

TCR

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At the start of a contest, type this in a terminal:

```
1 printf "set nu sw=4 ts=4 noet ai hls shellcmdflag=-ic\nsyntax on\nicolor slate" > ~/.vimrc
2 echo "alias gll='g++ -Wall -Wshadow -DDEBUG -std=c++11'" >> ~/.bashrc
```

template.cpp

```
1 #include<bits/stdc++.h>
2
3 using namespace std;
4
5 // Order statistics tree (if supported by judge!):
6 #include <ext/pb_ds/assoc_container.hpp>
7 #include <ext/pb_ds/tree_policy.hpp>
8 using namespace __gnu_pbds;
9
10 template<class TK, class TM>
11 using order_tree = tree<TK, TM, less<TK>, rb_tree_tag, tree_order_statistics_node_update>;
12 // iterator find_by_order(int r) (zero based)
13 // int order_of_key(TK v)
14 template<class TV>
15 using order_set = order_tree<TV, null_type>;
16
17 #define x first
18 #define y second
19 #define pb push_back
20 #define mp make_pair
21 #define eb emplace_back
22
23 typedef long long ll;
24 typedef pair<int, int> pii;
25 typedef vector<int> vi;
26 typedef vector<vi> vvi;
27
28 const int INF = 2147483647; // (1 << 30) - 1 + (1 << 30)
29 const ll LLINF = (1LL << 62) - 1 + (1LL << 62); // = 9.223.372.036.854.775.807
30 const double PI = acos(-1.0);
31
32 // lambda-expression: [] (args) -> retType { body }
33
34 #define DBG(x) cerr << __LINE__ << ": " << #x << " = " << (x) << endl
35
36 const bool LOG = false;
37 void Log() {
38     if (LOG) cerr << "\n\n";
39 }
40 template<class T, class... S>
41 void Log(T t, S... s) {
42     if (LOG) cerr << t << "\t", Log(s...);
43 }
44
45 template<class T>
46 using min_queue = priority_queue<T, vector<T>, greater<T>>;
47
48 int main() {
49     ios_base::sync_with_stdio(false); // faster IO
50     cin.tie(NULL); // faster IO
51     cerr << boolalpha; // (print true/false)
```

```

52     (cout << fixed).precision(10); // set floating point precision
53     // TODO: code
54     return 0;
55 }

```

Prime numbers: 982451653 , 81253449 , $10^3 + \{-9, -3, 9, 13\}$, $10^6 + \{-17, 3, 33\}$, $10^9 + \{7, 9, 21, 33, 87\}$

0.1 De winnende aanpak

- Goed slapen & een vroeg ritme hebben
- Genoeg drinken & eten tijdens de wedstrijd
- Een lijst van alle problemen met info waar het over gaat, en wie het goed kan oplossen
- Ludo moet de opgave goed lezen
- Test de kleine voorbeeldgevallen
- Houd na 2 uur een pauze en overleg waar iedereen mee bezig is
- Maak zelf wat test-cases
- Na een WA, print het probleem, en probeer het ook weg te leggen
- Typ de dingen uit de TCR, die je zeker nodig hebt, alvast in
- Peter moet meer papier gebruiken om fouten te voorkomen
- Als iemand niks te doen heeft, kan hij nodige dingen uit de TCR typen.
- We moeten ook een voorbeeld test-case voor TCR algoritmes hebben om te testen of het goed overgetypt is
- Bij geometrie moeten we om kunnen gaan met meerdere input manieren (voor bv. lijnen)
- Gebruik veel long long's
- Bij een verkeerd antwoord, kijk naar genoeg debug output

0.2 Detecting overflow

These are GNU builtins, detect both over- and underflow. Returns a boolean upon failure, otherwise the result is present in ref. Follow the template:

```
_builtin_[u|s][add|mul|sub](ll)?_overflow(a, b, &res)
```

0.3 Wrong Answer

- Edge cases: $n \in \{-1, 0, 1, 2\}$. Empty list/graph?
- Beware of typos
- Test sample input; make custom testcases
- Read carefully
- Check bounds (use long long or long double)
- Off by one error (in indices or loop bounds)
- Not enough precision
- Assertions
- Missing modulo operators
- Cases that need a (completely) different approach

0.4 Covering problems

Minimum edge cover \iff Maximum independent set

Matching A set of edges without common vertices (*Maximum is the **largest** such set, maximal is a set which you cannot add more edges to without breaking the property*).

Minimum Vertex Cover A set vertices (cover) such that each edge in the graph is incident to at least one vertex of the set.

Minimum Edge Cover A set of edges (cover) such that every vertex is incident to at least one edge of the set.

Maximum Independent Set A set of vertices in a graph such that no two of them are adjacent.

König's theorem In any bipartite graph, the number of edges in a maximum matching equals the number of vertices in a minimum vertex cover

A useful identity: $\bigoplus_{x=0}^{a-1} x = \{0, a-1, 1, a\}[a \bmod 4]$.

