {
81     if (pos < a || pos >= b)
82         blocks[numBlocks++] = newBlocks[i];
83     pos += newBlocks[i].sz();
84 }
85
86 // Then add blocks in [a, b)
87 pos = 0;
88 for (int i = 0; i < curBlock; i++) {
89     if (pos >= a && pos < b)
90         blocks[numBlocks++] = newBlocks[i];
91     pos += newBlocks[i].sz();
92 }
93 }
94 // Example usage
95 int main() {
96     cin >> s;
97     n = s.size();
98     numBlocks = 1;
99     blocks[0] = {0, n};
100
101     int q; cin >> q;
102     while (q--) {
103         int a, b;
104         cin >> a >> b;
105         cut(a, b); // move [a, b) to the end
106
107         if (numBlocks > MAXI) rebuildDecomp();
108     }
109
110     rebuildDecomp(); // flatten before output
111     cout << s << '\n';
112 }

```

### 3.37 Treap

```

1 std::mt19937 rng(std::chrono::steady_clock::now().time_since_epoch().
  count());
2

```

```

3 struct Node {
4     Node *l = 0, *r = 0;
5     int val, y, c = 1;
6     Node(int val) : val(val), y(rng()) {}
7     void recalc();
8 };
9
10 int cnt(Node* n) { return n ? n->c : 0; }
11 void Node::recalc() { c = cnt(l) + cnt(r) + 1; }
12
13 template<class F> void each(Node* n, F f) {
14     if (n) { each(n->l, f); f(n->val); each(n->r, f); }
15 }
16
17 pair<Node*, Node*> split(Node* n, int k) {
18     if (!n) return {};
19     if (cnt(n->l) >= k) { // "n->val >= k" for lower_bound(k)
20         auto pa = split(n->l, k);
21         n->l = pa.second;
22         n->recalc();
23         return {pa.first, n};
24     } else {
25         auto pa = split(n->r, k - cnt(n->l) - 1); // and just "k"
26         n->r = pa.first;
27         n->recalc();
28         return {n, pa.second};
29     }
30 }
31
32 Node* merge(Node* l, Node* r) {
33     if (!l) return r;
34     if (!r) return l;
35     if (l->y > r->y) {
36         l->r = merge(l->r, r);
37         l->recalc();
38         return l;
39     } else {
40         r->l = merge(l, r->l);
41         r->recalc();
42         return r;
43     }
44 }
45

```

```

46 Node* ins(Node* t, Node* n, int pos) {
47     auto pa = split(t, pos);
48     return merge(merge(pa.first, n), pa.second);
49 }
50
51 // Example application: move the range [l, r) to index k
52 void move(Node& t, int l, int r, int k) {
53     Node *a, *b, *c;
54     tie(a,b) = split(t, l); tie(b,c) = split(b, r - l);
55     if (k <= l) t = merge(ins(a, b, k), c);
56     else t = merge(a, ins(c, b, k - r));
57 }
58
59 // Usage
60 // create treap
61 // Node* name=nullptr;
62 // insert element
63 // name=ins(name, new Node(val), pos);
64 // Node* x = new Node(val);
65 // name = ins(name, x, pos);
66 // merge two treaps (name before x)
67 // name=merge(name, x);
68 // split treap (this will split treap in two treaps,
69 // first with elements [0, pos) and second with elements [pos, n))
70 // pa will be pair of two treaps
71 // auto pa = split(name, pos);
72 // move range [l, r) to index k
73 // move(name, l, r, k);
74 // iterate over treap
75 // each(name, [&](int val) {
76 //     cout << val << ' ';
77 // });

```

### 3.38 Treap 2

```

1 typedef struct item * pitem;
2 struct item {
3     int prior, value, cnt;
4     bool rev;
5     pitem l, r;
6 };
7
8 int cnt (pitem it) {

```

```

9     return it ? it->cnt : 0;
10 }
11
12 void upd_cnt (pitem it) {
13     if (it)
14         it->cnt = cnt(it->l) + cnt(it->r) + 1;
15 }
16
17 void push (pitem it) {
18     if (it && it->rev) {
19         it->rev = false;
20         swap (it->l, it->r);
21         if (it->l) it->l->rev ^= true;
22         if (it->r) it->r->rev ^= true;
23     }
24 }
25
26 void merge (pitem & t, pitem l, pitem r) {
27     push (l);
28     push (r);
29     if (!l || !r)
30         t = l ? l : r;
31     else if (l->prior > r->prior)
32         merge (l->r, l->r, r), t = l;
33     else
34         merge (r->l, l, r->l), t = r;
35     upd_cnt (t);
36 }
37
38 void split (pitem t, pitem & l, pitem & r, int key, int add = 0) {
39     if (!t)
40         return void( l = r = 0 );
41     push (t);
42     int cur_key = add + cnt(t->l);
43     if (key <= cur_key)
44         split (t->l, l, t->l, key, add), r = t;
45     else
46         split (t->r, t->r, r, key, add + 1 + cnt(t->l)), l = t;
47     upd_cnt (t);
48 }
49
50 void reverse (pitem t, int l, int r) {
51     pitem t1, t2, t3;

```

```

52     split (t, t1, t2, l);
53     split (t2, t2, t3, r-l+1);
54     t2->rev ^= true;
55     merge (t, t1, t2);
56     merge (t, t, t3);
57 }
58
59 void output (pitem t) {
60     if (!t) return;
61     push (t);
62     output (t->l);
63     printf ("%d_", t->value);
64     output (t->r);
65 }

```

### 3.39 Treap With Inversion

```

1  std::mt19937 rng(std::chrono::steady_clock::now().time_since_epoch().
    count());
2
3  struct Node {
4      Node *l = 0, *r = 0;
5      int val, y, c = 1;
6      bool rev = 0;
7      Node(int val) : val(val), y(rng()) {}
8      void recalc();
9      void push();
10 };
11
12 int cnt(Node* n) { return n ? n->c : 0; }
13 void Node::recalc() { c = cnt(l) + cnt(r) + 1; }
14 void Node::push() {
15     if (rev) {
16         rev = 0;
17         swap(l, r);
18         if (l) l->rev ^= 1;
19         if (r) r->rev ^= 1;
20     }
21 }
22
23 template<class F> void each(Node* n, F f) {
24     if (n) { n->push(); each(n->l, f); f(n->val); each(n->r, f); }
25 }

```

```

26
27 pair<Node*, Node*> split(Node* n, int k) {
28     if (!n) return {};
29     n->push();
30     if (cnt(n->l) >= k) {
31         auto pa = split(n->l, k);
32         n->l = pa.second;
33         n->recalc();
34         return {pa.first, n};
35     } else {
36         auto pa = split(n->r, k - cnt(n->l) - 1);
37         n->r = pa.first;
38         n->recalc();
39         return {n, pa.second};
40     }
41 }
42
43 Node* merge(Node* l, Node* r) {
44     if (!l) return r;
45     if (!r) return l;
46     l->push();
47     r->push();
48     if (l->y > r->y) {
49         l->r = merge(l->r, r);
50         l->recalc();
51         return l;
52     } else {
53         r->l = merge(l, r->l);
54         r->recalc();
55         return r;
56     }
57 }
58
59 Node* ins(Node* t, Node* n, int pos) {
60     auto pa = split(t, pos);
61     return merge(merge(pa.first, n), pa.second);
62 }
63
64 // Example application: reverse the range [l, r]
65 void reverse(Node*& t, int l, int r) {
66     Node *a, *b, *c;
67     tie(a,b) = split(t, l);
68     tie(b,c) = split(b, r - l + 1);

```

```

69     b->rev ^= 1;
70     t = merge(merge(a, b), c);
71 }
72
73 void move(Node*& t, int l, int r, int k) {
74     Node *a, *b, *c;
75     tie(a,b) = split(t, l);
76     tie(b,c) = split(b, r - l);
77     if (k <= l) t = merge(ins(a, b, k), c);
78     else t = merge(a, ins(c, b, k - r));
79 }

```

### 3.40 Treap With Inversions and Range Updates

```

1  #include <bits/stdc++.h>
2  using namespace std;
3
4  typedef long long ll;
5
6  const int mod = 998244353;
7
8  template<int MOD>
9  struct ModInt {
10     ll v;
11     ModInt(ll _v = 0) {v = (-MOD < _v && _v < MOD) ? _v : _v % MOD; if (v
        < 0) v += MOD;}
12     ModInt& operator += (const ModInt &other) {v += other.v; if (v >= MOD)
        v -= MOD; return *this;}
13     ModInt& operator -= (const ModInt &other) {v -= other.v; if (v < 0) v
        += MOD; return *this;}
14     ModInt& operator *= (const ModInt &other) {v = v * other.v % MOD;
        return *this;}
15     ModInt& operator /= (const ModInt &other) {return *this *= inverse(
        other);}
16     bool operator == (const ModInt &other) const {return v == other.v;}
17     bool operator != (const ModInt &other) const {return v != other.v;}
18     friend ModInt operator + (ModInt a, const ModInt &b) {return a += b;}
19     friend ModInt operator - (ModInt a, const ModInt &b) {return a -= b;}
20     friend ModInt operator * (ModInt a, const ModInt &b) {return a *= b;}
21     friend ModInt operator / (ModInt a, const ModInt &b) {return a /= b;}
22     friend ModInt operator - (const ModInt &a) {return 0 - a;}
23     friend ModInt power(ModInt a, ll b) {ModInt ret(1); while (b > 0) {if
        (b & 1) ret *= a; a *= a; b >>= 1;} return ret;}

```

```

24     friend ModInt inverse(ModInt a) {return power(a, MOD - 2);}
25     friend istream& operator >> (istream &is, ModInt &m) {is >> m.v; m.v =
        (-MOD < m.v && m.v < MOD) ? m.v : m.v % MOD; if (m.v < 0) m.v +=
        MOD; return is;}
26     friend ostream& operator << (ostream &os, const ModInt &m) {return os
        << m.v;}
27 };
28
29 struct Line{
30     ModInt<mod> b = 1, c = 0;
31     ModInt<mod> operator()(ModInt<mod> x){ return b * x + c;}
32     Line operator()(Line other) {return Line{b * other.b, other.c * b + c
        };}
33     operator bool() const{
34         return b != 1 || c != 0;
35     };
36 };
37
38 std::mt19937 rng(std::chrono::steady_clock::now().time_since_epoch().
    count());
39
40 struct Node {
41     Node *l = 0, *r = 0;
42     int y, c = 1;
43     ModInt<mod> val, sum;
44     Line line;
45     bool rev = 0;
46     Node(int val) : val(val), sum(val), y(rng()) {}
47     void recalc();
48     void push();
49 };
50
51 int cnt(Node* n) { return n ? n->c : 0; }
52 ModInt<mod> sum1(Node* n) { return n ? n->sum : ModInt<mod>(0); }
53 void Node::recalc() { if(l) l->push(); if(r) r->push(); c = cnt(l) +
    cnt(r) + 1; sum = sum1(l) + sum1(r) + val;}
54 void Node::push(){
55     if(rev){
56         rev = 0;
57         swap(l, r);
58         if(l) l->rev ^= 1;
59         if(r) r->rev ^= 1;
60     }

```

```

61     if(line){
62         val = line(val);
63         sum = sum * line.b + line.c * c;
64         if(l){
65             l -> line = line(l -> line);
66         }
67         if(r){
68             r -> line = line(r -> line);
69         }
70         line = {1, 0};
71     }
72 }
73
74 template<class F> void each(Node* n, F f) {
75     if (n) { n -> push(); each(n->l, f); f(n->val); each(n->r, f); }
76 }
77
78 pair<Node*, Node*> split(Node* n, int k) {
79     if (!n) return {};
80     n -> push();
81     if (cnt(n->l) >= k) { // "n->val >= k" for lower_bound(k)
82         auto [L,R] = split(n->l, k);
83         n->l = R;
84         n->recalc();
85         return {L, n};
86     } else {
87         auto [L,R] = split(n->r, k - cnt(n->l) - 1); // and just "k"
88         n->r = L;
89         n->recalc();
90         return {n, R};
91     }
92 }
93
94 Node* merge(Node* l, Node* r) {
95     if (!l) return r;
96     if (!r) return l;
97     l -> push();
98     r -> push();
99     if (l->y > r->y) {
100         l->r = merge(l->r, r);
101         return l->recalc(), l;
102     } else {
103         r->l = merge(l, r->l);

```

```

104         return r->recalc(), r;
105     }
106 }
107
108 Node* ins(Node* t, Node* n, int pos) {
109     auto [l,r] = split(t, pos);
110     return merge(merge(l, n), r);
111 }
112
113 void move(Node*& t, int l, int r, int k){
114     Node *a, *b, *c;
115     tie(a, b) = split(t, l); tie(b, c) = split(b, r - l);
116     if(k <= l) t = merge(ins(a, b, k), c);
117     else t = merge(a, ins(c, b, k - r));
118 }
119
120 void revv(Node*& t, int l, int r){
121     Node *a, *b, *c;
122     tie(a, b) = split(t, l); tie(b, c) = split(b, r - l);
123     b -> rev ^= 1;
124     t = merge(merge(a, b), c);
125 }
126
127 ModInt<mod> query(Node*& t, int l, int r){
128     Node *a, *b, *c;
129     tie(a, b) = split(t, l); tie(b, c) = split(b, r - l);
130     ModInt<mod> res = sum1(b);
131     t = merge(merge(a, b), c);
132     return res;
133 }
134
135 void remove(Node*& t, int x){
136     Node *a, *b, *c;
137     tie(a, b) = split(t, x); tie(b, c) = split(b, 1);
138     t = merge(a, c);
139 }
140
141 void update(Node*& t, int l, int r, ll X, ll Y){
142     Node *a, *b, *c;
143     tie(a, b) = split(t, l); tie(b, c) = split(b, r - l);
144     b -> line = Line{X, Y}(b -> line);
145     t = merge(a, merge(b, c));
146 }

```

```

147
148 int main(){
149     ios_base::sync_with_stdio(false); cin.tie(NULL);
150     int n, q; cin >> n >> q;
151     vector<int> a(n);
152     for(int i = 0; i < n; i++){
153         cin >> a[i];
154     }
155     Node* treap = nullptr;
156     for(int i = 0; i < n; i++){
157         treap = ins(treap, new Node(a[i]), i);
158     }
159     while(q--){
160         int t; cin >> t;
161         if(t == 0){
162             int i, x; cin >> i >> x;
163             treap = ins(treap, new Node(x), i);
164         }
165         else if(t == 1){
166             int x; cin >> x;
167             remove(treap, x);
168         }
169         else if(t == 2){
170             int l, r; cin >> l >> r;
171             revv(treap, l, r);
172         }
173         else if(t == 3){
174             int l, r, b, c; cin >> l >> r >> b >> c;
175             update(treap, l, r, b, c);
176         }
177         else{
178             int l, r; cin >> l >> r;
179             cout << query(treap, l, r) << endl;
180         }
181     }
182 }

```

## 4 Dynamic Programming

### 4.1 CHT Deque

```

1 /*
2 Convex Hull Trick (CHT) - Min Query with Increasing Slopes

```

```

3 -----
4 Indexing: 1-based for 'a', 'dp', 's'
5 Bounds:
6     - i from 1 to m // number of elements in the array
7     - j from 1 to p // number of transitions
8 Time Complexity: O(m * p)
9 Requires:
10     - Lines inserted in increasing slope order for min query
11     - Queries made with increasing x values
12
13 dp[i][j] = min over k < i of { dp[k][j-1] + a[i] * (i - k) + s[i] - s[
14     k+1] }
15 dp[i][j] = min over k < i of { dp[k][j-1] + cost(k, i) }
16
17 We reformulate:
18     y = m * x + c
19     line: m = -k - 1, c = dp[k][j-1] - s[k+1]
20     eval: m * a[i] + c + a[i] * i + s[i]
21 */
22 struct Line {
23     ll a, b; // y = ax + b
24     Line(ll A, ll B) : a(A), b(B) {}
25     ll eval(ll x) const {
26         return a * x + b;
27     }
28     // Returns intersection x-coordinate with another line
29     double intersect(const Line& other) const {
30         return (double)(other.b - b) / (a - other.a);
31     }
32 };
33
34 // this finds the minimum and slope in increasing
35 // Deques for each dp stage
36 deque<Line> cht[p+1];
37 // Fill dp
38 cht[0].push_back(Line(-1, -s[1])); // base case
39 for (int i = 1; i <= m; i++) {
40     for (int j = p; j >= 1; j--) {
41         if (j > i) continue;
42         // Maintain front of deque to find minimum
43         while (cht[j - 1].size() >= 2 && cht[j - 1][1].eval(a[i]) <= cht[j -
44             1][0].eval(a[i])) {

```

```

44     cht[j - 1].pop_front();
45 }
46 // Evaluate best line
47 dp[i][j] = cht[j - 1].front().eval(a[i]) + a[i] * i + s[i];
48 // Create new line for current i
49 Line curr(-i - 1, dp[i][j] - s[i + 1]);
50 // Maintain convexity: remove worse lines from back
51 while (cht[j].size() >= 2) {
52     Line& l1 = cht[j][cht[j].size() - 2];
53     Line& l2 = cht[j].back();
54     if (curr.intersect(l1) <= l2.intersect(l1)) {
55         cht[j].pop_back();
56     } else break;
57 }
58 cht[j].push_back(curr);
59 }
60 }

```

## 4.2 Digit DP

```

1  /*
2  Digit Dynamic Programming (Digit DP)
3  -----
4  Goal: Count numbers in range [0, x] that do not have two adjacent
       equal digits.
5  State:
6  - pos: current digit position
7  - last: digit placed at previous position (0 to 9)
8  - f: tight flag (0 = must match prefix of x, 1 = already below x)
9  - z: leading zero flag (1 = still in leading zero zone)
10 Notes:
11 - Solve up to x using 'solve(x)'
12 - Can be modified to count palindromes, digits divisible by 3, etc.
13 */
14
15 vector<int> num;
16 ll DP[20][20][2][2]; // pos, last digit, f (tight), z (leading zero)
17
18 ll g(int pos, int last, int f, int z) {
19     if (pos == num.size()) return 1; // reached end, valid number
20     if (DP[pos][last][f][z] != -1) return DP[pos][last][f][z];
21     ll res = 0;
22     int limit = f ? 9 : num[pos]; // upper digit bound based on tight flag

```

```

23     for (int dgt = 0; dgt <= limit; dgt++) {
24         // Skip if digit equals last (unless it's a leading zero)
25         if (dgt == last && !(dgt == 0 && z == 1)) continue;
26         int nf = f;
27         if (!f && dgt < limit) nf = 1;
28         if (z && dgt == 0) res += g(pos + 1, dgt, nf, 1); // still leading
               zeros
29         else res += g(pos + 1, dgt, nf, 0); // now in significant digits
30     }
31     return DP[pos][last][f][z] = res;
32 }
33
34 ll solve(ll x) {
35     if (x == -1) return 0;
36     num.clear();
37     while (x > 0) {
38         num.push_back(x % 10);
39         x /= 10;
40     }
41     reverse(num.begin(), num.end());
42     memset(DP, -1, sizeof(DP));
43     return g(0, 0, 0, 1);
44 }

```

## 4.3 Divide and Conquer DP

```

1  /*
2  Divide and Conquer DP Optimization
3  -----
4  Problem:
5  - dp[i][j] = min over k <= j of { dp[i-1][k] + C(k, j) }
6  - C(k, j) must satisfy the quadrangle inequality:
7      - C(a, c) + C(b, d) <= C(a, d) + C(b, c) for a <= b <= c <= d
8      - or monotonicity of opt[i][j] <= opt[i][j+1]
9
10 Indexing: 0-based
11 Time Complexity: O(m * n * log n)
12 Space Complexity: O(n)
13
14 dp_cur[j]: current dp[i][j] layer
15 dp_before[j]: previous dp[i-1][j] layer
16 */
17

```

```

18 int n, m;
19 vector<ll> dp_before, dp_cur;
20 ll C(int i, int j); // Cost function defined by user
21
22 // Recursively compute dp_cur[l..r] with optimal k in [optl, optr]
23 void compute(int l, int r, int optl, int optr) {
24     if (l > r) return;
25     int mid = (l + r) / 2;
26     pair<ll, int> best = {LLONG_MAX, -1};
27     for (int k = optl; k <= min(mid, optr); k++) {
28         ll val = (k > 0 ? dp_before[k - 1] : 0) + C(k, mid);
29         if (val < best.first) best = {val, k};
30     }
31     dp_cur[mid] = best.first;
32     int opt = best.second;
33     compute(l, mid - 1, optl, opt);
34     compute(mid + 1, r, opt, optr);
35 }
36
37 // Entry point: computes dp[m-1][n-1]
38 ll solve() {
39     dp_before.assign(n, 0);
40     dp_cur.assign(n, 0);
41     for (int i = 0; i < n; i++) {
42         dp_before[i] = C(0, i);
43     }
44     for (int i = 1; i < m; i++) {
45         compute(0, n - 1, 0, n - 1);
46         dp_before = dp_cur;
47     }
48     return dp_before[n - 1];
49 }

```

#### 4.4 Edit Distance

```

1 /*
2  Given strings s and t, compute the minimum number of operations
3  (insert, delete, substitute) to convert s into t.
4  Indexing: 0-based (strings), DP is 1-based with offset
5  dp[i][j] = cost to convert s[0..i-1] into t[0..j-1]
6  Time Complexity: O(n * m)
7  Transitions:
8      - insert: dp[i][j-1] + 1

```

```

9      - delete: dp[i-1][j] + 1
10     - replace/match: dp[i-1][j-1] + (s[i-1] != t[j-1])
11 */
12 const int MAXN = 5005;
13 int dp[MAXN][MAXN];
14
15 string s, t; cin >> s >> t;
16 int n = s.length(), m = t.length();
17 // Initialize all to a large number
18 for (int i = 0; i <= n; i++) {
19     fill(dp[i], dp[i] + m + 1, 1e9);
20 }
21 dp[0][0] = 0;
22 for (int i = 0; i <= n; i++) {
23     for (int j = 0; j <= m; j++) {
24         if (j) { // insert
25             dp[i][j] = min(dp[i][j], dp[i][j - 1] + 1);
26         }
27         if (i) { // delete
28             dp[i][j] = min(dp[i][j], dp[i - 1][j] + 1);
29         }
30         if (i && j) { // replace or match
31             int cost = (s[i - 1] != t[j - 1]) ? 1 : 0;
32             dp[i][j] = min(dp[i][j], dp[i - 1][j - 1] + cost);
33         }
34     }
35 }

```

#### 4.5 Knuth's Algorithm

```

1 #include<bits/stdc++.h>
2 using namespace std;
3
4 const int N = 1010;
5 using ll = long long;
6 /*
7  Knuths optimization works for optimization over sub arrays
8  for which optimal middle point depends monotonously on the end points.
9  Let mid[l,r] be the first middle point for (l,r) sub array which gives
10     optimal result.
11  It can be proven that mid[l,r-1] <= mid[l,r] <= mid[l+1,r]
12  - this means monotonicity of mid by l and r.
13  Applying this optimization reduces time complexity from O(k^3) to O(k^2)

```



```

13 because with fixed s (sub array length) we have m_right(l) = mid[l+1][r]
    = m_left(l+1).
14 That's why nested l and m loops require not more than 2k iterations
    overall.
15 */
16
17 int n, k;
18 int a[N], mid[N][N];
19 ll res[N][N];
20 ll solve() {
21     for (int s = 0; s <= k; s++) {          // s - length of the subarray
22         for (int l = 0; l + s <= k; l++) { // l - left point
23             int r = l + s;                  // r - right point
24             if (s < 2) {
25                 res[l][r] = 0;              // base case- nothing to break
26                 mid[l][r] = l;              // mid is equal to left border
27                 continue;
28             }
29             int mleft = mid[l][r - 1];
30             int mright = mid[l + 1][r];
31             res[l][r] = 2e18;
32             for (int m = mleft; m <= mright; m++) { // iterating for m in
                the bounds only
33                 ll tmp = res[l][m] + res[m][r] + (a[r] - a[l]);
34                 if (res[l][r] > tmp) {          // relax current solution
35                     res[l][r] = tmp;
36                     mid[l][r] = m;
37                 }
38             }
39         }
40     }
41     ll ans = res[0][k];
42     return ans;
43 }
44 int main() {
45     int i, j, m;
46     while(cin >> n >> k) {
47         for(i = 1; i <= k; i++) cin >> a[i];
48         a[0] = 0;
49         a[k + 1] = n;
50         k++;
51         cout << solve() << endl;
52     }

```

```

53     return 0;
54 }
55 // https://vjudge.net/problem/ZOJ-2860

```

## 4.6 LCS

```

1 string s, t; cin >> s >> t;
2 int n=s.length(), m=t.length();
3 int dp[n+1][m+1];
4 memset(dp, 0, sizeof(dp));
5 for(int i=1;i<=n;i++){
6     for(int j=1;j<=m;j++){
7         dp[i][j]=max(dp[i-1][j], dp[i][j-1]);
8         if(s[i-1]==t[j-1]){
9             dp[i][j]=dp[i-1][j-1]+1;
10        }
11    }
12 }
13 int i=n, j=m;
14 string ans="";
15 while(i && j){
16     if(s[i-1]==t[j-1]){
17         ans+=s[i-1];
18         i--; j--;
19     }
20     else if(dp[i][j-1]>=dp[i-1][j]){
21         j--;
22     }
23     else{
24         i--;
25     }
26 }
27 reverse(all(ans));
28 cout << ans << endl;
29
30 // For two permutations one can create new array that will map each
    element from the first permutation to the second.
31 // For each element a[i] in the first permutatio, you find which j is a[
    i] == b[j].
32 // After creating this new array, run LIS (Longest Increasing
    subsequence).

```

## 4.7 Line Container

```

1  /*
2  Line Container (Dynamic Convex Hull Trick)
3  -----
4  Supports:
5    - Adding lines:  $y = k * x + m$ 
6    - Querying maximum  $y$  at given  $x$ 
7  Indexing: arbitrary, supports any  $x$ 
8  Time Complexity:
9    - add(): amortized  $O(\log n)$ 
10   - query( $x$ ):  $O(\log n)$ 
11  Space Complexity:  $O(n)$ 
12  For min queries: negate slopes and intercepts on insert and result on
    query
13  Structure:
14    - Stores lines in slope-sorted order ( $k$ )
15    - Each line keeps its intersection point 'p' with the next line
16    - Binary search on 'p' to answer queries
17  */
18 struct Line {
19     mutable ll k, m, p;
20     bool operator<(const Line& o) const { return k < o.k; } // Sort by
        slope
21     bool operator<(ll x) const { return p < x; } // Query
        comparator
22 };
23
24 struct LineContainer : multiset<Line, less<>> {
25     // (for doubles, use inf = 1/.0, div(a,b) = a/b)
26     static const ll inf = LLONG_MAX;
27     ll div(ll a, ll b) { // Floored division
28         return a / b - ((a ^ b) < 0 && a % b);
29     }
30     // Update intersection point  $x \rightarrow p$  with  $y$ 
31     bool isect(iterator x, iterator y) {
32         if (y == end()) return  $x \rightarrow p = \text{inf}$ , false;
33         if ( $x \rightarrow k == y \rightarrow k$ )
34              $x \rightarrow p = (x \rightarrow m > y \rightarrow m ? \text{inf} : -\text{inf})$ ; // higher line wins
35         else
36              $x \rightarrow p = \text{div}(y \rightarrow m - x \rightarrow m, x \rightarrow k - y \rightarrow k)$ ;
37         return  $x \rightarrow p \geq y \rightarrow p$ ;
38     }
39     // Add new line:  $y = k * x + m$ 
40     void add(ll k, ll m) {

```

```

41         auto z = insert({k, m, 0}), y = z++, x = y;
42         // Remove dominated lines after y
43         while (isect(y, z)) z = erase(z);
44         // Remove dominated lines before y
45         if (x != begin() && isect(--x, y))
46             isect(x, y = erase(y));
47         // Further cleanup to preserve order
48         while ((y = x) != begin() && (--x) -> p >= y -> p)
49             isect(x, erase(y));
50     }
51     // Query max  $y$  at given  $x$ 
52     ll query(ll x) {
53         assert(!empty());
54         auto l = *lower_bound(x);
55         return l.k * x + l.m;
56     }
57 };
58 // Example usage:
59 LineContainer cht;
60 cht.add(3, 5); //  $y = 3x + 5$ 
61 cht.add(2, 7); //  $y = 2x + 7$ 
62 cout << cht.query(4) << '\n'; // max  $y$  at  $x = 4$ 

```

## 4.8 Longest Increasing Subsequence

```

1  /*
2  Longest Increasing Subsequence + (Recover Sequence)  $O(n \log n)$ 
3  -----
4  If no recovery is needed, use dp[] only.
5  dp.size() gives the length of LIS.
6  For non-decreasing use upper_bound instead of lower_bound.
7  */
8  vector<int> dp; // smallest tail values of LIS length i+1
9  vector<int> dp_index; // index in original array
10 vector<int> parent(n, -1); // parent[i] = index of previous element
    in LIS
11 vector<int> last_pos(n + 1); // last_pos[len] = index in v[] ending LIS
    of length len
12 for (int i = 0; i < n; i++) {
13     auto it = lower_bound(dp.begin(), dp.end(), v[i]);
14     int len = it - dp.begin();
15     if (it == dp.end()) {
16         dp.push_back(v[i]);

```

```

17     dp_index.push_back(i); // Ignore if no recovery
18 } else {
19     *it = v[i];
20     dp_index[len] = i; // Ignore if no recovery
21 }
22 if (len > 0) parent[i] = dp_index[len - 1]; // Ignore if no recovery
23 }
24 // Reconstruct LIS
25 vector<int> lis;
26 int pos = dp_index.back();
27 while (pos != -1) {
28     lis.push_back(v[pos]);
29     pos = parent[pos];
30 }
31 reverse(lis.begin(), lis.end());

```

#### 4.9 SOS DP

```

1 vector<int> SOS_DP(vector<int> A, int k) {
2     vector<int> Ap = A;
3     for (int i = k - 1; i >= 0; i--)
4         for (int mk = 0; mk < (1 << k); mk++)
5             if (mk & (1 << i))
6                 Ap[mk] += Ap[mk - (1 << i)];
7     return Ap;
8 }
9
10 vector<int> SOS_DP_inv (vector<int> Ap, int k) {
11     vector<int> A = Ap;
12     for (int i = 0; i < k; i++)
13         for (int mk = 0; mk < (1 << k); mk++)
14             if (mk & (1 << i))
15                 A[mk] -= A[mk - (1 << i)];
16     return A;
17 }
18
19 vector<int> SUPER_SOS_DP(vector<int> A, int k) {
20     vector<int> Ap = A;
21     for (int i = k - 1; i >= 0; i--)
22         for (int mk = 0; mk < (1 << k); mk++)
23             if (~mk & (1 << i))
24                 Ap[mk] += Ap[mk + (1 << i)];
25     return Ap;

```

```

26 }
27
28 vector<int> SUPER_SOS_DP_inv (vector<int> Ap, int k) {
29     vector<int> A = Ap;
30     for (int i = 0; i < k; i++)
31         for (int mk = (1 << k) - 1; mk >= 0; mk--)
32             if (~mk & (1 << i))
33                 A[mk] -= A[mk + (1 << i)];
34     return A;
35 }
36
37 // or convolution
38 Ap = SOS_DP(A, k);
39 Bp = SOS_DP(B, k);
40
41 for (int i = 0; i < (1 << k); i++)
42     Cp[i] = Ap[i] * Bp[i];
43
44 C = SOS_DP_inv(Cp, k);
45
46 // and convolution
47 Ap = SUPER_SOS_DP(A, k);
48 Bp = SUPER_SOS_DP(B, k);
49
50 for (int i = 0; i < (1 << k); i++)
51     Cp[i] = Ap[i] * Bp[i];
52
53 C = SUPER_SOS_DP_inv(Cp, k);

```

## 5 Flow

### 5.1 Dinic

```

1 // Si en el grafo todos los vertices distintos
2 // de s y t cumplen que solo tienen una arista
3 // de entrada o una de salida la y dicha arista
4 // tiene capacidad 1 entonces la complejidad es
5 //  $O(E \sqrt{v})$ 
6
7 // si todas las aristas tienen capacidad 1
8 // el algoritmo tiene complejidad  $O(E \sqrt{E})$ 
9
10 // to find min cut run bfs from source and find all vertices that can be

```

```

11 // edges between vertices that can be reached and the ones that cant are
    reached
    the min cut
12 struct FlowEdge {
13     int v, u;
14     long long cap, flow = 0;
15     FlowEdge(int v, int u, long long cap) : v(v), u(u), cap(cap) {}
16 };
17
18 struct Dinic {
19     const long long flow_inf = 1e18;
20     vector<FlowEdge> edges;
21     vector<vector<int>> adj;
22     vector<int> sz;
23     int n, m = 0;
24     int s, t;
25     vector<int> level, ptr;
26     queue<int> q;
27
28     Dinic(int n, int s, int t) : n(n), s(s), t(t) {
29         adj.resize(n);
30         level.resize(n);
31         ptr.resize(n);
32         sz.resize(n);
33     }
34
35     void add_edge(int v, int u, long long cap) {
36         edges.emplace_back(v, u, cap);
37         edges.emplace_back(u, v, 0);
38         adj[v].push_back(m);
39         adj[u].push_back(m + 1);
40         m += 2;
41     }
42
43     bool bfs() {
44         while (!q.empty()) {
45             int v = q.front();
46             q.pop();
47             for (int id : adj[v]) {
48                 if (edges[id].cap - edges[id].flow < 1)
49                     continue;
50                 if (level[edges[id].u] != -1)
51                     continue;

```

```

52                 level[edges[id].u] = level[v] + 1;
53                 q.push(edges[id].u);
54             }
55         }
56         return level[t] != -1;
57     }
58
59     long long dfs(int v, long long pushed) {
60         if (pushed == 0)
61             return 0;
62         if (v == t)
63             return pushed;
64         for (int& cid = ptr[v]; cid < (int)adj[v].size(); cid++) {
65             int id = adj[v][cid];
66             int u = edges[id].u;
67             if (level[v] + 1 != level[u] || edges[id].cap - edges[id].flow
68                 < 1)
69                 continue;
70             long long tr = dfs(u, min(pushed, edges[id].cap - edges[id].
71                 flow));
72             if (tr == 0)
73                 continue;
74             edges[id].flow += tr;
75             edges[id ^ 1].flow -= tr;
76             return tr;
77         }
78         return 0;
79     }
80
81     long long flow() {
82         long long f = 0;
83         while (true) {
84             fill(level.begin(), level.end(), -1);
85             level[s] = 0;
86             q.push(s);
87             if (!bfs())
88                 break;
89             fill(ptr.begin(), ptr.end(), 0);
90             while (long long pushed = dfs(s, flow_inf)) {
91                 f += pushed;
92             }
93         }
94         return f;

```

