

Misc

Template

```

1 // #pragma GCC optimize("Ofast")
2 #include <bits/stdc++.h>
3 #define all(x) begin(x), end(x)
4 using namespace std;
5 using ll = long long;
6 int main() {
7     ios_base::sync_with_stdio(false);
8     cin.tie(nullptr);
9 }

```

Compilation Script

```

1 #!/bin/bash
2 g++ --std=c++17 -Wall -Wshadow -Wno-conversion -ftrapv -g $1 -o ${1%.cpp}.bin

```

Polynomial Hash

```

1 using lll = __int128_t;
2 ll P = 12233720368547789LL;
3 ll B = 260;
4 struct PolyHash {
5     vector<ll> hashes, ex;
6     PolyHash(const string& s) : hashes(s.size() + 1), ex(s.size() + 1) {
7         hashes[0] = 1; ex[0] = 1; ex[1] = B;
8         for (size_t i = 0; i < s.size(); i++) {
9             hashes[i + 1] = ((hashes[i] * B) % P + s[i] + 1) % P;
10            ex[i + 1] = (ex[i] * B) % P;
11        }
12    }
13    ll hash(ll lo, ll hi) {
14        return ((lll)hashes[hi] - (lll)hashes[lo] * (lll)ex[hi - lo] % P + P) % P;
15    }
16 };

```

Binary Search

```

1 while (lo < hi) {
2     ll mid = lo + (hi - lo) / 2;
3     if (f(mid)) // f should be false, then true
4         hi = mid;
5     else
6         lo = mid + 1;
7 }
8 // lo is now the first index where f is true

```

Ternary Search

Find the smallest i in $[a, b]$ that maximizes $f(i)$, assuming that $f(a) < \dots < f(i) \geq \dots \geq f(b)$.

If there is a range of $f(i) \dots f(j)$ that are equal, change according to the comments to get the last index instead of the first.

<pre> 1 template<class F> 2 ll ternarySearch(ll a, ll b, F f) { 3 assert(a <= b); 4 while (b - a >= 5) { 5 ll mid = (a + b) / 2; 6 if (f(mid) < f(mid+1)) <i>// <= for last index</i> 7 a = mid; 8 else 9 b = mid+1; 10 } 11 <i>// for (ll i = b; i > a; i--) to get last index</i> 12 for (ll i = a + 1; i <= b; i++) 13 if (f(a) < f(i)) 14 a = i; 15 return a; 16 } </pre>	<pre> 1 def ternarySearch(a, b, f): 2 assert a <= b 3 while b - a >= 5: 4 mid = (a + b) // 2 5 if f(mid) < f(mid+1): <i># <= for last index</i> 6 a = mid 7 else: 8 b = mid + 1 9 <i># for i in range(b, a-1, -1): to get last index</i> 10 for i in range(a+1, b+1): 11 if f(a) < f(i): 12 a = i 13 return a </pre>
--	---

Geometry

Geometry Template (Python)

```

1 def vecsub(a, b):
2     return (a[0] - b[0], a[1] - b[1])
3 def vecadd(a, b):
4     return (a[0] + b[0], a[1] + b[1])
5 def dot(a, b):
6     return a[0] * b[0] + a[1] * b[1]
7 def cross(a, b, o = (0, 0)):
8     return (a[0] - o[0]) * (b[1] - o[1]) - (a[1] - o[1]) * (b[0] - o[0])
9 def len2(a):
10    return a[0] ** 2 + a[1] ** 2
11 def dist2(a, b):
12    return len2(vecsub(a, b))
13 def sign(x):
14    return (x > 0) - (x < 0)
15 def zero(x):
16    return abs(x) < 1E-9

```

Geometry Template (C++)

```

1 template <typename T> struct point {
2     T x, y;
3     point() { x=y=0; }
4     point(T xx, T yy) : x(xx), y(yy) { }
5     template <typename U> point(point<U> o) : x(o.x), y(o.y) { }
6     point operator+(point o) const { return { x+o.x, y+o.y }; }
7     point operator-(point o) const { return { x-o.x, y-o.y }; }
8     point operator*(T o) const { return { x*o, y*o }; }
9     point operator/(T o) const { return { x/o, y/o }; }
10    bool operator==(point o) const { return x==o.x && y==o.y; };
11    bool operator<(point o) const { return tie(x, y) < tie(o.x, o.y); };
12    T dot(point o) const { return x*o.x + y*o.y; }
13    T cross(point b) const { return x*b.y - y*b.x; }
14    T cross(point b, point o) const { return (*this-o).cross(b-o); }
15    T len2() const { return x*x + y*y; }
16 };
17 using ipoint = point<ll>;
18 using dpoint = point<double>;
19 ll sign(auto x) { return (x>0) - (x<0); }
20 bool zero(double x) { return abs(x) < 1E-9; }

```

Check if point is on a line segment

```

1 def onSegment(s, e, p):
2     # return zero(distPS(s, e, p)) if floating-point is OK
3     return cross(s, e, p) == 0 and dot(vecsub(s, p), vecsub(e, p)) <= 0

1 bool onSegment(ipoint s, ipoint e, ipoint p) { return s.cross(e, p) == 0 && (s - p).dot(e - p) <= 0; }

```

Distance between point and line segment

Returns the distance from the point p to the line segment starting at s and ending at e.

<pre> 1 double distPS(ipoint s, ipoint e, ipoint p) { 2 if (s == e) 3 return sqrt((p - s).len2()); 4 auto se = e - s; 5 auto sp = p - s; 6 ll d = se.len2(); 7 ll t = min(d, max(0LL, (p - s).dot(e - s))); 8 return sqrt((sp * d - se * t).len2()) / d; 9 } </pre>	<pre> 1 def distPS(s, e, p): 2 if s == e: 3 return sqrt(dist2(p, s)) 4 se, sp = vecsub(e, s), vecsub(p, s) 5 d = len2(se) 6 t = min(d, max(0, dot(vecsub(p,s), vecsub(e,s)))) 7 return sqrt(dist2(8 (sp[0]*d, sp[1]*d), 9 (se[0]*t, se[1]*t) 10)) / d </pre>
---	---

Distance between point and line

Returns the signed distance from the point p to the line passing through the points a and b.

```
1 double distPL(ipoint a, ipoint b, ipoint p) {
2     return b.cross(p, a) / sqrt((a - b).len2());
3 }
1 def distPL(a, b, p):
2     return cross(b, p, a) / sqrt(dist2(a, b))
```

Project point to line (or reflect)

Projects the point p onto the line passing through a and b. Set refl=True to get reflection of point p across the line instead.

```
1 dpoint projPL(ipoint a, ipoint b, ipoint p, bool
    ↪ refl = false) {
2     auto v = b - a;
3     double s = (1 + refl) * b.cross(p, a) / v.len2();
4     return { p.x + v.x * s, p.y - v.y * s };
5 }
1 def projPL(a, b, p, refl = False):
2     v = vecsub(b, a)
3     s = (1 + refl) * cross(b, p, a) / len2(v)
4     return (p[0] + v[1] * s, p[1] - v[0] * s)
```

Intersection between two lines

If a unique intersection point of the lines going through s1,e1 and s2,e2 exists (1,point) is returned.