1 Mathematics

```

1 int abs(int x) { return x > 0 ? x : -x; }
2 int sign(int x) { return (x > 0) - (x < 0); }
3
4 // greatest common divisor
5 ll gcd(ll a, ll b) { while (b) { a %= b; swap(a, b); } return a; }
6 // least common multiple
7 ll lcm(ll a, ll b) { return a / gcd(a, b) * b; }
8 ll mod(ll a, ll m) { return ((a % b) + b) % b; }
9
10 // safe multiplication (ab % m) for m <= 4e18 in O(log b)
11 ll modmul(ll a, ll b, ll m) {
12     ll r = 0;
13     while (b) {
14         if (b & 1) r = mod(r + a, m);
15         a = mod(a + a, m);
16         b >>= 1;
17     }
18     return r;
19 }
20
21 // safe exponentiation (a^b % m) for m <= 2e9 in O(log b)
22 ll modpow(ll a, ll b, ll m) {
23     ll r = 1;
24     while (b) {
25         if (b & 1) r = (r * a) % m;
26         a = (a * a) % m;
27         b >>= 1;
28     }
29     return r;
30 }
31
32 // returns x, y such that ax + by = gcd(a, b)
33 ll egcd(ll a, ll b, ll &x, ll &y) {
34     ll xx = y = 0, yy = x = 1;
35     while (b) {
36         x -= a / b * xx; swap(x, xx);
37         y -= a / b * yy; swap(y, yy);
38         a %= b; swap(a, b);
39     }
40     return a;
41 }
42
43 // Chinese remainder theorem
44 const pll NO_SOLUTION(0, -1);
45 // Returns (u, v) such that x = u % v <=> x = a % n and x = b % m
46 pll crt(ll a, ll n, ll b, ll m) {
47     ll s, t, d = egcd(n, m, s, t), nm = n * m;
48     if (mod(a - b, d)) return NO_SOLUTION;
49     return pll(mod(s * b * n + t * a * m, nm) / d, nm / d);
50     /* when n, m > 10^6, avoid overflow:
51     return pll(mod(modmul(modmul(s, b, nm), n, nm) +
52                     modmul(modmul(t, a, nm), m, nm), nm) / d, nm / d); */
53 }
54
```

```

55 int phi[N]; // phi[i] = #{ j | gcd(i, j) = 1 }
56
57 void sievePhi() {
58     for (int i = 0; i < N; i++) phi[i] = i;
59     for (int i = 2; i < N; i++)
60         if (phi[i] == i)
61             for (int j = i; j < N; j += i)
62                 phi[j] -= phi[j] / i * (i - 1);
63 }
64
65 // calculate nCk % p (p prime!)
66 ll lucas(ll n, ll k, ll p) {
67     ll ans = 1;
68     while (n) {
69         ll np = n % p, kp = k % p;
70         if (np < kp) return 0;
71         ans = mod(ans * binom(np, kp), p); // (np C kp)
72         n /= p; k /= p;
73     }
74     return ans;
75 }

```

2 Datastructures

2.1 Standard segment tree $\mathcal{O}(\log n)$

```

1 typedef /* Tree element */ S;
2 const int n = 1 << 20;
3 S t[2 * n];
4
5 // required axiom: associativity
6 S combine(S l, S r) { return l + r; } // sum segment tree
7 S combine(S l, S r) { return max(l, r); } // max segment tree
8
9 void build() {
10     for (int i = n; --i; ) t[i] = combine(t[2 * i], t[2 * i + 1]);
11 }
12
13 // set value v on position i
14 void update(int i, S v) {
15     for (t[i += n] = v; i /= 2; ) t[i] = combine(t[2 * i], t[2 * i + 1]);
16 }
17
18 // sum on interval [l, r)
19 S query(int l, int r) {
20     S resL, resR;
21     for (l += n, r += n; l < r; l /= 2, r /= 2) {
22         if (l & 1) resL = combine(resL, t[l++]);
23         if (r & 1) resR = combine(t[--r], resR);
24     }
25     return combine(resL, resR);
26 }

```

2.2 Binary Indexed Tree $\mathcal{O}(\log n)$

Use one-based indices ($i > 0$)!

```

1 int bit[MAXN + 1];
2
3 // arr[i] += v
4 void update(int i, int v) {
5     while (i <= MAXN) bit[i] += v, i += i & -i;
6 }

```

```

7
8 // returns sum of arr[i], where i: [1, i]
9 int query(int i) {
10     int v = 0; while (i) v += bit[i], i -= i & -i; return v;
11 }

```

2.3 Disjoint-Set / Union-Find $\mathcal{O}(\alpha(n))$

```

1 int par[MAXN], rnk[MAXN];
2
3 void uf_init(int n) {
4     fill_n(par, n, -1);
5     fill_n(rnk, n, 0);
6 }
7
8 int uf_find(int v) {
9     return par[v] < 0 ? v : par[v] = uf_find(par[v]);
10 }
11
12 void uf_union(int a, int b) {
13     if ((a = uf_find(a)) == (b = uf_find(b))) return;
14     if (rnk[a] < rnk[b]) swap(a, b);
15     if (rnk[a] == rnk[b]) rnk[a]++;
16     par[b] = a;
17 }

```

3 Graph Algorithms

3.1 Maximum matching $\mathcal{O}(nm)$

This problem could be solved with a flow algorithm like Dinic's algorithm which runs in $\mathcal{O}(\sqrt{V}E)$, too.

```

1 const int sizeL = 1e4, sizeR = 1e4;
2 bool vis[sizeR];
3 int par[sizeR]; // par : R -> L
4 vi adj[sizeL]; // adj : L -> (N -> R)
5
6 bool match(int u) {
7     for (int v : adj[u]) {
8         if (vis[v]) continue;
9         vis[v] = true;
10        if (par[v] == -1 || match(par[v])) {
11            par[v] = u;
12            return true;
13        }
14    }
15    return false;
16 }
17
18 // perfect matching iff ret == sizeL == sizeR
19 int maxmatch() {
20     fill_n(par, sizeR, -1);
21     int ret = 0;
22     for (int i = 0; i < sizeL; i++) {
23         fill_n(vis, sizeR, false);
24         ret += match(i);
25     }
26     return ret;
27 }