```

93 }
94
95
96 vector<pair<int, int>> minCut(){
97     vector<pair<int, int>> ans;
98     queue<int> q;
99     q.push(s);
100     vector<bool> vis(n, 0);
101     while((int)q.size()){
102         int cur = q.front();
103         q.pop();
104         vis[cur] = 1;
105         for(int id: adj[cur]){
106             if(edges[id].cap - edges[id].flow <= 0) continue;
107             if(vis[edges[id].u]) continue;
108             vis[edges[id].u] = 1;
109             q.push(edges[id].u);
110         }
111     }
112     for(auto edge: edges){
113         if(vis[edge.v] && !vis[edge.u] && edge.flow > 0) {
114             ans.push_back({edge.v, edge.u});
115         }
116     }
117     return ans;
118 }
119
120 bool getPath(int cur, vector<int> &path){
121     path.push_back(cur);
122     for(int &i = sz[cur]; i >= 0; i--){
123         int edge_index = adj[cur][i];
124         if(edge_index & 1) continue;
125         if(edges[edge_index].cap - edges[edge_index].flow == 0){
126             i--;
127             getPath(edges[edge_index].u, path);
128             return true;
129         }
130     }
131     return false;
132 }
133
134 vector<vector<int>> getPaths(){
135     vector<vector<int>> ans;

```

```

136     vector<int> path;
137     for(int i = 0; i < n; i++) sz[i] = (int)adj[i].size() - 1;
138     while(getPath(s, path)){
139         ans.push_back(path);
140         path.clear();
141     }
142     return ans;
143 }
144 };

```

## 5.2 Hopcroft-Karp

```

1 // maximum matching in bipartite graph
2 vector<int> match, dist;
3 vector<vector<int>> g;
4 int n, m, k;
5 bool bfs()
6 {
7     queue<int> q;
8     // The alternating path starts with unmatched nodes
9     for (int node = 1; node <= n; node++)
10     {
11         if (!match[node])
12         {
13             q.push(node);
14             dist[node] = 0;
15         }
16         else
17         {
18             dist[node] = INF;
19         }
20     }
21
22     dist[0] = INF;
23
24     while (!q.empty())
25     {
26         int node = q.front();
27         q.pop();
28         if (dist[node] >= dist[0])
29         {
30             continue;
31         }

```

```

32     for (int son : g[node])
33     {
34         // If the match of son is matched
35         if (dist[match[son]] == INF)
36         {
37             dist[match[son]] = dist[node] + 1;
38             q.push(match[son]);
39         }
40     }
41 }
42 // Returns true if an alternating path has been found
43 return dist[0] != INF;
44 }
45
46 // Returns true if an augmenting path has been found starting from
47 // vertex node
48 bool dfs(int node)
49 {
50     if (node == 0)
51     {
52         return true;
53     }
54     for (int son : g[node])
55     {
56         if (dist[match[son]] == dist[node] + 1 && dfs(match[son]))
57         {
58             match[node] = son;
59             match[son] = node;
60             return true;
61         }
62     }
63     dist[node] = INF;
64     return false;
65 }
66
67 int hopcroft_karp()
68 {
69     int cnt = 0;
70     // While there is an alternating path
71     while (bfs())
72     {
73         for (int node = 1; node <= n; node++)
74         {

```

```

74         // If node is unmatched but we can match it using an augmenting
75         // path
76         if (!match[node] && dfs(node))
77         {
78             cnt++;
79         }
80     }
81     return cnt;
82 }
83 // usage
84 // n numero de puntos en la izquierda
85 // m numero de puntos en la derecha
86 // las aristas se guardan en g
87 // los puntos estan 1 indexados
88 // el punto 1 de m es el punto n+1 de g
89 // hopcroft_karp() devuelve el tamaño del máximo matching
90 // match contiene el match de cada punto
91 // si match de i es 0, entonces i no está matcheado
92 //
93 // https://judge.yosupo.jp/submission/247277

```

### 5.3 Hungarian

```

1  #define forn(i,n) for(int i=0;i<int(n);++i)
2  #define forsn(i,s,n) for(int i=s;i<int(n);++i)
3  #define forall(i,c) for(typeof(c.begin()) i=c.begin();i!=c.end();++i)
4  #define DBG(X) cerr << #X << " = " << X << endl;
5  typedef vector<int> vint;
6  typedef vector<vint> vvint;
7
8  void showmt();
9
10 /* begin notebook */
11
12 #define MAXN 256
13 #define INFTO 0x7f7f7f7f
14 int n;
15 int mt[MAXN][MAXN]; // Matriz de costos (X * Y)
16 int xy[MAXN], yx[MAXN]; // Matching resultante (X->Y, Y->X)
17
18 int lx[MAXN], ly[MAXN], slk[MAXN], slkx[MAXN], prv[MAXN];
19 char S[MAXN], T[MAXN];

```

```

20
21 void updtree(int x) {
22     forn(y, n) if (lx[x] + ly[y] - mt[x][y] < slk[y]) {
23         slk[y] = lx[x] + ly[y] - mt[x][y];
24         slkx[y] = x;
25     }
26 }
27 int hungar() {
28     forn(i, n) {
29         ly[i] = 0;
30         lx[i] = *max_element(mt[i], mt[i]+n);
31     }
32     memset(xy, -1, sizeof(xy));
33     memset(yx, -1, sizeof(yx));
34
35     forn(m, n) {
36         memset(S, 0, sizeof(S));
37         memset(T, 0, sizeof(T));
38         memset(prv, -1, sizeof(prv));
39         memset(slk, 0x7f, sizeof(slk));
40         queue<int> q;
41         #define bpone(e, p) { q.push(e); prv[e] = p; S[e] = 1; updtree(e); }
42         forn(i, n) if (xy[i] == -1) { bpone(i, -2); break; }
43
44         int x=0, y=-1;
45         while (y== -1) {
46             while (!q.empty() && y== -1) {
47                 x = q.front(); q.pop();
48                 forn(j, n) if (mt[x][j] == lx[x] + ly[j] && !T[j]) {
49                     if (yx[j] == -1) { y = j; break; }
50                     T[j] = 1;
51                     bpone(yx[j], x);
52                 }
53             }
54             if (y!= -1) break;
55             int dlt = INFT0;
56             forn(j, n) if (!T[j]) dlt = min(dlt, slk[j]);
57             forn(k, n) {
58                 if (S[k]) lx[k] -= dlt;
59                 if (T[k]) ly[k] += dlt;
60                 if (!T[k]) slk[k] -= dlt;
61             }
62             // q = queue<int>();

```

```

63         forn(j, n) if (!T[j] && !slk[j]) {
64             if (yx[j] == -1) {
65                 x = slkx[j]; y = j; break;
66             } else {
67                 T[j] = 1;
68                 if (!S[yx[j]]) bpone(yx[j], slkx[j]);
69             }
70         }
71     }
72     if (y!= -1) {
73         for(int p = x; p != -2; p = prv[p]) {
74             yx[y] = p;
75             int ty = xy[p]; xy[p] = y; y = ty;
76         }
77     } else break;
78 }
79 int res = 0;
80 forn(i, n) res += mt[i][xy[i]];
81 return res;
82 }

```

## 5.4 Max Flow Min Cost

```

1 // dado un acomodo de flujos con costos
2 // devuelve el costo minimo para un flujo especificado
3
4 struct Edge
5 {
6     int from, to, capacity, cost;
7     Edge(int _from, int _to, int _capacity, int _cost)
8     {
9         from = _from;
10        to = _to;
11        capacity = _capacity;
12        cost = _cost;
13    }
14 };
15
16 vector<vector<int>> adj, cost, capacity;
17
18 const int INF = 1e9;
19
20 void shortest_paths(int n, int v0, vector<int> &d, vector<int> &p)

```

```

21 {
22     d.assign(n, INF);
23     d[v0] = 0;
24     vector<bool> inq(n, false);
25     queue<int> q;
26     q.push(v0);
27     p.assign(n, -1);
28
29     while (!q.empty())
30     {
31         int u = q.front();
32         q.pop();
33         inq[u] = false;
34         for (int v : adj[u])
35         {
36             if (capacity[u][v] > 0 && d[v] > d[u] + cost[u][v])
37             {
38                 d[v] = d[u] + cost[u][v];
39                 p[v] = u;
40                 if (!inq[v])
41                 {
42                     inq[v] = true;
43                     q.push(v);
44                 }
45             }
46         }
47     }
48 }
49
50 int min_cost_flow(int N, vector<Edge> edges, int K, int s, int t)
51 {
52     adj.assign(N, vector<int>());
53     cost.assign(N, vector<int>(N, 0));
54     capacity.assign(N, vector<int>(N, 0));
55     for (Edge e : edges)
56     {
57         adj[e.from].push_back(e.to);
58         adj[e.to].push_back(e.from);
59         cost[e.from][e.to] = e.cost;
60         cost[e.to][e.from] = -e.cost;
61         capacity[e.from][e.to] = e.capacity;
62     }
63

```

```

64     int flow = 0;
65     int cost = 0;
66     vector<int> d, p;
67     while (flow < K)
68     {
69         shortest_paths(N, s, d, p);
70         if (d[t] == INF)
71             break;
72
73         // find max flow on that path
74         int f = K - flow;
75         int cur = t;
76         while (cur != s)
77         {
78             f = min(f, capacity[p[cur]][cur]);
79             cur = p[cur];
80         }
81
82         // apply flow
83         flow += f;
84         cost += f * d[t];
85         cur = t;
86         while (cur != s)
87         {
88             capacity[p[cur]][cur] -= f;
89             capacity[cur][p[cur]] += f;
90             cur = p[cur];
91         }
92     }
93
94     if (flow < K)
95         return -1;
96     else
97         return cost;
98 }

```

## 5.5 Max Flow

```

1 long long max_flow(vector<vector<int>> adj, vector<vector<long long>>
2     capacity,
3     int source, int sink)
4 {
5     int n = adj.size();

```



```

5  vector<int> parent(n, -1);
6  // Find a way from the source to sink on a path with non-negative
   capacities
7  auto reachable = [&]() -> bool
8  {
9      queue<int> q;
10     q.push(source);
11     while (!q.empty())
12     {
13         int node = q.front();
14         q.pop();
15         for (int son : adj[node])
16         {
17             long long w = capacity[node][son];
18             if (w <= 0 || parent[son] != -1)
19                 continue;
20             parent[son] = node;
21             q.push(son);
22         }
23     }
24     return parent[sink] != -1;
25 };
26
27 long long flow = 0;
28 // While there is a way from source to sink with non-negative
   capacities
29 while (reachable())
30 {
31     int node = sink;
32     // The minimum capacity on the path from source to sink
33     long long curr_flow = LLONG_MAX;
34     while (node != source)
35     {
36         curr_flow = min(curr_flow, capacity[parent[node]][node]);
37         node = parent[node];
38     }
39     node = sink;
40     while (node != source)
41     {
42         // Subtract the capacity from capacity edges
43         capacity[parent[node]][node] -= curr_flow;
44         // Add the current flow to flow backedges
45         capacity[node][parent[node]] += curr_flow;

```

```

46     node = parent[node];
47     }
48     flow += curr_flow;
49     fill(parent.begin(), parent.end(), -1);
50 }
51
52 return flow;
53 }
54
55
56 //vector<vector<long long>> capacity(n, vector<long long>(n));
57 //vector<vector<int>> adj(n);
58 //adj[a].push_back(b);
59 //adj[b].push_back(a);
60 //capacity[a][b] += c;

```

## 5.6 Min Cost Max Flow

```

1  /**
2   * If costs can be negative, call setpi before maxflow, but note that
   negative cost cycles are not supported.
3   * To obtain the actual flow, look at positive values only
4   * Time:  $O(F E \log(V))$  where F is max flow.  $O(VE)$  for setpi.
5   */
6  #include <bits/stdc++.h>
7  using namespace std;
8
9  #include <ext/pb_ds/priority_queue.hpp>
10 using namespace __gnu_pbds;
11
12 #define rep(i, a, b) for(int i = a; i < (b); ++i)
13 #define all(x) begin(x), end(x)
14 #define sz(x) (int)(x).size()
15 typedef long long ll;
16 typedef pair<int, int> pii;
17 typedef vector<int> vi;
18
19 #pragma once
20
21 // #include <bits/extc++.h> /// include-line, keep-include
22
23 const ll INF = numeric_limits<ll>::max() / 4;

```

```

24
25 struct MCMF {
26     struct edge {
27         int from, to, rev;
28         ll cap, cost, flow;
29     };
30     int N;
31     vector<vector<edge>> ed;
32     vi seen;
33     vector<ll> dist, pi;
34     vector<edge*> par;
35
36     MCMF(int N) : N(N), ed(N), seen(N), dist(N), pi(N), par(N) {}
37
38     void addEdge(int from, int to, ll cap, ll cost) {
39         if (from == to) return;
40         ed[from].push_back(edge{ from,to,sz(ed[to]),cap,cost,0 });
41         ed[to].push_back(edge{ to,from,sz(ed[from])-1,0,-cost,0 });
42     }
43
44     void path(int s) {
45         fill(all(seen), 0);
46         fill(all(dist), INF);
47         dist[s] = 0; ll di;
48
49         __gnu_pbds::priority_queue<pair<ll, int>> q;
50         vector<decltype(q)::point_iterator> its(N);
51         q.push({ 0, s });
52
53         while (!q.empty()) {
54             s = q.top().second; q.pop();
55             seen[s] = 1; di = dist[s] + pi[s];
56             for (edge& e : ed[s]) if (!seen[e.to]) {
57                 ll val = di - pi[e.to] + e.cost;
58                 if (e.cap - e.flow > 0 && val < dist[e.to]) {
59                     dist[e.to] = val;
60                     par[e.to] = &e;
61                     if (its[e.to] == q.end())
62                         its[e.to] = q.push({ -dist[e.to], e.to });
63                     else
64                         q.modify(its[e.to], { -dist[e.to], e.to });
65                 }
66             }

```

```

67     }
68     rep(i,0,N) pi[i] = min(pi[i] + dist[i], INF);
69 }
70
71 pair<ll, ll> maxflow(int s, int t) {
72     ll totflow = 0, totcost = 0;
73     while (path(s), seen[t]) {
74         ll fl = INF;
75         for (edge* x = par[t]; x; x = par[x->from])
76             fl = min(fl, x->cap - x->flow);
77
78         totflow += fl;
79         for (edge* x = par[t]; x; x = par[x->from]) {
80             x->flow += fl;
81             ed[x->to][x->rev].flow -= fl;
82         }
83     }
84     rep(i,0,N) for(edge& e : ed[i]) totcost += e.cost * e.flow;
85     return {totflow, totcost/2};
86 }
87
88 // If some costs can be negative, call this before maxflow:
89 void setpi(int s) { // (otherwise, leave this out)
90     fill(all(pi), INF); pi[s] = 0;
91     int it = N, ch = 1; ll v;
92     while (ch-- && it--)
93         rep(i,0,N) if (pi[i] != INF)
94             for (edge& e : ed[i]) if (e.cap)
95                 if ((v = pi[i] + e.cost) < pi[e.to])
96                     pi[e.to] = v, ch = 1;
97     assert(it >= 0); // negative cost cycle
98 }
99 };

```

## 5.7 Push Relabel

```

1 const int inf = 1000000000;
2
3 int n;
4 vector<vector<int>> capacity, flow;
5 vector<int> height, excess, seen;
6 queue<int> excess_vertices;
7

```

```

8 void push(int u, int v) {
9     int d = min(excess[u], capacity[u][v] - flow[u][v]);
10    flow[u][v] += d;
11    flow[v][u] -= d;
12    excess[u] -= d;
13    excess[v] += d;
14    if (d && excess[v] == d)
15        excess_vertices.push(v);
16 }
17
18 void relabel(int u) {
19     int d = inf;
20     for (int i = 0; i < n; i++) {
21         if (capacity[u][i] - flow[u][i] > 0)
22             d = min(d, height[i]);
23     }
24     if (d < inf)
25         height[u] = d + 1;
26 }
27
28 void discharge(int u) {
29     while (excess[u] > 0) {
30         if (seen[u] < n) {
31             int v = seen[u];
32             if (capacity[u][v] - flow[u][v] > 0 && height[u] > height[v])
33                 push(u, v);
34             else
35                 seen[u]++;
36         } else {
37             relabel(u);
38             seen[u] = 0;
39         }
40     }
41 }
42
43 int max_flow(int s, int t) {
44     height.assign(n, 0);
45     height[s] = n;
46     flow.assign(n, vector<int>(n, 0));
47     excess.assign(n, 0);
48     excess[s] = inf;
49     for (int i = 0; i < n; i++) {
50         if (i != s)

```

```

51         push(s, i);
52     }
53     seen.assign(n, 0);
54
55     while (!excess_vertices.empty()) {
56         int u = excess_vertices.front();
57         excess_vertices.pop();
58         if (u != s && u != t)
59             discharge(u);
60     }
61
62     int max_flow = 0;
63     for (int i = 0; i < n; i++)
64         max_flow += flow[i][t];
65     return max_flow;
66 }

```

## 6 Geometry

### 6.1 Point Struct

```

1 typedef long long T;
2 struct pt {
3     T x,y;
4     pt operator+(pt p) {return {x+p.x, y+p.y};}
5     pt operator-(pt p) {return {x-p.x, y-p.y};}
6     pt operator*(T d) {return {x*d, y*d};}
7     pt operator/(T d) {return {x/d, y/d};}
8 };
9
10 // cross product
11 // positivo si el segundo esta en sentido antihorario
12 // 0 si el angulo es 180
13 // negativo si el segundo esta en sentido horario
14 T cross(pt v, pt w) {return v.x*w.y - v.y*w.x;}
15
16 // dot product
17 // positivo si el angulo entre los vectores es agudo
18 // 0 si son perpendiculares
19 // negativo si el angulo es obtuso
20 T dot(pt v, pt w) {return v.x*w.x + v.y*w.y;}
21
22 T orient(pt a, pt b, pt c) {return cross(b-a,c-a);}

```

```

23
24 T dist(pt a,pt b){
25     pt aux=b-a;
26     return sqrtl(aux.x*aux.x+aux.y*aux.y);
27 }

```

## 6.2 Sort Points

```

1 // This comparator sorts the points clockwise
2 // starting from the first quarter
3
4 bool getQ(Point a){
5     if(a.y!=0){
6         if(a.y>0)return 0;
7         return 1;
8     }
9     if(a.x>0)return 0;
10    return 1;
11 }
12 bool comp(Point a, Point b){
13     if(getQ(a)!=getQ(b))return getQ(a)<getQ(b);
14     return a*b>0;
15 }

```

## 6.3 Point Struct2

```

1 #include <bits/stdc++.h>
2 using namespace std;
3 using ld = long double;
4 const ld eps = 1e-9, inf = numeric_limits<ld>::max(), pi = acos(-1);
5 // For use with integers, just set eps=0 and everything remains the same
6 bool geq(ld a, ld b){return a-b >= -eps;} //a >= b
7 bool leq(ld a, ld b){return b-a >= -eps;} //a <= b
8 bool ge(ld a, ld b){return a-b > eps;} //a > b
9 bool le(ld a, ld b){return b-a > eps;} //a < b
10 bool eq(ld a, ld b){return abs(a-b) <= eps;} //a == b
11 bool neq(ld a, ld b){return abs(a-b) > eps;} //a != b
12
13 struct point{
14     ld x, y;
15     point(): x(0), y(0){}
16     point(ld x, ld y): x(x), y(y){}
17

```

```

18     point operator+(const point & p) const{return point(x + p.x, y + p.y)
19         ;}
20     point operator-(const point & p) const{return point(x - p.x, y - p.y)
21         ;}
22     point operator*(const ld & k) const{return point(x * k, y * k);}
23     point operator/(const ld & k) const{return point(x / k, y / k);}
24
25     point operator+=(const point & p){*this = *this + p; return *this;}
26     point operator-=(const point & p){*this = *this - p; return *this;}
27     point operator*=(const ld & p){*this = *this * p; return *this;}
28     point operator/=(const ld & p){*this = *this / p; return *this;}
29
30     point rotate(const ld & a) const{return point(x*cos(a) - y*sin(a), x*
31         sin(a) + y*cos(a));}
32     point perp() const{return point(-y, x);}
33     ld ang() const{
34         ld a = atan2l(y, x); a += le(a, 0) ? 2*pi : 0; return a;
35     }
36     ld dot(const point & p) const{return x * p.x + y * p.y;}
37     ld cross(const point & p) const{return x * p.y - y * p.x;}
38     ld norm() const{return x * x + y * y;}
39     ld length() const{return sqrtl(x * x + y * y);}
40     point unit() const{return (*this) / length();}
41
42     bool operator==(const point & p) const{return eq(x, p.x) && eq(y, p.y)
43         ;}
44     bool operator!=(const point & p) const{return !(*this == p);}
45     bool operator<(const point & p) const{return le(x, p.x) || (eq(x, p.x)
46         && le(y, p.y));}
47     bool operator>(const point & p) const{return ge(x, p.x) || (eq(x, p.x)
48         && ge(y, p.y));}
49     bool half(const point & p) const{return le(p.cross(*this), 0) || (eq(p
50         .cross(*this), 0) && le(p.dot(*this), 0));}
51 };
52
53 istream &operator>>(istream &is, point & p){return is >> p.x >> p.y;}
54 ostream &operator<<(ostream &os, const point & p){return os << "(" << p.
55     x << ", " << p.y << ")";}
56
57 int sgn(ld x){
58     if(ge(x, 0)) return 1;
59     if(le(x, 0)) return -1;
60     return 0;

```

```

53 }
54
55 void polarSort(vector<point> & P, const point & o, const point & v){
56     //sort points in P around o, taking the direction of v as first angle
57     sort(P.begin(), P.end(), [&](const point & a, const point & b){
58         return point((a - o).half(v), 0) < point((b - o).half(v), (a - o).
59             cross(b - o));
60     });
61 }

```

## 6.4 Antipodal Pairs

```

1 vector<pair<int, int>> antipodalPairs(vector<point> & P){
2     vector<pair<int, int>> ans;
3     int n = P.size(), k = 1;
4     auto f = [&](int u, int v, int w){return abs((P[v%n]-P[u%n]).cross(P[w
5         %n]-P[u%n]));};
6     while(ge(f(n-1, 0, k+1), f(n-1, 0, k))) ++k;
7     for(int i = 0, j = k; i <= k && j < n; ++i){
8         ans.emplace_back(i, j);
9         while(j < n-1 && ge(f(i, i+1, j+1), f(i, i+1, j)))
10             ans.emplace_back(i, ++j);
11     }
12     return ans;
13 }

```

## 6.5 Area and Perimeter

```

1 ld perimeter(vector<point> & P){
2     int n = P.size();
3     ld ans = 0;
4     for(int i = 0; i < n; i++){
5         ans += (P[i] - P[(i + 1) % n]).length();
6     }
7     return ans;
8 }
9
10 ld area(vector<point> & P){
11     int n = P.size();
12     ld ans = 0;
13     for(int i = 0; i < n; i++){
14         ans += P[i].cross(P[(i + 1) % n]);
15     }
16     return abs(ans / 2);
17 }

```

```

17 }

```

## 6.6 Area Union Circles

```

1 struct circ{
2     point c;
3     ld r;
4     circ() {}
5     circ(const point & c, ld r): c(c), r(r) {}
6     set<pair<ld, ld>> ranges;
7
8     void disable(ld l, ld r){
9         ranges.emplace(l, r);
10    }
11
12    auto getActive() const{
13        vector<pair<ld, ld>> ans;
14        ld maxi = 0;
15        for(const auto & dis : ranges){
16            ld l, r;
17            tie(l, r) = dis;
18            if(l > maxi){
19                ans.emplace_back(maxi, l);
20            }
21            maxi = max(maxi, r);
22        }
23        if(!eq(maxi, 2*pi)){
24            ans.emplace_back(maxi, 2*pi);
25        }
26        return ans;
27    }
28 };
29
30 ld areaUnionCircles(const vector<circ> & circs){
31     vector<circ> valid;
32     for(const circ & curr : circs){
33         if(eq(curr.r, 0)) continue;
34         circ nuevo = curr;
35         for(circ & prev : valid){
36             if(circleInsideCircle(prev.c, prev.r, nuevo.c, nuevo.r)){
37                 nuevo.disable(0, 2*pi);
38             }else if(circleInsideCircle(nuevo.c, nuevo.r, prev.c, prev.r)){
39                 prev.disable(0, 2*pi);
40             }
41         }
42         valid.push_back(nuevo);
43     }
44     return area(vector<point>());
45 }

```

```

40 }else{
41     auto cruce = intersectionCircles(prev.c, prev.r, nuevo.c, nuevo.
        r);
42     if(cruce.size() == 2){
43         ld a1 = (cruce[0] - prev.c).ang();
44         ld a2 = (cruce[1] - prev.c).ang();
45         ld b1 = (cruce[1] - nuevo.c).ang();
46         ld b2 = (cruce[0] - nuevo.c).ang();
47         if(a1 < a2){
48             prev.disable(a1, a2);
49         }else{
50             prev.disable(a1, 2*pi);
51             prev.disable(0, a2);
52         }
53         if(b1 < b2){
54             nuevo.disable(b1, b2);
55         }else{
56             nuevo.disable(b1, 2*pi);
57             nuevo.disable(0, b2);
58         }
59     }
60 }
61 }
62 valid.push_back(nuevo);
63 }
64 ld ans = 0;
65 for(const circ & curr : valid){
66     for(const auto & range : curr.getActive()){
67         ld l, r;
68         tie(l, r) = range;
69         ans += curr.r*(curr.c.x * (sin(r) - sin(l)) - curr.c.y * (cos(r) -
            cos(l))) + curr.r*curr.r*(r-l);
70     }
71 }
72 return ans/2;
73 };

```

## 6.7 Centroid

```

1 point centroid(vector<point> & P){
2     point num;
3     ld den = 0;
4     int n = P.size();

```

```

5     for(int i = 0; i < n; ++i){
6         ld cross = P[i].cross(P[(i + 1) % n]);
7         num += (P[i] + P[(i + 1) % n]) * cross;
8         den += cross;
9     }
10    return num / (3 * den);
11 }

```

## 6.8 Circle Inside Circle

```

1 int circleInsideCircle(const point & c1, ld r1, const point & c2, ld r2)
    {
2     //test if circle 2 is inside circle 1
3     //returns "-1" if 2 touches internally 1, "1" if 2 is inside 1, "0" if
        they overlap
4     ld l = r1 - r2 - (c1 - c2).length();
5     return (ge(l, 0) ? 1 : (eq(l, 0) ? -1 : 0));
6 }

```

## 6.9 Circle Outside Circle

```

1 int circleOutsideCircle(const point & c1, ld r1, const point & c2, ld r2)
    ){
2     //test if circle 2 is outside circle 1
3     //returns "-1" if they touch externally, "1" if 2 is outside 1, "0" if
        they overlap
4     ld l = (c1 - c2).length() - (r1 + r2);
5     return (ge(l, 0) ? 1 : (eq(l, 0) ? -1 : 0));
6 }

```

## 6.10 Closest Pair of Points

```

1 bool comp1(const point & a, const point & b){
2     return le(a.y, b.y);
3 }
4 pair<point, point> closestPairOfPoints(vector<point> P){
5     sort(P.begin(), P.end(), comp1);
6     set<point> S;
7     ld ans = inf;
8     point p, q;
9     int pos = 0;
10    for(int i = 0; i < P.size(); ++i){
11        while(pos < i && geq(P[i].y - P[pos].y, ans)){
12            S.erase(P[pos++]);

```

```

13     }
14     auto lower = S.lower_bound({P[i].x - ans - eps, -inf});
15     auto upper = S.upper_bound({P[i].x + ans + eps, -inf});
16     for(auto it = lower; it != upper; ++it){
17         ld d = (P[i] - *it).length();
18         if(le(d, ans)){
19             ans = d;
20             p = P[i];
21             q = *it;
22         }
23     }
24     S.insert(P[i]);
25 }
26 return {p, q};
27 }

```

### 6.11 Common Tangents

```

1 vector<vector<point>> tangents(const point & c1, ld r1, const point & c2
  , ld r2, bool inner){
2     //returns a vector of segments or a single point
3     if(inner) r2 = -r2;
4     point d = c2 - c1;
5     ld dr = r1 - r2, d2 = d.norm(), h2 = d2 - dr*dr;
6     if(eq(d2, 0) || le(h2, 0)) return {};
7     point v = d*dr/d2;
8     if(eq(h2, 0)) return {{c1 + v*r1}};
9     else{
10         point u = d.perp()*sqrt(h2)/d2;
11         return {{c1 + (v - u)*r1, c2 + (v - u)*r2}, {c1 + (v + u)*r1, c2 + (
          v + u)*r2}};
12     }
13 }

```

### 6.12 Convex Hull

```

1 vector<point> convexHull(vector<point> P){
2     sort(P.begin(), P.end());
3     vector<point> L, U;
4     for(int i = 0; i < P.size(); i++){
5         while(L.size() >= 2 && leq((L[L.size() - 2] - P[i]).cross(L[L.size()
          - 1] - P[i]), 0)){
6             L.pop_back();
7         }

```

```

8         L.push_back(P[i]);
9     }
10    for(int i = P.size() - 1; i >= 0; i--){
11        while(U.size() >= 2 && leq((U[U.size() - 2] - P[i]).cross(U[U.size()
          - 1] - P[i]), 0)){
12            U.pop_back();
13        }
14        U.push_back(P[i]);
15    }
16    L.pop_back();
17    U.pop_back();
18    L.insert(L.end(), U.begin(), U.end());
19    return L;
20 }

```

### 6.13 Segment Intersection with Ray

```

1 bool crossesRay(const point & a, const point & b, const point & p){
2     return (geq(b.y, p.y) - geq(a.y, p.y)) * sgn((a - p).cross(b - p)) >
3         0;

```

### 6.14 Cut Polygon

```

1 vector<point> cutPolygon(const vector<point> & P, const point & a, const
  point & v){
2     //returns the part of the convex polygon P on the left side of line a+
    tv
3     int n = P.size();
4     vector<point> lhs;
5     for(int i = 0; i < n; ++i){
6         if(geq(v.cross(P[i] - a), 0)){
7             lhs.push_back(P[i]);
8         }
9         if(intersectLineSegmentInfo(a, v, P[i], P[(i+1)%n]) == 1){
10             point p = intersectLines(a, v, P[i], P[(i+1)%n] - P[i]);
11             if(p != P[i] && p != P[(i+1)%n]){
12                 lhs.push_back(p);
13             }
14         }
15     }
16     return lhs;
17 }

```

## 6.15 Delaunay Triangulation

```

1 //Delaunay triangulation in O(n log n)
2 const point inf_pt(inf, inf);
3
4 struct QuadEdge{
5     point origin;
6     QuadEdge* rot = nullptr;
7     QuadEdge* onext = nullptr;
8     bool used = false;
9     QuadEdge* rev() const{return rot->rot;}
10    QuadEdge* lnext() const{return rot->rev()->onext->rot;}
11    QuadEdge* oprev() const{return rot->onext->rot;}
12    point dest() const{return rev()->origin;}
13 };
14
15 QuadEdge* make_edge(const point & from, const point & to){
16     QuadEdge* e1 = new QuadEdge;
17     QuadEdge* e2 = new QuadEdge;
18     QuadEdge* e3 = new QuadEdge;
19     QuadEdge* e4 = new QuadEdge;
20     e1->origin = from;
21     e2->origin = to;
22     e3->origin = e4->origin = inf_pt;
23     e1->rot = e3;
24     e2->rot = e4;
25     e3->rot = e2;
26     e4->rot = e1;
27     e1->onext = e1;
28     e2->onext = e2;
29     e3->onext = e4;
30     e4->onext = e3;
31     return e1;
32 }
33
34 void splice(QuadEdge* a, QuadEdge* b){
35     swap(a->onext->rot->onext, b->onext->rot->onext);
36     swap(a->onext, b->onext);
37 }
38
39 void delete_edge(QuadEdge* e){
40     splice(e, e->oprev());
41     splice(e->rev(), e->rev()->oprev());

```

```

42     delete e->rot;
43     delete e->rev()->rot;
44     delete e;
45     delete e->rev();
46 }
47
48 QuadEdge* connect(QuadEdge* a, QuadEdge* b){
49     QuadEdge* e = make_edge(a->dest(), b->origin);
50     splice(e, a->lnext());
51     splice(e->rev(), b);
52     return e;
53 }
54
55 bool left_of(const point & p, QuadEdge* e){
56     return ge((e->origin - p).cross(e->dest() - p), 0);
57 }
58
59 bool right_of(const point & p, QuadEdge* e){
60     return le((e->origin - p).cross(e->dest() - p), 0);
61 }
62
63 ld det3(ld a1, ld a2, ld a3, ld b1, ld b2, ld b3, ld c1, ld c2, ld c3) {
64     return a1 * (b2 * c3 - c2 * b3) - a2 * (b1 * c3 - c1 * b3) + a3 * (b1
        * c2 - c1 * b2);
65 }
66
67 bool in_circle(const point & a, const point & b, const point & c, const
    point & d) {
68     ld det = -det3(b.x, b.y, b.norm(), c.x, c.y, c.norm(), d.x, d.y, d.
        norm());
69     det += det3(a.x, a.y, a.norm(), c.x, c.y, c.norm(), d.x, d.y, d.norm()
        );
70     det -= det3(a.x, a.y, a.norm(), b.x, b.y, b.norm(), d.x, d.y, d.norm()
        );
71     det += det3(a.x, a.y, a.norm(), b.x, b.y, b.norm(), c.x, c.y, c.norm()
        );
72     return ge(det, 0);
73 }
74
75 pair<QuadEdge*, QuadEdge*> build_tr(int l, int r, vector<point> & P){
76     if(r - l + 1 == 2){
77         QuadEdge* res = make_edge(P[l], P[r]);
78         return {res, res->rev()};

```