If no intersection point exists (0, (0,0)) is returned and if infinitely many exist (-1, (0,0)) is returned.

```
1 pair<int, dpoint> intersectLL(ipoint s1, ipoint e1,
    ↪ ipoint s2, ipoint e2) {
2     auto d = (e1 - s1).cross(e2 - s2);
3     if (zero(d)) # parallel
4         return { -int(zero(e1.cross(s2, s1))), {} };
5     auto p = e1.cross(e2, s2);
6     auto q = e2.cross(s1, s2);
7     return { 1, dpoint(
8         (s1.x * p + e1.x * q),
9         (s1.y * p + e1.y * q)
10    ) / d };
11 }
1 def intersectLL(s1, e1, s2, e2):
2     d = cross(vecsub(e1, s1), vecsub(e2, s2))
3     if zero(d): # parallel
4         return (-zero(cross(e1, s2, s1)), (0, 0))
5     p, q = cross(e1, e2, s2), cross(e2, s1, s2)
6     return (1, (
7         (s1[0] * p + e1[0] * q) / d,
8         (s1[1] * p + e1[1] * q) / d
9     ))
```

Intersection between two line segments

If a unique intersection is found, returns a list with only this point. If the segments intersect in many points, returns a list of 2 elements containing the start and end of the common line segment. If no intersection, returns an empty list

```
1 vector<dpoint> intersectSS(ipoint s1, ipoint e1,
    ↪ ipoint s2, ipoint e2) {
2     auto oa = e2.cross(s1, s2);
3     auto ob = e2.cross(e1, s2);
4     auto oc = e1.cross(s2, s1);
5     auto od = e1.cross(e2, s1);
6     if (sign(oa)*sign(ob)<0 && sign(oc)*sign(od)<0) {
7         return { dpoint(s1.x * ob - e1.x * oa,
8             s1.y * ob - e1.y * oa)
9             / double(ob - oa) };
10    }
11    set<ipoint> s;
12    if (onSegment(s2, e2, s1)) s.insert(s1);
13    if (onSegment(s2, e2, e1)) s.insert(e1);
14    if (onSegment(s1, e1, s2)) s.insert(s2);
15    if (onSegment(s1, e1, e2)) s.insert(e2);
16    return {all(s)};
17 }
1 def intersectSS(s1, e1, s2, e2):
2     oa = cross(e2, s1, s2)
3     ob = cross(e2, e1, s2)
4     oc = cross(e1, s2, s1)
5     od = cross(e1, e2, s1)
6     if sign(oa)*sign(ob)<0 and sign(oc)*sign(od)<0:
7         div = ob - oa
8         return [(
9             (s1[0] * ob - e1[0] * oa) / div,
10            (s1[1] * ob - e1[1] * oa) / div
11        )]
12    s = set()
13    if onSegment(s2, e2, s1): s.add(s1)
14    if onSegment(s2, e2, e1): s.add(e1)
15    if onSegment(s1, e1, s2): s.add(s2)
16    if onSegment(s1, e1, e2): s.add(e2)
17    return list(s)
```

Polygon area

Returns twice the signed area of a polygon. Clockwise enumeration gives negative area.

```
1 ll polygonArea2(const vector<ipoint>& v) {
2     ll a = 0;
3     for (ll i = 0; i < (ll)v.size(); i++)
4         a += v[i].cross(v[(i+1) % v.size()]);
5     return a;
6 }
1 def polygonArea2(v):
2     return sum(map(lambda i: cross(v[i - 1], v[i]),
    ↪ range(len(v))))
```

Point inside polygon

Returns true if the point `pt` lies within the polygon `poly`. If `strict` is true, returns false for points on the boundary.

```

1 def pointInPolygon(poly, pt, strict = True):
2     c = False
3     for i in range(len(poly)):
4         q = poly[i - 1]
5         if onSegment(q, poly[i], pt):
6             return not strict
7         c ^= ((pt[1] < q[1]) - (pt[1] < poly[i][1])) * cross(q, poly[i], pt) > 0
8     return c

1 bool pointInPolygon(const vector<ipoint>& poly, ipoint p, bool strict = true) {
2     bool c = false;
3     auto prev = poly.back();
4     for (auto cur : poly) {
5         if (onSegment(prev, cur, p)) return !strict;
6         c ^= ((p.y < prev.y) - (p.y < cur.y)) * prev.cross(cur, p) > 0;
7         prev = cur;
8     }
9     return c;
10 }
```

Intersection between two circles

Computes the pair of points at which two circles intersect. Returns `None` in case of no intersection.

```

1 template <typename T> optional<array<dpoint, 2>>
2 intersectCC(point<T> c1, point<T> c2, T r1, T r2) {
3     if (c1 == c2) {
4         assert(r1 != r2);
5         return { };
6     }
7     auto vec = c2 - c1;
8     T d2 = vec.len2(), sm = r1 + r2, dif = r1 - r2;
9     if (sm * sm < d2 || dif * dif > d2)
10         return { };
11     double p = double(d2 + r1*r1 - r2*r2) / (d2 * 2);
12     dpoint mid(c1.x + vec.x * p, c1.y + vec.y * p);
13     dpoint per = dpoint(-vec.y, vec.x) *
14         sqrt(max(0.0, r1 * r1 - p * p * d2) / d2);
15     return { { mid+per, mid-per } };

1 def intersectCC(c1, c2, r1, r2):
2     if c1 == c2:
3         assert(r1 != r2)
4         return None
5     vec = vecsub(c2, c1)
6     d2 = len2(vec)
7     if (r1 + r2) ** 2 < d2 or (r1 - r2) ** 2 > d2:
8         return None
9     p = (d2 + r1 ** 2 - r2 ** 2) / (d2 * 2)
10    h2 = r1 ** 2 - p * p * d2
11    mid = (c1[0] + vec[0] * p, c1[1] + vec[1] * p)
12    plen = sqrt(max(0, h2) / d2)
13    per = (-vec[1] * plen, vec[0] * plen)
14    return (vecadd(mid, per), vecsub(mid, per))
```

Intersection between circle and line

Computes the intersection between a circle and a line. Returns a list of either 0, 1, or 2 intersection points.

```

1 vector<dpoint> intersectCL(dpoint c, double r,
2     dpoint a, dpoint b) {
3     dpoint ab = b - a;
4     dpoint p = a + ab * (c-a).dot(ab) / ab.len2();
5     double s = a.cross(b, c);
6     double h2 = r*r - s*s / ab.len2();
7     if (h2 < 0) return { };
8     if (h2 == 0) return {p};
9     dpoint h = ab * sqrt(h2 / ab.len2());
10    return {p - h, p + h};

1 def intersectCL(c, r, a, b):
2     ab = vecsub(b, a)
3     ps = dot(vecsub(c, a), ab) / len2(ab)
4     p = (a[0] + ab[0] * ps, a[1] + ab[1] * ps)
5     h2 = r ** 2 - cross(a, b, c) ** 2 / len2(ab)
6     if h2 < 0: return []
7     if h2 == 0: return [p]
8     h2 = sqrt(h2 / ab.len2())
9     h = (ab[0] * h2, ab[1] * h2);
10    return [vecsub(p, h), vecadd(p, h)]
```

Convex hull

Returns a list of points on the convex hull in counter-clockwise order. Points on the edge of the hull between two other points are not considered part of the hull. Time complexity: $\mathcal{O}(n \log n)$

```

1 auto convexHull(vector<ipoint> pts) {
2     if (pts.size() <= 1) return pts;
3     sort(all(pts));
4     decltype(pts) h;
5     auto f = [&](ll s) {
6         for (auto p : pts) {
7             while ((ll)h.size() >= s + 2 &&
8                 ↪ h.back().cross(p, h[h.size() - 2]) <= 0)
9                 h.pop_back();
10            h.push_back(p);
11        }
12        h.pop_back();
13    };
14    f(0);
15    reverse(all(pts));
16    f(h.size());
17    if (h.size() == 2 && h[0] == h[1]) h.pop_back();
18    return h;
19 }

```

```

1 def convexHull(pts):
2     if len(pts) <= 1:
3         return pts
4     pts.sort()
5     t, s, h = 0, 0, [0] * (len(pts) + 1)
6     for i in range(2):
7         for p in pts:
8             while t >= s + 2 and cross(h[t - 1], p,
9                 ↪ h[t - 2]) <= 0:
10                t -= 1
11            h[t], t = p, t + 1
12            s = t - 1
13            pts.reverse()
14    return h[:t - (t == 2 and h[0] == h[1])]