```

3.2 Strongly Connected Components $\mathcal{O}(V + E)$

```

1 vvi adj, comps;
2 vi tidx, lnk, cnr, st;
3 vector<bool> vis;
4 int age, ncomps;
5
6 void tarjan(int v) {
7     tidx[v] = lnk[v] = ++age;
8     vis[v] = true;
9     st.pb(v);
10
11     for (int w : adj[v]) {
12         if (!tidx[w]) tarjan(w), lnk[v] = min(lnk[v], lnk[w]);
13         else if (vis[w]) lnk[v] = min(lnk[v], tidx[w]);
14     }
15
16     if (lnk[v] != tidx[v]) return;
17
18     comps.pb(vi());
19     int w;
20     do {
21         vis[w = st.back()] = false;
22         cnr[w] = ncomps;
23         comps.back().pb(w);
24         st.pop_back();
25     } while (w != v);
26     ncomps++;
27 }
28
29 void findSCC(int n) {
30     age = ncomps = 0;
31     vis.assign(n, false);
32     tidx.assign(n, 0);
33     lnk.resize(n);
34     cnr.resize(n);
35     comps.clear();
36
37     for (int i = 0; i < n; i++)
38         if (tidx[i] == 0) tarjan(i);
39 }

```

3.2.1 2-SAT $\mathcal{O}(V + E)$

Include findSCC.

```

1 void init2sat(int n) { adj.assign(2 * n, vi()); }
2
3 // vl, vr = true -> variable l, variable r should be negated.
4 void imply(int xl, bool vl, int xr, bool vr) {
5     adj[2 * xl + vl].pb(2 * xr + vr);
6     adj[2 * xr + !vr].pb(2 * xl + !vl);
7 }
8
9 void satOr(int xl, bool vl, int xr, bool vr) { imply(xl, !vl, xr, vr); }
10 void satConst(int x, bool v) { imply(x, !v, x, v); }
11 void satIff(int xl, bool vl, int xr, bool vr) {
12     imply(xl, vl, xr, vr);
13     imply(xr, vr, xl, vl);
14 }
15
16 bool solve2sat(int n, vector<bool> &sol) {
17     findSCC(2 * n);
18     for (int i = 0; i < n; i++)
19         if (cnr[2 * i] == cnr[2 * i + 1]) return false;
20     vector<bool> seen(n, false);

```

```

21     sol.assign(n, false);
22     for (vi &comp : comps) {
23         for (int v : comp) {
24             if (seen[v / 2]) continue;
25             seen[v / 2] = true;
26             sol[v / 2] = v & 1;
27         }
28     }
29     return true;
30 }

```

3.3 Shortest path

3.3.1 Floyd-Warshall $\mathcal{O}(V^3)$

```

1 int n = 100, d[MAXN][MAXN];
2 for (int i = 0; i < n; i++) fill_n(d[i], n, INF / 3);
3 // set direct distances from i to j in d[i][j] (and d[j][i])
4 for (int i = 0; i < n; i++)
5     for (int j = 0; j < n; j++)
6         for (int k = 0; k < n; k++)
7             d[j][k] = min(d[j][k], d[j][i] + d[i][k]);

```

3.3.2 Bellman Ford $\mathcal{O}(VE)$

This is only useful if there are edges with weight $w_{ij} < 0$ in the graph.

```

1 vector< pair<pii,int> > edges; // ((from, to), weight)
2 vi dist;
3
4 // when undirected, add back edges
5 bool bellman_ford(int V, int source) {
6     dist.assign(V, INF / 3);
7     dist[source] = 0;
8
9     bool updated = true;
10    int loops = 0;
11    while (updated && loops < n) {
12        updated = false;
13        for (auto e : edges) {
14            int alt = dist[e.x.x] + e.y;
15            if (alt < dist[e.x.y]) {
16                dist[e.x.y] = alt;
17                updated = true;
18            }
19        }
20    }
21    return loops < n; // loops >= n: negative cycles
22 }

```

3.4 Max-flow min-cut

3.4.1 Dinic's Algorithm $\mathcal{O}(V^2E)$

Let's hope this algorithm works correctly! ...

```

1 // http://www.slideshare.net/KuoE0/acmicpc-dinics-algorithm
2 struct edge {
3     int to, rev;
4     ll cap, flow;
5     edge(int t, int r, ll c) : to(t), rev(r), cap(c), flow(0) {}
6 };
7

```

```

8 int s, t, level[MAXN]; // s = source, t = sink
9 vector<edge> g[MAXN];
10
11 void add_edge(int fr, int to, ll cap) {
12     g[fr].pb(edge(to, g[to].size(), cap));
13     g[to].pb(edge(fr, g[fr].size() - 1, 0));
14 }
15
16 bool dinic_bfs() {
17     fill_n(level, MAXN, 0);
18     level[s] = 1;
19
20     queue<int> q;
21     q.push(s);
22     while (!q.empty()) {
23         int cur = q.front();
24         q.pop();
25         for (edge e : g[cur]) {
26             if (level[e.to] == 0 && e.flow < e.cap) {
27                 level[e.to] = level[cur] + 1;
28                 q.push(e.to);
29             }
30         }
31     }
32     return level[t] != 0;
33 }
34
35 ll dinic_dfs(int cur, ll maxf) {
36     if (cur == t) return maxf;
37
38     ll f = 0;
39     bool isSat = true;
40     for (edge &e : g[cur]) {
41         if (level[e.to] != level[cur] + 1 || e.flow >= e.cap)
42             continue;
43         ll df = dinic_dfs(e.to, min(maxf - f, e.cap - e.flow));
44         f += df;
45         e.flow += df;
46         g[e.to][e.rev].flow -= df;
47         isSat &= e.flow == e.cap;
48         if (maxf == f) break;
49     }
50     if (isSat) level[cur] = 0;
51     return f;
52 }
53
54 ll dinic_maxflow() {
55     ll f = 0;
56     while (dinic_bfs()) f += dinic_dfs(s, LLINF);
57     return f;
58 }