```

79     }
80     if(r - l + 1 == 3){
81         QuadEdge *a = make_edge(P[l], P[l + 1]), *b = make_edge(P[l + 1], P[
            r]);
82         splice(a->rev(), b);
83         int sg = sgn((P[l + 1] - P[l]).cross(P[r] - P[l]));
84         if(sg == 0)
85             return {a, b->rev()};
86         QuadEdge* c = connect(b, a);
87         if(sg == 1)
88             return {a, b->rev()};
89         else
90             return {c->rev(), c};
91     }
92     int mid = (l + r) / 2;
93     QuadEdge *ldo, *ldi, *rdo, *rdi;
94     tie(ldo, ldi) = build_tr(l, mid, P);
95     tie(rdi, rdo) = build_tr(mid + 1, r, P);
96     while(true){
97         if(left_of(rdi->origin, ldi)){
98             ldi = ldi->lnext();
99             continue;
100         }
101         if(right_of(ldi->origin, rdi)){
102             rdi = rdi->rev()->onext;
103             continue;
104         }
105         break;
106     }
107     QuadEdge* basel = connect(rdi->rev(), ldi);
108     auto valid = [&basel](QuadEdge* e){return right_of(e->dest(), basel)
        ;};
109     if(ldi->origin == ldo->origin)
110         ldo = basel->rev();
111     if(rdi->origin == rdo->origin)
112         rdo = basel;
113     while(true){
114         QuadEdge* lcand = basel->rev()->onext;
115         if(valid(lcand)){
116             while(in_circle(basel->dest(), basel->origin, lcand->dest(), lcand
                ->onext->dest())){
117                 QuadEdge* t = lcand->onext;
118                 delete_edge(lcand);

```

```

119         lcand = t;
120     }
121     }
122     QuadEdge* rcand = basel->oprev();
123     if(valid(rcand)){
124         while(in_circle(basel->dest(), basel->origin, rcand->dest(), rcand
            ->oprev()->dest())){
125             QuadEdge* t = rcand->oprev();
126             delete_edge(rcand);
127             rcand = t;
128         }
129     }
130     if(!valid(lcand) && !valid(rcand))
131         break;
132     if(!valid(lcand) || (valid(rcand) && in_circle(lcand->dest(), lcand
        ->origin, rcand->origin, rcand->dest())))
133         basel = connect(rcand, basel->rev());
134     else
135         basel = connect(basel->rev(), lcand->rev());
136     }
137     return {ldo, rdo};
138 }
139
140 vector<tuple<point, point, point>> delaunay(vector<point> & P){
141     sort(P.begin(), P.end());
142     auto res = build_tr(0, (int)P.size() - 1, P);
143     QuadEdge* e = res.first;
144     vector<QuadEdge*> edges = {e};
145     while(le((e->dest() - e->onext->dest()).cross(e->origin - e->onext->
        dest()), 0))
146         e = e->onext;
147     auto add = [&P, &e, &edges]() {
148         QuadEdge* curr = e;
149         do{
150             curr->used = true;
151             P.push_back(curr->origin);
152             edges.push_back(curr->rev());
153             curr = curr->lnext();
154         }while(curr != e);
155     };
156     add();
157     P.clear();
158     int kek = 0;

```

```

159 while(kek < (int)edges.size())
160     if(!(e = edges[kek++])>used)
161         add();
162 vector<tuple<point, point, point>> ans;
163 for(int i = 0; i < (int)P.size(); i += 3){
164     ans.emplace_back(P[i], P[i + 1], P[i + 2]);
165 }
166 return ans;
167 }

```

## 6.16 Diameter and Width

```

1 pair<ld, ld> diameterAndWidth(vector<point> & P){
2     int n = P.size(), k = 0;
3     auto dot = [&](int a, int b){return (P[(a+1)%n]-P[a]).dot(P[(b+1)%n]-P[b]);};
4     auto cross = [&](int a, int b){return (P[(a+1)%n]-P[a]).cross(P[(b+1)%n]-P[b]);};
5     ld diameter = 0;
6     ld width = inf;
7     while(ge(dot(0, k), 0)) k = (k+1) % n;
8     for(int i = 0; i < n; ++i){
9         while(ge(cross(i, k), 0)) k = (k+1) % n;
10        //pair: (i, k)
11        diameter = max(diameter, (P[k] - P[i]).length());
12        width = min(width, distancePointLine(P[i], P[(i+1)%n] - P[i], P[k]));
13    }
14    return {diameter, width};
15 }

```

## 6.17 Distance Between Point and Circle

```

1 ld distancePointCircle(const point & c, ld r, const point & p){
2     //point p, circle with center c and radius r
3     return max((ld)0, (p - c).length() - r);
4 }

```

## 6.18 Distance Between Point and Line

```

1 ld distancePointLine(const point & a, const point & v, const point & p){
2     //line: a + tv, point p
3     return abs(v.cross(p - a)) / v.length();
4 }

```

## 6.19 Example of Geometry

```

1 int main(){
2     /*vector<pair<point, point>> centers = {{point(-2, 5), point(-8, -7)},
3         {point(14, 4), point(18, 6)}, {point(9, 20), point(9, 28)},
4         {point(21, 20), point(21, 29)}, {point(8, -10),
5             point(14, -10)}, {point(24, -6), point(34, -6)},
6             {point(34, 8), point(36, 9)}, {point(50, 20),
7                 point(56, 24.5)}};
8     vector<pair<ld, ld>> radii = {{7, 4}, {3, 5}, {4, 4}, {4, 5}, {3, 3},
9         {4, 6}, {5, 1}, {10, 2.5}};
10    int n = centers.size();
11    for(int i = 0; i < n; ++i){
12        cout << "\n" << centers[i].first << " " << radii[i].first << " " <<
13            centers[i].second << " " << radii[i].second << "\n";
14        auto extLines = tangents(centers[i].first, radii[i].first, centers[i].second, radii[i].second, false);
15        cout << "Exterior tangents:\n";
16        for(auto par : extLines){
17            for(auto p : par){
18                cout << p << " ";
19            }
20            cout << "\n";
21        }
22        auto intLines = tangents(centers[i].first, radii[i].first, centers[i].second, radii[i].second, true);
23        cout << "Interior tangents:\n";
24        for(auto par : intLines){
25            for(auto p : par){
26                cout << p << " ";
27            }
28            cout << "\n";
29        }
30    }
31    /*int n;
32    cin >> n;
33    vector<point> P(n);
34    for(auto & p : P) cin >> p;
35    auto triangulation = delaunay(P);
36    for(auto triangle : triangulation){
37        cout << get<0>(triangle) << " " << get<1>(triangle) << " " << get

```

```

    <2>(triangle) << "\n";
34 */
35
36 /*int n;
37 cin >> n;
38 vector<point> P(n);
39 for(auto & p : P) cin >> p;
40 auto ans = smallestEnclosingCircle(P);
41 cout << ans.first << " " << ans.second << "\n";*/
42
43 /*vector<point> P;
44 srand(time(0));
45 for(int i = 0; i < 1000; ++i){
46     P.emplace_back(rand() % 1000000000, rand() % 1000000000);
47 }
48 point o(rand() % 1000000000, rand() % 1000000000), v(rand() %
49     1000000000, rand() % 1000000000);
50 polarSort(P, o, v);
51 auto ang = [&](point p){
52     ld th = atan2(p.y, p.x);
53     if(th < 0) th += acosl(-1)*2;
54     ld t = atan2(v.y, v.x);
55     if(t < 0) t += acosl(-1)*2;
56     if(th < t) th += acosl(-1)*2;
57     return th;
58 };
59 for(int i = 0; i < P.size()-1; ++i){
60     assert(leq(ang(P[i] - o), ang(P[i+1] - o)));
61 }*/
62 return 0;
63 }

```

## 6.20 Half Plane Intersection

```

1 struct plane{
2     point a, v;
3     plane(): a(), v(){}
4     plane(const point& a, const point& v): a(a), v(v){}
5
6     point intersect(const plane& p) const{
7         ld t = (p.a - a).cross(p.v) / v.cross(p.v);
8         return a + v*t;
9     }

```

```

10
11 bool outside(const point& p) const{ // test if point p is strictly
12     outside
13     return le(v.cross(p - a), 0);
14 }
15
16 bool inside(const point& p) const{ // test if point p is inside or in
17     the boundary
18     return geq(v.cross(p - a), 0);
19 }
20
21 bool operator<(const plane& p) const{ // sort by angle
22     auto lhs = make_tuple(v.half({1, 0}), ld(0), v.cross(p.a - a));
23     auto rhs = make_tuple(p.v.half({1, 0}), v.cross(p.v), ld(0));
24     return lhs < rhs;
25 }
26
27 bool operator==(const plane& p) const{ // paralell and same directions
28     , not really equal
29     return eq(v.cross(p.v), 0) && ge(v.dot(p.v), 0);
30 }
31
32 vector<point> halfPlaneIntersection(vector<plane> planes){
33     planes.push_back({{0, -inf}, {1, 0}});
34     planes.push_back({{inf, 0}, {0, 1}});
35     planes.push_back({{0, inf}, {-1, 0}});
36     planes.push_back({{-inf, 0}, {0, -1}});
37     sort(planes.begin(), planes.end());
38     planes.erase(unique(planes.begin(), planes.end()), planes.end());
39     deque<plane> ch;
40     deque<point> poly;
41     for(const plane& p : planes){
42         while(ch.size() >= 2 && p.outside(poly.back())) ch.pop_back(), poly.
43             pop_back();
44         while(ch.size() >= 2 && p.outside(poly.front())) ch.pop_front(),
45             poly.pop_front();
46         if(p.v.half({1, 0}) && poly.empty()) return {};
47         ch.push_back(p);
48         if(ch.size() >= 2) poly.push_back(ch[ch.size()-2].intersect(ch[ch.
49             size()-1]));
50     }
51     while(ch.size() >= 3 && ch.front().outside(poly.back())) ch.pop_back()

```

```

    , poly.pop_back();
47 while(ch.size() >= 3 && ch.back().outside(poly.front())) ch.pop_front
    (), poly.pop_front();
48 poly.push_back(ch.back().intersect(ch.front()));
49 return vector<point>(poly.begin(), poly.end());
50 }
51
52 vector<point> halfPlaneIntersectionRandomized(vector<plane> planes){
53     point p = planes[0].a;
54     int n = planes.size();
55     random_shuffle(planes.begin(), planes.end());
56     for(int i = 0; i < n; ++i){
57         if(planes[i].inside(p)) continue;
58         ld lo = -inf, hi = inf;
59         for(int j = 0; j < i; ++j){
60             ld A = planes[j].v.cross(planes[i].v);
61             ld B = planes[j].v.cross(planes[j].a - planes[i].a);
62             if(ge(A, 0)){
63                 lo = max(lo, B/A);
64             }else if(le(A, 0)){
65                 hi = min(hi, B/A);
66             }else{
67                 if(ge(B, 0)) return {};
68             }
69             if(ge(lo, hi)) return {};
70         }
71         p = planes[i].a + planes[i].v*lo;
72     }
73     return {p};
74 }

```

### 6.21 Incircle

```

1 pair<point, ld> getCircle(const point & m, const point & n, const point
    & p){
2     //find circle that passes through points p, q, r
3     point c = intersectLines((n + m) / 2, (n - m).perp(), (p + n) / 2, (p
        - n).perp());
4     ld r = (c - m).length();
5     return {c, r};
6 }

```

### 6.22 Intersection of Two Circles

```

1 vector<point> intersectionCircles(const point & c1, ld r1, const point &
    c2, ld r2){
2     //circle 1 with center c1 and radius r1
3     //circle 2 with center c2 and radius r2
4     point d = c2 - c1;
5     ld d2 = d.norm();
6     if(eq(d2, 0)) return {}; //concentric circles
7     ld pd = (d2 + r1*r1 - r2*r2) / 2;
8     ld h2 = r1*r1 - pd*pd/d2;
9     point p = c1 + d*pd/d2;
10    if(eq(h2, 0)) return {p}; //circles touch at one point
11    else if(le(h2, 0)) return {}; //circles don't intersect
12    else{
13        point u = d.perp() * sqrt(h2/d2);
14        return {p - u, p + u};
15    }
16 }

```

### 6.23 Intersection Line and Circle

```

1 vector<point> intersectLineCircle(const point & a, const point & v,
    const point & c, ld r){
2     //line a+tv, circle with center c and radius r
3     ld h2 = r*r - v.cross(c - a) * v.cross(c - a) / v.norm();
4     point p = a + v * v.dot(c - a) / v.norm();
5     if(eq(h2, 0)) return {p}; //line tangent to circle
6     else if(le(h2, 0)) return {}; //no intersection
7     else{
8         point u = v.unit() * sqrt(h2);
9         return {p - u, p + u}; //two points of intersection (chord)
10    }
11 }

```

### 6.24 Intersection Polygon and Circle

```

1 ld signed_angle(const point & a, const point & b){
2     return sgn(a.cross(b)) * acosl(a.dot(b) / (a.length() * b.length()));
3 }
4
5 ld intersectPolygonCircle(const vector<point> & P, const point & c, ld r
    ){
6     //Gets the area of the intersection of the polygon with the circle
7     int n = P.size();
8     ld ans = 0;

```

```

9   for(int i = 0; i < n; ++i){
10       point p = P[i], q = P[(i+1)%n];
11       bool p_inside = (pointInCircle(c, r, p) != 0);
12       bool q_inside = (pointInCircle(c, r, q) != 0);
13       if(p_inside && q_inside){
14           ans += (p - c).cross(q - c);
15       }else if(p_inside && !q_inside){
16           point s1 = intersectSegmentCircle(p, q, c, r)[0];
17           point s2 = intersectSegmentCircle(c, q, c, r)[0];
18           ans += (p - c).cross(s1 - c) + r*r * signed_angle(s1 - c, s2 - c);
19       }else if(!p_inside && q_inside){
20           point s1 = intersectSegmentCircle(c, p, c, r)[0];
21           point s2 = intersectSegmentCircle(p, q, c, r)[0];
22           ans += (s2 - c).cross(q - c) + r*r * signed_angle(s1 - c, s2 - c);
23       }else{
24           auto info = intersectSegmentCircle(p, q, c, r);
25           if(info.size() <= 1){
26               ans += r*r * signed_angle(p - c, q - c);
27           }else{
28               point s2 = info[0], s3 = info[1];
29               point s1 = intersectSegmentCircle(c, p, c, r)[0];
30               point s4 = intersectSegmentCircle(c, q, c, r)[0];
31               ans += (s2 - c).cross(s3 - c) + r*r * (signed_angle(s1 - c, s2 -
                    c) + signed_angle(s3 - c, s4 - c));
32           }
33       }
34   }
35   return abs(ans)/2;
36 }

```

## 6.25 Intersection Segment and Circle

```

1   vector<point> intersectSegmentCircle(const point & a, const point & b,
        const point & c, ld r){
2       //segment ab, circle with center c and radius r
3       vector<point> P = intersectLineCircle(a, b - a, c, r), ans;
4       for(const point & p : P){
5           if(pointInSegment(a, b, p)) ans.push_back(p);
6       }
7       return ans;
8   }

```

## 6.26 Line Intersection

```

1   int intersectLinesInfo(const point & a1, const point & v1, const point &
        a2, const point & v2){
2       //lines a1+tv1 and a2+tv2
3       ld det = v1.cross(v2);
4       if(eq(det, 0)){
5           if(eq((a2 - a1).cross(v1), 0)){
6               return -1; //infinity points
7           }else{
8               return 0; //no points
9           }
10      }else{
11          return 1; //single point
12      }
13  }

14
15  point intersectLines(const point & a1, const point & v1, const point &
        a2, const point & v2){
16      //lines a1+tv1, a2+tv2
17      //assuming that they intersect
18      ld det = v1.cross(v2);
19      return a1 + v1 * ((a2 - a1).cross(v2) / det);
20  }

```

## 6.27 Minkowski Sum

```

1   vector<point> minkowskiSum(vector<point> A, vector<point> B){
2       int na = (int)A.size(), nb = (int)B.size();
3       if(A.empty() || B.empty()) return {};
4
5       rotate(A.begin(), min_element(A.begin(), A.end()), A.end());
6       rotate(B.begin(), min_element(B.begin(), B.end()), B.end());
7
8       int pa = 0, pb = 0;
9       vector<point> M;
10
11      while(pa < na && pb < nb){
12          M.push_back(A[pa] + B[pb]);
13          ld x = (A[(pa + 1) % na] - A[pa]).cross(B[(pb + 1) % nb] - B[pb]);
14          if(leq(x, 0)) pb++;
15          if(geq(x, 0)) pa++;
16      }
17
18      while(pa < na) M.push_back(A[pa++] + B[0]);

```

```

19 while(pb < nb) M.push_back(B[pb++] + A[0]);
20
21 return M;
22 }

```

### 6.28 Point in Circle

```

1 int pointInCircle(const point & c, ld r, const point & p){
2     //test if point p is inside the circle with center c and radius r
3     //returns "0" if it's outside, "-1" if it's in the perimeter, "1" if
        it's inside
4     ld l = (p - c).length() - r;
5     return (le(l, 0) ? 1 : (eq(l, 0) ? -1 : 0));
6 }

```

### 6.29 Point in Convex Hull

```

1 //point in convex polygon in O(log n)
2 //make sure that P is convex and in ccw
3 //before the queries, do the preprocess on P:
4 // rotate(P.begin(), min_element(P.begin(), P.end()), P.end());
5 // int right = max_element(P.begin(), P.end()) - P.begin();
6 //returns 0 if p is outside, 1 if p is inside, -1 if p is in the
    perimeter
7 int pointInConvexPolygon(const vector<point> & P, const point & p, int
    right){
8     if(p < P[0] || P[right] < p) return 0;
9     int orientation = sgn((P[right] - P[0]).cross(p - P[0]));
10    if(orientation == 0){
11        if(p == P[0] || p == P[right]) return -1;
12        return (right == 1 || right + 1 == P.size()) ? -1 : 1;
13    }else if(orientation < 0){
14        auto r = lower_bound(P.begin() + 1, P.begin() + right, p);
15        int det = sgn((p - r[-1]).cross(r[0] - r[-1])) - 1;
16        if(det == -2) det = 1;
17        return det;
18    }else{
19        auto l = upper_bound(P.rbegin(), P.rend() - right - 1, p);
20        int det = sgn((p - l[0]).cross((l == P.rbegin() ? P[0] : l[-1]) - l
            [0])) - 1;
21        if(det == -2) det = 1;
22        return det;
23    }
24 }

```

### 6.30 Point in Line

```

1 bool pointInLine(const point & a, const point & v, const point & p){
2     //line a+tv, point p
3     return eq((p - a).cross(v), 0);
4 }

```

### 6.31 Point in Perimeter

```

1 bool pointInPerimeter(const vector<point> & P, const point & p){
2     int n = P.size();
3     for(int i = 0; i < n; i++){
4         if(pointInSegment(P[i], P[(i + 1) % n], p)){
5             return true;
6         }
7     }
8     return false;
9 }

```

### 6.32 Point in Polygon

```

1 int pointInPolygon(const vector<point> & P, const point & p){
2     if(pointInPerimeter(P, p)){
3         return -1; //point in the perimeter
4     }
5     int n = P.size();
6     int rays = 0;
7     for(int i = 0; i < n; i++){
8         rays += crossesRay(P[i], P[(i + 1) % n], p);
9     }
10    return rays & 1; //0: point outside, 1: point inside
11 }

```

### 6.33 Point in Segment

```

1 bool pointInSegment(const point & a, const point & b, const point & p){
2     //segment ab, point p
3     return pointInLine(a, b - a, p) && leq((a - p).dot(b - p), 0);
4 }

```

### 6.34 Points Tangency

```

1 pair<point, point> pointsOfTangency(const point & c, ld r, const point &
    p){

```

```

2 //point p (outside the circle), circle with center c and radius r
3 point v = (p - c).unit() * r;
4 ld d2 = (p - c).norm(), d = sqrt(d2);
5 point v1 = v * (r / d), v2 = v.perp() * (sqrt(d2 - r*r) / d);
6 return {c + v1 - v2, c + v1 + v2};
7 }

```

### 6.35 Projection Point Circle

```

1 point projectionPointCircle(const point & c, ld r, const point & p){
2 //point p (outside the circle), circle with center c and radius r
3 return c + (p - c).unit() * r;
4 }

```

### 6.36 Segment Intersection

```

1 int intersectLineSegmentInfo(const point & a, const point & v, const
  point & c, const point & d){
2 //line a+tv, segment cd
3 point v2 = d - c;
4 ld det = v.cross(v2);
5 if(eq(det, 0)){
6   if(eq((c - a).cross(v), 0)){
7     return -1; //infinity points
8   }else{
9     return 0; //no point
10  }
11 }else{
12   return sgn(v.cross(c - a)) != sgn(v.cross(d - a)); //1: single point
13   , 0: no point
14 }
15 }
16 int intersectSegmentsInfo(const point & a, const point & b, const point
  & c, const point & d){
17 //segment ab, segment cd
18 point v1 = b - a, v2 = d - c;
19 int t = sgn(v1.cross(c - a)), u = sgn(v1.cross(d - a));
20 if(t == u){
21   if(t == 0){
22     if(pointInSegment(a, b, c) || pointInSegment(a, b, d) ||
23       pointInSegment(c, d, a) || pointInSegment(c, d, b)){
24       return -1; //infinity points
25     }else{

```

```

25     return 0; //no point
26   }
27 }else{
28   return 0; //no point
29 }
30 }else{
31   return sgn(v2.cross(a - c)) != sgn(v2.cross(b - c)); //1: single
32   point, 0: no point
33 }
34 }

```

### 6.37 Smallest Enclosing Circle

```

1 pair<point, ld> mec2(vector<point> & S, const point & a, const point & b
  , int n){
2   ld hi = inf, lo = -hi;
3   for(int i = 0; i < n; ++i){
4     ld si = (b - a).cross(S[i] - a);
5     if(eq(si, 0)) continue;
6     point m = getCircle(a, b, S[i]).first;
7     ld cr = (b - a).cross(m - a);
8     if(le(si, 0)) hi = min(hi, cr);
9     else lo = max(lo, cr);
10  }
11  ld v = (ge(lo, 0) ? lo : le(hi, 0) ? hi : 0);
12  point c = (a + b) / 2 + (b - a).perp() * v / (b - a).norm();
13  return {c, (a - c).norm()};
14 }
15
16 pair<point, ld> mec(vector<point> & S, const point & a, int n){
17   random_shuffle(S.begin(), S.begin() + n);
18   point b = S[0], c = (a + b) / 2;
19   ld r = (a - c).norm();
20   for(int i = 1; i < n; ++i){
21     if(ge((S[i] - c).norm(), r)){
22       tie(c, r) = (n == S.size() ? mec(S, S[i], i) : mec2(S, a, S[i], i)
23         );
24     }
25   }
26   return {c, r};
27 }
28 pair<point, ld> smallestEnclosingCircle(vector<point> S){

```



```

29  assert(!S.empty());
30  auto r = mec(S, S[0], S.size());
31  return {r.first, sqrt(r.second)};
32  }

```

### 6.38 Smallest Enclosing Rectangle

```

1  pair<ld, ld> smallestEnclosingRectangle(vector<point> & P){
2      int n = P.size();
3      auto dot = [&](int a, int b){return (P[(a+1)%n]-P[a]).dot(P[(b+1)%n]-P
4          [b]);};
5      auto cross = [&](int a, int b){return (P[(a+1)%n]-P[a]).cross(P[(b+1)%
6          n]-P[b]);};
7      ld perimeter = inf, area = inf;
8      for(int i = 0, j = 0, k = 0, m = 0; i < n; ++i){
9          while(ge(dot(i, j), 0)) j = (j+1) % n;
10         if(!i) k = j;
11         while(ge(cross(i, k), 0)) k = (k+1) % n;
12         if(!i) m = k;
13         while(le(dot(i, m), 0)) m = (m+1) % n;
14         //pairs: (i, k) , (j, m)
15         point v = P[(i+1)%n] - P[i];
16         ld h = distancePointLine(P[i], v, P[k]);
17         ld w = distancePointLine(P[j], v.perp(), P[m]);
18         perimeter = min(perimeter, 2 * (h + w));
19         area = min(area, h * w);
20     }
21     return {area, perimeter};
22 }

```

### 6.39 Vantage Point Tree

```

1  struct vantage_point_tree{
2      struct node
3      {
4          point p;
5          ld th;
6          node *l, *r;
7      }*root;
8
9      vector<pair<ld, point>> aux;
10
11      vantage_point_tree(vector<point> &ps){
12          for(int i = 0; i < ps.size(); ++i)

```

```

13         aux.push_back({ 0, ps[i] });
14         root = build(0, ps.size());
15     }
16
17     node *build(int l, int r){
18         if(l == r)
19             return 0;
20         swap(aux[l], aux[l + rand() % (r - l)]);
21         point p = aux[l++].second;
22         if(l == r)
23             return new node({ p });
24         for(int i = l; i < r; ++i)
25             aux[i].first = (p - aux[i].second).dot(p - aux[i].second);
26         int m = (l + r) / 2;
27         nth_element(aux.begin() + l, aux.begin() + m, aux.begin() + r);
28         return new node({ p, sqrt(aux[m].first), build(l, m), build(m, r) });
29     };
30
31     priority_queue<pair<ld, node*>> que;
32
33     void k_nn(node *t, point p, int k){
34         if(!t)
35             return;
36         ld d = (p - t->p).length();
37         if(que.size() < k)
38             que.push({ d, t });
39         else if(ge(que.top().first, d)){
40             que.pop();
41             que.push({ d, t });
42         }
43         if(!t->l && !t->r)
44             return;
45         if(le(d, t->th)){
46             k_nn(t->l, p, k);
47             if(leq(t->th - d, que.top().first))
48                 k_nn(t->r, p, k);
49         }else{
50             k_nn(t->r, p, k);
51             if(leq(d - t->th, que.top().first))
52                 k_nn(t->l, p, k);
53         }
54     }

```



```

25     used[v] = true;
26     for (int u : adj[v]) {
27         if (!used[u])
28             dfs1(u);
29     }
30     order.push_back(v); // Save the vertex post-DFS for reverse ordering
31 }

```

```
32
33 // Second DFS pass on the transposed graph to label components
```

```

34 void dfs2(int v, int cl) {
35     comp[v] = cl;
36     for (int u : adj_t[v]) {
37         if (comp[u] == -1)
38             dfs2(u, cl);
39     }
40 }

```

[illegible]

```

66     }
67     return true;
68 }
69
70 // Adds a disjunction (a v b) to the implication graph
71 // 'na' and 'nb' indicate negation: if true means !a or !b
72 // Variables are 0-indexed. Bounds are inclusive for each literal (i.e
73 //   ., 0 to n_vars - 1)
74 void add_disjunction(int a, bool na, int b, bool nb) {
75     // Each variable 'x' has two nodes:
76     // x => 2*x, !x => 2*x + 1
77     // We encode (a v b) as (!a -> b) and (!b -> a)
78     a = 2 * a ^ na;
79     b = 2 * b ^ nb;
80     int neg_a = a ^ 1;
81     int neg_b = b ^ 1;
82
83     adj[neg_a].push_back(b);
84     adj[neg_b].push_back(a);
85     adj_t[b].push_back(neg_a);
86     adj_t[a].push_back(neg_b);
87 }

```

## 7.2 Articulation Points

```

1  /*
2  Articulation Points (Cut Vertices) in an Undirected Graph
3  -----
4  Indexing: 0-based
5  Node Bounds: [0, n-1] inclusive
6  Time Complexity: O(V + E)
7  Space Complexity: O(V)
8
9  Use Case:
10 - Identifies vertices whose removal increases the number of
    connected components.
11 - Works on undirected graphs (connected or disconnected).
12 */
13
14 int n; // Number of nodes in the graph
15 vector<vector<int>> adj; // Adjacency list of the undirected graph
16

```

```

17 vector<bool> visited; // Marks if a node was visited during DFS
18 vector<int> tin, low; // tin[v]: discovery time; low[v]: lowest
    discovery time reachable from subtree
19 int timer; // Global time counter for DFS
20
21 // DFS traversal to identify articulation points
22 void dfs(int v, int p = -1) {
23     visited[v] = true;
24     tin[v] = low[v] = timer++;
25     int children = 0;
26     for (int to : adj[v]) {
27         if (to == p) continue; // Skip the parent edge
28         if (visited[to]) {
29             // Back edge
30             low[v] = min(low[v], tin[to]);
31         } else {
32             dfs(to, v);
33             low[v] = min(low[v], low[to]);
34             // Articulation point condition for non-root
35             if (low[to] >= tin[v] && p != -1) {
36                 // v is an articulation point
37                 // handle_cutpoint(v);
38             }
39             ++children;
40         }
41     }
42     // Articulation point condition for root
43     if (p == -1 && children > 1) {
44         // v is an articulation point
45         // handle_cutpoint(v);
46     }
47 }
48
49 // Initializes structures and launches DFS
50 void find_cutpoints() {
51     timer = 0;
52     visited.assign(n, false);
53     tin.assign(n, -1);
54     low.assign(n, -1);
55
56     for (int i = 0; i < n; ++i) {
57         if (!visited[i])
58             dfs(i);

```

```
59 }
60 }
```

### 7.3 Bellman-Ford

```
1  /*
2  Bellman-Ford (SPFA variant) for Shortest Paths
3  -----
4  Indexing: 0-based
5  Node Bounds: [0, n-1] inclusive
6  Time Complexity: O(V * E) worst-case (amortized better)
7  Space Complexity: O(V + E)
8
9  Features:
10     - Handles negative edge weights
11     - Detects negative weight cycles (returns false if one exists)
12     - Works on directed or undirected graphs
13
14  Path Reconstruction:
15     - To recover the path from source 's' to any node 'u':
16         vector<int> path;
17         for (int v = u; v != -1; v = parent[v])
18             path.push_back(v);
19         reverse(path.begin(), path.end());
20 */
21
22 const int INF = 1<<30; // Large value to represent "infinity"
23 vector<vector<pair<int, int>>> adj; // adj[v] = list of (neighbor,
24     weight) pairs
25 vector<int> parent; // parent(n, -1) for path reconstruction
26
27 // SPFA implementation to find shortest paths from source s
28 // d[i] will contain shortest distance from s to i
29 // Returns false if a negative cycle is detected
30 // For path reconstruction add vector<int>& parent as parameter
31 bool spfa(int s, vector<int>& d, vector<int>& parent) {
32     int n = adj.size();
33     d.assign(n, INF);
34     vector<int> cnt(n, 0); // Count how many times each node has
35         been relaxed
36     vector<bool> inqueue(n, false); // Tracks if a node is currently in
37         queue
38     queue<int> q;
```

```
36
37 d[s] = 0;
38 q.push(s);
39 inqueue[s] = true;
40
41 while (!q.empty()) {
42     int v = q.front();
43     q.pop();
44     inqueue[v] = false;
45
46     for (auto edge : adj[v]) {
47         int to = edge.first;
48         int len = edge.second;
49
50         if (d[v] + len < d[to]) {
51             parent[to] = v; // For path reconstruction
52             d[to] = d[v] + len;
53             if (!inqueue[to]) {
54                 q.push(to);
55                 inqueue[to] = true;
56                 cnt[to]++;
57                 if (cnt[to] > n)
58                     return false; // Negative weight cycle detected
59             }
60         }
61     }
62 }
63
64 return true; // No negative cycles; shortest paths computed
65 }
```

### 7.4 Bipartite Checker

```
1  /*
2  Bipartite Graph Checker (BFS-based)
3  -----
4  Indexing: 0-based
5  Time Complexity: O(V + E)
6  Space Complexity: O(V)
7
8  Handles disconnected graphs
9  */
10
```

```

11 int n; // Number of nodes
12 vector<vector<int>> adj; // Adjacency list of the undirected graph
13
14 vector<int> side(n, -1); // -1 = unvisited, 0/1 = sides of bipartition
15 bool is_bipartite = true;
16 queue<int> q;
17
18 for (int st = 0; st < n; ++st) {
19     if (side[st] == -1) {
20         q.push(st);
21         side[st] = 0; // Start with side 0
22         while (!q.empty()) {
23             int v = q.front();
24             q.pop();
25             for (int u : adj[v]) {
26                 if (side[u] == -1) {
27                     // Assign opposite side to neighbor
28                     side[u] = side[v] ^ 1;
29                     q.push(u);
30                 } else {
31                     // Conflict: adjacent nodes on same side
32                     is_bipartite &= side[u] != side[v];
33                 }
34             }
35         }
36     }
37 }
38
39 cout << (is_bipartite ? "YES" : "NO") << endl;

```

## 7.5 Bipartite Maximum Matching

```

1 /*
2  Maximum Bipartite Matching (Kuhn's Algorithm)
3  -----
4  Indexing: 0-based
5  Time Complexity: O(N * (E + N)) worst case
6  Space Complexity: O(N + K + E)
7
8  Input:
9  - n: number of nodes on the left side
10 - k: number of nodes on the right side
11 - g: adjacency list where g[v] contains all right nodes adjacent to

```

```

        left node v
12
13 Output:
14 - Prints the pairs (left, right) in the matching
15 - mt[r] = 1 means right node r is matched to left node l
16 */
17
18 int n, k; // n: number of left nodes, k: number of right nodes
19 vector<vector<int>> g; // g[l]: list of right-side neighbors of left
        node l
20 vector<int> mt; // mt[r]: matched left node for right node r (or
        -1 if unmatched)
21 vector<bool> used; // used[l]: visited status for left node l during
        DFS
22
23 // Try to find an augmenting path from left node v
24 bool try_kuhn(int v) {
25     if (used[v])
26         return false;
27     used[v] = true;
28     for (int to : g[v]) {
29         if (mt[to] == -1 || try_kuhn(mt[to])) {
30             mt[to] = v;
31             return true;
32         }
33     }
34     return false;
35 }
36
37 int main() {
38     //... reading the graph ...
39
40     mt.assign(k, -1); // Right-side nodes initially unmatched
41     for (int v = 0; v < n; ++v) {
42         used.assign(n, false); // Reset visited for each left node
43         try_kuhn(v);
44     }
45     // Output matched pairs (left+1, right+1 for 1-based output)
46     for (int i = 0; i < k; ++i) {
47         if (mt[i] != -1)
48             printf("%d_%d\n", mt[i] + 1, i + 1);
49     }
50     return 0;

```

51 | }

## 7.6 Bipartite Minimum Maximum Matching2