```

Data Structures

Segment Tree

```

1 struct SegTree {
2     using T = ll;
3     T f(T a, T b) { return a + b; }
4     static constexpr T UNIT = 0; //neutral value for f
5
6     vector<T> s; ll n;
7     SegTree(ll len) : s(2 * len, UNIT), n(len) {}
8     void set(ll pos, T val) {
9         for (s[pos += n] = val; pos /= 2;)
10            s[pos] = f(s[pos * 2], s[pos * 2 + 1]);
11    }
12    T query(ll lo, ll hi) { // hi not included
13        T ra = UNIT, rb = UNIT;
14        for (lo += n, hi += n; lo < hi; lo /= 2, hi /= 2) {
15            if (lo % 2) ra = f(ra, s[lo++]);
16            if (hi % 2) rb = f(s[--hi], rb);
17        }
18        return f(ra, rb);
19    }
20 };

```

```

1 class SegTree:
2     def f(a, b):
3         return a + b
4     UNIT = 0 # neutral value for f
5
6     def __init__(self, n):
7         self.s = [self.UNIT] * (2 * n)
8         self.n = n
9     def set(self, pos, val):
10        pos += self.n
11        self.s[pos] = val
12        while pos > 1:
13            pos //= 2
14            self.s[pos] = SegTree.f(self.s[pos * 2],
15                ↪ self.s[pos * 2 + 1])
16    def query(self, lo, hi): # hi not included
17        ra, rb = self.UNIT, self.UNIT
18        lo, hi = lo + self.n, hi + self.n
19        while lo < hi:
20            if lo % 2:
21                ra = SegTree.f(ra, self.s[lo])
22                lo += 1
23            if hi % 2:
24                hi -= 1
25                rb = SegTree.f(self.s[hi], rb)
26        lo, hi = lo // 2, hi // 2
27        return SegTree.f(ra, rb)

```

Fenwick Tree

```

1 struct FenwickTree {
2     FenwickTree(ll n) : v(n + 1, 0) {}
3     ll lsb(ll x) { return x & (-x); }
4     ll prefixSum(ll n) { //sum of the first n items (nth not included)
5         ll sum = 0;
6         for (; n; n -= lsb(n))
7             sum += v[n];
8         return sum;
9     }
10    void adjust(ll i, ll delta) {
11        for (i++; i < v.size(); i += lsb(i))
12            v[i] += delta;
13    }
14    vector<ll> v;
15 };

```

Sparse Table

```

1 struct SparseTable {
2     using T = ll;
3     ll node(ll l, ll i) { return i + l * n; }
4     ll n; vector<T> v;
5     SparseTable(vector<T> values) : n(values.size()), v(move(values)) {
6         ll d = log2(n);
7         v.resize((d + 1) * n);
8         for (ll L = 0, s = 1; L < d; L++, s *= 2) {
9             for (ll i = 0; i < n; i++) {
10                 v[node(L + 1, i)] = min(v[node(L, i)], v[node(L, min(i + s, n - 1))]);
11             }
12         }
13     }
14     T query(ll lo, ll hi) { assert(hi > lo);
15         ll l = (ll)log2(hi - lo);
16         return min(v[node(l, lo)], v[node(l, hi - (1 << l))]);
17     }
18 };

```

Lazy Segment Tree

Segment tree with support for range updates. Use T = pair of value and index to get index from queries.

All ranges are (lo, hi] (hi is not included). fQuery defines the function to be used for queries (currently min) and fUpdate defines the function to be used for updates (currently addition).

```

1 struct LazyST {
2     using T = ll;
3     T f(T a, T b) { return min(a, b); }
4     static const T QUERY_UNIT = LLONG_MAX; // neutral value for f
5
6     struct Node {
7         T val = QUERY_UNIT; // current value of this segment
8         optional<T> p; // value being pushed down into this segment
9     };
10    int len; vector<Node> nodes;
11    LazyST(int l) : len(pow(2, ceil(log2(l)))), nodes(len * 2) { }
12    void update(int lo, int hi, T val) { u(lo, hi, val, 1, 0, len); }
13    T query(int lo, int hi) { return q(lo, hi, 1, 0, len); }
14 private:
15    #define LST_NEXT int l = n * 2; int r = l + 1; int mid = (nlo + nhi) / 2
16    void push(int n, int nlo, int nhi) {
17        if (!nodes[n].p) return;
18        LST_NEXT;
19        u(nlo, nhi, *nodes[n].p, l, nlo, mid);
20        u(nlo, nhi, *nodes[n].p, r, mid, nhi);
21        nodes[n].p = {};
22    }
23    void u(int qlo, int qhi, T val, int n, int nlo, int nhi) {
24        if (nhi <= qlo || nlo >= qhi) return;
25        if (nlo >= qlo && nhi <= qhi) {
26            //for interval set:
27            nodes[n].p = val;
28            nodes[n].val = val; // val * (nhi - nlo) for sum queries
29            //for interval add:
30            nodes[n].p = nodes[n].p.value_or(0) + val;
31            nodes[n].val += val; // val * (nhi - nlo) for sum queries
32        } else {
33            push(n, nlo, nhi); LST_NEXT;
34            u(qlo, qhi, val, l, nlo, mid);
35            u(qlo, qhi, val, r, mid, nhi);
36            nodes[n].val = f(nodes[l].val, nodes[r].val);
37        }
38    }
39    T q(int qlo, int qhi, int n, int nlo, int nhi) {
40        if (nhi <= qlo || nlo >= qhi) return QUERY_UNIT;
41        if (nlo >= qlo && nhi <= qhi) return nodes[n].val;
42        push(n, nlo, nhi); LST_NEXT;
43        return f(q(qlo, qhi, l, nlo, mid), q(qlo, qhi, r, mid, nhi));
44    }
45 };

```

Line Container

Container where you can add lines of the form $kx + m$, and query maximum values at points x . All operations are $\mathcal{O}(\log(n))$. For doubles, use `inf = 1/.0` and `div(a,b) = a/b`

```

1 struct Line {
2     mutable ll k, m, p;
3     bool operator<(const Line& o) const { return k < o.k; }
4     bool operator<(ll x) const { return p < x; }
5 };
6 struct LineContainer : multiset<Line, less<>> {
7     const ll inf = LLONG_MAX;
8     ll div(ll a, ll b) { // floored division
9         return a / b - ((a ^ b) < 0 && a % b);
10    }
11    bool isect(iterator x, iterator y) {
12        if (y == end()) { x->p = inf; return false; }
13        if (x->k == y->k) x->p = x->m > y->m ? inf : -inf;
14        else x->p = div(y->m - x->m, x->k - y->k);
15        return x->p >= y->p;
16    }
17    void add(ll k, ll m) {
18        auto z = insert({k, m, 0}), y = z++, x = y;
19        while (isect(y, z)) z = erase(z);
20        if (x != begin() && isect(--x, y)) isect(x, y = erase(y));
21        while ((y = x) != begin() && (--x)->p >= y->p) isect(x, erase(y));
22    }
23    ll query(ll x) { assert(!empty());
24        auto l = *lower_bound(x);
25        return l.k * x + l.m;
26    }
27 };