```

3.5 Min-cost max-flow

Find the cheapest possible way of sending a certain amount of flow through a flow network.

```

1 struct edge {
2     // to, rev, flow, capacity, weight
3     int t, r;
4     ll f, c, w;
5     edge(int _t, int _r, ll _c, ll _w) : t(_t), r(_r), f(0), c(_c), w(_w) {}
6 };
7
8 int n, par[MAXN];
9 vector<edge> adj[MAXN];
10 ll dist[MAXN];
11

```

```

12 bool findPath(int s, int t) {
13     fill_n(dist, n, LLINF);
14     fill_n(par, n, -1);
15
16     priority_queue<pii, vector<pii>, greater<pii> > q;
17     q.push(pii(dist[s] = 0, s));
18
19     while (!q.empty()) {
20         int d = q.top().x, v = q.top().y;
21         q.pop();
22         if (d > dist[v]) continue;
23
24         for (edge e : adj[v]) {
25             if (e.f < e.c && d + e.w < dist[e.t]) {
26                 q.push(pii(dist[e.t] = d + e.w, e.t));
27                 par[e.t] = e.r;
28             }
29         }
30     }
31     return dist[t] < INF;
32 }
33
34 pair<ll, ll> minCostMaxFlow(int s, int t) {
35     ll cost = 0, flow = 0;
36     while (findPath(s, t)) {
37         ll f = INF, c = 0;
38         int cur = t;
39         while (cur != s) {
40             const edge &rev = adj[cur][par[cur]], &e = adj[rev.t][rev.r];
41             f = min(f, e.c - e.f);
42             cur = rev.t;
43         }
44         cur = t;
45         while (cur != s) {
46             edge &rev = adj[cur][par[cur]], &e = adj[rev.t][rev.r];
47             c += e.w;
48             e.f += f;
49             rev.f -= f;
50             cur = rev.t;
51         }
52         cost += f * c;
53         flow += f;
54     }
55     return pair<ll, ll>(cost, flow);
56 }
57
58 inline void addEdge(int from, int to, ll cap, ll weight) {
59     adj[from].pb(edge(to, adj[to].size(), cap, weight));
60     adj[to].pb(edge(from, adj[from].size() - 1, 0, -weight));
61 }

```

3.6 Minimal Spanning Tree

3.6.1 Kruskal $\mathcal{O}(E \log V)$

```

1 struct edge { int x, y, w; };
2 edge edges[MAXM];
3
4 ll kruskal(int n, int m) { // n: #vertices, m: #edges
5     uf_init(n);
6     sort(edges, edges + m, [] (edge a, edge b) -> bool { return a.w < b.w; });
7     ll ret = 0;
8     while (m--) {
9         if (uf_find(edges[m].x) == uf_find(edges[m].y)) continue;
10        ret += edges[m].w;
11        uf_union(edges[m].x, edges[m].y);

```

```

12     }
13     return ret;
14 }

```

4 String algorithms

4.1 Trie

```

1  const int SIGMA = 26;
2
3  struct trie {
4      bool word;
5      trie **adj;
6
7      trie() : word(false), adj(new trie*[SIGMA]) {
8          for (int i = 0; i < SIGMA; i++) adj[i] = NULL;
9      }
10
11     void addWord(const string &str) {
12         trie *cur = this;
13         for (char ch : str) {
14             int i = ch - 'a';
15             if (!cur->adj[i]) cur->adj[i] = new trie();
16             cur = cur->adj[i];
17         }
18         cur->word = true;
19     }
20
21     bool isWord(const string &str) {
22         trie *cur = this;
23         for (char ch : str) {
24             int i = ch - 'a';
25             if (!cur->adj[i]) return false;
26             cur = cur->adj[i];
27         }
28         return cur->word;
29     }
30 };

```

4.2 Z-algorithm $\mathcal{O}(n)$

```

1  // z[i] = length of longest substring starting from s[i] which is also a prefix of s.
2  vi z_function(const string &s) {
3      int n = (int) s.length();
4      vi z(n);
5      for (int i = 1, l = 0, r = 0; i < n; ++i) {
6          if (i <= r) z[i] = min (r - i + 1, z[i - l]);
7          while (i + z[i] < n && s[z[i]] == s[i + z[i]]) ++z[i];
8          if (i + z[i] - 1 > r) l = i, r = i + z[i] - 1;
9      }
10     return z;
11 }

```

4.3 Suffix array $\mathcal{O}(n \log^2 n)$

This creates an array $P[0], P[1], \dots, P[n-1]$ such that the suffix $S[i \dots n]$ is the $P[i]^{th}$ suffix of S when lexicographically sorted.

```

1  typedef pair<pii, int> tii;
2