```

1  /*
2  THIS CODE HAS NOT BEEN TESTED BEFOREHAND
3  Maximum Bipartite Matching - Hopcroft-Karp Algorithm
4  -----
5  Indexing: 0-based
6  Time Complexity: O(sqrt(V) * E)
7  Space Complexity: O(V + E)
8
9  Input:
10     - n: number of nodes on the left
11     - m: number of nodes on the right
12     - g[l]: adjacency list for left node l (list of right-side neighbors
13         )
14
15  Output:
16     - match_right[r] = l means right node r is matched to left node l
17     - match_left[l] = r means left node l is matched to right node r
18     - Function returns total number of matching pairs
19 */
20 const int INF = 1e9;
21
22 int n, m; // Number of nodes on left and right
23 vector<vector<int>> g; // Adjacency list: g[l] contains neighbors
24                       // of left node l
25 vector<int> match_left, match_right; // match_left[l], match_right[r]
26 vector<int> dist; // Distance levels for BFS
27
28 // BFS to build layer graph, returns true if there's at least one
29 // unmatched node on the right reachable from left
30 bool bfs() {
31     queue<int> q;
32     dist.assign(n, INF);
33
34     for (int l = 0; l < n; ++l) {
35         if (match_left[l] == -1) {
36             dist[l] = 0;
37             q.push(l);
38         }
39     }
40
41     while (!q.empty()) {
42         int l = q.front(); q.pop();
43         for (int r : g[l]) {
44             int matched_l = match_right[r];
45             if (matched_l == -1) {
46                 found = true; // Free right node reachable -> potential
47                             // augmenting path
48             } else if (dist[matched_l] == INF) {
49                 dist[matched_l] = dist[l] + 1;
50                 q.push(matched_l);
51             }
52         }
53     }
54
55     return found;
56 }
57
58 // DFS to find augmenting paths in the layered graph
59 bool dfs(int l) {
60     for (int r : g[l]) {
61         int matched_l = match_right[r];
62         if (matched_l == -1 || (dist[matched_l] == dist[l] + 1 && dfs(
63             matched_l))) {
64             match_left[l] = r;
65             match_right[r] = l;
66             return true;
67         }
68     }
69     dist[l] = INF;
70     return false;
71 }
72
73 // Main function to compute maximum matching
74 int hopcroft_karp() {
75     match_left.assign(n, -1);
76     match_right.assign(m, -1);
77
78     int matching = 0;
79     while (bfs()) {
80         for (int l = 0; l < n; ++l) {
81             if (match_left[l] == -1) {
82                 dfs(l);
83                 matching++;
84             }
85         }
86     }
87
88     return matching;
89 }

```

```

37 }
38
39 bool found = false;
40
41 while (!q.empty()) {
42     int l = q.front(); q.pop();
43     for (int r : g[l]) {
44         int matched_l = match_right[r];
45         if (matched_l == -1) {
46             found = true; // Free right node reachable -> potential
47                             // augmenting path
48         } else if (dist[matched_l] == INF) {
49             dist[matched_l] = dist[l] + 1;
50             q.push(matched_l);
51         }
52     }
53 }
54
55 return found;
56 }
57
58 // DFS to find augmenting paths in the layered graph
59 bool dfs(int l) {
60     for (int r : g[l]) {
61         int matched_l = match_right[r];
62         if (matched_l == -1 || (dist[matched_l] == dist[l] + 1 && dfs(
63             matched_l))) {
64             match_left[l] = r;
65             match_right[r] = l;
66             return true;
67         }
68     }
69     dist[l] = INF;
70     return false;
71 }
72
73 // Main function to compute maximum matching
74 int hopcroft_karp() {
75     match_left.assign(n, -1);
76     match_right.assign(m, -1);
77
78     int matching = 0;
79     while (bfs()) {
80         for (int l = 0; l < n; ++l) {
81             if (match_left[l] == -1) {
82                 dfs(l);
83                 matching++;
84             }
85         }
86     }
87
88     return matching;
89 }

```

```

78     for (int l = 0; l < n; ++l) {
79         if (match_left[l] == -1 && dfs(l)) {
80             ++matching;
81         }
82     }
83 }
84 return matching;
85 }
86
87 int main() {
88     cin >> n >> m;
89     g.assign(n, {});
90     int e; cin >> e;
91     while (e--) {
92         int u, v;
93         cin >> u >> v;
94         g[u].push_back(v); // u in [0, n-1], v in [0, m-1]
95     }
96
97     int res = hopcroft_karp();
98     cout << "Maximum_matching_size:_" << res << '\n';
99     for (int r = 0; r < m; ++r) {
100         if (match_right[r] != -1) {
101             cout << match_right[r] + 1 << "_" << r + 1 << '\n'; // 1-based
102                                     output
103         }
104     }
105 }

```

## 7.7 Block Cut Tree

```

1  /*
2  Block-Cut Tree from Biconnected Components
3  -----
4  Indexing: 0-based
5  Node Bounds: [0, n-1] inclusive
6  Time Complexity: O(V + E)
7  Space Complexity: O(V + E)
8
9  Features:
10 - Identifies articulation points (cut vertices)
11 - Extracts all biconnected components (BCCs)
12 - Constructs the Block-Cut Tree:

```

```

13 - Each BCC becomes a node in the tree
14 - Each articulation point becomes its own node
15 - An edge connects a BCC-node to each cutpoint in it
16
17 Output:
18 - 'is_cutpoint': true if node is an articulation point
19 - 'id[v]': node ID of 'v' in the block-cut tree
20 - Returns the block-cut tree as an adjacency list
21 */
22
23 vector<vector<int>> biconnected_components(vector<vector<int>> &g, //
24     Adjacency list of the undirected graph
25     vector<bool> &is_cutpoint, //
26     Output vector (resized
27     internally)
28     vector<int> &id) { // Output
29     vector (resized
30     internally)
31
32     int n = g.size();
33     vector<vector<int>> comps; // Stores all biconnected components
34     vector<int> stk; // Stack of visited nodes for current
35     component
36     vector<int> num(n), low(n); // DFS discovery time and low-link values
37     is_cutpoint.assign(n, false);
38
39     // DFS to find BCCs and articulation points
40     function<void(int, int, int&>> dfs = [&](int node, int parent, int &
41     timer) {
42         num[node] = low[node] = ++timer;
43         stk.push_back(node);
44         for (int son : g[node]) {
45             if (son == parent) continue;
46             if (num[son]) {
47                 // Back edge
48                 low[node] = min(low[node], num[son]);
49             } else {
50                 dfs(son, node, timer);
51                 low[node] = min(low[node], low[son]);
52                 // Check articulation point condition
53                 if (low[son] >= num[node]) {
54                     is_cutpoint[node] = (num[node] > 1 || num[son] > 2); // For
55                     root and non-root
56                 }
57             }
58         }
59     };
60     dfs(0, -1, 0);
61     return {comps, is_cutpoint, id};
62 }

```

```

48     comps.push_back({node});
49     while (comps.back().back() != son) {
50         comps.back().push_back(stk.back());
51         stk.pop_back();
52     }
53 }
54 }
55 }
56 };
57
58 int timer = 0;
59 dfs(0, -1, timer);
60
61 id.resize(n); // Maps each original node to its block-cut tree node ID
62
63 // Build block-cut tree using articulation points and BCCs
64 function<vector<vector<int>>>()> build_tree = [&]() {
65     vector<vector<int>> t(1); // Dummy index 0 (not used)
66     int node_id = 1; // Start assigning block-cut tree IDs from 1
67     // Assign unique tree node IDs to cutpoints
68     for (int node = 0; node < n; ++node) {
69         if (is_cutpoint[node]) {
70             id[node] = node_id++;
71             t.push_back({});
72         }
73     }
74     // Assign each component a new node and connect it to its cutpoints
75     for (auto &comp : comps) {
76         int bcc_node = node_id++;
77         t.push_back({});
78         for (int u : comp) {
79             if (!is_cutpoint[u]) {
80                 id[u] = bcc_node;
81             } else {
82                 t[bcc_node].push_back(id[u]);
83                 t[id[u]].push_back(bcc_node);
84             }
85         }
86     }
87     return t;
88 };
89
90 return build_tree(); // Return the block-cut tree

```

```

91 }

```

## 7.8 Blossom

```

1  /*
2  Edmonds' Blossom Algorithm (Maximum Matching in General Graphs)
3  -----
4  Indexing: 1-based
5  Node Bounds: [1, n]
6  Time Complexity: O(n^3) in worst case
7  Space Complexity: O(n^2)
8
9  Features:
10     - Handles odd-length cycles (blossoms)
11     - Works on any undirected graph (not just bipartite)
12     - Uses BFS with blossom contraction and path augmentation
13
14  Input:
15     - n: number of vertices
16     - add_edge(u, v): undirected edges between nodes (1 <= u,v <= n)
17
18  Output:
19     - maximum_matching(): returns size of max matching
20     - match[u]: matched vertex for node u (or 0 if unmatched)
21  */
22
23 const int N = 2009;
24 mt19937 rnd(chrono::steady_clock::now().time_since_epoch().count());
25
26 struct Blossom {
27     int vis[N]; // vis[u]: -1 = unvisited, 0 = in queue, 1 = outer
28     layer
29     int par[N]; // par[u]: parent in alternating tree
30     int orig[N]; // orig[u]: base of blossom u belongs to
31     int match[N]; // match[u]: matched partner of u (0 if unmatched)
32     int aux[N]; // aux[u]: visit marker for LCA
33     int t; // global timestamp for LCA markers
34     int n; // number of nodes
35     bool ad[N]; // ad[u]: whether u is reachable in an alternating
36     path
37     vector<int> g[N]; // g[u]: adjacency list
38     queue<int> Q; // BFS queue
39

```

```

38 // Constructor: initializes data for n nodes
39 Blossom() {}
40 Blossom(int _n) {
41     n = _n;
42     t = 0;
43     for (int i = 0; i <= n; ++i) {
44         g[i].clear();
45         match[i] = par[i] = vis[i] = aux[i] = ad[i] = orig[i] = 0;
46     }
47 }
48
49 void add_edge(int u, int v) {
50     g[u].push_back(v);
51     g[v].push_back(u);
52 }
53
54 // Augment the matching along the alternating path from u to v
55 void augment(int u, int v) {
56     int pv = v, nv;
57     do {
58         pv = par[v];
59         nv = match[pv];
60         match[v] = pv;
61         match[pv] = v;
62         v = nv;
63     } while (u != pv);
64 }
65
66 int lca(int v, int w) {
67     ++t; // Increment timestamp for LCA markers
68     while (true) {
69         if (v) {
70             if (aux[v] == t) return v;
71             aux[v] = t;
72             v = orig[par[match[v]]]; // Move to the parent in the
                                   // alternating tree
73         }
74         swap(v, w);
75     }
76 }
77
78 // Contract a blossom from v and w with common ancestor a
79 void blossom(int v, int w, int a) {

```

```

80     while (orig[v] != a) {
81         par[v] = w;
82         w = match[v];
83         ad[v] = true;
84         if (vis[w] == 1) Q.push(w), vis[w] = 0;
85         orig[v] = orig[w] = a;
86         v = par[w];
87     }
88 }
89
90 // Find augmenting path starting from unmatched node u
91 bool bfs(int u) {
92     fill(vis + 1, vis + n + 1, -1);
93     iota(orig + 1, orig + n + 1, 1);
94     Q = queue<int>();
95     Q.push(u);
96     vis[u] = 0;
97
98     while (!Q.empty()) {
99         int v = Q.front(); Q.pop();
100         ad[v] = true;
101         for (int x : g[v]) {
102             if (vis[x] == -1) {
103                 par[x] = v;
104                 vis[x] = 1;
105                 if (!match[x]) {
106                     augment(u, x);
107                     return true;
108                 }
109                 Q.push(match[x]);
110                 vis[match[x]] = 0;
111             } else if (vis[x] == 0 && orig[v] != orig[x]) {
112                 int a = lca(orig[v], orig[x]);
113                 blossom(x, v, a);
114                 blossom(v, x, a);
115             }
116         }
117     }
118     return false;
119 }
120
121 // Computes maximum matching and returns the size
122 int maximum_matching() {

```



```

123     int ans = 0;
124     vector<int> p(n - 1);
125     iota(p.begin(), p.end(), 1);
126     shuffle(p.begin(), p.end(), rnd);
127     for (int i = 1; i <= n; ++i) {
128         shuffle(g[i].begin(), g[i].end(), rnd);
129     }
130
131     // Greedy matching: try to match unmatched nodes directly
132     for (int u : p) {
133         if (!match[u]) {
134             for (int v : g[u]) {
135                 if (!match[v]) {
136                     match[u] = v;
137                     match[v] = u;
138                     ++ans;
139                     break;
140                 }
141             }
142         }
143     }
144
145     // Augmenting path phase
146     for (int i = 1; i <= n; ++i) {
147         if (!match[i] && bfs(i)) ++ans;
148     }
149
150     return ans;
151 }
152 } M;
153
154 int main() {
155     ios_base::sync_with_stdio(0);
156     cin.tie(0);
157
158     int t;
159     cin >> t;
160     while (t--) {
161         int n, m;
162         cin >> n >> m;
163         M = Blossom(n);
164         // Read all edges
165         for (int i = 0; i < m; i++) {

```

```

166         int u, v;
167         cin >> u >> v;
168         M.add_edge(u, v);
169     }
170     // Compute max matching
171     int matched = M.maximum_matching();
172     if (matched * 2 == n) {
173         // Perfect matching
174         cout << 0 << '\n';
175     } else {
176         // Find reachable unmatched nodes in alternating trees
177         memset(M.ad, 0, sizeof M.ad);
178         for (int i = 1; i <= n; i++) {
179             if (M.match[i] == 0) M.bfs(i);
180         }
181         int unmatched_reachable = 0;
182         for (int i = 1; i <= n; i++) {
183             unmatched_reachable += M.ad[i];
184         }
185         cout << unmatched_reachable << '\n';
186     }
187 }
188 return 0;
189 }

```

## 7.9 Bridges

```

1  /*
2  Bridge-Finding in an Undirected Graph
3  -----
4  Indexing: 0-based
5  Node Bounds: [0, n-1] inclusive
6  Time Complexity: O(V + E)
7  Space Complexity: O(V)
8
9  Input:
10     n    - Number of nodes in the graph
11     adj  - Adjacency list of the undirected graph
12
13  Output:
14     - Call 'find_bridges()' to populate bridge information.
15     - Modify the DFS 'Bridge' section to store or print the bridges.
16     A bridge is an edge (v, to) such that removing it increases the

```

```

        number of connected components.
17 */
18
19 int n; // Number of nodes
20 vector<vector<int>> adj; // Adjacency list
21
22 vector<bool> visited; // Marks visited nodes
23 vector<int> tin, low; // tin[v]: discovery time; low[v]: lowest ancestor
    reachable
24 int timer; // Global DFS timer
25
26 // DFS to detect bridges
27 void dfs(int v, int p = -1) {
28     visited[v] = true;
29     tin[v] = low[v] = timer++;
30     for (int to : adj[v]) {
31         if (to == p) continue; // Skip edge to parent
32         if (visited[to]) {
33             // Back edge
34             low[v] = min(low[v], tin[to]);
35         } else {
36             dfs(to, v);
37             low[v] = min(low[v], low[to]);
38             // Bridge condition: if no back edge connects subtree rooted at '
                to' to ancestors of 'v'
39             if (low[to] > tin[v]) {
40                 // (v, to) is a bridge
41                 // Example: bridges.push_back({v, to});
42             }
43         }
44     }
45 }
46
47 // Initialize tracking structures and run DFS
48 void find_bridges() {
49     timer = 0;
50     visited.assign(n, false);
51     tin.assign(n, -1);
52     low.assign(n, -1);
53     for (int i = 0; i < n; ++i) {
54         if (!visited[i])
55             dfs(i);
56     }

```

57 }

## 7.10 Bridges Online

```

1  /*
2  Online Bridge-Finding (Dynamic Edge Insertion)
3  -----
4  Indexing: 0-based
5  Node Bounds: [0, n-1] inclusive
6  Time Complexity:
7      - Amortized  $O(\log^2 N)$  per edge addition
8  Space Complexity:  $O(V)$ 
9
10 Features:
11     - Maintains the number of bridges dynamically as edges are added one
        by one.
12     - Detects if adding an edge merges different 2-edge-connected
        components.
13     - No deletions supported.
14
15 Input:
16     init(n)      - Initializes the data structure for a graph with n
        nodes.
17     add_edge(a, b) - Adds an undirected edge between nodes a and b.
18
19 Output:
20     'bridges' - Global variable representing the current number of
        bridges.
21 */
22
23 vector<int> par, dsu_2ecc, dsu_cc, dsu_cc_size;
24 int bridges; // Number of bridges in the graph
25 int lca_iteration;
26 vector<int> last_visit;
27
28 // Initializes the data structures
29 void init(int n) {
30     par.resize(n);
31     dsu_2ecc.resize(n);
32     dsu_cc.resize(n);
33     dsu_cc_size.resize(n);
34     last_visit.assign(n, 0);
35     lca_iteration = 0;

```

```

36 bridges = 0;
37
38 for (int i = 0; i < n; ++i) {
39     par[i] = -1;
40     dsu_2ecc[i] = i;
41     dsu_cc[i] = i;
42     dsu_cc_size[i] = 1;
43 }
44 }
45
46 // Finds the representative of the 2-edge-connected component of node v
47 int find_2ecc(int v) {
48     if (v == -1) return -1;
49     return dsu_2ecc[v] == v ? v : dsu_2ecc[v] = find_2ecc(dsu_2ecc[v]);
50 }
51
52 // Finds the connected component representative of the component
53 // containing v
54 int find_cc(int v) {
55     v = find_2ecc(v);
56     return dsu_cc[v] == v ? v : dsu_cc[v] = find_cc(dsu_cc[v]);
57 }
58
59 // Makes node v the root of its tree, rerouting parent pointers upward
60 void make_root(int v) {
61     int root = v;
62     int child = -1;
63     while (v != -1) {
64         int p = find_2ecc(par[v]);
65         par[v] = child;
66         dsu_cc[v] = root;
67         child = v;
68         v = p;
69     }
70     dsu_cc_size[root] = dsu_cc_size[child];
71 }
72
73 // Merges paths from a and b to their lowest common ancestor in the 2ECC
74 // forest
75 void merge_path(int a, int b) {
76     ++lca_iteration;
77     vector<int> path_a, path_b;
78     int lca = -1;

```

```

77
78 while (lca == -1) {
79     if (a != -1) {
80         a = find_2ecc(a);
81         path_a.push_back(a);
82         if (last_visit[a] == lca_iteration) {
83             lca = a;
84             break;
85         }
86         last_visit[a] = lca_iteration;
87         a = par[a];
88     }
89     if (b != -1) {
90         b = find_2ecc(b);
91         path_b.push_back(b);
92         if (last_visit[b] == lca_iteration) {
93             lca = b;
94             break;
95         }
96         last_visit[b] = lca_iteration;
97         b = par[b];
98     }
99 }
100
101 // Merge all nodes on path_a and path_b into the same 2ECC
102 for (int v : path_a) {
103     dsu_2ecc[v] = lca;
104     if (v == lca) break;
105     --bridges;
106 }
107 for (int v : path_b) {
108     dsu_2ecc[v] = lca;
109     if (v == lca) break;
110     --bridges;
111 }
112 }
113
114 // Adds an undirected edge between a and b and updates bridge count
115 void add_edge(int a, int b) {
116     a = find_2ecc(a);
117     b = find_2ecc(b);
118     if (a == b) return; // Already in the same 2ECC
119

```

```

120 int ca = find_cc(a);
121 int cb = find_cc(b);
122
123 if (ca != cb) {
124     // Bridge found - connects two different components
125     ++bridges;
126     // Union by size
127     if (dsu_cc_size[ca] > dsu_cc_size[cb]) {
128         swap(a, b);
129         swap(ca, cb);
130     }
131     make_root(a);
132     par[a] = b;
133     dsu_cc[a] = b;
134     dsu_cc_size[cb] += dsu_cc_size[a];
135 } else {
136     // No new bridge, but must merge paths to unify 2ECCs
137     merge_path(a, b);
138 }
139 }
140
141 // Example usage
142 int main() {
143     init(n);
144     for (auto [u, v] : edges) {
145         add_edge(u, v);
146         cout << "Current_bridge_count: " << bridges << '\n';
147     }
148 }

```

## 7.11 Dijkstra

```

1 vector<vector<pair<int, int>>> adj(n); // Adjacency list (node, weight)
2 vector<ll> dist(n, 1LL << 61); // Distance array initialized to infinity
3
4 priority_queue<pair<ll, int>> q; // Max-heap, so we push negative
   weights to simulate min-heap
5 dist[0] = 0; // Starting node distance
6 q.push({0, 0}); // (distance, vertex)
7
8 while (!q.empty()) {
9     auto [w, v] = q.top(); q.pop();
10    w = -w; // Convert back to positive

```

```

11    if (w > dist[v]) continue; // Skip outdated entry
12    for (auto [u, cost] : adj[v]) {
13        if (dist[v] + cost < dist[u]) {
14            dist[u] = dist[v] + cost;
15            q.push({-dist[u], u}); // Push updated distance (negated)
16        }
17    }
18 }

```

## 7.12 Eulerian Path

An Eulerian Path is a path that passes through every edge once. For an undirected graph an eulerian path exists if the degree of every node is even or the degree of exactly two nodes is odd. In the first case, the eulerian path is also an eulerian circuit or cycle. In a directed graph, an eulerian path exists if at most one node has  $out_i - in_i = 1$  and at most one node has  $in_i - out_i = 1$ . A cycle exists if  $in_i - out_i = 0$  for all  $i$ .

```

1 /*
2  Eulerian Path (Hierholzer's Algorithm)
3  This will find an Eulerian Circuit.
4  For directed graph eulerian path must start on vertex with outdegree[i]
   ] == indegree[i] + 1 and ends on indegree[i] = outdegree[i] + 1.
5  For directed graph eulerian Cycle only exists if indegree[i] =
   outdegree[i] for all i.
6  For undirected graph eulerian path must start on vertex with odd
   degree and will end in the other vertex with odd degree.
7  For undirected graph eulerian Cycle only exists degree is even for all
   vertices.
8
9  -----
10 Time Complexity: O(E)
11 Space Complexity: O(V + E)
12
13 Input:
14 - g: adjacency list of the graph
15   * Directed: vector<vector<pair<int, int>>> g
16     where g[v] = list of {to, edge_index}
17   * Undirected: vector<vector<int>>> g
18     where g[v] = list of neighbors
19 - seen: vector<bool> seen(E) - only needed for directed version
20 - path: vector<int> path - will be filled in reverse order of
   traversal
21   reverse(path.begin(), path.end());

```

```

22 */
23
24 // Directed Version //
25 void dfs_directed(int node) {
26     while (!g[node].empty()) {
27         auto [son, idx] = g[node].back();
28         g[node].pop_back();
29         if (seen[idx]) continue; // Skip if edge already visited
30         seen[idx] = true;
31         dfs_directed(son);
32     }
33     path.push_back(node); // Post-order insertion (reverse of actual path)
34 }
35
36 // Undirected Version //
37 // Be careful with graph not being connected. Add set to not repeat
38 // edges(going from u to v and then from v to u)
39 void dfs_undirected(int node) {
40     while (!g[node].empty()) {
41         int son = g[node].back();
42         g[node].pop_back();
43         dfs_undirected(son);
44     }
45     path.push_back(node); // Post-order insertion
46 }

```

### 7.13 Floyd-Warshall

```

1 /*
2 Floyd-Warshall Algorithm (All-Pairs Shortest Paths)
3 -----
4 Indexing: 0-based
5 Time Complexity:  $O(V^3)$ 
6 Space Complexity:  $O(V^2)$ 
7
8 Input:
9 - d: distance matrix of size n x n
10   * d[i][j] should be initialized as:
11     - 0 if i == j
12     - weight of edge (i, j) if exists
13     - INF (e.g. 1e18) otherwise
14 */

```

```

15 vector<vector<ll>> d(n, vector<ll>(n, 1e18)); // distance matrix
16
17 // This version is by default adapted for UNDIRECTED graphs.
18 for (int k = 0; k < n; k++) {
19     for (int i = 0; i < n; i++) {
20         for (int j = i + 1; j < n; j++) { // For directed graphs, use j = 0;
21             j < n; j++
22             long long new_dist = d[i][k] + d[k][j];
23             if (new_dist < d[i][j]) {
24                 d[i][j] = d[j][i] = new_dist; // update both directions for
25                 // undirected graph
26             }
27         }
28     }
29 }

```

### 7.14 Kruskal

```

1 /*
2 Kruskal's Algorithm (Minimum Spanning Tree - MST)
3 -----
4 Indexing: 0-based for nodes in edges
5 Time Complexity:  $O(E \log E)$ 
6 Space Complexity:  $O(N)$ 
7
8 Input:
9 - N: number of nodes
10 - edges: list of weighted edges in form {weight, {u, v}}
11
12 Output:
13 - Returns total weight of the MST if the graph is connected
14 - Returns -1 if MST cannot be formed (i.e., graph is disconnected)
15
16 Note:
17 - Requires a Disjoint Set Union (DSU) / Union-Find data structure
18   with:
19   - unite(a, b): merges components, returns true if successful
20   - size(v): returns size of component containing v
21 */
22
23 template <class T>
24 T kruskal(int N, vector<pair<T, pair<int, int>>> edges) {

```

```

24 sort(edges.begin(), edges.end()); // Sort by weight (non-decreasing)
25 T ans = 0;
26 DSU D(N); // Disjoint Set Union for N nodes
27 for (auto &[w, uv] : edges) {
28     int u = uv.first, v = uv.second;
29     if (D.unite(u, v)) {
30         ans += w; // Add edge to MST if u and v are in different
                    // components
31     }
32 }
33 // Check if MST spans all nodes (i.e., one component of size N)
34 return (D.size(0) == N ? ans : -1);
35 }

```

## 7.15 Marriage

```

1  /*
2  Male-Optimal Stable Marriage Problem (Gale-Shapley Algorithm)
3  -----
4  Indexing: 0-based
5  Bounds: 0 <= i, j < n
6  Time Complexity: O(n^2)
7  Space Complexity: O(n^2)
8
9  Input:
10 - n: Number of men/women (equal)
11 - gv[i][j]: j-th most preferred woman for man i
12 - om[i][j]: j-th most preferred man for woman i
13   * Both are permutations of {0, ..., n-1}
14   * om must be inverted to get om[w][m] = woman w's ranking of man
    m
15
16 Output:
17 - pm[i]: Woman matched to man i (i.e. pairings)
18 - pv[i]: Man matched to woman i
19 */
20
21 #define MAXN 1000
22 int gv[MAXN][MAXN], om[MAXN][MAXN]; // Male and female preference lists
23 int pv[MAXN], pm[MAXN]; // pv[woman] = man, pm[man] = woman
24 int pun[MAXN]; // pun[man] = next woman to propose
    to
25

```

```

26 void stableMarriage(int n) {
27     fill_n(pv, n, -1); // All women initially unmatched
28     fill_n(pm, n, -1); // All men initially unmatched
29     fill_n(pun, n, 0); // Each man starts at his top preference
30
31     int unmatched = n; // Number of free men
32     int i = n - 1; // Current man index (rotates over all men)
33
34     #define engage pm[j] = i; pv[i] = j;
35
36     while (unmatched) {
37         while (pm[i] == -1) {
38             int j = gv[i][pun[i]++]; // Next woman on man i's list
39
40             if (pv[j] == -1) {
41                 // Woman j is free -> engage with man i
42                 unmatched--;
43                 engage;
44             } else if (om[j][i] < om[j][pv[j]]) {
45                 // Woman j prefers i over her current partner
46                 int loser = pv[j];
47                 pm[loser] = -1;
48                 engage;
49                 i = loser; // Reconsider the rejected man
50             }
51         }
52
53         // Move to next unmatched man
54         i--;
55         if (i < 0) i = n - 1;
56     }
57
58     #undef engage
59 }

```

## 7.16 SCC

```

1  /*
2  Strongly Connected Components (Kosaraju's Algorithm)
3  -----
4  Indexing: 0-based
5  Time Complexity: O(V + E)
6  Space Complexity: O(V + E)

```

```

7
8 Input:
9   - n: number of nodes
10  - m: number of directed edges
11  - adj: original graph
12  - adjr: reversed graph
13
14 Output:
15   - comp[i]: component ID of node i
16   - order[]: nodes in reverse post-order (1st DFS)
17   - nc: is the number of unique comp values
18 */
19
20 vector<vector<int>> adj, adjr;
21 vector<bool> vis;
22 vector<int> order, comp;
23
24 // First DFS: post-order on original graph
25 void dfs(int v) {
26     vis[v] = true;
27     for (int u : adj[v]) {
28         if (!vis[u])
29             dfs(u);
30     }
31     order.push_back(v); // Record post-order
32 }
33
34 // Second DFS: assign component IDs on reversed graph
35 void dfsr(int v, int k) {
36     vis[v] = true;
37     comp[v] = k;
38     for (int u : adjr[v]) {
39         if (!vis[u])
40             dfsr(u, k);
41     }
42 }
43
44 void solve() {
45     int n, m;
46     cin >> n >> m;
47     adj.assign(n, vector<int>());
48     adjr.assign(n, vector<int>());
49     comp.resize(n);

```

```

50 // Read edges and build both original and reversed graphs
51 for (int i = 0; i < m; i++) {
52     int a, b;
53     cin >> a >> b;
54     a--; b--;
55     adj[a].push_back(b);
56     adjr[b].push_back(a);
57 }
58 // First pass: DFS on original graph to get order
59 vis.assign(n, false);
60 order.clear();
61 for (int i = 0; i < n; i++) {
62     if (!vis[i]) dfs(i);
63 }
64 // Second pass: DFS on reversed graph using reverse post-order
65 vis.assign(n, false);
66 int nc = 0;
67 for (int i = n - 1; i >= 0; i--) {
68     int v = order[i];
69     if (!vis[v]) {
70         dfsr(v, nc++);
71     }
72 }
73 // comp[i] now holds the component ID for node i (0-based)
74 // nc = number of strongly connected components
75 }

```

## 7.17 Stoer-Wagner

```

1 /*
2
3     -----
4
5     Solves the minimum cut problem in undirected weighted graphs with non-
6     negative weights.
7
8     Time Complexity:  $O(V^3)$ 
9     Space Complexity:  $O(V^2)$ 
10 */
11 mt19937 rnd(chrono::steady_clock::now().time_since_epoch().count());
12 struct StoerWagner {
13     int n;

```

```

13 long long G[N][N], dis[N];
14 int idx[N];
15 bool vis[N];
16 const long long inf = 1e18;
17 StoerWagner() {}
18 StoerWagner(int _n) {
19     n = _n;
20     memset(G, 0, sizeof G);
21 }
22 void add_edge(int u, int v, long long w) { //undirected edge, multiple
    edges are merged into one edge
23     if (u != v) {
24         G[u][v] += w;
25         G[v][u] += w;
26     }
27 }
28 long long solve() {
29     long long ans = inf;
30     for (int i = 0; i < n; ++ i) idx[i] = i + 1;
31     shuffle(idx, idx + n, rnd);
32     while (n > 1) {
33         int t = 1, s = 0;
34         for (int i = 1; i < n; ++ i) {
35             dis[idx[i]] = G[idx[0]][idx[i]];
36             if (dis[idx[i]] > dis[idx[t]]) t = i;
37         }
38         memset(vis, 0, sizeof vis);
39         vis[idx[0]] = true;
40         for (int i = 1; i < n; ++ i) {
41             if (i == n - 1) {
42                 if (ans > dis[idx[t]]) ans = dis[idx[t]]; //idx[s] - idx[t] is
                    in two halves of the mincut
43                 if (ans == 0) return 0;
44                 for (int j = 0; j < n; ++ j) {
45                     G[idx[s]][idx[j]] += G[idx[j]][idx[t]];
46                     G[idx[j]][idx[s]] += G[idx[j]][idx[t]];
47                 }
48                 idx[t] = idx[-- n];
49             }
50             vis[idx[t]] = true;
51             s = t;
52             t = -1;
53             for (int j = 1; j < n; ++ j) {

```

```

54         if (!vis[idx[j]]) {
55             dis[idx[j]] += G[idx[s]][idx[j]];
56             if (t == -1 || dis[idx[t]] < dis[idx[j]]) t = j;
57         }
58     }
59 }
60 }
61 return ans;
62 }
63 };
64
65 int32_t main() {
66     ios_base::sync_with_stdio(0);
67     cin.tie(0);
68     int t, cs = 0;
69     cin >> t;
70     while (t--) {
71         int n, m;
72         cin >> n >> m;
73         StoerWagner st(n);
74         while (m--) {
75             int u, v, w;
76             cin >> u >> v >> w;
77             st.add_edge(u, v, w);
78         }
79         cout << "Case_#" << ++cs << ":_#" << st.solve() << '\n';
80     }
81     return 0;
82 }

```

## 8 Linear Algebra

### 8.1 Gaussian Elimination

```

1  /*
2  Gaussian elimination
3  -----
4  Utilized for solving linear systems of equations.
5
6  If the system is modulo 2, use GaussianEliminationModulo instead.
7
8  Time Complexity: O(n ^ 3)
9  */

```



```

10
11
12 const double eps = 1e-9;
13 int Gauss(vector<vector<double>> a, vector<double> &ans) {
14     int n = (int)a.size(), m = (int)a[0].size() - 1;
15     vector<int> pos(m, -1);
16     double det = 1; int rank = 0;
17     for(int col = 0, row = 0; col < m && row < n; ++col) {
18         int mx = row;
19         for(int i = row; i < n; i++) if(fabs(a[i][col]) > fabs(a[mx][col]))
20             mx = i;
21         if(fabs(a[mx][col]) < eps) {det = 0; continue;}
22         for(int i = col; i <= m; i++) swap(a[row][i], a[mx][i]);
23         if (row != mx) det = -det;
24         det *= a[row][col];
25         pos[col] = row;
26         for(int i = 0; i < n; i++) {
27             if(i != row && fabs(a[i][col]) > eps) {
28                 double c = a[i][col] / a[row][col];
29                 for(int j = col; j <= m; j++) a[i][j] -= a[row][j] * c;
30             }
31         }
32         ++row; ++rank;
33     }
34     ans.assign(m, 0);
35     for(int i = 0; i < m; i++) {
36         if(pos[i] != -1) ans[i] = a[pos[i]][m] / a[pos[i]][i];
37     }
38     for(int i = 0; i < n; i++) {
39         double sum = 0;
40         for(int j = 0; j < m; j++) sum += ans[j] * a[i][j];
41         if(fabs(sum - a[i][m]) > eps) return -1; //no solution
42     }
43     for(int i = 0; i < m; i++) if(pos[i] == -1) return 2; //infinte
44     return 1; //unique solution
45 }
46 int main() {
47     int n, m; cin >> n >> m;
48     vector< vector<double> > v(n);
49     for(int i = 0; i < n; i++) {
50         for(int j = 0; j <= m; j++) {

```