```

Treap

```

1 struct Treap {
2     Treap *l = 0, *r = 0;
3     int val, y, c = 1;
4     Treap(int v) : val(v), y(rand()) { }
5 };
6 int trCount(Treap* n) { // returns the number of nodes in treap n
7     return n ? n->c : 0;
8 }
9 void trRecount(Treap* n) {
10     n->c = trCount(n->l) + trCount(n->r) + 1;
11 }
12 Treap* trAt(Treap* n, int idx) { // returns the treap node at the specified index
13     if (!n || idx == trCount(n->l)) return n;
14     if (idx > trCount(n->l))
15         return trAt(n->r, idx - trCount(n->l) - 1);
16     return trAt(n->l, idx);
17 }
18 template<class F> void trForeach(Treap* n, F f) { // invokes f for every item in the treap n
19     if (n) { trForeach(n->l, f); f(n->val); trForeach(n->r, f); }
20 }
21 pair<Treap*, Treap*> trSplit(Treap* n, int k) { // splits the treap n on index (or value) k
22     if (!n) return {};
23     if (trCount(n->l) >= k) { // use "if (n->val >= k)" to split on value instead of index
24         auto pa = trSplit(n->l, k);
25         n->l = pa.second;
26         trRecount(n);
27         return {pa.first, n};
28     } else {
29         // use "auto pa = trSplit(n->r, k);" to split on value instead of index
30         auto pa = trSplit(n->r, k - trCount(n->l) - 1);
31         n->r = pa.first;
32         trRecount(n);
33         return {n, pa.second};
34     }
35 }
36 Treap* trJoin(Treap* l, Treap* r) {
37     if (!l) return r;
38     if (!r) return l;

```

```

39     if (l->y > r->y) {
40         l->r = trJoin(l->r, r);
41         trRecount(l);
42         return l;
43     } else {
44         r->l = trJoin(l, r->l);
45         trRecount(r);
46         return r;
47     }
48 }
49 // inserts the treap n into t at index pos (or value pos, depending on implementation of trSplit)
50 Treap* trInsert(Treap* t, Treap* n, int pos) {
51     auto pa = trSplit(t, pos);
52     return trJoin(trJoin(pa.first, n), pa.second);
53 }

```

Link Cut Tree

Represents a forest of unrooted trees. You can add and remove edges (as long as the result is still a forest), and check whether two nodes are in the same tree. All operations are amortized $\mathcal{O}(\log(n))$.

```

1 struct Node { // Splay tree. Root's pp contains tree's parent.
2     Node *p = 0, *pp = 0, *c[2];
3     bool flip = 0;
4     Node() { c[0] = c[1] = 0; fix(); }
5     void fix() {
6         if (c[0]) c[0]->p = this;
7         if (c[1]) c[1]->p = this;
8         // (+ update sum of subtree elements etc. if wanted)
9     }
10    void pushFlip() {
11        if (!flip) return;
12        flip = 0; swap(c[0], c[1]);
13        if (c[0]) c[0]->flip ^= 1;
14        if (c[1]) c[1]->flip ^= 1;
15    }
16    int up() { return p ? p->c[1] == this : -1; }
17    void rot(int i, int b) {
18        int h = i ^ b;
19        Node *x = c[i], *y = b == 2 ? x : x->c[h], *z = b ? y : x;
20        if ((y->p = p)) p->c[up()] = y;
21        c[i] = z->c[i ^ 1];
22        if (b < 2) {
23            x->c[h] = y->c[h ^ 1];
24            z->c[h ^ 1] = b ? x : this;
25        }
26        y->c[i ^ 1] = b ? this : x;
27        fix(); x->fix(); y->fix();
28        if (p) p->fix();
29        swap(pp, y->pp);
30    }
31    void splay() { /// Splay this up to the root. Always finishes without flip set.
32        for (pushFlip(); p; ) {
33            if (p->p) p->p->pushFlip();
34            p->pushFlip(); pushFlip();
35            int c1 = up(), c2 = p->up();
36            if (c2 == -1) p->rot(c1, 2);
37            else p->p->rot(c2, c1 != c2);
38        }
39    }
40    Node* first() { /// Return the min element of the subtree rooted at this, splayed to the top.
41        pushFlip();
42        return c[0] ? c[0]->first() : (splay(), this);
43    }
44 };
45 struct LinkCut {
46     vector<Node> node;
47     LinkCut(int N) : node(N) {}
48     void link(int u, int v) { // add an edge (u, v)
49         assert(!connected(u, v));
50         makeRoot(&node[u]);
51         node[u].pp = &node[v];
52     }

```



```

53 void cut(int u, int v) { // remove an edge (u, v)
54     Node *x = &node[u], *top = &node[v];
55     makeRoot(top); x->splay();
56     assert(top == (x->pp ?: x->c[0]));
57     if (x->pp) x->pp = 0;
58     else {
59         x->c[0] = top->p = 0;
60         x->fix();
61     }
62 }
63 bool connected(int u, int v) { // are u, v in the same tree?
64     Node* nu = access(&node[u])->first();
65     return nu == access(&node[v])->first();
66 }
67 void makeRoot(Node* u) { /// Move u to root of represented tree.
68     access(u);
69     u->splay();
70     if (u->c[0]) {
71         u->c[0]->p = 0;
72         u->c[0]->flip ^= 1;
73         u->c[0]->pp = u;
74         u->c[0] = 0;
75         u->fix();
76     }
77 }
78 Node* access(Node* u) { /// Move u to root aux tree. Return the root of the root aux tree.
79     u->splay();
80     while (Node* pp = u->pp) {
81         pp->splay(); u->pp = 0;
82         if (pp->c[1]) {
83             pp->c[1]->p = 0; pp->c[1]->pp = pp; }
84         pp->c[1] = u; pp->fix(); u = pp;
85     }
86     return u;
87 }
88 };

```

Graph Algorithms

Dijkstra's Algorithm

```

1 template<typename T> vector<T> dijkstra(ll start, const vector<vector<pair<ll, T>>>& adj) {
2     vector<T> dist(adj.size(), numeric_limits<T>::max());
3     dist[start] = 0;
4     priority_queue<pair<T, ll>, vector<pair<T, ll>>, greater<>> pq;
5     pq.emplace(dist[start], start);
6     while (!pq.empty()) {
7         ll cn = pq.top().second; pq.pop();
8         for (auto [n, d] : adj[cn]) {
9             T nd = dist[cn] + d;
10            if (nd < dist[n]) pq.emplace(dist[n] = nd, n);
11        }
12    }
13    return dist;
14 }
```

Maximum Flow (Dinic's Algorithm)

Constructor takes number of nodes, call addEdge to add edges and calc to find maximum flow. To obtain the actual flow, look at positive values of Edge::cap only.

Time complexity: $O(VE \log U)$ where $U = \max |cap|$.

$O(\min(E^{1/2}, V^{2/3})E)$ if $U = 1$.

$O(\sqrt{VE})$ for bipartite matching.

```

1 struct Dinic {
2     struct Edge {
3         int to, rev;
4         ll c, oc;
5         ll flow() { return max(oc - c, 0LL); }
6     };
7     vector<int> lvl, ptr, q;
8     vector<vector<Edge>> adj;
9     Dinic(int n) : lvl(n), ptr(n), q(n), adj(n) {}
10    void addEdge(int a, int b, ll c, ll rcap = 0) {
11        adj[a].push_back({b, (int)adj[b].size(), c, c});
12        adj[b].push_back({a, (int)adj[a].size() - 1, rcap, rcap});
13    }
14    ll dfs(int v, int t, ll f) {
15        if (v == t || !f) return f;
16        for (int& i = ptr[v]; i < adj[v].size(); i++) {
17            Edge& e = adj[v][i];
18            if (lvl[e.to] == lvl[v] + 1)
19                if (ll p = dfs(e.to, t, min(f, e.c))) {
20                    e.c -= p, adj[e.to][e.rev].c += p;
21                    return p;
22                }
23        }
24        return 0;
25    }
26    ll calc(int s, int t) {
27        ll flow = 0; q[0] = s;
28        for (int L = 0; L < 31; L++) do { // 'int L=30' maybe faster for random data
29            lvl = ptr = vector<int>(q.size());
30            int qi = 0, qe = lvl[s] = 1;
31            while (qi < qe && !lvl[t]) {
32                int v = q[qi++];
33                for (Edge e : adj[v])
34                    if (!lvl[e.to] && e.c >> (30 - L))
35                        q[qe++] = e.to, lvl[e.to] = lvl[v] + 1;
36            }
37            while (ll p = dfs(s, t, LLONG_MAX)) flow += p;
38        } while (lvl[t]);
39        return flow;
40    }
41    bool leftOfMinCut(int a) { return lvl[a] != 0; }
42 };
```