```

```

3  const int maxlogn = 17, int maxn = 1 << maxlogn;
4
5  tii make_triple(int a, int b, int c) { return tii(pii(a, b), c); }
6
7  int p[maxlogn + 1][maxn];
8  tii L[maxn];
9
10 int suffixArray(string S) {
11     int N = S.size(), stp = 1, cnt = 1;
12     for (int i = 0; i < N; i++) p[0][i] = S[i];
13     for (; cnt < N; stp++, cnt <= 1) {
14         for (int i = 0; i < N; i++) {
15             L[i] = tii(pii(p[stp-1][i], i + cnt < N ? p[stp-1][i + cnt] : -1), i);
16         }
17         sort(L, L + N);
18         for (int i = 0; i < N; i++) {
19             p[stp][L[i].y] = i > 0 && L[i].x == L[i-1].x ? p[stp][L[i-1].y] : i;
20         }
21     }
22     return stp - 1; // result is in p[stp - 1][0 .. (N - 1)]
23 }

```

4.4 Longest Common Subsequence $\mathcal{O}(n^2)$

SUBSTRING: *consecutive characters*!!!

```

1  int dp[STR_SIZE][STR_SIZE]; // DP problem
2
3  int lcs(const string &w1, const string &w2) {
4      int n1 = w1.size(), n2 = w2.size();
5      for (int i = 0; i < n1; i++) {
6          for (int j = 0; j < n2; j++) {
7              if (i == 0 || j == 0) dp[i][j] = 0;
8              else if (w1[i - 1] == w2[j - 1]) dp[i][j] = dp[i - 1][j - 1] + 1;
9              else dp[i][j] = max(dp[i - 1][j], dp[i][j - 1]);
10         }
11     }
12     return dp[n1][n2];
13 }
14
15 // backtrace
16 string getLCS(const string &w1, const string &w2) {
17     int i = w1.size(), j = w2.size();
18     string ret = "";
19     while (i > 0 && j > 0) {
20         if (w1[i - 1] == w2[j - 1]) ret += w1[--i], j--;
21         else if (dp[i][j - 1] > dp[i - 1][j]) j--;
22         else i--;
23     }
24     reverse(ret.begin(), ret.end());
25     return ret;
26 }

```

4.5 Levenshtein Distance $\mathcal{O}(n^2)$

Also known as the ‘Edit distance’.

```

1  int dp[MAX_SIZE][MAX_SIZE]; // DP problem
2
3  int levDist(const string &w1, const string &w2) {
4      int n1 = w1.size(), n2 = w2.size();
5      for (int i = 0; i <= n1; i++) dp[i][0] = i; // removal
6      for (int j = 0; j <= n2; j++) dp[0][j] = j; // insertion
7      for (int i = 1; i <= n1; i++)
8          for (int j = 1; j <= n2; j++)

```

```

9         dp[i][j] = min(
10             1 + min(dp[i - 1][j], dp[i][j - 1]),
11             dp[i - 1][j - 1] + (w1[i - 1] != w2[j - 1])
12         );
13     return dp[n1][n2];
14 }

```

4.6 Knuth-Morris-Pratt algorithm $\mathcal{O}(N + M)$

```

1 int kmp_search(const string &word, const string &text) {
2     int n = word.size();
3     vi T(n + 1, 0);
4     for (int i = 1, j = 0; i < n; ) {
5         if (word[i] == word[j]) T[++i] = ++j; // match
6         else if (j > 0) j = T[j]; // fallback
7         else i++; // no match, keep zero
8     }
9     int matches = 0;
10    for (int i = 0, j = 0; i < text.size(); ) {
11        if (text[i] == word[j]) {
12            i++;
13            if (++j == n) { // match at interval [i - n, i)
14                matches++;
15                j = T[j];
16            }
17        } else if (j > 0) j = T[j];
18        else i++;
19    }
20    return matches;
21 }

```

4.7 Aho-Corasick Algorithm $\mathcal{O}(N + \sum_{i=1}^m |S_i|)$

All given P must be unique!

```

1 const int MAXP = 100, MAXLEN = 200, SIGMA = 26, MAXTRIE = MAXP * MAXLEN;
2
3 int nP;
4 string P[MAXP], S;
5
6 int pnr[MAXTRIE], to[MAXTRIE][SIGMA], sLink[MAXTRIE], dLink[MAXTRIE], nnodes;
7
8 void ahoCorasick() {
9     fill_n(pnr, MAXTRIE, -1);
10    for (int i = 0; i < MAXTRIE; i++) fill_n(to[i], SIGMA, 0);
11    fill_n(sLink, MAXTRIE, 0);
12    fill_n(dLink, MAXTRIE, 0);
13    nnodes = 1;
14    // STEP 1: MAKE A TREE
15    for (int i = 0; i < nP; i++) {
16        int cur = 0;
17        for (char c : P[i]) {
18            int i = c - 'a';
19            if (to[cur][i] == 0) to[cur][i] = nnodes++;
20            cur = to[cur][i];
21        }
22        pnr[cur] = i;
23    }
24    // STEP 2: CREATE SUFFIX_LINKS AND DICT_LINKS
25    queue<int> q;
26    q.push(0);
27    while (!q.empty()) {
28        int cur = q.front();
29        q.pop();