```

51         }
52     }
53     vector<double> ans;
54     int k = Gauss(v, ans);
55     if(k) for(int i = 0; i < n; i++) cout << fixed << setprecision(5) <<
56         ans[i] << ' ';
57     else cout << "no solution\n";
58     return 0;
59 }

```

## 8.2 Gaussian Elimination Modulo

```

1  /*
2  Gaussian elimination Modulo 2
3  -----
4  Utilized for solving linear systems of equations modulo2.
5
6  Time Complexity: O(n ^ 3)
7  */
8
9  //n = number of equations, m = number of variables
10 int Gauss(int n, int m, vector<bitset<N>> a, bitset<N> &ans) {
11     //reversing for lexocgraphically largest solution
12     for (int i = 0; i < n; i++) {
13         bitset<N> tmp;
14         for (int j = 0; j < m; j++) tmp[j] = a[i][m - j - 1];
15         tmp[m] = a[i][m];
16         a[i] = tmp;
17     }
18     int rank = 0, det = 1;
19     vector<int> pos(N, -1);
20     for(int col = 0, row = 0; col < m && row < n; ++col) {
21         int mx = row;
22         for(int i = row; i < n; ++i) if(a[i][col]) { mx = i; break; }
23         if(!a[mx][col]) { det = 0; continue; }
24         swap(a[mx], a[row]);
25         if(row != mx) det = det == 0 ? 0 : 1;
26         det &= a[row][col];
27         pos[col] = row;
28         //forward elimination
29         for(int i = row + 1; i < n; ++i) if (i != row && a[i][col]) a[i] ^=
30             a[row];

```

```

31 }
32 ans.reset();
33 //backward substitution
34 for (int i = m - 1; i >= 0; i--) {
35     if (pos[i] == -1) ans[i] = true;
36     else {
37         int k = pos[i];
38         for (int j = i + 1; j < m; j++) if (a[k][j]) ans[i] = ans[i] ^
39             ans[j];
40         ans[i] = ans[i] ^ a[k][m];
41     }
42 }
43 for(int i = rank; i < n; ++i) if(a[i][m]) return -1; //no solution
44 //reversing again beacuse we reversed earlier
45 bitset<N> tmp;
46 for (int j = 0; j < m; j++) tmp[j] = ans[m - j - 1];
47 ans = tmp;
48 int free_var = 0;
49 for(int i = 0; i < m; ++i) if(pos[i] == -1) free_var++;
50 return free_var; //has solution
51 }
52 string read() {
53     string t;
54     if(!(cin >> t)) return "";
55     if(t.empty() || t == "and") return "";
56     while(t[0] == '(') t.erase(t.begin());
57     while(t.back() == ')') t.pop_back();
58     return t;
59 }
60 bool is_var(string t) { return t.size() > 0 && t[0] == 'x'; }
61 int get_var(string t) { return atoi(t.substr(1).c_str()) - 1; }
62 int32_t main() {
63     ios_base::sync_with_stdio(0);
64     cin.tie(0);
65     int n, m; cin >> n >> m;
66     vector<bitset<N>> bs(n, bitset<N>(0));
67     for(int i = 0; i < n; i++) {
68         string s;
69         bool eq = 1;
70         while((s = read()).size() > 0) {
71             if(is_var(s)) {
72                 int x = get_var(s);
73                 bs[i][x] = bs[i][x] ^ 1;

```

```

73     }
74     else if(s == "not") eq ^= 1;
75 }
76 bs[i][m] = eq;
77 }
78 bitset<N> ans;
79 int ok = Gauss(n, m, bs, ans);
80 if (ok == -1) cout << "impossible\n";
81 else {
82     for (int i = 0; i < m; i++) cout << "FT"[ans[i]]; cout << '\n';
83 }
84 return 0;
85 }
86 //https://codeforces.com/gym/101908/problem/M

```

### 8.3 Simplex

```

1  /*
2  Parametric Self-Dual Simplex method
3  Solve a canonical LP:
4      min or max. c x
5      s.t. A x <= b
6      x >= 0
7  */
8  #include <bits/stdc++.h>
9  using namespace std;
10 const double eps = 1e-9, oo = numeric_limits<double>::infinity();
11
12 typedef vector<double> vec;
13 typedef vector<vec> mat;
14
15 pair<vec, double> simplexMethodPD(const mat &A, const vec &b, const vec
16     &c, bool mini = true){
17     int n = c.size(), m = b.size();
18     mat T(m + 1, vec(n + m + 1));
19     vector<int> base(n + m), row(m);
20
21     for(int j = 0; j < m; ++j){
22         for(int i = 0; i < n; ++i)
23             T[j][i] = A[j][i];
24         row[j] = n + j;
25         T[j][n + j] = 1;
26         base[n + j] = 1;

```

```

26     T[j][n + m] = b[j];
27 }
28
29 for(int i = 0; i < n; ++i)
30     T[m][i] = c[i] * (mini ? 1 : -1);
31
32 while(true){
33     int p = 0, q = 0;
34     for(int i = 0; i < n + m; ++i)
35         if(T[m][i] <= T[m][p])
36             p = i;
37
38     for(int j = 0; j < m; ++j)
39         if(T[j][n + m] <= T[q][n + m])
40             q = j;
41
42     double t = min(T[m][p], T[q][n + m]);
43
44     if(t >= -eps){
45         vec x(n);
46         for(int i = 0; i < m; ++i)
47             if(row[i] < n) x[row[i]] = T[i][n + m];
48         return {x, T[m][n + m] * (mini ? -1 : 1)}; // optimal
49     }
50
51     if(t < T[q][n + m]){
52         // tight on c -> primal update
53         for(int j = 0; j < m; ++j)
54             if(T[j][p] >= eps)
55                 if(T[j][p] * (T[q][n + m] - t) >= T[q][p] * (T[j][n + m] - t))
56                     q = j;
57
58         if(T[q][p] <= eps)
59             return {vec(n), oo * (mini ? 1 : -1)}; // primal infeasible
60     }else{
61         // tight on b -> dual update
62         for(int i = 0; i < n + m + 1; ++i)
63             T[q][i] = -T[q][i];
64
65         for(int i = 0; i < n + m; ++i)
66             if(T[q][i] >= eps)
67                 if(T[q][i] * (T[m][p] - t) >= T[q][p] * (T[m][i] - t))
68                     p = i;

```

```

69
70     if(T[q][p] <= eps)
71         return {vec(n), oo * (mini ? -1 : 1)}; // dual infeasible
72 }
73
74 for(int i = 0; i < m + n + 1; ++i)
75     if(i != p) T[q][i] /= T[q][p];
76
77 T[q][p] = 1; // pivot(q, p)
78 base[p] = 1;
79 base[row[q]] = 0;
80 row[q] = p;
81
82 for(int j = 0; j < m + 1; ++j){
83     if(j != q){
84         double alpha = T[j][p];
85         for(int i = 0; i < n + m + 1; ++i)
86             T[j][i] -= T[q][i] * alpha;
87     }
88 }
89 }
90
91 return {vec(n), oo};
92 }
93
94 int main(){
95     int m, n;
96     bool mini = true;
97     cout << "Numero_de_restricciones:_";
98     cin >> m;
99     cout << "Numero_de_incognitas:_";
100    cin >> n;
101    mat A(m, vec(n));
102    vec b(m), c(n);
103    for(int i = 0; i < m; ++i){
104        cout << "Restriccion_#" << (i + 1) << ":_";
105        for(int j = 0; j < n; ++j){
106            cin >> A[i][j];
107        }
108        cin >> b[i];
109    }
110    cout << "[0]Max_o_1]Min?:_";
111    cin >> mini;

```

```

112 cout << "Coeficientes de" << (mini ? "min" : "max") << "z:";
113 for(int i = 0; i < n; ++i){
114     cin >> c[i];
115 }
116 cout.precision(6);
117 auto ans = simplexMethodPD(A, b, c, mini);
118 cout << (mini ? "Min" : "Max") << "z=" << ans.second << ", cuando:"
119     "\n";
120 for(int i = 0; i < ans.first.size(); ++i){
121     cout << "x_" << (i + 1) << "=" << ans.first[i] << "\n";
122 }
123 return 0;
124 }

```

## 9 Math

### 9.1 BinPow

```

1 ll binpow(ll a, ll b){
2     ll r=1;
3     while(b){
4         if(b%2)
5             r=(r*a)%MOD;
6         a=(a*a)%MOD;
7         b/=2;
8     }
9     return r;
10 }
11
12 ll divide(ll a, ll b){
13     return ((a%MOD)*binpow(b, MOD-2))%MOD;
14 }
15 void inverses(long long p) {
16     inv[MAXN] = exp(fac[MAXN], p - 2, p);
17     for (int i = MAXN; i >= 1; i--) { inv[i - 1] = inv[i] * i % p; }
18 }

```

### 9.2 Combination Rank

```

1 // Compute nCr (binomial coefficient)
2 long long nCr(int n, int r) {
3     if (r > n) return 0;
4     if (r == 0 || r == n) return 1;

```

```

5     long long res = 1;
6     for (int i = 1; i <= r; ++i) {
7         res = res * (n - i + 1) / i;
8     }
9     return res;
10 }
11
12 // Compute 0-indexed lexicographic rank of a combination
13 long long combinationRank0(const vector<int>& comb) {
14     long long rank = 0;
15     for (int i = 0; i < (int)comb.size(); ++i) {
16         rank += nCr(comb[i] - 1, i + 1);
17     }
18     return rank; // 0-indexed
19 }
20
21 // Given n, r, and rank (0-indexed), reconstruct the combination
22 vector<int> combinationUnrank0(int n, int r, long long rank) {
23     vector<int> comb;
24     int x = 1;
25
26     for (int i = r; i >= 1; --i) {
27         while (nCr(n - x, i) > rank) {
28             x++;
29         }
30         comb.push_back(x);
31         rank -= nCr(n - x, i);
32         x++;
33     }
34
35     return comb;
36 }

```

### 9.3 Chinese Remainder Theorem

```

1 ll euclid(ll a, ll b, ll &x, ll &y) {
2     if (!b) return x = 1, y = 0, a;
3     ll d = euclid(b, a % b, y, x);
4     return y -= a/b * x, d;
5 }
6
7 ll crt(ll a, ll m, ll b, ll n) {
8     if (n > m) swap(a, b), swap(m, n);

```

```

9  ll x, y, g = euclid(m, n, x, y);
10  if((a - b) % g != 0) return -1;
11  x = (b - a) % n * x % n / g * m + a;
12  return x < 0 ? x + m*n/g : x;
13 }

```

## 9.4 Diophantine

If one solution is  $(x_0, y_0)$  all solutions can be obtained by  $x = x_0 + k * \frac{b}{\gcd(a,b)}$  and  $y = y_0 - k * \frac{a}{\gcd(a,b)}$ .

```

1  int gcd(int a, int b, int& x, int& y) {
2      if (b == 0) {
3          x = 1;
4          y = 0;
5          return a;
6      }
7      int x1, y1;
8      int d = gcd(b, a % b, x1, y1);
9      x = y1;
10     y = x1 - y1 * (a / b);
11     return d;
12 }
13
14 bool find_any_solution(int a, int b, int c, int &x0, int &y0, int &g) {
15     g = gcd(abs(a), abs(b), x0, y0);
16     if (c % g) {
17         return false;
18     }
19
20     x0 *= c / g;
21     y0 *= c / g;
22     if (a < 0) x0 = -x0;
23     if (b < 0) y0 = -y0;
24     return true;
25 }
26
27
28
29 //n variables
30 vector<ll> find_any_solution(vector<ll> a, ll c) {
31     int n = a.size();
32     vector<ll> x;
33     bool all_zero = true;

```

```

34     for (int i = 0; i < n; i++) {
35         all_zero &= a[i] == 0;
36     }
37     if (all_zero) {
38         if (c) return {};
39         x.assign(n, 0);
40         return x;
41     }
42     ll g = 0;
43     for (int i = 0; i < n; i++) {
44         g = __gcd(g, a[i]);
45     }
46     if (c % g != 0) return {};
47     if (n == 1) {
48         return {c / a[0]};
49     }
50     vector<ll> suf_gcd(n);
51     suf_gcd[n - 1] = a[n - 1];
52     for (int i = n - 2; i >= 0; i--) {
53         suf_gcd[i] = __gcd(suf_gcd[i + 1], a[i]);
54     }
55     ll cur = c;
56     for (int i = 0; i + 1 < n; i++) {
57         ll x0, y0, g;
58         // solve for a[i] * x + suf_gcd[i + 1] * (y / suf_gcd[i + 1]) = cur
59         bool ok = find_any_solution(a[i], suf_gcd[i + 1], cur, x0, y0, g);
60         assert(ok);
61         {
62             // trying to minimize x0 in case x0 becomes big
63             // it is needed for this problem, not needed in general
64             ll shift = abs(suf_gcd[i + 1] / g);
65             x0 = (x0 % shift + shift) % shift;
66         }
67         x.push_back(x0);
68
69         // now solve for the next suffix
70         cur -= a[i] * x0;
71     }
72     x.push_back(a[n - 1] == 0 ? 0 : cur / a[n - 1]);
73     return x;
74 }

```

## 9.5 Discrete Logarithm

Finds discrete logarithm in  $O(\sqrt{m})$ .

```

1 // Returns minimum x for which a ^ x % m = b % m, a and m are coprime.
2 int solve(int a, int b, int m) {
3     a %= m, b %= m;
4     int n = sqrt(m) + 1;
5
6     int an = 1;
7     for (int i = 0; i < n; ++i)
8         an = (an * 111 * a) % m;
9
10    unordered_map<int, int> vals;
11    for (int q = 0, cur = b; q <= n; ++q) {
12        vals[cur] = q;
13        cur = (cur * 111 * a) % m;
14    }
15
16    for (int p = 1, cur = 1; p <= n; ++p) {
17        cur = (cur * 111 * an) % m;
18        if (vals.count(cur)) {
19            int ans = n * p - vals[cur];
20            return ans;
21        }
22    }
23    return -1;
24 }
25
26 // Returns minimum x for which a ^ x % m = b % m.
27 int solve(int a, int b, int m) {
28     a %= m, b %= m;
29     int k = 1, add = 0, g;
30     while ((g = gcd(a, m)) > 1) {
31         if (b == k)
32             return add;
33         if (b % g)
34             return -1;
35         b /= g, m /= g, ++add;
36         k = (k * 111 * a / g) % m;
37     }
38
39     int n = sqrt(m) + 1;
40     int an = 1;

```

```

41     for (int i = 0; i < n; ++i)
42         an = (an * 111 * a) % m;
43
44     unordered_map<int, int> vals;
45     for (int q = 0, cur = b; q <= n; ++q) {
46         vals[cur] = q;
47         cur = (cur * 111 * a) % m;
48     }
49
50     for (int p = 1, cur = k; p <= n; ++p) {
51         cur = (cur * 111 * an) % m;
52         if (vals.count(cur)) {
53             int ans = n * p - vals[cur] + add;
54             return ans;
55         }
56     }
57     return -1;
58 }

```

## 9.6 Divisors

```

1 ll numberOfDivisors(ll num) {
2     ll total = 1;
3     for (int i = 2; (ll)i * i <= num; i++) {
4         if (num % i == 0) {
5             int e = 0;
6             do {
7                 e++;
8                 num /= i;
9             } while (num % i == 0);
10            total *= e + 1;
11        }
12    }
13    if (num > 1) total *= 2;
14    return total;
15 }
16
17 ll SumOfDivisors(ll num) {
18     ll total = 1;
19     for (int i = 2; (ll)i * i <= num; i++) {
20         if (num % i == 0) {
21             int e = 0;

```

```

22     do {
23         e++;
24         num /= i;
25     } while (num % i == 0);
26     ll sum = 0, pow = 1;
27     do {
28         sum += pow;
29         pow *= i;
30     } while (e-- > 0);
31     total *= sum;
32 }
33 }
34 if (num > 1) total *= (1 + num);
35 return total;
36 }

```

## 9.7 Euler Totient (Phi)

```

1 //counts coprimes to each number from 1 to n
2 vector<int> phi1(int n) {
3     vector<int> phi(n + 1);
4     for (int i = 0; i <= n; i++) phi[i] = i;
5     for (int i = 2; i <= n; i++) {
6         if (phi[i] == i) {
7             for (int j = i; j <= n; j += i)
8                 phi[j] -= phi[j] / i;
9         }
10    }
11    return phi;
12 }

```

## 9.8 Fibonacci

```

1 // Fibonacci in O(log n)
2 void fib(ll n, ll&x, ll&y){
3     if(n==0){
4         x = 0;
5         y = 1;
6         return ;
7     }
8     if(n&1){
9         fib(n-1, y, x);
10        y=(y+x)%MOD;
11    } else {

```

```

12    ll a, b;
13    fib(n>>1, a, b);
14    y = (a*a+b*b)%MOD;
15    x = (a*b + a*(b-a+MOD))%MOD;
16 }
17 }
18 // Usage
19 ll x, y;
20 fib(10, x, y);
21 cout << x << "\n" << y << endl;
22 // This will output 55 89

```

## 9.9 Matrix Exponentiation

```

1 struct Mat {
2     int n, m;
3     vector<vector<int>>> a;
4     Mat() { }
5     Mat(int _n, int _m) {n = _n; m = _m; a.assign(n, vector<int>(m, 0)); }
6     Mat(vector< vector<int> > v) { n = v.size(); m = n ? v[0].size() : 0;
7         a = v; }
8     inline void make_unit() {
9         assert(n == m);
10        for (int i = 0; i < n; i++) {
11            for (int j = 0; j < n; j++) a[i][j] = i == j;
12        }
13    }
14    inline Mat operator + (const Mat &b) {
15        assert(n == b.n && m == b.m);
16        Mat ans = Mat(n, m);
17        for(int i = 0; i < n; i++) {
18            for(int j = 0; j < m; j++) {
19                ans.a[i][j] = (a[i][j] + b.a[i][j]) % mod;
20            }
21        }
22        return ans;
23    }
24    inline Mat operator - (const Mat &b) {
25        assert(n == b.n && m == b.m);
26        Mat ans = Mat(n, m);
27        for(int i = 0; i < n; i++) {
28            for(int j = 0; j < m; j++) {
29                ans.a[i][j] = (a[i][j] - b.a[i][j] + mod) % mod;

```

```

29     }
30 }
31 return ans;
32 }
33 inline Mat operator * (const Mat &b) {
34     assert(m == b.n);
35     Mat ans = Mat(n, b.m);
36     for(int i = 0; i < n; i++) {
37         for(int j = 0; j < b.m; j++) {
38             for(int k = 0; k < m; k++) {
39                 ans.a[i][j] = (ans.a[i][j] + 1LL * a[i][k] * b.a[k][j] % mod)
40                     % mod;
41             }
42         }
43     }
44     return ans;
45 }
46 inline Mat pow(long long k) {
47     assert(n == m);
48     Mat ans(n, n), t = a; ans.make_unit();
49     while (k) {
50         if (k & 1) ans = ans * t;
51         t = t * t;
52         k >>= 1;
53     }
54     return ans;
55 }
56 inline Mat& operator += (const Mat& b) { return *this = (*this) + b; }
57 inline Mat& operator -= (const Mat& b) { return *this = (*this) - b; }
58 inline Mat& operator *= (const Mat& b) { return *this = (*this) * b; }
59 inline bool operator == (const Mat& b) { return a == b.a; }
60 inline bool operator != (const Mat& b) { return a != b.a; }
61 };
62 // Usage
63 // Mat a(n, n);
64 // Mat b(n, n);
65 // Mat c = a * b;
66 // Mat d = a + b;
67 // Mat e = a - b;
68 // Mat f = a.pow(k);
69 // a.a[i][j] = x;

```

## 9.10 Miller Rabin Deterministic

```

1  using u64 = uint64_t;
2  using u128 = __uint128_t;
3
4  u64 binpower(u64 base, u64 e, u64 mod) {
5      u64 result = 1;
6      base %= mod;
7      while (e) {
8          if (e & 1)
9              result = (u128)result * base % mod;
10             base = (u128)base * base % mod;
11             e >>= 1;
12         }
13         return result;
14     }
15
16     bool check_composite(u64 n, u64 a, u64 d, int s) {
17         u64 x = binpower(a, d, n);
18         if (x == 1 || x == n - 1)
19             return false;
20         for (int r = 1; r < s; r++) {
21             x = (u128)x * x % n;
22             if (x == n - 1)
23                 return false;
24         }
25         return true;
26     };
27
28
29     bool MillerRabin(ll n) {
30         if (n < 2)
31             return false;
32
33         int r = 0;
34         ll d = n - 1;
35         while ((d & 1) == 0) {
36             d >>= 1;
37             r++;
38         }
39
40         for (int a : {2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37}) {
41             if (n == a)

```



```

42         return true;
43         if (check_composite(n, a, d, r))
44             return false;
45     }
46     return true;
47 }

```

### 9.11 Mobius

```

1 int mob[N];
2 void mobius() {
3     mob[1] = 1;
4     for (int i = 2; i < N; i++){
5         mob[i]--;
6         for (int j = i + i; j < N; j += i) {
7             mob[j] -= mob[i];
8         }
9     }
10 }

```

### 9.12 Permutation Rank

```

1 // Compute factorial (up to reasonable limits)
2 long long fact(int n) {
3     static vector<long long> f(21, -1); // cache up to 20!
4     if (n <= 1) return 1;
5     if (f[n] != -1) return f[n];
6     return f[n] = n * fact(n - 1);
7 }
8
9 // Compute 0-indexed lexicographic rank of a permutation
10 long long permutationRank0(const vector<int>& perm) {
11     int n = perm.size();
12     long long rank = 0;
13     vector<int> used(n + 1, 0);
14
15     for (int i = 0; i < n; ++i) {
16         int smaller_unused = 0;
17         for (int j = 1; j < perm[i]; ++j) {
18             if (!used[j]) smaller_unused++;
19         }
20         rank += smaller_unused * fact(n - i - 1);
21         used[perm[i]] = 1;
22     }

```

```

23     return rank;
24 }
25
26 // Given n and rank (0-indexed), reconstruct the permutation
27 vector<int> permutationUnrank0(int n, long long rank) {
28     vector<int> elems(n);
29     iota(elems.begin(), elems.end(), 1); // {1, 2, 3, ..., n}
30     vector<int> perm;
31
32     for (int i = n; i >= 1; --i) {
33         long long f = fact(i - 1);
34         int idx = rank / f;
35         rank %= f;
36         perm.push_back(elems[idx]);
37         elems.erase(elems.begin() + idx);
38     }
39
40     return perm;
41 }

```

### 9.13 Prefix Sum Phi

```

1 vector<ll> sieve(kMaxV + 1, 0);
2 vector<ll> phi(kMaxV + 1, 0);
3
4 void primes()
5 {
6     phi[1] = 1;
7     vector<ll> pr;
8     for (int i = 2; i < kMaxV; i++) {
9         if (sieve[i] == 0) {
10             sieve[i] = i;
11             pr.pb(i);
12             phi[i] = i - 1;
13         }
14         for (auto p : pr) {
15             if (p > sieve[i] || i * p > kMaxV) break;
16             sieve[i * p] = p;
17             phi[i * p] = (p == sieve[i] ? p : p - 1) * phi[i];
18         }
19     }
20     for (int i = 1; i < kMaxV; i++) {
21         phi[i] += phi[i - 1];

```

```

22     phi[i]%MOD;
23 }
24 }
25
26 map<ll,ll> m;
27 ll PHI(ll a){
28     if(a<kMaxV)return phi[a];
29     if(m.count(a))return m[a];
30     // if(a<3)return 1;
31     m[a]=(((a%MOD)*((a+1)%MOD))%MOD)*inverse(2));
32     m[a]%MOD;
33     long long i=2;
34     while(i<=a){
35         long long j=a/i;
36         j=a/j;
37         m[a]+=MOD;
38         m[a]-=((j-i+1)*PHI(a/i))%MOD;
39         m[a]%MOD;
40         i=j+1;
41     }
42     m[a]%MOD;
43     return m[a];
44 }

```

## 9.14 Sieve

```

1  const int kMaxV = 1e6;
2
3  int sieve[kMaxV + 1];
4
5  //stores some prime (not necessarily the minimum one)
6  void primes()
7  {
8      for (int i = 4; i <= kMaxV; i += 2)
9          sieve[i] = 2;
10     for (int i = 3; i <= kMaxV / i; i += 2)
11     {
12         if (sieve[i])
13             continue;
14         for (int j = i * i; j <= kMaxV; j += i)
15             sieve[j] = i;
16     }
17 }

```