Bellman Ford

Calculates shortest paths from s in a graph that might have negative edge weights. Unreachable nodes get $\text{dist} = \text{inf}$; nodes reachable through negative-weight cycles get $\text{dist} = -\text{inf}$. Assumes $V^2 \max |w_i| < 2^{63}$. Time complexity: $\mathcal{O}(VE)$

```

1  const ll inf = 1LL << 62;
2  struct Ed {
3      int a, b, w;
4      int s() { return a < b ? a : -a; }
5  };
6  struct Node { ll dist = inf; int prev = -1; };
7  void bellmanFord(vector<Node>& nodes, vector<Ed>& eds, int s) {
8      nodes[s].dist = 0;
9      sort(all(eds), [] (Ed a, Ed b) { return a.s() < b.s(); });
10     int lim = nodes.size() / 2 + 2;
11     for(int i = 0; i < lim; i++)
12         for(auto& ed : eds) {
13             Node cur = nodes[ed.a], &dest = nodes[ed.b];
14             if (abs(cur.dist) == inf) continue;
15             ll d = cur.dist + ed.w;
16             if (d < dest.dist) {
17                 dest.prev = ed.a;
18                 dest.dist = (i < lim - 1 ? d : -inf);
19             }
20         }
21     for(int i = 0; i < lim; i++)
22         for(auto& e : eds)
23             if (nodes[e.a].dist == -inf)
24                 nodes[e.b].dist = -inf;
25 }
```

Floyd Warshall

Calculates all-pairs shortest path in a directed graph. As output, $m[i][j]$ is set to the shortest distance between i and j , inf if no path, or $-\text{inf}$ if the path goes through a negative-weight cycle. Time complexity: $\mathcal{O}(N^3)$.

```

1  from math import inf
2  def floydWarshall(m): # m[i][j] should be inf if i and j are not adjacent
3      for i in range(len(m)):
4          m[i][i] = min(m[i][i], 0)
5      for k in range(len(m)):
6          for i in range(len(m)):
7              for j in range(len(m)):
8                  if m[i][k] != inf and m[k][j] != inf:
9                      m[i][j] = min(m[i][j], max(m[i][k] + m[k][j], -inf))
10     #only needed if weights can be negative:
11     for k in range(len(m)):
12         if m[k][k] < 0:
13             for i in range(len(m)):
14                 for j in range(len(m)):
15                     if m[i][k] != inf and m[k][j] != inf:
16                         m[i][j] = -inf

1  const ll inf = 1LL << 62;
2  void floydWarshall(vector<vector<ll>>& m) { // m[i][j] should be inf if i and j are not adjacent
3      int n = m.size();
4      for(int i = 0; i < n; i++)
5          m[i][i] = min(m[i][i], 0LL);
6      for(int k = 0; k < n; k++)
7          for(int i = 0; i < n; i++)
8              for(int j = 0; j < n; j++)
9                  if (m[i][k] != inf && m[k][j] != inf)
10                     m[i][j] = min(m[i][j], max(m[i][k] + m[k][j], -inf));
11     //only needed if weights can be negative:
12     for(int k = 0; k < n; k++)
13         if (m[k][k] < 0)
14             for(int i = 0; i < n; i++)
15                 for(int j = 0; j < n; j++)
16                     if (m[i][k] != inf && m[k][j] != inf)
17                         m[i][j] = -inf;
18 }
```

Biconnected Components

Finds all biconnected components in an undirected graph, and returns a list of edges in each. Time complexity: $\mathcal{O}(E + V)$. Note that a node can be in several components, and bridges are by default returned as a single-edge biconnected component.

```

1 struct BCC {
2     const vector<vector<ll>>& adj;
3     vector<ll> dfsNum;
4     ll nnum = 0;
5     vector<pair<ll, ll>> st;
6     vector<vector<pair<ll, ll>>> bccs;
7     ll dfs(ll cur, ll par) {
8         ll top = dfsNum[cur] = ++nnum;
9         for (ll nxt : (*adj)[cur]) {
10             if (nxt == par) continue;
11             if (dfsNum[nxt]) {
12                 top = min(top, dfsNum[nxt]);
13                 if (dfsNum[nxt] < dfsNum[cur])
14                     st.emplace_back(cur, nxt);
15                 continue;
16             }
17             ll si = st.size();
18             ll up = dfs(nxt, cur);
19             top = min(top, up);
20             if (up == dfsNum[cur]) {
21                 bccs.emplace_back(st.begin() + si, st.end());
22                 bccs.back().emplace_back(cur, nxt);
23                 st.resize(si);
24             } else if (up < dfsNum[cur]) {
25                 st.emplace_back(cur, nxt);
26             } else { //the edge (cur,nxt) is a bridge
27                 bccs.push_back({make_pair(cur, nxt)}); //remove if bridges should not form BCCs
28             }
29         }
30         return top;
31     }
32 };
33 vector<vector<pair<ll, ll>>> findBCC(const vector<vector<ll>>& adj) {
34     BCC bcc = { &adj, vector<ll>(adj.size()) };
35     for (ll i = 0; i < (ll)adj.size(); i++)
36         if (bcc.dfsNum[i] == 0)
37             bcc.dfs(i, -1);
38     return move(bcc.bccs);
39 }

```

Strongly Connected Components

Finds strongly connected components in a directed graph. Usage: `scc(graph, [&](vector<int>& v) { ... })` visits all components in reverse topological order. `comp[i]` holds the component index of a node (a component only has edges to components with lower index). `ncomps` will contain the number of components. Time complexity: $\mathcal{O}(E + V)$

```

1 vector<int> val, comp, z, cont; int Time, ncomps;
2 template<class G, class F> int dfs(int j, G& g, F& f) {
3     int low = val[j] = ++Time, x; z.push_back(j);
4     for(auto& e : g[j]) if (comp[e] < 0)
5         low = min(low, val[e] ? dfs(e, g, f));
6     if (low == val[j]) {
7         do {
8             x = z.back(); z.pop_back();
9             comp[x] = ncomps;
10            cont.push_back(x);
11        } while (x != j);
12        f(cont); cont.clear();
13        ncomps++;
14    }
15    return val[j] = low;
16 }
17 template<class G, class F> void scc(G& g, F f) {
18     val.assign(g.size(), 0);
19     comp.assign(g.size(), -1);
20     Time = ncomps = 0;
21     for(size_t i = 0; i < g.size(); i++)
22         if (comp[i] < 0) dfs(i, g, f);
23 }

```

2-SAT

Calculates a valid assignment to boolean variables in a 2-SAT problem. Negated variables are represented by bit-inversions ($\sim x$). Time complexity: $O(N + E)$, where N is the number of boolean variables, and E is the number of clauses.

```

1 struct TwoSat {
2     int N;
3     vector<vector<int>> gr;
4     vector<int> values; // 0 = false, 1 = true
5     TwoSat(int n = 0) : N(n), gr(2 * n) {}
6     void either(int f, int j) {
7         f = max(2 * f, -1-2*f);
8         j = max(2 * j, -1-2*j);
9         gr[f].push_back(j ^ 1);
10        gr[j].push_back(f ^ 1);
11    }
12    void set_value(int x) { either(x, x); }
13    vector<int> val, comp, z; int time = 0;
14    int dfs(int i) {
15        int low = val[i] = ++time, x;
16        z.push_back(i);
17        for(auto& e : gr[i])
18            if (!comp[e])
19                low = min(low, val[e] ? dfs(e));
20        if (low == val[i]) do {
21            x = z.back(); z.pop_back();
22            comp[x] = low;
23            if (values[x>>1] == -1)
24                values[x>>1] = x&1;
25        } while (x != i);
26        return val[i] = low;
27    }
28    bool solve() {
29        values.assign(N, -1);
30        val.assign(2 * N, 0); comp = val;
31        for (int i = 0; i < 2 * N; ++i)
32            if (!comp[i])
33                dfs(i);
34        for (int i = 0; i < N; ++i)
35            if (comp[2 * i] == comp[2 * i + 1])
36                return 0;
37        return 1;
38    }
39    /* optional */ int add_var() {
40        gr.emplace_back();
41        gr.emplace_back();
42        return N++;
43    }
44    /* optional */ void at_most_one(const vector<int>& li) {
45        if (li.size() <= 1) return;
46        int cur = ~li[0];
47        for(size_t i = 2; i < li.size(); i++) {
48            int next = add_var();
49            either(cur, ~li[i]);
50            either(cur, next);
51            either(~li[i], next);
52            cur = ~next;
53        }
54        either(cur, ~li[1]);
55    }
56 };