```

```

30     for (int c = 0; c < SIGMA; c++) {
31         if (to[cur][c]) {
32             int sl = sLink[to[cur][c]] = cur == 0 ? 0 : to[sLink[cur]][c];
33             // if all strings have equal length, remove this:
34             dLink[to[cur][c]] = pnr[sl] >= 0 ? sl : dLink[sl];
35             q.push(to[cur][c]);
36         } else to[cur][c] = to[sLink[cur]][c];
37     }
38 }
39 // STEP 3: TRAVERSE S
40 for (int cur = 0, i = 0, n = S.size(); i < n; i++) {
41     cur = to[cur][S[i] - 'a'];
42     for (int hit = pnr[cur] >= 0 ? cur : dLink[cur]; hit; hit = dLink[hit]) {
43         cerr << P[pnr[hit]] << " found at [" << (i + 1 - P[pnr[hit]].size()) << ", " << i
44             << "]" << endl;
45     }
46 }

```

5 Geometry

```

1  const double EPS = 1e-7;
2
3  typedef double NUM; // EITHER double OR long long
4  typedef pair<NUM, NUM> pt;
5
6  pt operator+(pt p, pt q) { return pt(p.x + q.x, p.y + q.y); }
7  pt operator-(pt p, pt q) { return pt(p.x - q.x, p.y - q.y); }
8
9  pt& operator+=(pt &p, pt q) { return p = p + q; }
10 pt& operator-=(pt &p, pt q) { return p = p - q; }
11
12 pt operator*(pt p, NUM l) { return pt(p.x * l, p.y * l); }
13 pt operator/(pt p, NUM l) { return pt(p.x / l, p.y / l); }
14
15 NUM operator*(pt p, pt q) { return p.x * q.x + p.y * q.y; }
16 NUM operator^(pt p, pt q) { return p.x * q.y - p.y * q.x; }
17
18 istream& operator>>(istream &in, pt &p) { return in >> p.x >> p.y; }
19 ostream& operator<<(ostream &out, pt p) { return out << '(' << p.x << ", " << p.y << ')'; }
20
21 NUM lenSq(pt p) { return p * p; }
22 NUM lenSq(pt p, pt q) { return lenSq(p - q); }
23 double len(pt p) { return hypot(p.x, p.y); } // more overflow safe
24 double len(pt p, pt q) { return len(p - q); }
25
26 // square distance from pt a to line bc
27 double distPtLineSq(pt a, pt b, pt c) {
28     a -= b, c -= b;
29     return (a ^ c) * (a ^ c) / ((double)(c * c));
30 }
31
32 // square distance from pt a to segment bc
33 double distPtSegmentSq(pt a, pt b, pt c) {
34     a -= b; c -= b;
35     NUM dot = a * c, len = c * c;
36     if (dot <= 0) return a * a;
37     if (dot >= len) return (a - c) * (a - c);
38     return a * a - dot * dot / ((double) len);
39     // pt proj = b + c * dot / ((double) len);
40 }
41
42 bool between(NUM x, NUM a, NUM b) { return min(a, b) <= x && x <= max(a, b); }
43 bool collinear(pt a, pt b, pt c) { return ((a - b) ^ (a - c)) == 0; }
44

```

```

45 // point a on segment bc
46 bool pointOnSegment(pt a, pt b, pt c) {
47     return collinear(a, b, c) && between(a.x, b.x, c.x) && between(a.y, b.y, c.y);
48 }
49
50 // REQUIRES DOUBLES
51 pt lineLineIntersection(pt a, pt b, pt c, pt d, bool &cross) {
52     NUM det = (a - b) ^ (c - d);
53     pt ret = (c - d) * (a ^ b) - (a - b) * (c ^ d);
54     return (cross = det != 0) ? (ret / det) : ret;
55 }
56
57 // REQUIRES DOUBLES
58 // Line segment a1 -- a2 intersects with b1 -- b2?
59 // returns 0: no, 1: yes at i1, 2: yes at i1 -- i2
60 int segmentsIntersect(pt a1, pt a2, pt b1, pt b2, pt &i1, pt &i2) {
61     if ((a2 - a1) ^ (b2 - b1) < 0) swap(a1, a2);
62     // assert(a1 != a2 && b1 != b2);
63     pt q = a2 - a1, r = b2 - b1, s = b1 - a1;
64     NUM cross = q ^ r, c1 = s ^ r, c2 = s ^ q;
65     if (cross == 0) {
66         // line segments are parallel
67         if ((q ^ s) != 0) return 0; // no intersection
68         NUM v1 = s * q, v2 = (b2 - a1) * q, v3 = q * q;
69         if (v2 < v1) swap(v1, v2), swap(b1, b2);
70
71         if (v1 > v3 || v2 < 0) return 0; // intersection empty
72         i1 = v2 > v3 ? a2 : b2;
73         i2 = v1 < 0 ? a1 : b1;
74         return i1 == i2 ? 1 : 2; // one point or overlapping
75     } else { // cross > 0
76         i1 = pt(a1) + pt(q) * (1.0 * c1 / cross); // needs double
77         return 0 <= c1 && c1 <= cross && 0 <= c2 && c2 <= cross;
78         // intersection inside segments
79     }
80 }
81
82 // REQUIRES DOUBLES
83 // TODO: Needs shortening
84 // complete intersection check
85 int segmentsIntersect2(pt a1, pt a2, pt b1, pt b2, pt &i1, pt &i2) {
86     if (a1 == a2 && b1 == b2) {
87         i1 = a1;
88         return a1 == b1;
89     } else if (a1 == a2) {
90         i1 = a1;
91         return pointOnSegment(a1, b1, b2);
92     } else if (b1 == b2) {
93         i1 = b1;
94         return pointOnSegment(b1, a1, a2);
95     } else return segmentsIntersect(a1, a2, b1, b2, i1, i2);
96 }
97
98 // Returns TWICE the area of a polygon to keep it an integer
99 NUM polygonTwiceArea(const vector<pt> &pts) {
100     NUM area = 0;
101     for (int N = pts.size(), i = 0, j = N - 1; i < N; j = i++)
102         area += pts[i] ^ pts[j];
103     return abs(area); // area < 0 <=> pts ccw
104 }
105
106 bool pointInPolygon(pt p, const vector<pt> &pts) {
107     double sum = 0;
108     for (int N = pts.size(), i = 0, j = N - 1; i < N; j = i++) {
109         if (pointOnSegment(p, pts[i], pts[j])) return true; // boundary
110         double angle = acos((pts[i] - p) * (pts[j] - p) / len(pts[i], p) / len(pts[j], p));
111         sum += ((pts[i] - p) ^ (pts[j] - p)) < 0 ? angle : -angle;
112     }