```

18
19 vector<int> PrimeFactors(int x)
20 {
21     if (x == 1)
22         return {};
23
24     unordered_set<int> primes;
25     while (sieve[x])
26     {
27         primes.insert(sieve[x]);
28         x /= sieve[x];
29     }
30     primes.insert(x);
31     return {primes.begin(), primes.end()};
32 }

```

## 9.15 Identities

$$C_n = \frac{2(2n-1)}{n+1} C_{n-1}$$

$$C_n = \frac{1}{n+1} \binom{2n}{n}$$

$$C_n \sim \frac{4^n}{n^{3/2} \sqrt{\pi}}$$

$$\sigma(n) = O(\log(\log(n))) \text{ (number of divisors of } n)$$

$$F_{2n+1} = F_n^2 + F_{n+1}^2$$

$$F_{2n} = F_{n+1}^2 - F_{n-1}^2$$

$$\sum_{i=1}^n F_i = F_{n+2} - 1$$

$$F_{n+i} F_{n+j} - F_n F_{n+i+j} = (-1)^n F_i F_j$$

$$\text{(Möbius Inv. Formula)} \mu(p^k) = [k=0] - [k=1] \text{ Let } g(n) = \sum_{d|n} f(d), \text{ then}$$

$$f(n) = \sum_{d|n} g(d) \mu\left(\frac{n}{d}\right).$$

$$\text{(Dirichlet Convolution) Let } f, g \text{ be arithmetic functions, then}$$

$$(f * g)(n) = \sum_{d|n} f(d) g\left(\frac{n}{d}\right). \text{ If } f, g \text{ are multiplicative, then so is } f * g.$$

$$n = \sum_{d|n} \phi(d)$$

$$\text{Lucas' Theorem: } \binom{m}{n} \equiv \prod_{i=0}^k \binom{m_i}{n_i} \pmod{p} \text{ where } m = \sum_{i=0}^k m_i p^i \text{ and}$$

$$n = \sum_{i=0}^k n_i p^i.$$

## 9.16 Burnside's Lemma

Dado un grupo  $G$  de permutaciones y un conjunto  $X$  de  $n$  elementos, el número de órbitas de  $X$  bajo la acción de  $G$  es igual al promedio del número de puntos fijos de las permutaciones en  $G$ .

Formalmente, el número de órbitas es  $\frac{1}{|G|} \sum_{g \in G} f(g)$  donde  $f(g)$  es el número de puntos fijos de  $g$ .

Ejemplo: Dado un collar con  $n$  cuentas y 2 colores, el número de collares diferentes

que se pueden formar es  $\frac{1}{n} \sum_{i=0}^n f(i)$  donde  $f(i)$  es el número de collares que quedan fijos bajo una rotación de  $i$  posiciones.

Para contar el número de collares que quedan fijos bajo una rotación de  $i$  posiciones, se puede usar la fórmula  $f(i) = 2^{\gcd(i,n)}$ .

Para un collar de  $n$  cuentas y  $k$  colores, el número de collares diferentes que se pueden formar es  $\frac{1}{n} \sum_{i=0}^n k^{\gcd(i,n)}$

Ejemplo: Dado un cubo con 6 caras y  $k$  colores, el número de cubos diferentes que se pueden formar es  $\frac{1}{24} \sum_{i=0}^{24} f(i)$  donde  $f(i)$  es el número de cubos que quedan fijos bajo una rotación de  $i$  posiciones. Esta formula es igual a  $\frac{1}{24}(n^6 + 3n^4 + 12n^3 + 8n^2)$

### 9.17 Recursion

Sea  $f(n) = \sum_{i=1}^k a_i f(n-i)$  entonces podemos considerar la matriz:

$$\begin{bmatrix} f(n) \\ f(n-1) \\ \vdots \\ f(n-k+1) \end{bmatrix} = \begin{bmatrix} a_1 & a_2 & \cdots & a_{k-1} & a_k \\ 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & 0 \end{bmatrix} \begin{bmatrix} f(n-1) \\ f(n-2) \\ \vdots \\ f(n-k) \end{bmatrix}$$

De aqui podemos calcular  $f(n)$  con exponenciación de matrices.

$$\begin{bmatrix} f(n) \\ f(n-1) \\ \vdots \\ f(n-k+1) \end{bmatrix} = \begin{bmatrix} a_1 & a_2 & \cdots & a_{k-1} & a_k \\ 1 & 0 & \cdots & 0 & 0 \\ 0 & 1 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \cdots & 1 & 0 \end{bmatrix}^{n-k} \begin{bmatrix} f(k) \\ f(k-1) \\ \vdots \\ f(1) \end{bmatrix}$$

### 9.18 Theorems

**Koeing's Theorem:** La cardinalidad del emparejamiento maximo de una grafica bipartita es igual al minimum vertex cover.

**Hall's Theorem:** Una grafica bipartita  $G$  tiene un emparejamiento que cubre todos los nodos de  $G$  si y solo si para todo subconjunto  $S$  de nodos de  $G$ , el número de vecinos de  $S$  es mayor o igual a  $|S|$ .

**Kuratowski's Theorem:** Una grafica es plana si y solo si no contiene un subgrafo homeomorfo a  $K_{3,3}$  o  $K_5$ .

### 9.19 Sums

$$c^a + c^{a+1} + \cdots + c^b = \frac{c^{b+1} - c^a}{c - 1}, c \neq 1$$

$$1 + 2 + 3 + \cdots + n = \frac{n(n+1)}{2}$$

$$1^2 + 2^2 + 3^2 + \cdots + n^2 = \frac{n(2n+1)(n+1)}{6}$$

$$1^3 + 2^3 + 3^3 + \cdots + n^3 = \frac{n^2(n+1)^2}{4}$$

$$1^4 + 2^4 + 3^4 + \cdots + n^4 = \frac{n(n+1)(2n+1)(3n^2+3n-1)}{30}$$

### 9.20 Catalan numbers

$$C_n = \frac{1}{n+1} \binom{2n}{n} = \binom{2n}{n} - \binom{2n}{n+1} = \frac{(2n)!}{(n+1)!n!}$$

$$C_0 = 1, C_{n+1} = \frac{2(2n+1)}{n+2} C_n, C_{n+1} = \sum C_i C_{n-i}$$

$$C_n = 1, 1, 2, 5, 14, 42, 132, 429, 1430, 4862, 16796, 58786, \dots$$

- sub-diagonal monotone paths in an  $n \times n$  grid.
- strings with  $n$  pairs of parenthesis, correctly nested. If prefix is given, number of ways is  $\binom{n}{\text{remaining\_closed}} - \binom{n}{\text{remaining\_closed}+1}$ .
- binary trees with  $n+1$  leaves (0 or 2 children).
- ordered trees with  $n+1$  vertices.
- ways a convex polygon with  $n+2$  sides can be cut into triangles by connecting vertices with straight lines.
- permutations of  $[n]$  with no 3-term increasing subseq.

### 9.21 Cayley's formula

Number of labeled trees of  $n$  vertices is  $n^{n-2}$ . Number of rooted forest of  $n$  vertices is  $(n+1)^{n-1}$ .

### 9.22 Geometric series

$$\begin{array}{l} \text{Infinite} \\ a + ar + ar^2 + ar^3 + \dots + \sum_{k=0}^{\infty} ar^k \\ \text{Sum} = \frac{a}{1-r} \\ \text{Finite} \\ a + ar + ar^2 + ar^3 + \dots + \sum_{k=0}^n ar^k \\ \text{Sum} = \frac{a(1-r^{n+1})}{1-r} \end{array}$$

## 9.23 Estimates For Divisors

$$\sum_{d|n} d = O(n \log \log n).$$

The number of divisors of  $n$  is at most around 100 for  $n < 5e4$ , 500 for  $n < 1e7$ , 2000 for  $n < 1e10$ , 200 000 for  $n < 1e19$ .

## 9.24 Sum of divisors

$$\sum d|n = \frac{p_1^{\alpha_1+1}-1}{p_1-1} + \frac{p_2^{\alpha_2+1}-1}{p_2-1} + \dots + \frac{p_n^{\alpha_n+1}-1}{p_n-1}$$

## 9.25 Pythagorean Triplets

The Pythagorean triples are uniquely generated by

$$a = k \cdot (m^2 - n^2), \quad b = k \cdot (2mn), \quad c = k \cdot (m^2 + n^2),$$

with  $m > n > 0$ ,  $k > 0$ ,  $m \perp n$ , and either  $m$  or  $n$  even.

## 9.26 Derangements

Permutations of a set such that none of the elements appear in their original position.

$$D(n) = (n-1)(D(n-1) + D(n-2)) = nD(n-1) + (-1)^n = \left\lfloor \frac{n!}{e} \right\rfloor$$

# 10 Game Theory

## 10.1 Sprague-Grundy theorem

<https://codeforces.com/blog/entry/66040> Dado un juego con pilas  $p_1, p_2, \dots, p_n$

sea  $g(p)$  el número de la pila  $p$ , entonces el número del juego es

$g(p_1) \oplus g(p_2) \oplus \dots \oplus g(p_n)$ . Para calcular el número de una pila, se puede usar la fórmula  $g(r) = \text{mex}(\{g(r_1), g(r_2), \dots, g(r_k)\})$  donde  $r_1, r_2, \dots, r_k$  son los posibles estados a los que se puede llegar desde  $r$  y  $g(r) = 0$  si  $r$  es un estado perdedor.

# 11 Fórmulas y notas

## 11.1 Números de Stirling del primer tipo

$\begin{bmatrix} n \\ k \end{bmatrix}$  representa el número de permutaciones de  $n$  elementos en exactamente  $k$  ciclos disjuntos.

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = 1$$

$$\begin{bmatrix} 0 \\ n \end{bmatrix} = \begin{bmatrix} n \\ 0 \end{bmatrix} = 0, \quad n > 0$$

$$\begin{bmatrix} n \\ k \end{bmatrix} = (n-1) \begin{bmatrix} n-1 \\ k \end{bmatrix} + \begin{bmatrix} n-1 \\ k-1 \end{bmatrix}, \quad k > 0$$

$$\sum_{k=0}^n \begin{bmatrix} n \\ k \end{bmatrix} = n!$$

$$\sum_{k=0}^{\infty} \begin{bmatrix} n \\ k \end{bmatrix} x^k = \prod_{k=0}^{n-1} (x+k)$$

## 11.2 Números de Stirling del segundo tipo

$\left\{ \begin{smallmatrix} n \\ k \end{smallmatrix} \right\}$  representa el número de formas de particionar un conjunto de  $n$  objetos distinguibles en  $k$  subconjuntos no vacíos.

$$\left\{ \begin{smallmatrix} 0 \\ 0 \end{smallmatrix} \right\} = 1$$

$$\left\{ \begin{smallmatrix} 0 \\ n \end{smallmatrix} \right\} = \left\{ \begin{smallmatrix} n \\ 0 \end{smallmatrix} \right\} = 0, \quad n > 0$$

$$\left\{ \begin{smallmatrix} n \\ k \end{smallmatrix} \right\} = k \left\{ \begin{smallmatrix} n-1 \\ k \end{smallmatrix} \right\} + \left\{ \begin{smallmatrix} n-1 \\ k-1 \end{smallmatrix} \right\}, \quad k > 0$$

$$= \sum_{j=0}^k \frac{j^n}{j!} \cdot \frac{(-1)^{k-j}}{(k-j)!}$$

## 11.3 Números de Euler

$\left\langle \begin{smallmatrix} n \\ k \end{smallmatrix} \right\rangle$  representa el número de permutaciones de 1 a  $n$  en donde exactamente  $k$  números son mayores que el número anterior, es decir, cuántas permutaciones tienen

$k$  “ascensos”.

$$\begin{aligned}\langle\langle 1 \rangle\rangle_0 &= 1 \\ \langle\langle n \rangle\rangle_k &= (n-k) \langle\langle n-1 \rangle\rangle_{k-1} + (k+1) \langle\langle n-1 \rangle\rangle_k, \quad n \geq 2 \\ &= \sum_{j=0}^k (-1)^j \binom{n+1}{j} (k+1-j)^n \\ \sum_{k=0}^{n-1} \langle\langle n \rangle\rangle_k &= n!\end{aligned}$$

### 11.4 Números de Catalan

$$\begin{aligned}C_0 &= 1 \\ C_n &= \frac{1}{n+1} \binom{2n}{n} = \sum_{j=0}^{n-1} C_j C_{n-1-j} \\ \sum_{n=0}^{\infty} C_n x^n &= \frac{1 - \sqrt{1-4x}}{2x}\end{aligned}$$

### 11.5 Números de Bell

$B_n$  representa el número de formas de particionar un conjunto de  $n$  elementos.

$$\begin{aligned}B_n &= \sum_{k=0}^n \left\{ \begin{matrix} n \\ k \end{matrix} \right\} = \sum_{k=0}^{n-1} \binom{n-1}{k} B_k \\ \sum_{n=0}^{\infty} \frac{B_n}{n!} x^n &= e^{e^x - 1}\end{aligned}$$

### 11.6 Números de Bernoulli

$$\begin{aligned}B_0^+ &= 1 \\ B_n^+ &= 1 - \sum_{k=0}^{n-1} \binom{n}{k} \frac{B_k^+}{n-k+1} \\ \sum_{n=0}^{\infty} \frac{B_n^+ x^n}{n!} &= \frac{x}{1-e^{-x}} = \frac{1}{\frac{1}{1!} - \frac{x}{2!} + \frac{x^2}{3!} - \frac{x^3}{4!} + \dots}\end{aligned}$$

### 11.7 Fórmula de Faulhaber

$$S_p(n) = \sum_{k=1}^n k^p = \frac{1}{p+1} \sum_{k=0}^p \binom{p+1}{k} B_k^+ n^{p+1-k}$$

### 11.8 Función Beta

$$\begin{aligned}B(x, y) &= \frac{\Gamma(x)\Gamma(y)}{\Gamma(x+y)} = 2 \int_0^{\pi/2} \sin^{2x-1}(\theta) \cos^{2y-1}(\theta) d\theta \\ &= \int_0^1 t^{x-1} (1-t)^{y-1} dt = \int_0^{\infty} \frac{t^{x-1}}{(1+t)^{x+y}} dt\end{aligned}$$

### 11.9 Función zeta de Riemann

La siguiente fórmula converge rápido para valores pequeños de  $n$  ( $n \approx 20$ ):

$$\begin{aligned}\zeta(s) &\approx \frac{1}{d_0(1-2^{1-s})} \sum_{k=1}^n \frac{(-1)^{k-1} d_k}{k^s} \\ d_k &= \sum_{j=k}^n \frac{4^j}{n+j} \binom{n+j}{2j}\end{aligned}$$

### 11.10 Funciones generadoras

$$\begin{aligned}\sum_{n=0}^{\infty} \left( \sum_{k=0}^n a_k \right) x^n &= \frac{1}{1-x} \sum_{n=0}^{\infty} a_n x^n \\ \sum_{n=0}^{\infty} \binom{n+k-1}{k-1} x^n &= \frac{1}{(1-x)^k} \\ \sum_{n=0}^{\infty} p_n x^n &= \frac{1}{\prod_{k=1}^{\infty} (1-x^k)} = \frac{1}{\sum_{n=-\infty}^{\infty} (-1)^n x^{\frac{1}{2}n(3n+1)}} \\ \sum_{p=0}^{\infty} \frac{S_p(n)}{p!} x^p &= \frac{e^{x(n+1)} - e^x}{e^x - 1} \\ \sum_{n=0}^{\infty} n^k x^n &= \frac{\sum_{i=0}^{k-1} \langle\langle k \rangle\rangle_i x^{i+1}}{(1-x)^{k+1}}, \quad k \geq 1\end{aligned}$$

Sean  $a_1, a_2, \dots, a_n$  números complejos. Sean  $p_m = \sum_{i=1}^n a_i^m$  y  $s_m$  el  $m$ -ésimo polinomio elemental simétrico de  $a_1, a_2, \dots, a_n$ . Entonces se cumple que  $xS'(x) + P(x)S(x) = 0$ , donde  $P(x) = \sum_{m=1}^{\infty} p_m x^m$  y  $S(x) = \prod_{i=1}^n (1 - a_i x) = \sum_{m=0}^n (-1)^m s_m x^m$ .

### 11.11 Números armónicos

$$H_n = \sum_{k=1}^n \frac{1}{k} \approx \ln(n) + \gamma + \frac{1}{2n} - \frac{1}{12n^2}$$

$$\gamma \approx 0.577215664901532860606512$$

### 11.12 Aproximación de Stirling

$$\ln(n!) \approx n \ln(n) - n + \frac{1}{2} \ln(2\pi n)$$

$$\# \text{ de dígitos de } n! = 1 + \left\lfloor n \log\left(\frac{n}{e}\right) + \frac{1}{2} \log(2\pi n) \right\rfloor \quad (n \geq 30)$$

### 11.13 Ternas pitagóricas

- Una terna de enteros positivos  $(a, b, c)$  es pitagórica si  $a^2 + b^2 = c^2$ . Además es primitiva si  $\gcd(a, b, c) = 1$ .
- Generador de ternas primitivas:

$$\begin{aligned} a &= m^2 - n^2 \\ b &= 2mn \\ c &= m^2 + n^2 \end{aligned}$$

donde  $n \geq 1$ ,  $m > n$ ,  $\gcd(m, n) = 1$  y  $m, n$  tienen distinta paridad.

- Árbol de ternas pitagóricas primitivas: al multiplicar cualquiera de estas matrices:

$$\begin{pmatrix} 1 & -2 & 2 \\ 2 & -1 & 2 \\ 2 & -2 & 3 \end{pmatrix}, \quad \begin{pmatrix} -1 & 2 & 2 \\ -2 & 1 & 2 \\ -2 & 2 & 3 \end{pmatrix}, \quad \begin{pmatrix} 1 & 2 & 2 \\ 2 & 1 & 2 \\ 2 & 2 & 3 \end{pmatrix}$$

por una terna primitiva  $\mathbf{v}^T$ , obtenemos otra terna primitiva diferente. En particular, si empezamos con  $\mathbf{v} = (3, 4, 5)$ , podremos generar todas las ternas primitivas.

### 11.14 Árbol de Stern–Brocot

Todos los racionales positivos se pueden representar como un árbol binario de búsqueda completo infinito con raíz  $\frac{1}{1}$ .

- Dado un racional  $q = [a_0; a_1, a_2, \dots, a_k]$  donde  $a_k \neq 1$ , sus hijos serán  $[a_0; a_1, a_2, \dots, a_k + 1]$  y  $[a_0; a_1, a_2, \dots, a_k - 1, 2]$ , y su padre será  $[a_0; a_1, a_2, \dots, a_k - 1]$ .
- Para hallar el camino de la raíz  $\frac{1}{1}$  a un racional  $q$ , se usa búsqueda binaria iniciando con  $L = \frac{0}{1}$  y  $R = \frac{1}{0}$ . Para hallar  $M$  se supone que  $L = \frac{a}{b}$  y  $R = \frac{c}{d}$ , entonces  $M = \frac{a+c}{b+d}$ .

### 11.15 Combinatoria

- Principio de las casillas: al colocar  $n$  objetos en  $k$  lugares hay al menos  $\lceil \frac{n}{k} \rceil$  objetos en un mismo lugar.
- Número de funciones: sean  $A$  y  $B$  conjuntos con  $m = |A|$  y  $n = |B|$ . Sea  $f: A \rightarrow B$ :
  - Si  $m \leq n$ , entonces hay  $m! \binom{n}{m}$  funciones inyectivas  $f$ .
  - Si  $m = n$ , entonces hay  $n!$  funciones biyectivas  $f$ .
  - Si  $m \geq n$ , entonces hay  $n! \left\{ \begin{smallmatrix} m \\ n \end{smallmatrix} \right\}$  funciones suprayectivas  $f$ .
- Barras y estrellas: ¿cuántas soluciones en los enteros no negativos tiene la ecuación  $\sum_{i=1}^k x_i = n$ ? Tiene  $\binom{n+k-1}{k-1}$  soluciones.
- ¿Cuántas soluciones en los enteros positivos tiene la ecuación  $\sum_{i=1}^k x_i = n$ ? Tiene  $\binom{n-1}{k-1}$  soluciones.
- Desordenamientos:  $a_0 = 1$ ,  $a_1 = 0$ ,  $a_n = (n-1)(a_{n-1} + a_{n-2}) = na_{n-1} + (-1)^n$ .
- Sea  $f(x)$  una función. Sea  $g_n(x) = xg'_{n-1}(x)$  con  $g_0(x) = f(x)$ . Entonces  $g_n(x) = \sum_{k=0}^n \left\{ \begin{smallmatrix} n \\ k \end{smallmatrix} \right\} x^k f^{(k)}(x)$ .
- Supongamos que tenemos  $m+1$  puntos:  $(0, y_0), (1, y_1), \dots, (m, y_m)$ . Entonces el polinomio  $P(x)$  de grado  $m$  que pasa por todos ellos es:

$$P(x) = \left[ \prod_{i=0}^m (x - i) \right] (-1)^m \sum_{i=0}^m \frac{y_i (-1)^i}{(x - i)! (m - i)!}$$

- Sea  $a_0, a_1, \dots$  una recurrencia lineal homogénea de grado  $d$  dada por  $a_n = \sum_{i=1}^d b_i a_{n-i}$  para  $n \geq d$  con términos iniciales  $a_0, a_1, \dots, a_{d-1}$ . Sean  $A(x)$  y  $B(x)$  las funciones generadoras de las sucesiones  $a_n$  y  $b_n$  respectivamente, entonces se cumple que  $A(x) = \frac{A_0(x)}{1-B(x)}$ , donde  $A_0(x) = \sum_{i=0}^{d-1} \left[ a_i - \sum_{j=0}^{i-1} a_j b_{i-j} \right] x^i$ .
- Si queremos obtener otra recurrencia  $c_n$  tal que  $c_n = a_{kn}$ , las raíces del polinomio característico de  $c_n$  se obtienen al elevar todas las raíces del polinomio característico de  $a_n$  a la  $k$ -ésima potencia; y sus términos iniciales serán  $a_0, a_k, \dots, a_{k(d-1)}$ .

### 11.16 Grafos

- Sea  $d_n$  el número de grafos con  $n$  vértices etiquetados:  $d_n = 2^{\binom{n}{2}}$ .
- Sea  $c_n$  el número de grafos conexos con  $n$  vértices etiquetados. Tenemos la recurrencia:  $c_1 = 1$  y  $d_n = \sum_{k=1}^n \binom{n-1}{k-1} c_k d_{n-k}$ . También se cumple, usando funciones generadoras exponenciales, que  $C(x) = 1 + \ln(D(x))$ .
- Sea  $t_n$  el número de torneos fuertemente conexos en  $n$  nodos etiquetados. Tenemos la recurrencia  $t_1 = 1$  y  $d_n = \sum_{k=1}^n \binom{n}{k} t_k d_{n-k}$ . Usando funciones generadoras exponenciales, tenemos que  $T(x) = 1 - \frac{1}{D(x)}$ .
- Número de spanning trees en un grafo completo con  $n$  vértices etiquetados:  $n^{n-2}$ .
- Número de bosques etiquetados con  $n$  vértices y  $k$  componentes conexas:  $kn^{n-k-1}$ .
- Para un grafo no dirigido simple  $G$  con  $n$  vértices etiquetados de 1 a  $n$ , sea  $Q = D - A$ , donde  $D$  es la matriz diagonal de los grados de cada nodo de  $G$  y  $A$  es la matriz de adyacencia de  $G$ . Entonces el número de spanning trees de  $G$  es igual a cualquier cofactor de  $Q$ .
- Sea  $G$  un grafo. Se define al polinomio  $P_G(x)$  como el polinomio cromático de  $G$ , en donde  $P_G(k)$  nos dice cuántas  $k$ -coloraciones de los vértices admite  $G$ . Ejemplos comunes:
  - Grafo completo de  $n$  nodos:  $P(x) = x(x-1)(x-2)\dots(x-(n-1))$
  - Grafo vacío de  $n$  nodos:  $P(x) = x^n$
  - Árbol de  $n$  nodos:  $P(x) = x(x-1)^{n-1}$
  - Ciclo de  $n$  nodos:  $P(x) = (x-1)^n + (-1)^n(x-1)$

### 11.17 Teoría de números

$$\begin{aligned}
 (f * e)(n) &= f(n) \\
 (\varphi * \mathbf{1})(n) &= n \\
 (\mu * \mathbf{1})(n) &= e(n) \\
 \varphi(n^k) &= n^{k-1} \varphi(n) \\
 \sum_{\substack{k=1 \\ \gcd(k,n)=1}}^n k &= \frac{n\varphi(n)}{2}, \quad n \geq 2 \\
 \sum_{k=1}^n \text{lcm}(k, n) &= \frac{n}{2} + \frac{n}{2} \sum_{d|n} d\varphi(d) = \frac{n}{2} + \frac{n}{2} \prod_{p^a|n} \frac{p^{2a+1} + 1}{p+1} \\
 \sum_{k=1}^n \gcd(k, n) &= \sum_{d|n} d\varphi\left(\frac{n}{d}\right) = \prod_{p^a|n} p^{a-1}(1 + (a+1)(p-1))
 \end{aligned}$$

- Lifting the exponent: sea  $p$  un primo,  $x, y$  enteros y  $n$  un entero positivo tal que  $p \mid x - y$  pero  $p \nmid x$  ni  $p \nmid y$ . Entonces:
  - Si  $p$  es impar:  $v_p(x^n - y^n) = v_p(x - y) + v_p(n)$
  - Si  $p = 2$  y  $n$  es par:  $v_p(x^n - y^n) = v_p(x - y) + v_p(n) + v_p(x + y) - 1$
 donde  $v_p(n)$  es el exponente de  $p$  en la factorización en primos de  $n$ .
- Suma de dos cuadrados: sea  $\chi_4(n)$  una función multiplicativa igual a 1 si  $n \equiv 1 \pmod{4}$ ,  $-1$  si  $n \equiv 3 \pmod{4}$  y cero en otro caso. Entonces, el número de soluciones enteras  $(a, b)$  de la ecuación  $a^2 + b^2 = n$  es  $4(\chi_4 * 1)(n) = 4 \sum_{d|n} \chi_4(d)$ .
- Teorema de Lucas:

$$\begin{aligned}
 \binom{m}{n} &\equiv \prod_{i=0}^k \binom{m_i}{k_i} \pmod{p} \\
 m &= \sum_{i=0}^k m_i p^i, \quad n = \sum_{i=0}^k n_i p^i \\
 0 &\leq m_i, n_i < p
 \end{aligned}$$

- Sean  $a, b, c \in \mathbb{Z}$  con  $a \neq 0$  y  $b \neq 0$ . La ecuación  $ax + by = c$  tiene como soluciones:

$$\begin{aligned}
 x &= \frac{x_0 c - b k}{d} \\
 y &= \frac{y_0 c + a k}{d}
 \end{aligned}$$

para toda  $k \in \mathbb{Z}$  si y solo si  $d|c$ , donde  $ax_0 + by_0 = \gcd(a, b) = d$  (Euclides extendido). Si  $a$  y  $b$  tienen el mismo signo, hay exactamente  $\max\left(\left\lfloor \frac{x_0 c}{|b|} \right\rfloor + \left\lfloor \frac{y_0 c}{|a|} \right\rfloor + 1, 0\right)$  soluciones no negativas. Si tienen el signo distinto, hay infinitas soluciones no negativas.

- Dada una función aritmética  $f$  con  $f(1) \neq 0$ , existe otra función aritmética  $g$  tal que  $(f * g)(n) = e(n)$ , dada por:

$$g(1) = \frac{1}{f(1)}$$

$$g(n) = -\frac{1}{f(1)} \sum_{d|n, d < n} f\left(\frac{n}{d}\right) g(d) \quad , \quad n > 1$$

- Sean  $h(n) = \sum_{k=1}^n f\left(\left\lfloor \frac{n}{k} \right\rfloor\right) g(k)$ ,  $G(n) = \sum_{k=1}^n g(k)$  y  $m = \lfloor \sqrt{n} \rfloor$ , entonces:

$$h(n) = \sum_{k=1}^{\lfloor n/m \rfloor} f\left(\left\lfloor \frac{n}{k} \right\rfloor\right) g(k) + \sum_{k=1}^{m-1} \left( G\left(\left\lfloor \frac{n}{k} \right\rfloor\right) - G\left(\left\lfloor \frac{n}{k+1} \right\rfloor\right) \right) f(k)$$

- Sean  $F(n) = \sum_{k=1}^n f(k)$ ,  $G(n) = \sum_{k=1}^n g(k)$ ,  $h(n) = (f * g)(n) = \sum_{d|n} f(d)g\left(\frac{n}{d}\right)$  y

$$H(n) = \sum_{k=1}^n h(k), \text{ entonces:}$$

$$H(n) = \sum_{k=1}^n f(k)G\left(\left\lfloor \frac{n}{k} \right\rfloor\right)$$

- Sean  $\Phi_p(n) = \sum_{k=1}^n k^p \varphi(k)$  y  $M_p(n) = \sum_{k=1}^n k^p \mu(k)$ . Aplicando lo anterior, podemos

calcular  $\Phi_p(n)$  y  $M_p(n)$  con complejidad  $O(n^{2/3})$  si precalculamos con fuerza bruta los primeros  $\lfloor n^{2/3} \rfloor$  valores, y para los demás, usamos las siguientes recurrencias (DP con map):

$$\Phi_p(n) = S_{p+1}(n) - \sum_{k=2}^{\lfloor n/m \rfloor} k^p \Phi_p\left(\left\lfloor \frac{n}{k} \right\rfloor\right) - \sum_{k=1}^{m-1} \left( S_p\left(\left\lfloor \frac{n}{k} \right\rfloor\right) - S_p\left(\left\lfloor \frac{n}{k+1} \right\rfloor\right) \right) \Phi_p(k)$$

$$M_p(n) = 1 - \sum_{k=2}^{\lfloor n/m \rfloor} k^p M_p\left(\left\lfloor \frac{n}{k} \right\rfloor\right) - \sum_{k=1}^{m-1} \left( S_p\left(\left\lfloor \frac{n}{k} \right\rfloor\right) - S_p\left(\left\lfloor \frac{n}{k+1} \right\rfloor\right) \right) M_p(k)$$

- En general, si queremos hallar  $F(n)$  y existe una función mágica  $g(n)$  tal que  $G(n)$  y  $H(n)$  se puedan calcular en  $O(1)$ , entonces:

$$F(n) = \frac{1}{g(1)} \left[ H(n) - \sum_{k=2}^{\lfloor n/m \rfloor} g(k) F\left(\left\lfloor \frac{n}{k} \right\rfloor\right) - \sum_{k=1}^{m-1} \left( G\left(\left\lfloor \frac{n}{k} \right\rfloor\right) - G\left(\left\lfloor \frac{n}{k+1} \right\rfloor\right) \right) F(k) \right]$$

## 11.18 Primos

$10^2 + 1, 10^3 + 9, 10^4 + 7, 10^5 + 3, 10^6 + 3, 10^7 + 19, 10^8 + 7, 10^9 + 7, 10^{10} + 19,$   
 $10^{11} + 3, 10^{12} + 39, 10^{13} + 37, 10^{14} + 31, 10^{15} + 37, 10^{16} + 61, 10^{17} + 3, 10^{18} + 3.$   
 $10^2 - 3, 10^3 - 3, 10^4 - 27, 10^5 - 9, 10^6 - 17, 10^7 - 9, 10^8 - 11, 10^9 - 63, 10^{10} - 33,$   
 $10^{11} - 23, 10^{12} - 11, 10^{13} - 29, 10^{14} - 27, 10^{15} - 11, 10^{16} - 63, 10^{17} - 3, 10^{18} - 11.$

## 11.19 Números primos de Mersenne

Números primos de la forma  $M_p = 2^p - 1$  con  $p$  primo. Todos los números perfectos pares son de la forma  $2^{p-1}M_p$  y viceversa.

Los primeros 47 valores de  $p$  son: 2, 3, 5, 7, 13, 17, 19, 31, 61, 89, 107, 127, 521, 607, 1279, 2203, 2281, 3217, 4253, 4423, 9689, 9941, 11213, 19937, 21701, 23209, 44497, 86243, 110503, 132049, 216091, 756839, 859433, 1257787, 1398269, 2976221, 3021377, 6972593, 13466917, 20996011, 24036583, 25964951, 30402457, 32582657, 37156667, 42643801, 43112609.

## 11.20 Números primos de Fermat

Números primos de la forma  $F_p = 2^{2^p} + 1$ , solo se conocen cinco: 3, 5, 17, 257, 65537.

Un polígono de  $n$  lados es construible si y solo si  $n$  es el producto de algunas potencias de dos y distintos primos de Fermat.

## 12 More Topics

### 12.1 2D Prefix Sum

```

1 | int b[MAXN] [MAXN] ;
2 | int a[MAXN] [MAXN] ;
3 | for (int i = 1; i <= N; i++) {
4 |     for (int j = 1; j <= N; j++) {
5 |         b[i] [j] = a[i] [j] + b[i - 1] [j] +
6 |             b[i] [j - 1] - b[i - 1] [j - 1];
7 |     }
8 | }
9 | for (int q = 0; q < Q; q++) {
```



```

10 int from_row, to_row, from_col, to_col;
11 cin >> from_row >> from_col >> to_row >> to_col;
12 cout << b[to_row][to_col] - b[from_row - 1][to_col] -
13         b[to_row][from_col - 1] +
14         b[from_row - 1][from_col - 1]
15         << '\n';
16 }

```

## 12.2 Custom Comparators

```

1 bool cmp(const Edge &x, const Edge &y) { return x.w < y.w; }
2
3 sort(a.begin(), a.end(), cmp);
4
5 set<int, greater<int>> a;
6 map<int, string, greater<int>> b;
7 priority_queue<int, vector<int>, greater<int>> c;

```

## 12.3 Day of the Week

```

1 int dayOfWeek(int d, int m, lli y){
2     if(m == 1 || m == 2){
3         m += 12;
4         --y;
5     }
6     int k = y % 100;
7     lli j = y / 100;
8     return (d + 13*(m+1)/5 + k + k/4 + j/4 + 5*j) % 7;
9 }

```

## 12.4 Directed MST

```

1 #include<bits/stdc++.h>
2 using namespace std;
3
4 const int N = 3e5 + 9;
5
6 const long long inf = 1e18;
7
8 template<typename T> struct PQ {
9     long long sum = 0;
10    priority_queue<T, vector<T>, greater<T>> Q;
11    void push(T x) { x.w -= sum; Q.push(x); }
12    T pop() { auto ans = Q.top(); Q.pop(); ans.w += sum; return ans; }

```

```

13 int size() { return Q.size(); }
14 void add(long long x) { sum += x; }
15 void merge(PQ &&x) {
16     if (size() < x.size()) swap(sum, x.sum), swap(Q, x.Q);
17     while (x.size()) {
18         auto tmp = x.pop();
19         tmp.w -= sum;
20         Q.push(tmp);
21     }
22 }
23 };
24 struct edge {
25     int u, v; long long w;
26     bool operator > (const edge &rhs) const { return w > rhs.w; }
27 };
28 struct DSU {
29     vector<int> par;
30     DSU (int n) : par(n, -1) {}
31     int root(int i) { return par[i] < 0 ? i : par[i] = root(par[i]); }
32     void set_par(int c, int p) { par[c] = p; }
33 };
34 // returns parents of each vertex
35 // each edge should be distinct
36 // it assumes that a solution exists (all vertices are reachable from
37 // root)
38 // 0 indexed
39 // Takes ~300ms for n = 2e5
40 vector<int> DMST(int n, int root, const vector<edge> &edges) {
41     vector<int> u(2 * n - 1, -1), par(2 * n - 1, -1);
42     edge par_edge[2 * n - 1];
43     vector<int> child[2 * n - 1];
44
45     PQ<edge> Q[2 * n - 1];
46     for (auto e : edges) Q[e.v].push(e);
47     for (int i = 0; i < n; i++) Q[(i + 1) % n].push({i, (i + 1) % n, inf});
48
49     int super = n;
50     DSU dsu(2 * n - 1);
51     int head = 0;
52     while (Q[head].size()) {
53         auto x = Q[head].pop();
54         int nxt_root = dsu.root(x.u);

```

```

54     if (nxt_root == head) continue;
55     u[head] = nxt_root;
56     par_edge[head] = x;
57     if (u[nxt_root] == -1) head = nxt_root;
58     else {
59         int j = nxt_root;
60         do {
61             Q[j].add(-par_edge[j].w);
62             Q[super].merge(move(Q[j]));
63             assert(u[j] != -1);
64             child[super].push_back(j);
65             j = dsu.root(u[j]);
66         } while (j != nxt_root);
67         for (auto u : child[super]) par[u] = super, dsu.set_par(u, super);
68         head = super++;
69     }
70 }
71 vector<int> res(2 * n - 1, -1);
72 queue<int> q; q.push(root);
73 while (q.size()) {
74     int u = q.front();
75     q.pop();
76     while (par[u] != -1) {
77         for (auto v : child[par[u]]) {
78             if (v != u) {
79                 res[par_edge[v].v] = par_edge[v].u;
80                 q.push(par_edge[v].v);
81                 par[v] = -1;
82             }
83         }
84         u = par[u];
85     }
86 }
87 res[root] = root; res.resize(n);
88 return res;
89 }
90 int32_t main() {
91     ios_base::sync_with_stdio(0);
92     cin.tie(0);
93     int n, m, root; cin >> n >> m >> root;
94     vector<edge> edges(m);
95     for (auto &e : edges) cin >> e.u >> e.v >> e.w;
96     auto res = DMST(n, root, edges);

```

```

97 unordered_map<int, int> W[n];
98 for (auto u : edges) W[u.v][u.u] = u.w;
99
100
101 long long ans = 0;
102 for (int i = 0; i < n; i++) if (i != root) ans += W[i][res[i]];
103 cout << ans << '\n';
104 for (auto x : res) cout << x << '␣'; cout << '\n';
105 return 0;
106 }
107 // https://judge.yosupo.jp/problem/directedmst
108 // http://www.cs.tau.ac.il/~zwick/grad-algo-13/directed-mst.pdf

```

## 12.5 GCD Convolution

```

1  /*
2   GCD Convolution via Multiple Zeta and Mobius Transforms
3   -----
4   Given two sequences A[0..n] and B[0..n], computes C where
5   C[d] = sum_{i, j: gcd(i, j) = d} A[i] * B[j]
6   Indexing: 1-based, vectors of size n+1 (ignore index 0)
7   Bounds:
8   - i, j, d in [1..n]
9   Time Complexity: O(n log log n + n log n) per convolution
10  Space Complexity: O(n)
11  Steps:
12  1. Multiple Zeta Transform: for each prime p, v[i] += v[i*p]
13  2. Pointwise multiply transformed A and B
14  3. Multiple Mobius Transform: for each prime p, v[i] -= v[i*p]
15  */
16  // Enumerate primes up to n in O(n)
17  vector<int> PrimeEnumerate(int n) {
18      vector<bool> isPrime(n+1, true);
19      vector<int> P;
20      for (int i = 2; i <= n; i++) {
21          if (isPrime[i]) P.push_back(i);
22          for (int p : P) {
23              if (i * p > n) break;
24              isPrime[i*p] = false;
25              if (i % p == 0) break;
26          }
27      }
28      return P;

```

```

29 }
30 // Multiple Zeta Transform (over divisibility poset)
31 template<typename T>
32 void MultipleZetaTransform(vector<T>& v) {
33     int n = (int)v.size() - 1;
34     for (int p : PrimeEnumerate(n)) {
35         for (int i = n/p; i >= 1; i--) {
36             v[i] += v[i * p];
37         }
38     }
39 }
40 // Multiple Mobius Transform (inverse of zeta)
41 template<typename T>
42 void MultipleMobiusTransform(vector<T>& v) {
43     int n = (int)v.size() - 1;
44     for (int p : PrimeEnumerate(n)) {
45         for (int i = 1; i * p <= n; i++) {
46             v[i] -= v[i * p];
47         }
48     }
49 }
50 // GCD convolution of A and B, both size n+1
51 template<typename T>
52 vector<T> GCDCConvolution(vector<T> A, vector<T> B) {
53     int n = (int)A.size() - 1;
54     MultipleZetaTransform(A);
55     MultipleZetaTransform(B);
56     for (int i = 1; i <= n; i++) {
57         A[i] *= B[i]; // pointwise multiplication
58     }
59     MultipleMobiusTransform(A);
60     return A; // result C[0..n], where C[d] = sum_{gcd(i,j)=d} A[i]*B[j]
61 }
62 // Example usage
63 vector<long long> A(n+1), B(n+1);
64 for (int i = 1; i <= n; i++) cin >> A[i];
65 for (int i = 1; i <= n; i++) cin >> B[i];
66 auto C = GCDCConvolution<long long>(A, B);
67 for (int d = 1; d <= n; d++){
68     cout << C[d] << (d==n?'\\n':' ');
69 }

```

## 12.6 int128

```

1 //cout for __int128
2 ostream &operator<<(ostream &os, const __int128 & value){
3     char buffer[64];
4     char *pos = end(buffer) - 1;
5     *pos = '\\0';
6     __int128 tmp = value < 0 ? -value : value;
7     do{
8         --pos;
9         *pos = tmp % 10 + '0';
10        tmp /= 10;
11    }while(tmp != 0);
12    if(value < 0){
13        --pos;
14        *pos = '-';
15    }
16    return os << pos;
17 }
18
19 //cin for __int128
20 istream &operator>>(istream &is, __int128 & value){
21     char buffer[64];
22     is >> buffer;
23     char *pos = begin(buffer);
24     int sgn = 1;
25     value = 0;
26     if(*pos == '-'){
27         sgn = -1;
28         ++pos;
29     }else if(*pos == '+'){
30         ++pos;
31     }
32     while(*pos != '\\0'){
33         value = (value << 3) + (value << 1) + (*pos - '0');
34         ++pos;
35     }
36     value *= sgn;
37     return is;
38 }
39
40
41 ll mult(__int128 a, __int128 b){ return ((a*1LL*b)%MOD + MOD)%MOD; }

```

## 12.7 Iterating Over All Subsets

```

1 for (int mk = 0; mk < (1 << k); mk++) {
2     Ap[mk] = 0;
3     for (int s = mk;; s = (s - 1) & mk) {
4         Ap[mk] += A[s];
5         if (!s) break;
6     }
7 }

```

## 12.8 LCM Convolution

```

1 /*
2  LCM Convolution via Divisor Zeta and Mobius Transforms
3  -----
4  Given two sequences A[1..n] and B[1..n], computes C where
5  C[d] = sum_{i, j: lcm(i, j) = d} A[i] * B[j]
6  Indexing: 1-based (vectors of size n+1, ignore index 0)
7  Bounds:
8  - i, j, d in [1..n]
9  Time Complexity: O(n log log n + n log n)
10 Space Complexity: O(n)
11 Steps:
12 1. Divisor Zeta Transform: for each prime p, v[i*p] += v[i]
13 2. Pointwise multiply transformed A and B
14 3. Divisor Mobius Transform: for each prime p, v[i*p] -= v[i]
15 */
16 // Sieve primes up to n in O(n)
17 vector<int> PrimeEnumerate(int n) {
18     vector<bool> isPrime(n+1, true);
19     vector<int> P;
20     for (int i = 2; i <= n; i++) {
21         if (isPrime[i]) P.push_back(i);
22         for (int p : P) {
23             if (i * p > n) break;
24             isPrime[i*p] = false;
25             if (i % p == 0) break;
26         }
27     }
28     return P;
29 }
30 // Divisor Zeta Transform: v[d] = sum_{d|k} original_v[k]
31 template<typename T>

```