```

Usage example:

```

1 TwoSat ts(number of boolean variables);
2 ts.either(0, ~3); // Var 0 is true or var 3 is false
3 ts.set_value(2); // Var 2 is true
4 ts.at_most_one({0,~1,2}); // <= 1 of vars 0, ~1 and 2 are true
5 ts.solve(); // Returns true iff it is solvable. ts.values holds the assigned values to the variables

```

Minimum Cost Maximum Flow

Calculates min-cost max-flow. $\text{cap}[i][j] \neq \text{cap}[j][i]$ is allowed; double edges are not. To obtain the actual flow, look at positive values only. Time complexity: $\mathcal{O}(E^2)$. If costs can be negative, call `setpi` before `maxflow`. Negative cost cycles are not supported.

```

1 #include <bits/extc++.h>
2 const ll INF = LLONG_MAX / 4;
3 struct MCMF {
4     int N;
5     vector<vector<int>>> ed, red;
6     vector<vector<ll>>> cap, flow, cost;
7     vector<int> seen;
8     vector<ll> dist, pi;
9     vector<pair<int, int>> par;
10    MCMF(int N) : N(N), ed(N), red(N), cap(N, vector<ll>(N)),
11        flow(cap), cost(cap), seen(N), dist(N), pi(N), par(N) { }
12    void addEdge(int from, int to, ll cap, ll cost) {
13        this->cap[from][to] = cap;
14        this->cost[from][to] = cost;
15        ed[from].push_back(to);
16        red[to].push_back(from);
17    }
18    void path(int s) {
19        fill(all(seen), 0);
20        fill(all(dist), INF);
21        dist[s] = 0; ll di;
22        __gnu_pbds::priority_queue<pair<ll, int>> q;
23        vector<decltype(q)::point_iterator> its(N);
24        q.push({0, s});
25        auto relax = [&](int i, ll cap, ll cost, int dir) {
26            ll val = di - pi[i] + cost;
27            if (cap && val < dist[i]) {
28                dist[i] = val;
29                par[i] = {s, dir};
30                if (its[i] == q.end())
31                    its[i] = q.push({-dist[i], i});
32                else
33                    q.modify(its[i], {-dist[i], i});
34            }
35        };
36        while (!q.empty()) {
37            s = q.top().second; q.pop();
38            seen[s] = 1;
39            di = dist[s] + pi[s];
40            for (auto& i : ed[s]) if (!seen[i])
41                relax(i, cap[s][i] - flow[s][i], cost[s][i], 1);
42            for (auto& i : red[s]) if (!seen[i])
43                relax(i, flow[i][s], -cost[i][s], 0);
44        }
45        for (int i = 0; i < N; i++)
46            pi[i] = min(pi[i] + dist[i], INF);
47    }
48    pair<ll, ll> maxflow(int s, int t) {
49        ll totflow = 0, totcost = 0;
50        while (path(s), seen[t]) {
51            ll fl = INF;
52            for (int p, r, x = t; tie(p, r) = par[x], x != s; x = p)
53                fl = min(fl, r ? cap[p][x] - flow[p][x] : flow[x][p]);
54            totflow += fl;
55            for (int p, r, x = t; tie(p, r) = par[x], x != s; x = p) {
56                if (r) flow[p][x] += fl;
57                else flow[x][p] -= fl;
58            }
59        }
60        for (int i = 0; i < N; i++)
61            for (int j = 0; j < N; j++)
62                totcost += cost[i][j] * flow[i][j];
63        return { totflow, totcost };
64    }
65    void setpi(int s) { // optional, if some costs can be negative, call this before maxflow
66        fill(all(pi), INF); pi[s] = 0;
67        int it = N, ch = 1; ll v;
68        while (ch-- && it--)
69            for (int i = 0; i < N; i++) if (pi[i] != INF)

```

```

70         for(auto& to : ed[i]) if (cap[i][to])
71             if ((v = pi[i] + cost[i][to]) < pi[to])
72                 pi[to] = v, ch = 1;
73         assert(it >= 0); // negative cost cycle
74     }
75 };

```

Weighted Bipartite Matching

Given a weighted bipartite graph, matches every node on the left with a node on the right such that no nodes are in two matchings and the sum of the edge weights is minimal.

Takes $\text{cost}[N][M]$, where $\text{cost}[i][j] = \text{cost for } L[i] \text{ to be matched with } R[j]$ and returns $(\text{min cost}, \text{match})$, where $L[i]$ is matched with $R[\text{match}[i]]$. Negate costs for max cost. Requires $N \leq M$. Time complexity: $\mathcal{O}(N^2M)$

```

1 pair<ll, vector<ll>> hungarian(const vector<vector<ll>> &a) {
2     if (a.empty()) return {0, {}};
3     ll n = a.size() + 1;
4     ll m = a[0].size() + 1;
5     vector<ll> u(n), v(m), p(m), ans(n - 1);
6     for (ll i = 1; i < n; i++) {
7         p[0] = i;
8         ll j0 = 0;
9         vector<ll> dist(m, LLONG_MAX), pre(m, -1);
10        vector<bool> done(m + 1);
11        do {
12            done[j0] = true;
13            ll i0 = p[j0], j1, delta = LLONG_MAX;
14            for (ll j = 1; j < m; j++) if (!done[j]) {
15                auto cur = a[i0 - 1][j - 1] - u[i0] - v[j];
16                if (cur < dist[j]) dist[j] = cur, pre[j] = j0;
17                if (dist[j] < delta) delta = dist[j], j1 = j;
18            }
19            for (ll j = 0; j < m; j++) {
20                if (done[j]) u[p[j]] += delta, v[j] -= delta;
21                else dist[j] -= delta;
22            }
23            j0 = j1;
24        } while (p[j0]);
25        while (j0) {
26            ll j1 = pre[j0];
27            p[j0] = p[j1], j0 = j1;
28        }
29    }
30    for (ll j = 1; j < m; j++) if (p[j]) ans[p[j] - 1] = j - 1;
31    return {-v[0], ans};
32 }

```

Math

Fast Modulo Operations

```

1 using ull = unsigned long long;
2 ull modmul(ull a, ull b, ull M) {
3     ll ret = a * b - M * ull(1.L / M * a * b);
4     return ret + M * (ret < 0) - M * (ret >= (ll)M);
5 }
6 ull modpow(ull b, ull e, ull mod) {
7     ull ans = 1;
8     for (; e; b = modmul(b, b, mod), e /= 2)
9         if (e & 1) ans = modmul(ans, b, mod);
10    return ans;
11 }

```

Is Prime (Miller-Rabin)