```

```

113     return abs(abs(sum) - 2 * PI) < EPS;
114 }

```

5.1 Convex Hull $\mathcal{O}(n \log n)$

```

1 // points are given by: pts[ret[0]], pts[ret[1]], ... pts[ret[ret.size()-1]]
2 vi convexHull(const vector<pt> &pts) {
3     if (pts.empty()) return vi();
4     vi ret;
5     // find one outer point:
6     int fsti = 0, n = pts.size();
7     pt fstpt = pts[0];
8     for(int i = n; i--;) {
9         if (pts[i] < fstpt) fstpt = pts[i];
10    }
11    ret.pb(fstpt);
12    pt refr = pts[fstpt];
13
14    vi ord; // index into pts
15    for (int i = n; i--;) {
16        if (pts[i] != refr) ord.pb(i);
17    }
18    sort(ord.begin(), ord.end(), [&pts, &refr] (int a, int b) -> bool {
19        NUM cross = (pts[a] - refr) ^ (pts[b] - refr);
20        return cross != 0 ? cross > 0 : lenSq(refr, pts[a]) < lenSq(refr, pts[b]);
21    });
22    for (int i : ord) {
23        // NOTE: > INCLUDES points on the hull-line, >= EXCLUDES
24        while (ret.size() > 1 &&
25            ((pts[ret[ret.size()-2]] - pts[ret.back()]) ^ (pts[i] - pts[ret.back()])) >= 0)
26            ret.pop_back();
27        ret.pb(i);
28    }
29    return ret;
30 }

```

5.2 Rotating Calipers $\mathcal{O}(n)$

Finds the longest distance between two points in a convex hull.

```

1 NUM rotatingCalipers(vector<pt> &hull) {
2     int n = hull.size(), a = 0, b = 1;
3     if (n <= 1) return 0.0;
4     while (((hull[1] - hull[0]) ^ (hull[(b + 1) % n] - hull[b])) > 0) b++;
5     NUM ret = 0.0;
6     while (a < n) {
7         ret = max(ret, lenSq(hull[a], hull[b]));
8         if (((hull[(a + 1) % n] - hull[a]) ^ (hull[(b + 1) % n] - hull[b])) <= 0) a++;
9         else if (++b == n) b = 0;
10    }
11    return ret;
12 }

```

5.3 Closest points $\mathcal{O}(n \log n)$

```

1 int n;
2 pt pts[maxn];
3
4 struct byY {
5     bool operator()(int a, int b) const { return pts[a].y < pts[b].y; }
6 };
7

```

```

8 inline NUM dist(pii p) {
9     return hypot(pts[p.x].x - pts[p.y].x, pts[p.x].y - pts[p.y].y);
10 }
11
12 pii minpt(pii p1, pii p2) {
13     return (dist(p1) < dist(p2)) ? p1 : p2;
14 }
15
16 // closest pts (by index) inside pts[l ... r], with sorted y values in ys
17 pii closest(int l, int r, vi &ys) {
18     if (r - l == 2) { // don't assume l here.
19         ys = { l, l + 1 };
20         return pii(l, l + 1);
21     } else if (r - l == 3) { // brute-force
22         ys = { l, l + 1, l + 2 };
23         sort(ys.begin(), ys.end(), byY());
24         return minpt(pii(l, l + 1), minpt(pii(l, l + 2), pii(l + 1, l + 2)));
25     }
26     int m = (l + r) / 2;
27     vi yl, yr;
28     pii delta = minpt(closest(l, m, yl), closest(m, r, yr));
29     NUM ddelta = dist(delta), xm = .5 * (pts[m-1].x + pts[m].x);
30     merge(yl.begin(), yl.end(), yr.begin(), yr.end(), back_inserter(ys), byY());
31     deque<int> q;
32     for (int i : ys) {
33         if (abs(pts[i].x - xm) <= ddelta) {
34             for (int j : q) delta = minpt(delta, pii(i, j));
35             q.pb(i);
36             if (q.size() > 8) q.pop_front(); // magic from Introduction to Algorithms.
37         }
38     }
39     return delta;
40 }

```

6 Miscellaneous

6.1 Binary search $\mathcal{O}(\log(hi - lo))$

```

1 bool test(int n);
2
3 int search(int lo, int hi) {
4     // assert(test(lo) && !test(hi));
5     while (hi - lo > 1) {
6         int m = (lo + hi) / 2;
7         (test(m) ? lo : hi) = m;
8     }
9     // assert(test(lo) && !test(hi));
10    return lo;
11 }