```

32 void DivisorZetaTransform(vector<T>& v) {
33     int n = (int)v.size() - 1;
34     auto primes = PrimeEnumerate(n);
35     for (int p : primes) {
36         for (int i = 1; i * p <= n; i++) {
37             v[i * p] += v[i];
38         }
39     }
40 }
41 // Divisor Mobius Transform (inverse of zeta)
42 template<typename T>
43 void DivisorMobiusTransform(vector<T>& v) {
44     int n = (int)v.size() - 1;
45     auto primes = PrimeEnumerate(n);
46     for (int p : primes) {
47         for (int i = n / p; i >= 1; i--) {
48             v[i * p] -= v[i];
49         }
50     }
51 }
52 // LCM convolution of A and B (each size n+1)
53 template<typename T>
54 vector<T> LCMConvolution(vector<T> A, vector<T> B) {
55     int n = (int)A.size() - 1;
56     DivisorZetaTransform(A);
57     DivisorZetaTransform(B);
58     for (int d = 1; d <= n; d++) {
59         A[d] *= B[d]; // pointwise multiplication
60     }
61     DivisorMobiusTransform(A);
62     return A; // result C[1..n], C[d] = sum_{lcm(i,j)=d} A[i]*B[j]
63 }
64 // Example usage
65 vector<long long> A(n+1), B(n+1);
66 for (int i = 1; i <= n; i++) cin >> A[i];
67 for (int i = 1; i <= n; i++) cin >> B[i];
68 auto C = LCMConvolution<long long>(A, B);
69 for (int d = 1; d <= n; d++){
70     cout << C[d] << (d==n?'\\n':' ');
71 }

```

## 12.9 Manhattan MST

```

1  /*
2  Manhattan MST Edge Generation
3  -----
4  Given n points ps[0..n-1], returns a list of candidate edges
5  (weight, u, v) for the Manhattan MST, where
6  weight = |x[u]-x[v]| + |y[u]-y[v]|.
7  Indexing: 0-based for points and returned edges
8  Time Complexity: O(n log n)
9  */
10 struct Point {
11     ll x, y;
12 };
13
14 vector<tuple<ll,int,int>> manhattan_mst_edges(vector<Point> ps) {
15     int n = ps.size();
16     vector<int> order(n);
17     iota(order.begin(), order.end(), 0);
18     vector<tuple<ll,int,int>> edges;
19     edges.reserve(n * 4);
20     // Repeat for 4 orientations
21     for (int r = 0; r < 4; r++) {
22         // Sort by x+y ascending
23         sort(order.begin(), order.end(), [&](int i, int j) {
24             return ps[i].x + ps[i].y < ps[j].x + ps[j].y;
25         });
26         // Active map: key = x-coordinate, value = point index
27         map<ll,int,greater<ll>> active;
28         for (int i : order) {
29             // For all active points with x >= ps[i].x
30             for (auto it = active.lower_bound(ps[i].x); it != active.end();
31                  active.erase(it++)) {
32                 int j = it->second;
33                 if (ps[i].x - ps[i].y > ps[j].x - ps[j].y) break;
34                 assert(ps[i].x >= ps[j].x && ps[i].y >= ps[j].y);
35                 edges.emplace_back((ps[i].x - ps[j].x) + (ps[i].y - ps[j].y), i
36                                     , j));
37             }
38             active[ps[i].x] = i;
39         }
40         // Rotate points 90 degrees: (x,y) -> (y,-x)
41         for (auto &p : ps) {

```

```

42         p.y = -tx;
43     }
44 }
45 return edges;
46 }

```

## 12.10 Max Manhattan Distance

```

1  /*
2  Max Manhattan distance
3  -----
4  Finds maximum manhattan distance for any two points with d dimensions.
5  Generalized code for d dimensions.
6  Time Complexity: (n * 2 ^ d * d)
7  */
8
9
10 long long ans = 0;
11 for (int msk = 0; msk < (1 << d); msk++) {
12     long long mx = LLONG_MIN, mn = LLONG_MAX;
13     for (int i = 0; i < n; i++) {
14         long long cur = 0;
15         for (int j = 0; j < d; j++) {
16             if (msk & (1 << j)) cur += p[i][j];
17             else cur -= p[i][j];
18         }
19         mx = max(mx, cur);
20         mn = min(mn, cur);
21     }
22     ans = max(ans, mx - mn);
23 }

```

## 12.11 Mo

```

1  /*
2  Mo's Algorithm (Sqrt Decomposition for Offline Queries)
3  -----
4  Problem: Answer q range queries [L, R] over array of length n
5           using add/remove operations efficiently
6  Indexing: 0-based
7  Bounds:
8           - arr[0..n-1]
9           - queries input as 1-based and converted to 0-based
10 Time Complexity: O((n + q) * sqrt(n)) per query batch

```

```

11 Space Complexity: O(n + q)
12 Usage:
13     - Fill in logic for add/remove operations (update cur)
14     - Fill answers[] indexed by original query order
15 */
16
17 const int MAXN = 200500;
18 ll n, q;
19 ll arr[MAXN]; // input array
20 ll cnt[1000005]; // frequency count
21 ll answers[MAXN]; // output array
22 ll cur = 0; // current query result
23 ll BLOCK_SIZE;
24
25 pair< pair<ll, ll>, ll> queries[MAXN]; // {{L, R}, query_index}
26
27 // Sort by block and then by R
28 inline bool cmp(const pair< pair<ll, ll>, ll> &x, const pair< pair<ll,
    ll>, ll> &y) {
29     ll block_x = x.first.first / BLOCK_SIZE;
30     ll block_y = y.first.first / BLOCK_SIZE;
31     if (block_x != block_y) return block_x < block_y;
32     return x.first.second < y.first.second;
33 }
34
35 int main() {
36     cin >> n >> q;
37     BLOCK_SIZE = sqrt(n);
38     for (int i = 0; i < n; i++) cin >> arr[i];
39     for (int i = 0; i < q; i++) {
40         int l, r;
41         cin >> l >> r;
42         --l; --r; // convert to 0-based
43         queries[i] = {{l, r}, i};
44     }
45     sort(queries, queries + q, cmp);
46     ll l = 0, r = -1;
47     for (int i = 0; i < q; i++) {
48         int left = queries[i].first.first;
49         int right = queries[i].first.second;
50         // Expand to right
51         while (r < right) {
52             r++;

```

```

53         // Operations to add arr[r], implement exactly here
54     }
55     // Shrink from right
56     while (r > right) {
57         // Operations to remove arr[r], implement exactly here
58         r--;
59     }
60     // Expand to left
61     while (l < left) {
62         // Operations to remove arr[l], implement exactly here
63         l++;
64     }
65     // Shrink from left
66     while (l > left) {
67         l--;
68         // Operations to add arr[l], implement exactly here
69     }
70     answers[queries[i].second] = cur; // Current answer
71 }
72 for (int i = 0; i < q; i++) cout << answers[i] << '\n';
73 }

```

## 12.12 MOD INT

```

1 template<int MOD>
2 struct ModInt {
3     ll v;
4     ModInt(ll _v = 0) {v = (-MOD < _v && _v < MOD) ? _v : _v % MOD; if (v
        < 0) v += MOD;}
5     ModInt& operator += (const ModInt &other) {v += other.v; if (v >= MOD)
        v -= MOD; return *this;}
6     ModInt& operator -= (const ModInt &other) {v -= other.v; if (v < 0) v
        += MOD; return *this;}
7     ModInt& operator *= (const ModInt &other) {v = v * other.v % MOD;
        return *this;}
8     ModInt& operator /= (const ModInt &other) {return *this *= inverse(
        other);}
9     bool operator == (const ModInt &other) const {return v == other.v;}
10    bool operator != (const ModInt &other) const {return v != other.v;}
11    friend ModInt operator + (ModInt a, const ModInt &b) {return a += b;}
12    friend ModInt operator - (ModInt a, const ModInt &b) {return a -= b;}
13    friend ModInt operator * (ModInt a, const ModInt &b) {return a *= b;}
14    friend ModInt operator / (ModInt a, const ModInt &b) {return a /= b;}

```

```

15 friend ModInt operator - (const ModInt &a) {return 0 - a;}
16 friend ModInt power(ModInt a, ll b) {ModInt ret(1); while (b > 0) {if
    (b & 1) ret *= a; a *= a; b >>= 1;} return ret;}
17 friend ModInt inverse(ModInt a) {return power(a, MOD - 2);}
18 friend istream& operator >> (istream &is, ModInt &m) {is >> m.v; m.v =
    (-MOD < m.v && m.v < MOD) ? m.v : m.v % MOD; if (m.v < 0) m.v +=
    MOD; return is;}
19 friend ostream& operator << (ostream &os, const ModInt &m) {return os
    << m.v;}
20 };

```

### 12.13 Next Permutation

```

1 sort(v.begin(),v.end());
2 while(next_permutation(v.begin(),v.end())){
3     for(auto u:v){
4         cout<<u<<" ";
5     }
6     cout<<endl;
7 }
8
9 string s="asdfassd";
10 sort(s.begin(),s.end());
11 while(next_permutation(s.begin(),s.end())){
12     cout<<s<<endl;
13 }

```

### 12.14 Next and Previous Smaller/Greater Element

```

1 /*
2  Next and Previous Smaller / Greater Elements
3  -----
4  Given: array a[0..n-1]
5  nextSmaller[i]: index of next element smaller than a[i], or n if none
6  prevSmaller[i]: index of previous element smaller than a[i], or -1 if
    none
7  For GREATER, replace a[s.top()] < a[i] with a[s.top()] > a[i]
8  Indexing: 0-based
9  */
10 vector<int> nextSmaller(vector<int> a, int n) {
11     stack<int> s;
12     vector<int> res(n, n); // default: no smaller to right
13     for (int i = 0; i < n; i++) {
14         while (!s.empty() && a[s.top()] > a[i]) {

```

```

15         res[s.top()] = i;
16         s.pop();
17     }
18     s.push(i);
19 }
20 return res;
21 }
22 vector<int> prevSmaller(vector<int> a, int n) {
23     stack<int> s;
24     vector<int> res(n, -1); // default: no smaller to left
25     for (int i = n - 1; i >= 0; i--) {
26         while (!s.empty() && a[s.top()] > a[i]) {
27             res[s.top()] = i;
28             s.pop();
29         }
30         s.push(i);
31     }
32     return res;
33 }

```

### 12.15 Parallel Binary Search

```

1  /*
2  Parallel Binary Search
3  -----
4  Solves: k independent queries where each answer lies in range [lo, hi]
5  - At each iteration, test the midpoint for a batch of queries
6  Indexing: 0-based
7  Bounds:
8  - i in [0, m-1] for the structure version
9  - q in [0, k-1] for each of the k queries
10 Time Complexity: O((m + k) * log M)
11 Space Complexity: O(k + m)
12 You must:
13 - Reset data structures before each iteration
14 - Implement apply_change(i) and check_query(q)
15 */
16 int lo[MAXN], hi[MAXN]; // binary search bounds for each query
17 vector<int> tocheck[MAXN]; // tocheck[mid] = list of queries to check
    at mid
18
19 bool done = false;
20 while (!done) {

```



```

21 done = true;
22 // Reset changes of structure to 0 before each iteration
23 // Assign queries to current midpoint
24 for (int q = 0; q < k; q++) {
25     if (lo[q] < hi[q]) {
26         tocheck[(lo[q] + hi[q]) / 2].push_back(q);
27     }
28 }
29 // Apply changes and evaluate queries
30 for (int i = 0; i < m; i++) {
31     // Apply change for ith query to your data structure
32     apply_change(i);
33     for (int q : tocheck[i]) {
34         done = false; // at least one query is not done
35         // Evaluate query q using the updated structure
36         if (operationToCheck(q)) {
37             hi[q] = i; // condition is true, try earlier
38         } else {
39             lo[q] = i + 1; // condition false, try later
40         }
41     }
42 }
43 }

```

## 12.16 Random Number Generators

```

1 //to avoid hacks
2 mt19937 mt(chrono::steady_clock::now().time_since_epoch().count());
3 mt19937_64 mt(chrono::steady_clock::now().time_since_epoch().count());
4 //you can also just write seed_value if hacks are not an issue
5
6 // rng() for generating random numbers between 0 and 2<<31-1
7
8 // for generating numbers with uniform probability in range
9 uniform_int_distribution<int> rng(0, numeric_limits<int>::max());
10
11 // then for generating random values just do
12 int random_value = rng(mt);
13
14 // if you do not want to create variable
15 uniform_int_distribution<int>(0, n)(mt)
16
17 // other distributions

```

```

18 // Normal distribution: mean = 0.0, stddev = 1.0
19 normal_distribution<double> normal_dist(0.0, 1.0);
20
21 // Exponential distribution: lambda = 1.5
22 exponential_distribution<double> exp_dist(1.5);
23
24 // for shuffling array
25 shuffle(permutation.begin(), permutation.end(), rng);

```

## 12.17 setprecision

```
1 cout<<fixed<<setprecision(10);
```

## 12.18 Ternary Search

```

1 /*
2 Ternary Search (for continuous unimodal functions)
3 -----
4 Finds the maximum (or minimum) value of a unimodal function f(x) in [l
5 , r]
6 Indexing: continuous domain (double)
7 Bounds:
8 - Search range is [l, r]
9 - Precision controlled by eps
10 Time Complexity: O(log((r - l) / eps))
11 - For minimum, reverse the condition (if f1 > f2 then l = m1)
12 */
13 double ternary_search(double l, double r) {
14     double eps = 1e-9; // precision error
15     while (r - l > eps) {
16         double m1 = l + (r - l) / 3;
17         double m2 = r - (r - l) / 3;
18         double f1 = f(m1); // evaluate function at m1
19         double f2 = f(m2); // evaluate function at m2
20         if (f1 < f2)
21             l = m1; // move left bound up if increasing
22         else
23             r = m2; // move right bound down if decreasing
24     }
25     return f(l); // return value at the best point
26 }

```

## 12.19 Ternary Search Int



```

1 int lo = -1, hi = n;
2 while (hi - lo > 1){
3     int mid = (hi + lo)>>1;
4     if (f(mid) > f(mid + 1)) hi = mid;
5     else lo = mid;
6 }
7 //lo + 1 is the answer

```

## 12.20 XOR Convolution

```

1 /*
2  Fast Walsh-Hadamard Transform (FWHT) for XOR Convolution
3  -----
4  Given two arrays A[0..N-1], B[0..N-1], with N = 1<<k (power of two).
5  Computes C[d] = sum_{i xor j = d} A[i] * B[j].
6  Indexing: 0-based
7  Bounds:
8      - N must be a power of two
9  Time Complexity: O(N * log(N))
10 Steps:
11     1. fwht(A, false); fwht(B, false); // forward transform
12     2. for i in [0..N): C[i] = A[i] * B[i]
13     3. fwht(C, true); // inverse transform
14 */
15 void FWHT (int A[], int k, int inv) {
16     for (int j = 0; j < k; j++)
17         for (int i = 0; i < (1 << k); i++)
18             if (~i & (1 << j)) {
19                 int p0 = A[i];
20                 int p1 = A[i | (1 << j)];
21                 A[i] = p0 + p1;
22                 A[i | (1 << j)] = p0 - p1;
23                 if (inv) {
24                     A[i] /= 2;
25                     A[i | (1 << j)] /= 2;
26                 }
27             }
28 }
29 void XOR_conv (int A[], int B[], int C[], int k) {
30     FWHT(A, k, false);
31     FWHT(B, k, false);
32     for (int i = 0; i < (1 << k); i++)
33         C[i] = A[i] * B[i];

```

```

34     FWHT(A, k, true);
35     FWHT(B, k, true);
36     FWHT(C, k, true);
37 }
38 // Example usage:
39 int A[1 << 20], B[1 << 20], C[1 << 20];
40 XOR_conv(A, B, C, 20);
41 for (int d = 0; d < (1<<20); d++){
42     cout << C[d] << (d==(1<<20)?'\n':' ');
43 }

```

## 12.21 XOR Basis

```

1 /*
2  XOR Basis (Linear Basis over GF(2))
3  -----
4  Supports insertion of numbers into a basis and querying the maximum
5  XOR of any subset with a given value.
6
7  Bit Width: up to D bits (here D = 60 for 64-bit integers)
8  Indexing: basis[0] is for bit 0 (least significant), basis[D-1] for
9             bit D-1
10 Bounds:
11     - Values x inserted must satisfy 0 <= x < 2^D
12 Time Complexity:
13     - insert(x): O(D)
14     - getMax(x): O(D)
15 Space Complexity: O(D)
16
17 Notes:
18     - We maintain one basis vector per bit position.
19     - On insert, we reduce x by existing basis vectors, then store it
20       in the highest bit it still has.
21     - To query max XOR, we greedily try to xor with basis vectors
22       from highest bit down.
23 */
24 const int D = 31; // Maximum number of bits in the numbers
25 int basis[D]; // basis[i] keeps the mask of the vector whose i value is
26               i
27 int sz; // Current size of the basis
28
29 void insertVector(int mask) {
30     //turn for around if you want max xor

```

```

29 for (int i = 0; i < D; i++) {
30     if ((mask & 1 << i) == 0) continue; // continue if i != f(mask)
31     if (!basis[i]) { // If there is no basis vector with the ith bit set
        , then insert this vector into the basis
32     basis[i] = mask;
33     ++sz;
34     return;
35 }
36 mask ^= basis[i]; // Otherwise subtract the basis vector from this
        vector
37 }
38 }
39
40 // V2: If you dont need the basis sorted.
41 vector<ll> basis;
42 void add(ll x)
43 {
44     for (int i = 0; i < basis.size(); i++)
45     {
46         x = min(x, x ^ basis[i]);
47     }
48     if (x != 0)
49     {
50         basis.pb(x);
51     }
52 }

```

## 12.22 XOR Basis Online

```

1 int rebuild_and_delete (int id) {
2     int pos = 0, mn = inf, p2 = 0;
3     for (int i = 0; i < basis.size(); i++) {
4         if (basis[i].id == id) {
5             pos = i;
6         }
7     }
8     int bits = 0;
9     for (int i = 0; i < basis.size(); i++) {
10        if (basis[i].mask & (1 << pos)) {
11            if (mn > basis[i].high) {
12                mn = basis[i].high;
13                p2 = i;
14            }

```

```

15        bits ^= 1 << basis[i].high;
16    }
17 }
18
19 if (p2 != pos) {
20     swap(basis[p2].id, basis[pos].id);
21     for (auto &i : basis) {
22         swap_bits(i.mask, pos, p2); // just swaps pos-th and p2-th bit
            in i.mask
23     }
24     pos = p2;
25 }
26 for (int i = 0; i < basis.size(); i++) {
27     if (i != pos) {
28         if (basis[i].mask & (1 << pos)) {
29             basis[i].val ^= basis[pos].val;
30             basis[i].mask ^= basis[pos].mask;
31         }
32     }
33 }
34 int good = (1 << pos) - 1;
35 int other = ((1 << len(basis)) - 1) ^ (good | (1 << pos));
36 basis.erase(basis.begin() + pos);
37 for (auto &i : basis) {
38     i.mask = ((i.mask & other) >> 1) | (i.mask & good);
39 }
40 return bits;
41 }
42
43 C++
44 41 lines
45 1161 bytes
46
47
48 int get_the_same_high_bit (int bits, vector <int> &val) {
49     for (auto &i : basis) {
50         if (__builtin_popcount(val[i.id] & bits) & 1) {
51             return i.id;
52         }
53     }
54     return -1;
55 }
56

```

57 C++  
58 8 lines  
59 200 bytes

61 Thus, we have learned to `delete` in  $O(m^2)$ .

63 Here is full version of the code:

64 Code

```
65
66 // #pragma GCC optimize("Ofast", "unroll-loops")
67 // #pragma GCC target("sse", "sse2", "sse3", "ssse3", "sse4")
68
69 #include <bits/stdc++.h>
70
71 #define all(a) a.begin(), a.end()
72 #define len(a) (int)(a.size())
73 #define mp make_pair
74 #define pb push_back
75 #define fir first
76 #define sec second
77 #define fi first
78 #define se second
79
80 using namespace std;
81
82 typedef pair<int, int> pii;
83 typedef long long ll;
84 typedef long double ld;
85
86 template<typename T>
87 bool umin(T &a, T b) {
88     if (b < a) {
89         a = b;
90         return true;
91     }
92     return false;
93 }
94
95 template<typename T>
96 bool umax(T &a, T b) {
97     if (a < b) {
98         a = b;
99         return true;
100     }
101 }
```

```
100     return false;
101 }
102
103 #ifdef KIVI
104 #define DEBUG for (bool _FLAG = true; _FLAG; _FLAG = false)
105 #define LOG(...) print(#__VA_ARGS__ " :", __VA_ARGS__) << endl
106 template <class ...Ts> auto &print(Ts ...ts) { return ((cerr << ts << "␣", ...)); }
107 #else
108 #define DEBUG while (false)
109 #define LOG(...)
110 #endif
111
112 const int max_n = -1, inf = 1000111222;
113
114 const int C = 20;
115
116 struct node {
117     int val, id, mask, high;
118 };
119
120
121
122 inline int get_high (int x) {
123     if (x == 0) {
124         return -1;
125     }
126     return 31 - __builtin_clz(x);
127 }
128
129 inline void swap_bits (int &x, int a, int b) {
130     int x1 = bool(x & (1 << a));
131     int x2 = bool(x & (1 << b));
132     x ^= (x1 ^ x2) << a;
133     x ^= (x1 ^ x2) << b;
134 }
135
136 struct xor_basis {
137     vector <node> basis;
138
139     inline bool add (int x, int id) {
140         int mask = 0;
141         for (auto &i : basis) {
```

```

142     if (umin(x, x ^ i.val)) {
143         mask ^= i.mask;
144     }
145 }
146 if (x) {
147     mask |= 1 << len(basis);
148     for (auto &i : basis) {
149         if (umin(i.val, i.val ^ x)) {
150             i.mask ^= mask;
151         }
152     }
153     basis.pb(node{val: x, id: id, mask: mask, high: get_high(x)});
154     return true;
155 }
156 return false;
157 }
158
159
160
161 inline int get_the_same_high_bit (int bits, const vector <int> &val) {
162     for (auto &i : basis) {
163         if (__builtin_popcount(val[i.id] & bits) & 1) {
164             return i.id;
165         }
166     }
167     return -1;
168 }
169
170
171 inline int rebuild_and_delete (int id) {
172     int pos = 0, mn = inf, p2 = 0;
173     for (int i = 0; i < len(basis); i++) {
174         if (basis[i].id == id) {
175             pos = i;
176         }
177     }
178     int bits = 0;
179     for (int i = 0; i < len(basis); i++) {
180         if (basis[i].mask & (1 << pos)) {
181             if (umin(mn, basis[i].high)) {
182                 p2 = i;
183             }
184             bits ^= 1 << basis[i].high;

```

```

185     }
186 }
187
188 if (p2 != pos) {
189     swap(basis[p2].id, basis[pos].id);
190     for (auto &i : basis) {
191         swap_bits(i.mask, pos, p2);
192     }
193     pos = p2;
194 }
195 for (int i = 0; i < len(basis); i++) {
196     if (i != pos) {
197         if (basis[i].mask & (1 << pos)) {
198             basis[i].val ^= basis[pos].val;
199             basis[i].mask ^= basis[pos].mask;
200         }
201     }
202 }
203 int good = (1 << pos) - 1;
204 int other = ((1 << len(basis)) - 1) ^ (good | (1 << pos));
205 basis.erase(basis.begin() + pos);
206 for (auto &i : basis) {
207     i.mask = ((i.mask & other) >> 1) | (i.mask & good);
208 }
209 return bits;
210 }
211
212 };
213
214 template<int max_bit> // not inclusive
215 struct xor_basis_online {
216
217     vector <xor_basis> baseses[max_bit + 1];
218
219     int mx;
220
221     vector <pii> where;
222     vector <int> val;
223
224     xor_basis_online() : mx(0), cur_id(0) {}
225
226     int cur_id;
227

```

```

228 inline int add (int x) {
229     val.pb(x);
230     where.pb(make_pair(-1, -1));
231     int id = cur_id++;
232     if (x == 0) {
233         return id;
234     }
235     for (int i = mx; i >= 0; i--) {
236         if (bases[i].empty()) {
237             continue;
238         }
239         if (bases[i].back().add(x, id)) {
240             bases[i + 1].pb(bases[i].back());
241             bases[i].pop_back();
242             umax(mx, i + 1);
243             for (auto &j : bases[i + 1].back().basis) {
244                 where[j.id] = make_pair(i + 1, len(bases[i + 1]) -
245                                     1);
246             }
247             return id;
248         }
249     }
250     bases[1].pb(xor_basis());
251     bases[1].back().add(x, id);
252     where.back() = make_pair(1, len(bases[1]) - 1);
253     umax(mx, 1);
254     return id;
255 }
256
257 inline int move_back (int sz, int pos) {
258     int to = len(bases[sz]) - 1;
259     if (to == pos) {
260         return pos;
261     }
262     for (auto &i : bases[sz][pos].basis) {
263         where[i.id].second = to;
264     }
265     for (auto &i : bases[sz][to].basis) {
266         where[i.id].second = pos;
267     }
268     swap(bases[sz][pos], bases[sz][to]);
269     return to;
270 }

```

```

270
271 inline void del (int id) {
272     if (val[id] == 0) {
273         return;
274     }
275     int sz, pos;
276     tie(sz, pos) = where[id];
277     pos = move_back(sz, pos);
278     while (true) {
279         int bits = bases[sz].back().rebuild_and_delete(id);
280         int i = sz - 1;
281         while (i > 0 && bases[i].empty()) {
282             --i;
283         }
284         int new_id = -1;
285         if (i > 0) {
286             new_id = bases[i].back().get_the_same_high_bit(bits, val
287                                     );
288         }
289         if (new_id == -1) {
290             if (sz > 1) {
291                 bases[sz - 1].pb(bases[sz].back());
292                 for (auto &j : bases[sz - 1].back().basis) {
293                     where[j.id] = make_pair(sz - 1, len(bases[sz -
294                                     1]) - 1);
295                 }
296             }
297             bases[sz].pop_back();
298             if (mx > 0 && bases[mx].empty()) {
299                 --mx;
300             }
301             return;
302         }
303         int cur = val[new_id];
304         assert(bases[sz].back().add(cur, new_id));
305         int new_sz = i;
306         int new_pos = len(bases[i]) - 1;
307         where[new_id] = make_pair(new_sz, new_pos);
308         id = new_id;
309         sz = new_sz;
310         pos = new_pos;
311     }

```

```

311
312 inline int size () {
313     return mx;
314 }
315 };
316
317 int main() {
318     // freopen("input.txt", "r", stdin);
319     // freopen("output.txt", "w", stdout);
320
321     ios_base::sync_with_stdio(0);
322     cin.tie(0);
323
324
325     // solution to https://basecamp.eolymp.com/uk/problems/11732
326     int n, q, add;
327     cin >> n >> add;
328     vector<int> p(n);
329     xor_basis_online<19> t;
330     vector<int> now(n);
331     for (int i = 0; i < n; i++) {
332         cin >> p[i];
333         now[i] = t.add(i ^ p[i]);
334     }
335     cin >> q;
336     int ans = t.size();
337     cout << ans << '\n';
338     for (int i = 0, l, r; i < q; i++) {
339         cin >> l >> r;
340         l = (l + ans * add) % n;
341         r = (r + ans * add) % n;
342         if (l != r) {
343             t.del(now[l]);
344             t.del(now[r]);
345             swap(p[l], p[r]);
346             now[l] = t.add(l ^ p[l]);
347             now[r] = t.add(r ^ p[r]);
348         }
349         ans = t.size();
350         cout << ans << '\n';
351     }
352 }

```

## 13 Polynomials

### 13.1 Berlekamp Massey

```

1 template<typename T>
2 vector<T> berlekampMassey(const vector<T> &s) {
3     vector<T> c; // the linear recurrence sequence we are building
4     vector<T> oldC; // the best previous version of c to use (the one
5                     // with the rightmost left endpoint)
6     int f = -1; // the index at which the best previous version of c
7                 // failed on
8     for (int i=0; i<(int)s.size(); i++) {
9         // evaluate c(i)
10        // delta = s_i - \sum_{j=1}^n c_j s_{i-j}
11        // if delta == 0, c(i) is correct
12        T delta = s[i];
13        for (int j=1; j<=(int)c.size(); j++)
14            delta -= c[j-1] * s[i-j]; // c_j is one-indexed, so we
15                                     // actually need index j - 1 in the code
16        if (delta == 0)
17            continue; // c(i) is correct, keep going
18        // now at this point, delta != 0, so we need to adjust it
19        if (f == -1) {
20            // this is the first time we're updating c
21            // s_i was the first non-zero element we encountered
22            // we make c of length i + 1 so that s_i is part of the base
23            // case
24            c.resize(i + 1);
25            mt19937 rng(chrono::steady_clock::now().time_since_epoch().
26                        count());
27            for (T &x : c)
28                x = rng(); // just to prove that the initial values don
29                            // 't matter in the first step, I will set to random
30                            // values
31            f = i;
32        } else {
33            // we need to use a previous version of c to improve on this
34            // one
35            // apply the 5 steps to build d
36            // 1. set d equal to our chosen sequence
37            vector<T> d = oldC;
38            // 2. multiply the sequence by -1
39            for (T &x : d)

```

```

32     x = -x;
33     // 3. insert a 1 on the left
34     d.insert(d.begin(), 1);
35     // 4. multiply the sequence by delta / d(f + 1)
36     T df1 = 0; // d(f + 1)
37     for (int j=1; j<=(int)d.size(); j++)
38         df1 += d[j-1] * s[f+1-j];
39     assert(df1 != 0);
40     T coef = delta / df1; // storing this in outer variable so
41                             // it's O(n^2) instead of O(n^2 log MOD)
42     for (T &x : d)
43         x *= coef;
44     // 5. insert i - f - 1 zeros on the left
45     vector<T> zeros(i - f - 1);
46     zeros.insert(zeros.end(), d.begin(), d.end());
47     d = zeros;
48     // now we have our new recurrence: c + d
49     vector<T> temp = c; // save the last version of c because it
50                             // might have a better left endpoint
51     c.resize(max(c.size(), d.size()));
52     for (int j=0; j<(int)d.size(); j++)
53         c[j] += d[j];
54     // finally, let's consider updating oldC
55     if (i - (int) temp.size() > f - (int) oldC.size()) {
56         // better left endpoint, let's update!
57         oldC = temp;
58         f = i;
59     }
60     return c;
61 }

```

## 13.2 FFT

```

1 using cd = complex<double>;
2 const double PI = acos(-1);
3 //declare size of vectors used like this
4 const int MAXN=2<<19;
5
6 void fft(vector<cd> & a, bool invert) {
7     int n = (int)a.size();
8

```

```

9     for (int i = 1, j = 0; i < n; i++) {
10         int bit = n >> 1;
11         for (; j & bit; bit >>= 1)
12             j ^= bit;
13         j ^= bit;
14
15         if (i < j)
16             swap(a[i], a[j]);
17     }
18
19     for (int len = 2; len <= n; len <<= 1) {
20         double ang = 2 * PI / len * (invert ? -1 : 1);
21         cd wlen(cos(ang), sin(ang));
22         for (int i = 0; i < n; i += len) {
23             cd w(1);
24             for (int j = 0; j < len / 2; j++) {
25                 cd u = a[i+j], v = a[i+j+len/2] * w;
26                 a[i+j] = u + v;
27                 a[i+j+len/2] = u - v;
28             }
29             w *= wlen;
30         }
31     }
32
33     if (invert) {
34         for (cd & x : a)
35             x /= n;
36     }
37 }
38
39 vector<int> multiply(vector<int> const& a, vector<int> const& b) {
40     vector<cd> fa(a.begin(), a.end()), fb(b.begin(), b.end());
41     int n = 1;
42     while (n < a.size() + b.size())
43         n <<= 1;
44     fa.resize(n);
45     fb.resize(n);
46
47     fft(fa, false);
48     fft(fb, false);
49     for (int i = 0; i < n; i++)
50         fa[i] *= fb[i];
51     fft(fa, true);

```

```

52     vector<int> result(n);
53     for (int i = 0; i < n; i++)
54         result[i] = round(fa[i].real());
55     return result;
56 }
57
58 //normalizing for when mult is between 2 big numbers and not polynomials
59 int carry = 0;
60 for (int i = 0; i < n; i++){
61     result[i] += carry;
62     carry = result[i] / 10;
63     result[i] %= 10;
64 }
65

```

### 13.3 NTT

```

1 // number theory transform
2
3 const int MOD = 998244353, ROOT = 3;
4 // const int MOD = 7340033, ROOT = 5;
5 // const int MOD = 167772161, ROOT = 3;
6 // const int MOD = 469762049, ROOT = 3;
7
8 int power(int base, int exp) {
9     int res = 1;
10    while (exp) {
11        if (exp % 2) res = 1LL * res * base % MOD;
12        base = 1LL * base * base % MOD;
13        exp /= 2;
14    }
15    return res;
16 }
17
18 void ntt(vector<int>& a, bool invert) {
19     int n = a.size();
20     for (int i = 1, j = 0; i < n; i++) {
21         int bit = n >> 1;
22         for (; j & bit; bit >>= 1) j ^= bit;
23         j ^= bit;
24         if (i < j) swap(a[i], a[j]);
25     }
26     for (int len = 2; len <= n; len <= 1) {

```

```

27     int wlen = power(ROOT, (MOD - 1) / len);
28     if (invert) wlen = power(wlen, MOD - 2);
29     for (int i = 0; i < n; i += len) {
30         int w = 1;
31         for (int j = 0; j < len / 2; j++) {
32             int u = a[i + j], v = 1LL * a[i + j + len / 2] * w % MOD;
33             a[i + j] = u + v < MOD ? u + v : u + v - MOD;
34             a[i + j + len / 2] = u - v >= 0 ? u - v : u - v + MOD;
35             w = 1LL * w * wlen % MOD;
36         }
37     }
38 }
39 if (invert) {
40     int n_inv = power(n, MOD - 2);
41     for (int& x : a) x = 1LL * x * n_inv % MOD;
42 }
43 }
44
45 vector<int> multiply(vector<int>& a, vector<int>& b) {
46     int n = 1;
47     while (n < a.size() + b.size()) n <= 1;
48     a.resize(n), b.resize(n);
49     ntt(a, false), ntt(b, false);
50     for (int i = 0; i < n; i++) a[i] = 1LL * a[i] * b[i] % MOD;
51     ntt(a, true);
52     return a;
53 }
54 // usage
55 // vector<int> a = {1, 2, 3}, b = {4, 5, 6};
56 // vector<int> c = multiply(a, b);
57 // for (int x : c) cout << x << " ";

```

### 13.4 Roots NTT