Guaranteed to work for numbers up to $7 \cdot 10^{18}$. For larger numbers, use Python and extend A randomly.

```
1 #include "modmul.cpp"
2 bool isPrime(ull n) {
3     if (n < 2 || n % 6 % 4 != 1)
4         return (n | 1) == 3;
5     ull s = __builtin_ctzll(n-1);
6     for (ull a : {2, 325, 9375, 28178, 450775,
7         ↪ 9780504, 1795265022}) {
8         ull p = modpow(a % n, n >> s, n), i = s;
9         while (p != 1 && p != n - 1 && a % n && i--)
10             p = modmul(p, p, n);
11         if (p != n-1 && i != s) return 0;
12     }
13     return 1;
14 }
```

```
1 def ctz(x): return (x & -x).bit_length() - 1
2 A = [2,325,9375,28178,450775,9780504,1795265022]
3 def isPrime(n):
4     if n < 2 or n % 6 % 4 != 1:
5         return (n | 1) == 3
6     s = ctz(n-1)
7     for a in A:
8         p, i = pow(a % n, n >> s, n), s
9         while p != 1 and p != n - 1 and a % n and i:
10             p, i = p * p % n, i - 1
11         if p != n-1 and i != s:
12             return False
13     return True
```

Prime Factorization (Pollard-rho)

Returns prime factors of a number, in arbitrary order.

```
1 #include "is_prime.cpp"
2 ull pollard(ull n) {
3     auto f = [n](ull x) {return modmul(x, x, n)+1;};
4     ull x = 0, y = 0, t = 30, prd = 2, i = 1;
5     while (t++ % 40 || gcd(prd, n) == 1) {
6         if (x == y) x = ++i, y = f(x);
7         ull q = modmul(prd, max(x,y)-min(x,y), n);
8         if (q) prd = q;
9         x = f(x), y = f(f(y));
10    }
11    return gcd(prd, n);
12 }
13 vector<ull> factor(ull n) {
14     if (n == 1) return {};
15     if (isPrime(n)) return {n};
16     ull x = pollard(n);
17     auto l = factor(x), r = factor(n / x);
18     l.insert(l.end(), all(r));
19     return l;
20 }
```

```
1 from math import gcd
2 def pollard(n):
3     f = lambda x: x * x % n + 1
4     x, y, t, prd, i = 0, 0, 30, 2, 1
5     while t % 40 or gcd(prd, n) == 1:
6         if x == y:
7             i += 1
8             x, y = i, f(i)
9         if q := prd * (max(x,y) - min(x,y)) % n:
10             prd = q
11             x, y = f(x), f(f(y))
12             t += 1
13     return gcd(prd, n)
14 def factor(n):
15     if n == 1: return []
16     if isPrime(n): return [n]
17     x = pollard(n)
18     return factor(x) + factor(n // x)
```

Extended Euclidean Algorithm

Finds the Greatest Common Divisor to the integers a and b . Also finds two integers x and y , such that $ax + by = \gcd(a, b)$. Returns a tuple of $(\gcd(a, b), x, y)$. If a and b are coprime, then x is the inverse of $a \pmod{b}$.

```
1 ll extEuclid(ll a, ll b, ll& x, ll& y) {
2     if (b) {
3         ll d = extEuclid(b, a % b, y, x);
4         return y -= a / b * x, d;
5     }
6     return x = 1, y = 0, a;
7 }
```

```
1 def extEuclid(a, b):
2     if b:
3         d, x, y = extEuclid(b, a % b)
4         return (d, y, x - a // b * y)
5     return (a, 1, 0)
```

Chinese Remainder Theorem

Finds the smallest number x satisfying a system of congruences, each in the form $x \equiv r_i \pmod{m_i}$. All pairs of m_i must be coprime. eq is a list of tuples describing the equations, the i :th of which should be (r_i, m_i) .

```
1 //no overflow if the product of all eq.second < 2^62
2 ll crt(const vector<pair<ll, ll>>& eq) {
3     ll p = 1, res = 0;
4     for (auto e : eq) p *= e.second;
5     for (auto e : eq) {
6         ll pp = p / e.second, ppi, y;
7         extEuclid(pp, e.second, ppi, y);
8         res = (res + e.first * ppi * pp) % p;
9     }
10    return res;
11 }
```

```
1 def crt(eq):
2     p, res = 1, 0
3     for rem, md in eq:
4         p *= md
5     for rem, md in eq:
6         pp = p // md
7         res = (res + rem*extEuclid(pp, md)[1]*pp) % p
8     return res
```


Fraction Binary Search

Given f and N , finds the smallest fraction $p/q \in [0, 1]$ such that $f(p/q)$ is true, and $p, q \leq N$.

```

1 struct Frac { ll p, q; };
2 template<class F> Frac fractionBinarySearch(F f, ll N) {
3     bool dir = 1, A = 1, B = 1;
4     Frac lo{0, 1}, hi{1, 1}; // Set hi to 1/0 to search (0, N]
5     if (f(lo)) return lo;
6     assert(f(hi));
7     while (A || B) {
8         ll adv = 0, step = 1; // move hi if dir, else lo
9         for (ll si = 0; step; (step *= 2) >= si) {
10             adv += step;
11             Frac mid{lo.p * adv + hi.p, lo.q * adv + hi.q};
12             if (abs(mid.p) > N || mid.q > N || dir == !f(mid))
13                 adv -= step; si = 2;
14         }
15         hi.p += lo.p * adv;
16         hi.q += lo.q * adv;
17         dir = !dir;
18         swap(lo, hi);
19         A = B; B = !adv;
20     }
21     return dir ? hi : lo;
22 }

```

Solve Linear System of Equations

Solves $Ax = b$. If there are multiple solutions, an arbitrary one is returned. Returns rank, or -1 if no solutions. Time complexity: $\mathcal{O}(n^2m)$

```

1 int solveLinear(vector<vector<double>> A, vector<double> b, vector<double>& x) {
2     const double eps = 1e-12;
3     int n = A.size(), m = x.size(), rank = 0, br, bc;
4     if (n) assert((int)A[0].size() == m);
5     vector<int> col(m); iota(all(col), 0);
6     for(int i = 0; i < n; i++) {
7         double v, bv = 0;
8         for(int r = i; r < n; ++r) for(int c = i; c < m; c++)
9             if ((v = fabs(A[r][c])) > bv)
10                 br = r, bc = c, bv = v;
11         if (bv <= eps) {
12             for(int j = i; j < n; j++)
13                 if (fabs(b[j]) > eps) return -1;
14             break;
15         }
16         swap(A[i], A[br]);
17         swap(b[i], b[br]);
18         swap(col[i], col[bc]);
19         for(int j = 0; j < n; j++)
20             swap(A[j][i], A[j][bc]);
21         bv = 1 / A[i][i];
22         for(int j = i + 1; j < n; j++) {
23             double fac = A[j][i] * bv;
24             b[j] -= fac * b[i];
25             for(int k = i + 1; k < (m); ++k)
26                 A[j][k] -= fac * A[i][k];
27         }
28         rank++;
29     }
30     x.assign(m, 0);
31     for (int i = rank; i--;) {
32         b[i] /= A[i][i];
33         x[col[i]] = b[i];
34         for (int j = 0; j < i; j++)
35             b[j] -= A[j][i] * b[i];
36     }
37     return rank;
38 }