```

6.2 Fast Fourier Transform $\mathcal{O}(n \log n)$

Given two polynomials $A(x) = a_0 + a_1x + \dots + a_{n/2}x^{n/2}$ and $B(x) = b_0 + b_1x + \dots + b_{n/2}x^{n/2}$, FFT calculates all coefficients of $C(x) = A(x) \cdot B(x) = c_0 + c_1x + \dots + c_nx^n$, with $c_i = \sum_{j=0}^i a_j b_{i-j}$.

```

1 typedef complex<double> cpx;
2 const int logmaxn = 20, maxn = 1 << logmaxn;
3
4 cpx a[maxn] = {}, b[maxn] = {}, c[maxn];
5
6 void fft(cpx *src, cpx *dest) {
7     for (int i = 0, rep = 0; i < maxn; i++, rep = 0) {
8         for (int j = i, k = logmaxn; k-- >= 1; rep = (rep << 1) | (j & 1);

```

```

9      dest[rep] = src[i];
10  }
11  for (int s = 1, m = 1; m <= maxn; s++, m *= 2) {
12      cpx r = exp(cpx(0, 2.0 * PI / m));
13      for (int k = 0; k < maxn; k += m) {
14          cpx cr(1.0, 0.0);
15          for (int j = 0; j < m / 2; j++) {
16              NUM t = cr * dest[k + j + m / 2];
17              dest[k + j + m / 2] = dest[k + j] - t;
18              dest[k + j] += t;
19              cr *= r;
20          }
21      }
22  }
23 }
24
25 void multiply() {
26     fft(a, c);
27     fft(b, a);
28     for (int i = 0; i < maxn; i++) b[i] = conj(a[i] * c[i]);
29     fft(b, c);
30     for (int i = 0; i < maxn; i++) c[i] = conj(c[i]) / (1.0 * maxn);
31 }

```

6.3 Minimum Assignment (Hungarian Algorithm) $\mathcal{O}(n^3)$

```

1  int a[MAXN + 1][MAXM + 1]; // matrix, 1-based
2
3  int minimum_assignment(int n, int m) { // n rows, m columns
4      vi u(n + 1), v(m + 1), p(m + 1), way(m + 1);
5
6      for (int i = 1; i <= n; i++) {
7          p[0] = i;
8          int j0 = 0;
9          vi minv(m + 1, INF);
10         vector<char> used(m + 1, false);
11         do {
12             used[j0] = true;
13             int i0 = p[j0], delta = INF, j1;
14             for (int j = 1; j <= m; j++)
15                 if (!used[j]) {
16                     int cur = a[i0][j] - u[i0] - v[j];
17                     if (cur < minv[j]) minv[j] = cur, way[j] = j0;
18                     if (minv[j] < delta) delta = minv[j], j1 = j;
19                 }
20             for (int j = 0; j <= m; j++) {
21                 if (used[j]) u[p[j]] += delta, v[j] -= delta;
22                 else minv[j] -= delta;
23             }
24             j0 = j1;
25         } while (p[j0] != 0);
26         do {
27             int j1 = way[j0];
28             p[j0] = p[j1];
29             j0 = j1;
30         } while (j0);
31     }
32
33     // column j is assigned to row p[j]
34     // for (int j = 1; j <= m; ++j) ans[p[j]] = j;
35     return -v[0];
36 }

```

6.4 Partial linear equation solver $\mathcal{O}(N^3)$

```
1 typedef double NUM;
2
3 #define MAXN 110
4 #define EPS 1e-5
5
6 NUM mat[MAXN][MAXN + 1], vals[MAXN];
7 bool hasval[MAXN];
8
9 bool is_zero(NUM a) { return -EPS < a && a < EPS; }
10 bool eq(NUM a, NUM b) { return is_zero(a - b); }
11
12 int solvemmat(int n)
13 {
14     for(int i = 0; i < n; i++)
15         for (int j = 0; j < n; j++) cin >> mat[i][j];
16     for (int i = 0; i < n; i++) cin >> mat[i][n];
17
18     int pivrow = 0, pivcol = 0;
19     while (pivcol < n) {
20         int r = pivrow, c;
21         while (r < n && is_zero(mat[r][pivcol])) r++;
22         if (r == n) { pivcol++; continue; }
23
24         for (c = 0; c <= n; c++) swap(mat[pivrow][c], mat[r][c]);
25
26         r = pivrow++; c = pivcol++;
27         NUM div = mat[r][c];
28         for (int col = c; col <= n; col++) mat[r][col] /= div;
29         for (int row = 0; row < n; row++) {
30             if (row == r) continue;
31             NUM times = -mat[row][c];
32             for (int col = c; col <= n; col++) mat[row][col] += times * mat[r][col];
33         }
34     }
35     // now mat is in RREF
36     for (int r = pivrow; r < n; r++)
37         if (!is_zero(mat[r][n])) return 0;
38
39     fill_n(hasval, n, false);
40     for (int col = 0, row; col < n; col++) {
41         hasval[col] = !is_zero(mat[row][col]);
42         if (!hasval[col]) continue;
43         for (int c = col + 1; c < n; c++) {
44             if (!is_zero(mat[row][c])) hasval[c] = false;
45         }
46         if (hasval[col]) vals[col] = mat[row][n];
47         row++;
48     }
49
50     for (int i = 0; i < n; i++)
51         if (!hasval[i]) return 2;
52     return 1;
53 }
```