```

1 1*2^0 + 1 = 2, 1, 1
2 1*2^1 + 1 = 3, 2, 2
3 1*2^2 + 1 = 5, 2, 3
4 2*2^3 + 1 = 17, 2, 9
5 1*2^4 + 1 = 17, 3, 6
6 3*2^5 + 1 = 97, 19, 46
7 3*2^6 + 1 = 193, 11, 158
8 2*2^7 + 1 = 257, 9, 200
9 1*2^8 + 1 = 257, 3, 86

```



```

10 15*2^9 + 1 = 7681, 62, 1115
11 12*2^10 + 1 = 15361, 49, 1254
12 6*2^11 + 1 = 12289, 7, 8778
13 3*2^12 + 1 = 12289, 41, 4496
14 5*2^13 + 1 = 40961, 12, 23894
15 4*2^14 + 1 = 65537, 15, 30584
16 2*2^15 + 1 = 65537, 9, 7282
17 1*2^16 + 1 = 65537, 3, 21846
18 6*2^17 + 1 = 786433, 8, 688129
19 3*2^18 + 1 = 786433, 5, 471860
20 11*2^19 + 1 = 5767169, 12, 3364182
21 7*2^20 + 1 = 7340033, 5, 4404020
22 11*2^21 + 1 = 23068673, 38, 21247462
23 25*2^22 + 1 = 104857601, 21, 49932191
24 20*2^23 + 1 = 167772161, 4, 125829121
25 10*2^24 + 1 = 167772161, 2, 83886081
26 5*2^25 + 1 = 167772161, 17, 29606852
27 7*2^26 + 1 = 469762049, 30, 15658735
28 15*2^27 + 1 = 2013265921, 137, 749463956
29 12*2^28 + 1 = 3221225473, 8, 2818572289
30 6*2^29 + 1 = 3221225473, 14, 1150437669
31 3*2^30 + 1 = 3221225473, 13, 1734506024
32 35*2^31 + 1 = 75161927681, 93, 44450602392
33 18*2^32 + 1 = 77309411329, 106, 5105338484

```

## 14 Strings

### 14.1 Hashed String

```

1  /*
2
3      Hashed string
4      -----
5      Class for hashing string. Allows retrieval of hashes of any substring
        in the string.
6
7      Double hash or use big mod values to avoid problems with collisions
8
9      Important to take into account that the values used for the letters
        are not 0 to 26. it is ascii characters.
10
11      Time Complexity(Construction): O(n)
12      Space Complexity: O(n)

```

```

13  */
14
15  const ll MOD = 212345678987654321LL;
16  const ll base = 33;
17
18  class HashedString {
19  private:
20      static const long long M = 1e9 + 9;
21      static const long long B = 9973;
22
23      static vector<long long> pow;
24
25      vector<long long> p_hash;
26
27  public:
28      HashedString(const string &s) : p_hash(s.size() + 1) {
29          while (pow.size() <= s.size()) { pow.push_back((pow.back() * B) % M)
30              ; }
31
32          p_hash[0] = 0;
33          for (int i = 0; i < (int)s.size(); i++) {
34              p_hash[i + 1] = ((p_hash[i] * B) % M + s[i]) % M;
35          }
36
37          // substring [start, end]
38          long long get_hash(int start, int end) {
39              long long raw_val =
40                  (p_hash[end + 1] - (p_hash[start] * pow[end - start + 1]));
41              return (raw_val % M + M) % M;
42          }
43
44          // substring [start, end] with 1 added at the end. Remember it is
45          // ascii characters, not the number from 1 to 26 for the hash.
46          long long get_hash(int start, int end, int l){
47              if(start > end) return l;
48              long long val = ((p_hash[end + 1] * B) + 1 - (p_hash[start] * pow[
49                  end - start + 2]));
50              val = (val % M + M) % M;
51              return val;
52          }
53      };
54
55      // you cant skip this
56      vector<long long> HashedString::pow = {1};

```

## 14.2 KMP

```

1  /*
2      KMP
3      -----
4      Computes the prefix function for a string.
5
6      Maximum length of substring that ends at position i and is proper
7      prefix (not equal to string itself) of string
8      pf[i] is the length of the longest proper prefix of the substrings
9      [0.....i]$ which is also a suffix of this substring.
10
11     For matching, one can append the string with a delimiter like $
12     between them
13
14     Time Complexity: O(n)
15     Space Complexity: O(n)
16 */
17
18 vector<int> KMP(string s){
19     int n=(int)s.length();
20     vector<int> pf(n, 0);
21     for(int i=1;i<n;i++){
22         int j=pf[i-1];
23         while(j>0 && s[i]!=s[j]){
24             j=pf[j-1];
25         }
26         if(s[i]==s[j]){
27             pf[i]=j+1;
28         }
29     }
30     return pf;
31 }
32
33 // Counts how many times each prefix occurs
34 // Same thing can be done for two strings but only considering indices
35 // of second string
36 vector<int> count_occurrences_of_prefixes(vector<int> pf){
37     int n=(int)pf.size();
38     vector<int> ans(n + 1);
39     for (int i = 0; i < n; i++)
40         ans[pi[i]]++;
41     for (int i = n-1; i > 0; i--)

```

```

38     ans[pi[i-1]] += ans[i];
39     for (int i = 0; i <= n; i++)
40         ans[i]++;
41 }
42
43 // Computes automaton for string
44 // useful for not having to recalculate KMP of string s
45 // can be utilized when the second string (the one in which we are
46 // trying to count occurrences)
47 // is very large
48 void compute_automaton(string s, vector<vector<int>>& aut) {
49     s += '#';
50     int n = s.size();
51     vector<int> pi = KMP(s);
52     aut.assign(n, vector<int>(26));
53     for (int i = 0; i < n; i++) {
54         for (int c = 0; c < 26; c++) {
55             if (i > 0 && 'a' + c != s[i])
56                 aut[i][c] = aut[pi[i-1]][c];
57             else
58                 aut[i][c] = i + ('a' + c == s[i]);
59         }
60     }

```

## 14.3 Least Rotation String

```

1  /*
2      Min cyclic shift
3      -----
4      Finds the lexicographically minimum cyclic shift of a string
5
6      Time Complexity: O(n)
7      Space Complexity: O(n)
8  */
9
10 string least_rotation(string s)
11 {
12     s += s;
13     vector<int> f(s.size(), -1);
14     int k = 0;
15     for(int j = 1; j < s.size(); j++)
16     {

```

```

17 char sj = s[j];
18 int i = f[j - k - 1];
19 while(i != -1 && sj != s[k + i + 1])
20 {
21     if(sj < s[k + i + 1]){
22         k = j - i - 1;
23     }
24     i = f[i];
25 }
26 if(sj != s[k + i + 1])
27 {
28     if(sj < s[k]){
29         k = j;
30     }
31     f[j - k] = -1;
32 }
33 else
34     f[j - k] = i + 1;
35 }
36 return s.substr(k, s.size() / 2);
37 }

```

## 14.4 Manacher

```

1  /*
2      Manacher
3      -----
4      Computes the length of the longest palindrome centered at position i.
5
6      p[i] is length of biggest palindrome centered in this position.
7      Be careful with characters that are inserted to account for odd and
8      even palindromes
9
10     Time Complexity: O(n)
11     Space Complexity: O(n)
12 */
13
14 // Number of palindromes centered at each position
15
16 vector<int> manacher_odd(string s)
17 {
18     int n = s.size();

```

```

19     s = "$" + s + "^";
20     vector<int> p(n + 2);
21     int l = 1, r = 1;
22     for (int i = 1; i <= n; i++)
23     {
24         p[i] = max(0, min(r - i, p[l + (r - i)]));
25         while (s[i - p[i]] == s[i + p[i]])
26         {
27             p[i]++;
28         }
29         if (i + p[i] > r)
30         {
31             l = i - p[i], r = i + p[i];
32         }
33     }
34     return vector<int>(begin(p) + 1, end(p) - 1);
35 }
36 vector<int> manacher(string s)
37 {
38     string t;
39     for (auto c : s)
40     {
41         t += string("#") + c;
42     }
43     auto res = manacher_odd(t + "#");
44     return vector<int>(begin(res) + 1, end(res) - 1);
45 }
46
47 // usage
48 // vector<int> p = manacher("abacaba");
49 // this will return {2, 1, 4, 1, 2, 1, 8, 1, 2, 1, 4, 1, 2}
50 // vector<int> p = manacher("abaaba");
51 // this will return {2, 1, 4, 1, 2, 7, 2, 1, 4, 1, 2}

```

## 14.5 Suffix Array

```

1  /*
2      Suffix Array
3      -----
4      Computes the suffix array of a string in O(n log n).
5      Sorted array of all cyclic shifts of a string.
6
7      If you want sorted suffixes append $ to the end of the string.

```

```

8   lc is longest common prefix. Lcp of two substrings j > i is min(lc[i],
   ..... , lc[j - 1]).
9
10  To compute Largest common substring of multiple strings
11  Join all strings separating them with special character like $ (it has
   to be different for each string)
12  Sliding window on lcp array (all string have to appear on the sliding
   window and
13  the lcp of the interval will give the length of the substring that
   appears on all strings)
14
15  Time Complexity: O(n log n)
16  Space Complexity: O(n)
17
18  */
19
20  struct SuffixArray
21  {
22      int n;
23      string t;
24      vector<int> sa, rk, lc;
25      SuffixArray(const std::string &s)
26      {
27          n = s.length();
28          t = s;
29          sa.resize(n);
30          lc.resize(n - 1);
31          rk.resize(n);
32          std::iota(sa.begin(), sa.end(), 0);
33          std::sort(sa.begin(), sa.end(), [&](int a, int b)
34                  { return s[a] < s[b]; });
35          rk[sa[0]] = 0;
36          for (int i = 1; i < n; ++i)
37              rk[sa[i]] = rk[sa[i - 1]] + (s[sa[i]] != s[sa[i - 1]]);
38          int k = 1;
39          std::vector<int> tmp, cnt(n);
40          tmp.reserve(n);
41          while (rk[sa[n - 1]] < n - 1)
42          {
43              tmp.clear();
44              for (int i = 0; i < k; ++i)
45                  tmp.push_back(n - k + i);
46              for (auto i : sa)

```

```

47              if (i >= k)
48                  tmp.push_back(i - k);
49              std::fill(cnt.begin(), cnt.end(), 0);
50              for (int i = 0; i < n; ++i)
51                  ++cnt[rk[i]];
52              for (int i = 1; i < n; ++i)
53                  cnt[i] += cnt[i - 1];
54              for (int i = n - 1; i >= 0; --i)
55                  sa[--cnt[rk[tmp[i]]]] = tmp[i];
56              std::swap(rk, tmp);
57              rk[sa[0]] = 0;
58              for (int i = 1; i < n; ++i)
59                  rk[sa[i]] = rk[sa[i - 1]] + (tmp[sa[i - 1]] < tmp[sa[i]] || sa[i
   - 1] + k == n || tmp[sa[i - 1] + k] < tmp[sa[i] + k]);
60              k *= 2;
61          }
62          for (int i = 0, j = 0; i < n; ++i)
63          {
64              if (rk[i] == 0)
65              {
66                  j = 0;
67              }
68              else
69              {
70                  for (j -= j > 0; i + j < n && sa[rk[i] - 1] + j < n && s[i + j]
   == s[sa[rk[i] - 1] + j];)
71                      ++j;
72                  lc[rk[i] - 1] = j;
73              }
74          }
75      }
76
77      // Finds if string p appears as substring in the string
78      // might now work perfectly
79      int search(string &p){
80          int tam = p.size();
81          int l = 0, r = n;
82
83          string tmp = "";
84          while(r > l) {
85              int m = l + (r-l)/2;
86              tmp = t.substr(sa[m], min(n-sa[m], tam));
87              if(tmp >= p){

```

```

88         r = m;
89     } else {
90         l = m + 1;
91     }
92 }
93 if(l < n) {
94     tmp = t.substr(sa[l], min(n-sa[l], tam));
95 } else{
96     return -1;
97 }
98 if(tmp == p){
99     return l;
100 } else {
101     return -1;
102 }
103 }
104
105 // Counts number of times a string p appears as substring in string
106 int count(string &p) {
107     int x = search(p);
108     if(x == -1) return 0;
109     int cnt = 0;
110     int tam = p.size();
111     int maxx = 0;
112     while((1 << maxx) + x < n) maxx++;
113     int y = x;
114     for(int i = maxx-1; i >= 0; i--) {
115         if(x + (1 << i) >= n) continue;
116         string tmp = t.substr(sa[x + (1 << i)], min(n-sa[x + (1 << i)
117             ], tam));
118         if(tmp == p) x += (1 << i);
119     }
120     return x-y+1;
121 }
122 };
123 int main() {
124     cin.tie(0)->sync_with_stdio(0);
125     string s; cin >> s;
126     SuffixArray SA(s);
127
128     int q; cin >> q;
129     for(int t = 0; t < q; t++) {

```

```

130     string tmp; cin >> tmp;
131     cout << SA.count(tmp) << endl;
132 }
133
134     return 0;
135 }

```

## 14.6 Suffix Automaton

```

1  /*
2      Suffix Automaton
3  -----
4  Constructs suffix automaton for a given string.
5  Be careful with overlapping substrings.
6
7  Firstposition if first position string ends in.
8  If you want starting index you need to subtract length of the string
9      being searched.
10
11  len is length of longest string of state
12
13  Time Complexity(Construction): O(n)
14  Space Complexity: O(n)
15  */
16
17 struct state {
18     int len, link, firstposition;
19     vector<int> inv_link; // can skip for almost everything
20     map<char, int> next;
21 };
22
23 const int MAXN = 100000;
24 state st[MAXN * 2];
25 ll cnt[MAXN*2], cntPaths[MAXN*2], cntSum[MAXN*2], cnt1[2 * MAXN];
26 int sz, last;
27
28 // call this first
29 void initSuffixAutomaton() {
30     st[0].len = 0;
31     st[0].link = -1;
32     sz++;
33     last = 0;

```

```

34 }
35
36 // construction is O(n)
37 void insertChar(char c) {
38     int cur = sz++;
39     st[cur].len = st[last].len + 1;
40     st[cur].firstposition = st[last].len;
41     int p = last;
42     while (p != -1 && !st[p].next.count(c)) {
43         st[p].next[c] = cur;
44         p = st[p].link;
45     }
46     if (p == -1) {
47         st[cur].link = 0;
48     } else {
49         int q = st[p].next[c];
50         if (st[p].len + 1 == st[q].len) {
51             st[cur].link = q;
52         } else {
53             int clone = sz++;
54             st[clone].len = st[p].len + 1;
55             st[clone].next = st[q].next;
56             st[clone].link = st[q].link;
57             st[clone].firstposition = st[q].firstposition;
58             while (p != -1 && st[p].next[c] == q) {
59                 st[p].next[c] = clone;
60                 p = st[p].link;
61             }
62             st[q].link = st[cur].link = clone;
63         }
64     }
65     last = cur;
66     cnt[last] = 1;
67 }
68
69 // searches for the starting position in O(len(s)). Returns starting
70 // index of first occurrence or -1 if it does not appear.
71 int search(string s) {
72     int cur = 0, i = 0, n = (int)s.length();
73     while (i < n) {
74         if (!st[cur].next.count(s[i])) return -1;
75         cur = st[cur].next[s[i]];
76         i++;

```

```

76 }
77 //sumar 2 si se quiere 1 indexado
78 return st[cur].firstposition - n + 1;
79 }
80
81 void dfs(int cur) {
82     cntPaths[cur] = 1;
83     for (auto [x, y] : st[cur].next) {
84         if (cntPaths[y] == 0) dfs(y);
85         cntPaths[cur] += cntPaths[y];
86     }
87 }
88
89 // Counts how many paths exist from state. How many substrings exist
90 // from a specific state.
91 // Stored in cntPaths
92 void countPaths() {
93     dfs(0);
94 }
95
96 // Computes the number of times each state appears
97 void countOccurrences() {
98     vector<pair<int, int>> a;
99     for (int i = sz - 1; i > 0; i--) {
100         a.push_back({st[i].len, i});
101     }
102     sort(a.begin(), a.end());
103     for (int i = sz - 2; i >= 0; i--) {
104         cnt[st[a[i].second].link] += cnt[a[i].second];
105     }
106 }
107
108 void dfs1(int cur) {
109     for (auto [x, y] : st[cur].next) {
110         if (cntSum[y] == cnt[cur]) dfs1(y);
111         cntSum[cur] += cntSum[y];
112     }
113 }
114
115 // Computes the number of times each state or any of its children appear
116 // in the string.
117 void countSumOccurrences() {
118     for (int i = 0; i < sz; i++) {

```

```

117     cntSum[i]=cnt[i];
118 }
119 dfs1(0);
120 }
121
122
123 // Counts number of paths that can reach specific state.
124 void countPathsReverse(){
125     cnt1[0]=1;
126     queue<int> q;
127     q.push(0);
128     vector<int> in(2*MAXN, 0);
129     for(int i=0;i<sz;i++){
130         for(auto [x, y]:st[i].next){
131             in[y]++;
132         }
133     }
134     while((int)q.size()){
135         int cur=q.front();
136         q.pop();
137         for(auto [x, y]:st[cur].next){
138             cnt1[y]+=cnt1[cur];
139             in[y]--;
140             if(in[y]==0){
141                 q.push(y);
142             }
143         }
144     }
145 }
146
147 // Computes the kth smallest string that appears on the string (counting
148 // repetitions)
149 string kthSmallest(ll k){
150     string s="";
151     int cur=0;
152     while(k>0){
153         for(auto [c, y]:st[cur].next){
154             if(k>cntSum[y]) k-=cntSum[y];
155             else{
156                 k-=cnt[y];
157                 s+=c;
158                 cur=y;
159                 break;

```

```

159     }
160     }
161 }
162 return s;
163 }
164
165
166 // Computes the kth smallest string that appears on the string (without
167 // counting repetitions)
168 string kthSmallestDistinct(ll k){
169     string s="";
170     int cur=0;
171     while(k>0){
172         for(auto [c, y]:st[cur].next){
173             if(k>cntPaths[y]) k-=cntPaths[y];
174             else{
175                 k--;
176                 s+=c;
177                 cur=y;
178                 break;
179             }
180         }
181     }
182     return s;
183 }
184
185 // Precomputation to find all occurrences of a substring
186 void precoumpte_for_all_ocurrences(){
187     for (int v = 1; v < sz; v++) {
188         st[st[v].link].inv_link.push_back(v);
189     }
190 }
191
192 // Finding all occurrences of substring in string
193 // P_length is length of substring
194 // v is state where first occurrence happens
195 // be careful as indices can appear multiple times due to clone states
196 // if you want to avoid duplicate positions utilize set or have a flag
197 // for each state to know if it is clone or not
198 void output_all_occurrences(int v, int P_length) {
199     cout << st[v].firstposition - P_length + 1 << endl;
200     for (int u : st[v].inv_link)

```

```

200     output_all_occurrences(u, P_length);
201 }
202
203
204 //longest common substring
205 //build automaton for s first
206 string lcs (string S, string T) {
207     int v = 0, l = 0, best = 0, bestpos = 0;
208     for (int i = 0; i < T.size(); i++) {
209         while (v && !st[v].next.count(T[i])) {
210             v = st[v].link ;
211             l = st[v].len;
212         }
213         if (st[v].next.count(T[i])) {
214             v = st [v].next[T[i]];
215             l++;
216         }
217         if (l > best) {
218             best = l;
219             bestpos = i;
220         }
221     }
222     return T.substr(bestpos - best + 1, best);
223 }
224
225
226 int main(){
227     ios_base::sync_with_stdio(false); cin.tie(NULL);
228     string s; cin >> s;
229     initSuffixAutomaton();
230     for(char c:s){
231         insertChar(c);
232     }
233 }

```

## 14.7 Trie Ahocorasick

```

1  /*
2
3      Trie - AhoCorasick
4
5  -----
6  Builds a trie for subset of strings and computes suffix links.
7  KATCL implementation is cleaner.

```

```

7  Time Complexity(Construction): O(m) where m is sum
8  of lengths of strings
9  Space Complexity: O(m)
10 */
11
12
13
14 const int K = 26;
15
16 struct Vertex {
17     int next[K];
18     bool output = false;
19     int p = -1;
20     char pch;
21     int link = -1;
22     int go[K];
23
24     Vertex(int p=-1, char ch='$') : p(p), pch(ch) {
25         fill(begin(next), end(next), -1);
26         fill(begin(go), end(go), -1);
27     }
28 };
29
30 vector<Vertex> t(1);
31
32 void add_string(string const& s) {
33     int v = 0;
34     for (char ch : s) {
35         int c = ch - 'a';
36         if (t[v].next[c] == -1) {
37             t[v].next[c] = t.size();
38             t.emplace_back(v, ch);
39         }
40         v = t[v].next[c];
41     }
42     t[v].output = true;
43 }
44
45 int go(int v, char ch);
46
47 int get_link(int v) {
48     if (t[v].link == -1) {
49         if (v == 0 || t[v].p == 0)

```



```

50     t[v].link = 0;
51     else
52         t[v].link = go(get_link(t[v].p), t[v].pch);
53 }
54 return t[v].link;
55 }
56
57 int go(int v, char ch) {
58     int c = ch - 'a';
59     if (t[v].go[c] == -1) {
60         if (t[v].next[c] != -1)
61             t[v].go[c] = t[v].next[c];
62         else
63             t[v].go[c] = v == 0 ? 0 : go(get_link(v), ch);
64     }
65     return t[v].go[c];
66 }

```

## 14.8 Z Function

```

1  /*
2
3      Z_function
4      -----
5      Computes the z_function for any string.
6      ith element is equal to the greatest number of characters starting
7      from the position i that coincide with the first characters of s
8
9      z[i] length of the longest string that is, at the same time, a prefix
10     of s and a prefix of the suffix of $$$ starting at i.
11
12     to compress string, one can run z_function and then find the smallest
13     i that divides n such that i + z[i] = n
14
15     Time Complexity: O(n)
16     Space Complexity: O(n)
17 */
18
19 vector<int> z_function(string s) {
20     int n = s.size();
21     vector<int> z(n);
22     int l = 0, r = 0;
23     for(int i = 1; i < n; i++) {

```

```

21     if(i < r) {
22         z[i] = min(r - i, z[i - 1]);
23     }
24     while(i + z[i] < n && s[z[i]] == s[i + z[i]]) {
25         z[i]++;
26     }
27     if(i + z[i] > r) {
28         l = i;
29         r = i + z[i];
30     }
31 }
32 return z;
33 }
34
35 // usage
36 // vector<int> z = z_function("abacaba");
37 // this will return {0, 0, 1, 0, 3, 0, 1}
38 // vector<int> z = z_function("aaaaa");
39 // this will return {0, 4, 3, 2, 1}
40 // vector<int> z = z_function("aaabaab");
41 // this will return {0, 2, 1, 0, 2, 1, 0}

```

## 15 Trees

### 15.1 Centroid Decomposition

```

1  /*
2
3      Centroid Decomposition
4      -----
5      Finds the centroid decomposition of a given tree.
6      Any vertex can have at most log n centroid ancestors
7
8      The code below is the solution to Xenia and tree.
9      Given tree, queries of two types:
10     1) u - color vertex u
11     2) v - print minimum distance of vertex v to any colored vertex before
12
13     Time Complexity: O(n log n)
14     Space Complexity: O(n log n)
15 */
16 const int MAXN=200005;
17

```

```

18 vector<int> adj[MAXN];
19 vector<bool> is_removed(MAXN, false);
20 vector<int> subtree_size(MAXN, 0);
21 vector<int> dis(MAXN, 1e9);
22 vector<vector<pair<int, int>>> ancestor(MAXN);
23
24 int get_subtree_size(int node, int parent = -1) {
25     subtree_size[node] = 1;
26     for (int child : adj[node]) {
27         if (child == parent || is_removed[child]) { continue; }
28         subtree_size[node] += get_subtree_size(child, node);
29     }
30     return subtree_size[node];
31 }
32
33 int get_centroid(int node, int tree_size, int parent = -1) {
34     for (int child : adj[node]) {
35         if (child == parent || is_removed[child]) { continue; }
36         if (subtree_size[child] * 2 > tree_size) {
37             return get_centroid(child, tree_size, node);
38         }
39     }
40     return node;
41 }
42
43 void getDist(int cur, int centroid, int p=-1, int dist=1){
44     for (int child:adj[cur]){
45         if(child==p || is_removed[child])
46             continue;
47         dist++;
48         getDist(child, centroid, cur, dist);
49         dist--;
50     }
51     ancestor[cur].push_back(make_pair(centroid, dist));
52 }
53
54 void update(int cur){
55     for (int i=0;i<ancestor[cur].size();i++){
56         dis[ancestor[cur][i].first]=min(dis[ancestor[cur][i].first],
57             ancestor[cur][i].second);
58     }
59     dis[cur]=0;
60 }

```

```

60
61 int query(int cur){
62     int mini=dis[cur];
63     for (int i=0;i<ancestor[cur].size();i++){
64         mini=min(mini, ancestor[cur][i].second+dis[ancestor[cur][i].first
65             ]);
66     }
67     return mini;
68 }
69
70 void build_centroid_decomp(int node = 1) {
71     int centroid = get_centroid(node, get_subtree_size(node));
72     for (int child : adj[centroid]) {
73         if (is_removed[child]) { continue; }
74         getDist(child, centroid, centroid);
75     }
76     is_removed[centroid] = true;
77     for (int child : adj[centroid]) {
78         if (is_removed[child]) { continue; }
79         build_centroid_decomp(child);
80     }
81 }
82
83 }

```

## 15.2 Heavy Light Decomposition

```

1  /*
2
3      Heavy Light Decomposition(HLD)
4  -----
5  Constructs the heavy light decomposition of a tree
6
7  Splits the tree into several paths so that we can reach the root
8      vertex from any v by traversing at most log n paths.
9  In addition, none of these paths intersect with another.
10
11 Time Complexity(Creation): O(n log n)
12 Time Complexity(Query): O((log n) ^ 2) usually, depending on the query
13     itself
14 Space Complexity: O(n)
15 */

```

```

14 //call dfs1 first
15 struct SegmentTree {
16     vector<ll> a;
17     int n;
18
19     SegmentTree(int _n) : a(2 * _n, 0), n(_n) {}
20
21     void update(int pos, ll val) {
22         for (a[pos += n] = val; pos > 1; pos >>= 1) {
23             a[pos / 2] = (a[pos] ^ a[pos ^ 1]);
24         }
25     }
26
27     ll get(int l, int r) {
28         ll res = 0;
29         for (l += n, r += n; l < r; l >>= 1, r >>= 1) {
30             if (l & 1) {
31                 res ^= a[l++];
32             }
33             if (r & 1) {
34                 res ^= a[--r];
35             }
36         }
37         return res;
38     }
39 };
40
41 const int MAXN=500005;
42 vector<int> adj[MAXN];
43 SegmentTree st(MAXN);
44 int a[MAXN], sz[MAXN], to[MAXN], dpth[MAXN], s[MAXN], par[MAXN];
45 int cnt=0;
46
47 void dfs1(int cur, int p){
48     sz[cur]=1;
49     for(int x:adj[cur]){
50         if(x==p) continue;
51         dpth[x]=dpth[cur]+1;
52         par[x]=cur;
53         dfs1(x, cur);
54         sz[cur]+=sz[x];
55     }
56 }

```

```

57 }
58
59 void dfs(int cur, int p, int l){
60     st.update(cnt, a[cur]);
61     s[cur]=cnt++;
62     to[cur]=l;
63     int g=-1;
64     for(int x:adj[cur]){
65         if(x==p) continue;
66         if(g==-1 || sz[g]<sz[x]){
67             g=x;
68         }
69     }
70     if(g==-1) return;
71     dfs(g, cur, l);
72     for(int x:adj[cur]){
73         if(x==p || x==g) continue;
74         dfs(x, cur, x);
75     }
76 }
77
78 int query(int u, int v){
79     int res=0;
80     while(to[u]!=to[v]){
81         if(dpth[to[u]]<dpth[to[v]]) swap(u, v);
82         res^=st.get(s[to[u]], s[u]+1);
83         u=par[to[u]];
84     }
85     if(dpth[u]>dpth[v]) swap(u, v);
86     res^=st.get(s[u], s[v]+1);
87     return res;
88 }
89
90
91
92 //alternate implementation
93 vector<int> parent, depth, heavy, head, pos;
94 int cur_pos;
95
96 int dfs(int v, vector<vector<int>> const& adj) {
97     int size = 1;
98     int max_c_size = 0;

```

```

100     for (int c : adj[v]) {
101         if (c != parent[v]) {
102             parent[c] = v, depth[c] = depth[v] + 1;
103             int c_size = dfs(c, adj);
104             size += c_size;
105             if (c_size > max_c_size)
106                 max_c_size = c_size, heavy[v] = c;
107         }
108     }
109     return size;
110 }
111
112 void decompose(int v, int h, vector<vector<int>> const& adj) {
113     head[v] = h, pos[v] = cur_pos++;
114     if (heavy[v] != -1)
115         decompose(heavy[v], h, adj);
116     for (int c : adj[v]) {
117         if (c != parent[v] && c != heavy[v])
118             decompose(c, c, adj);
119     }
120 }
121
122 void init(vector<vector<int>> const& adj) {
123     int n = adj.size();
124     parent = vector<int>(n);
125     depth = vector<int>(n);
126     heavy = vector<int>(n, -1);
127     head = vector<int>(n);
128     pos = vector<int>(n);
129     cur_pos = 0;
130
131     dfs(0, adj);
132     decompose(0, 0, adj);
133 }
134
135 int query(int a, int b) {
136     int res = 0;
137     for (; head[a] != head[b]; b = parent[head[b]]) {
138         if (depth[head[a]] > depth[head[b]])
139             swap(a, b);
140         int cur_heavy_path_max = segment_tree_query(pos[head[b]], pos[b
141             ]);
142         res = max(res, cur_heavy_path_max);

```

```

142     }
143     if (depth[a] > depth[b])
144         swap(a, b);
145     int last_heavy_path_max = segment_tree_query(pos[a], pos[b]);
146     res = max(res, last_heavy_path_max);
147     return res;
148 }

```

### 15.3 Lowest Common Ancestor (LCA)

```

1  /*
2      LCA(Lowest Common Ancestor)
3  -----
4  Computes the lowest common ancestor of two vertices in a tree.
5
6  Be careful as implementation is indexed starting with 1
7
8  Time Complexity(Creation): O(n log n)
9  Time Complexity(Query): O(log n)
10 Space Complexity: O(n log n)
11 */
12
13 const int N=200005;
14 vector<int> adj[N];
15 vector<int> start(N), end1(N), depth(N);
16 vector<vector<int>> t(N, vi(32));
17 int timer=0;
18 int n, l;
19 // l=(int)ceil(log2(n))
20 // call dfs(1, 1, 0)
21 // 1 indexed, dont use 0 indexing
22
23
24 void dfs(int cur, int p, int cnt){
25     depth[cur]=cnt;
26     t[cur][0]=p;
27     start[cur]=timer++;
28     for(int i=1;i<=l;i++){
29         t[cur][i]=t[t[cur][i-1]][i-1];
30     }
31     for(int x:adj[cur]){
32         if(x==p) continue;
33         dfs(x, cur, cnt+1);

```

```

34     }
35     end1[cur]=++timer;
36 }
37
38 bool ancestor(int u, int v){
39     return start[u]<=start[v] && end1[u]>=end1[v];
40 }
41
42 int lca(int u, int v){
43     if(ancestor(u, v))
44         return u;
45     if (ancestor(v, u)){
46         return v;
47     }
48     for(int i=1;i>=0;i--){
49         if(!ancestor(t[u][i], v)){
50             u=t[u][i];
51         }
52     }
53     return t[u][0];
54 }

```

## 15.4 Tree Diameter

```

1  /*
2
3      Tree Diameter
4
5      -----
6      Finds the vertex most distant to vertex on which function is called.
7
8      The first value is the vertex itself and the second value is the
9      distance.
10
11     To find diameter run algorithm twice, first on random vertex and then
12     on the vertex that is farthest away.
13
14     The vertex that is the farthest away from any vertex in tree must be
15     an endpoint of the diameter.
16
17     Time Complexity: O(n)
18     Space Complexity: O(n)
19 */
20
21 pair<int, int> dfs(const vector<vector<int>> &tree, int node = 1,

```

```

17     int previous = 0, int length = 0) {
18     pair<int, int> max_path = {node, length};
19     for (const int &i : tree[node]) {
20         if (i == previous) { continue; }
21         pair<int, int> other = dfs(tree, i, node, length + 1);
22         if (other.second > max_path.second) { max_path = other; }
23     }
24     return max_path;
25 }

```

## 16 Scripts

### 16.1 build.sh

This file should be called before stress.sh or validate.sh. build.sh name.cpp

```

1 g++ -static -DLOCAL -lm -s -x c++ -Wall -Wextra -O2 -std=c++17 -o $1 $1.
   cpp

```

### 16.2 stress.sh

Format is stress.sh Awrong Aslow Agen Numtests

```

1  #!/usr/bin/env bash
2
3  for ((testNum=0;testNum<$4;testNum++))
4  do
5      ./$3 > input
6      ./$2 < input > outSlow
7      ./$1 < input > outWrong
8      H1='md5sum outWrong'
9      H2='md5sum outSlow'
10     if !(cmp -s "outWrong" "outSlow")
11     then
12         echo "Error found!"
13         echo "Input:"
14         cat input
15         echo "Wrong Output:"
16         cat outWrong
17         echo "Slow Output:"
18         cat outSlow
19         exit
20     fi
21 done

```

```
22 echo Passed $4 tests
```

### 16.3 validate.sh

Format is validate.sh Awrong Avalidator Agen NumTests

```
1  #!/usr/bin/env bash
2
3  for ((testNum=0;testNum<$4;testNum++))
4  do
5      ./ $3 > input
6      ./ $1 < input > out
7      cat input out > data
8      ./ $2 < data > res
9      result=$(cat res)
10     if [ "${result:0:2}" != "OK" ];
11     then
12         echo "Error_found!"
13         echo "Input:"
14         cat input
15         echo "Output:"
16         cat out
17         echo "Validator_Result:"
18         cat res
19         exit
20     fi
21 done
22 echo Passed $4 tests
```