```

Matrix Inverse

Invert matrix A . Returns rank; result is stored in A unless singular (rank < n). Time complexity: $\mathcal{O}(n^3)$

```

1 ll matInv(vector<vector<double>>& A) {
2     ll n = A.size();
3     vector<ll> col(n);
4     vector<vector<double>> tmp(n, vector<double>(n));
5     for (ll i = 0; i < n; i++) {
6         tmp[i][i] = 1;
7         col[i] = i;
8     }
9     for (ll i = 0; i < n; i++) {
10        ll r = i, c = i;
11        for (ll j = i; j < n; j++)
12            for (ll k = i; j < n; j++)
13                if (fabs(A[j][k]) > fabs(A[r][c]))
14                    r = j, c = k;
15        if (fabs(A[r][c]) < 1e-12) return i;
16        A[i].swap(A[r]); tmp[i].swap(tmp[r]);
17        for (ll j = 0; j < n; j++)
18            swap(A[j][i], A[j][c]), swap(tmp[j][i], tmp[j][c]);
19        swap(col[i], col[c]);
20        double v = A[i][i];
21        for (ll j = i+1; j < n; j++) {
22            double f = A[j][i] / v;
23            A[j][i] = 0;
24            for (ll k = i+1; k < n; k++) A[j][k] -= f*A[i][k];
25            for (ll k = 0; k < n; k++) tmp[j][k] -= f*tmp[i][k];
26        }
27        for (ll j = i+1; j < n; j++) A[i][j] /= v;
28        for (ll j = 0; j < n; j++) tmp[i][j] /= v;
29        A[i][i] = 1;
30    }
31    for (ll i = n-1; i > 0; --i) {
32        for (ll j = 0; j < i; j++) {
33            double v = A[j][i];
34            for (ll k = 0; k < n; k++) tmp[j][k] -= v*tmp[i][k];
35        }
36    }
37    for (ll i = 0; i < n; i++)
38        for (ll j = 0; j < n; j++)
39            A[col[i]][col[j]] = tmp[i][j];
40    return n;
41 }

```

Polynomial Roots

Finds the real roots of a polynomial. Time complexity: $\mathcal{O}(n^2 \log(1/\epsilon))$.

Usage (solves $x^2 - 3x + 2 = 0$): poly_roots({{ 2, -3, 1 }}, -1e9, 1e9)

```

1 struct Poly {
2     vector<double> a;
3     double operator()(double x) const {
4         double val = 0;
5         for(int i = a.size(); i--;)
6             (val *= x) += a[i];
7         return val;
8     }
9     void diff() {
10        for (size_t i = 1; i < a.size(); i++)
11            a[i-1] = i * a[i];
12        a.pop_back();
13    }
14 };
15 vector<double> poly_roots(Poly p, double xmin, double xmax) {
16     if (p.a.size() == 2) return { -p.a[0] / p.a[1] };
17     vector<double> ret;
18     Poly der = p;
19     der.diff();
20     auto dr = poly_roots(der, xmin, xmax);
21     dr.push_back(xmin - 1);
22     dr.push_back(xmax + 1);
23     sort(all(dr));

```

```

24     for (size_t i = 0; i < dr.size() - 1; i++) {
25         double l = dr[i], h = dr[i + 1];
26         bool sign = p(l) > 0;
27         if (sign ^ (p(h) > 0)) {
28             for (int it = 0; it < 60; it++) {
29                 double m = (l + h) / 2, f = p(m);
30                 if ((f <= 0) ^ sign) l = m;
31                 else h = m;
32             }
33             ret.push_back((l + h) / 2);
34         }
35     }
36     return ret;
37 }

```

FFT

`fft(a)` computes $\hat{f}(k) = \sum_x a[x] \exp(2\pi i \cdot kx/N)$ for all k . Useful for convolution: `conv(a, b)=c`, where $c[x] = \sum a[i]b[x-i]$.

Rounding is safe if $(\sum a_i^2 + \sum b_i^2) \log_2 N < 9 \cdot 10^{14}$ (in practice 10^{16} ; higher for random inputs).

Time complexity: $\mathcal{O}(N \log N)$ with $N = |A| + |B|$ (about 1s for $N = 4 \cdot 10^6$)

```

1  typedef complex<double> C;
2  void fft(vector<C>& a) {
3      int n = a.size(), L = 31 - __builtin_clz(n);
4      static vector<complex<long double>> R(2, 1);
5      static vector<C> rt(2, 1); // (^ 10% faster if double)
6      for (int k = 2; k < n; k *= 2) {
7          R.resize(n); rt.resize(n);
8          auto x = polar(1.0/L, M_PI / k);
9          for (int i = k; i < 2 * k; i++)
10             rt[i] = R[i] = i & 1 ? R[i / 2] * x : R[i / 2];
11     }
12     vector<int> rev(n);
13     for (int i = 0; i < n; i++)
14         rev[i] = (rev[i / 2] | (i & 1) << L) / 2;
15     for (int i = 0; i < n; i++)
16         if (i < rev[i]) swap(a[i], a[rev[i]]);
17     for (int k = 1; k < n; k *= 2)
18         for (int i = 0; i < n; i += 2 * k)
19             for (int j = 0; j < k; j++) {
20                 auto x = (double*)&rt[j + k], y = (double*)&a[i + j + k];
21                 C z(x[0] * y[0] - x[1] * y[1], x[0] * y[1] + x[1] * y[0]);
22                 a[i + j + k] = a[i + j] - z;
23                 a[i + j] += z;
24             }
25     }
26     vector<double> conv(const vector<double>& a, const vector<double>& b) {
27         if (a.empty() || b.empty()) return { };
28         vector<double> res(a.size() + b.size() - 1);
29         int L = 32 - __builtin_clz(res.size()), n = 1 << L;
30         vector<C> in(n), out(n);
31         copy(all(a), begin(in));
32         for (size_t i = 0; i < a.size(); i++)
33             in[i].imag(b[i]);
34         fft(in);
35         for (C& x : in) x *= x;
36         for (int i = 0; i < n; i++)
37             out[i] = in[-i & (n - 1)] - conj(in[i]);
38         fft(out);
39         for (size_t i = 0; i < res.size(); i++)
40             res[i] = imag(out[i]) / (4 * n);
41         return res;
42     }

```

ModFFT

`fft(a)` computes $\hat{f}(k) = \sum_x a[x]g^{xk}$ for all k , where $g = \text{root}^{(M-1)/N}$. N must be a power of 2.

For conv, M should be of the form $2^a b + 1$, and the convolution result should have size at most 2^a . Inputs must be in $[0, M)$.

```

1 constexpr ll M = 998244353, root = 62;
2 ll modpow(ll b, ll e) {
3     ll ans = 1;
4     for (; e; b = b * b % M, e /= 2)
5         if (e & 1) ans = ans * b % M;
6     return ans;
7 }
8 void fft(vector<ll> &a) {
9     ll n = a.size(), L = 31 - __builtin_clz(n);
10    static vector<ll> rt(2, 1);
11    for (static ll k = 2, s = 2; k < n; k *= 2, s++) {
12        rt.resize(n);
13        ll z[] = {1, modpow(root, M >> s)};
14        for (ll i = k; i < 2 * k; i++)
15            rt[i] = rt[i / 2] * z[i & 1] % M;
16    }
17    vector<ll> rev(n);
18    for (ll i = 0; i < n; i++)
19        rev[i] = (rev[i / 2] | (i & 1) << L) / 2;
20    for (ll i = 0; i < n; i++)
21        if (i < rev[i])
22            swap(a[i], a[rev[i]]);
23    for (ll k = 1; k < n; k *= 2)
24        for (ll i = 0; i < n; i += 2 * k) for (ll j = 0; j < k; j++) {
25            ll z = rt[j + k] * a[i + j + k] % M, &ai = a[i + j];
26            a[i + j + k] = ai - z + (z > ai ? M : 0);
27            ai += (ai + z >= M ? z - M : z);
28        }
29 }
30 vector<ll> conv(const vector<ll> &a, const vector<ll> &b) {
31     if (a.empty() || b.empty()) return {};
32     ll s = (ll)(a.size() + b.size()) - 1;
33     ll B = 32 - __builtin_clz(s);
34     ll n = 1 << B;
35     ll inv = modpow(n, M - 2);
36     vector<ll> L(a), R(b), out(n);
37     L.resize(n); R.resize(n);
38     fft(L); fft(R);
39     for (ll i = 0; i < n; i++)
40         out[-i & (n - 1)] = (ll)L[i] * R[i] % M * inv % M;
41     fft(out);
42     return { out.begin(), out.begin() + s };
43 }

```