Contents

1 Geometry

1.1 Line intersection

```
point intersection(point a, point b, point c, point d)
{
        point ab = b - a;
        point cd = d - c;
        point ac = c - a;
        double alpha = cross(ac, cd) / cross(ab, cd);
        return a + alpha * ab;
}
```

1.2 Line and circle intersection

```
// return pair<point, point> which is intersections point
// for each point if it's not exist, return (INF,INF)
#include<bits/stdc++.h>
#define X first
#define Y second
using namespace std;

typedef long double ld;
typedef pair<ld,ld> point;
typedef pair<point,point> ppp;

point operator + (point A, point B) { return point(A.X+B.X,A.Y+B.Y); }
point operator - (point A, point B) { return point(A.X-B.X,A.Y-B.Y); }
point operator * (double A, point B) { return point(A*B.X,A*B.Y); }
ld dist(point A, point B) { return (A-B).X * (A-B).X + (A-B).Y * (A-B)
    .Y; }
ld dot(point A,point B) { return A.X*B.X + A.Y*B.Y; }

const ld INF = 1e18;
const ld eps = 1e-15;

ppp line_circle_intersection(point p1,point p2,point o,ld r)
{
  point q = dot(o-p1,p2-p1)/dist(p1,p2)*(p2-p1) + p1;
  ld d = r*r - dist(o,q);
  if(d<eps && d>-eps) return ppp(q, point(INF,INF));
  if(d<0) return ppp(point(INF,INF), point(INF,INF));
  point dif = sqrt(d/dist(p1,p2))*(p1-p2);
  return ppp(q-dif,q+dif);
}
```

1.3 Intersection of 2 circle

```
#include <iostream>
#include <cmath>
#include <iomanip>
using namespace std;

double dist(double x1, double y1, double x2, double y2) { return hypot
    (x2-x1,y2-y1); }

double circle_area(double r) { return r*r*M_PI; }

double f(double l, double r, double R){
    double cosa = (l*l + r*r - R*R)/(2.0*r*l);
    double a = acos(cosa);
    return r*r*(a - sin(2*a)/2);
}

double intersection_area(double x1, double y1, double r1, double x2,
    double y2, double r2)
{
  double l = dist(x1, y1, x2, y2);
  if(l >= r1 + r2) return 0;
```

```
  else if(r2 >= l + r1) return circle_area(r1);
  else if(r1 >= l + r2) return circle_area(r2);
  return f(l, r1, r2) + f(l, r2, r1);
}
```

1.4 Convex hull 3D

```
/*
  GETS:
  n->number of vertices
  you should use add_edge(u,v) and
  add pair of vertices as edges (vertices are 0..n-1)

  GIVES:
  output of edmonds() is the maximum matching in general graph
  match[i] is matched pair of i (-1 if there isn't a matched pair)

  O(nh)
*/

#include<bits/stdc++.h>
using namespace std;
typedef pair<int,int> pii;

struct point{
  int X,Y,Z;
  point(int x=0,int y=0,int z=0){
    X=x;
    Y=y;
    Z=z;
  }
  bool operator==(const point& rhs) const {
    return (rhs.X==this->X && rhs.Y==this->Y && rhs.Z==this->Z);
  }
  bool operator<(const point& rhs) const {
    return rhs.X > this->X || (rhs.X == this->X && rhs.Y > this->Y) ||
          (rhs.X==this->X && rhs.Y==this->Y && rhs.Z>this->Z);
  }
};

const int maxn=1000;
int n;
point P[maxn];
vector<point>ans;
queue<pii>Q;
set<pii>mark;

int cross2d(point p,point q){ return p.X*q.Y-p.Y*q.X;}
point operator -(point p,point q){ return point(p.X-q.X,p.Y-q.Y,p.Z-q.
    Z); }
int dot(point v,point u){ return u.X*v.X+u.Y*v.Y+u.Z*v.Z; }
point _cross(point u,point v){ return point(u.Y*v.Z-u.Z*v.Y,u.Z*v.X-u.
    X*v.Z,u.X*v.Y-u.Y*v.X); }
point cross(point o,point p,point q){ return _cross(p-o,q-o);}

point shift(point p) { return point(p.Y,p.Z,p.X);}
point norm(point p)
{
  if(p.Y<p.X || p.Z<p.X) p=shift(p);
  if(p.Y<p.X) p=shift(p);
  return p;
}

int main()
{
  cin>>n;
  int mn=0;
  for(int i=0;i<n;i++){
    cin>>P[i].X>>P[i].Y>>P[i].Z;
    if(P[i]<P[mn]) mn=i;
  }
  int nx=(mn==0);
  for(int i=0;i<n;i++)
    if(i!=mn && i!=nx && cross2d(P[nx]-P[mn],P[i]-P[mn])>0)
      nx=i;
  Q.push(pii(mn,nx));
  while(!Q.empty())
    {
      int v=Q.front().first,u=Q.front().second;
      Q.pop();
      if(mark.find(pii(v,u))!=mark.end()) continue;
      mark.insert(pii(v,u));
      int p=-1;
      for(int q=0;q<n;q++)
        if(q!=v && q!=u)
          if(p==-1 || dot(cross(P[v],P[u],P[p]),P[q]-P[v])<0)
            p=q;
      ans.push_back(norm(point(v,u,p)));
      Q.push(pii(p,u));
      Q.push(pii(v,p));
    }
  sort(ans.begin(),ans.end());
  ans.resize(unique(ans.begin(),ans.end())-ans.begin());
  for(int i=0;i<ans.size();i++)
    cout<<ans[i].X<<" "<<ans[i].Y<<" "<<ans[i].Z<<endl;
}
```

1.5 Number of integer points inside polygon

```
S = I + B / 2 - 1
```

1.6 Half plane

```
#include <iostream>
#include <vector>
#include <algorithm>

using namespace std;

typedef int T;
typedef long long T2;
typedef long long T4; // maybe int128_t

const int MAXLINES = 100 * 1000 + 10;
const int INF = 20 * 1000 * 1000;

typedef pair<T, T> point;
typedef pair<point, point> line;
```

```
// REPLACE ZERO WITH EPS FOR DOUBLE

point operator - (const point &a, const point &b)
{
        return point(a.first - b.first, a.second - b.second);
}


T2 cross(point a, point b)
{
        return ((T2)a.first * b.second - (T2)a.second * b.first);
}

bool cmp(line a, line b)
{
        bool aa = a.first < a.second;
        bool bb = b.first < b.second;
        if (aa == bb)
        {
                point v1 = a.second - a.first;
                point v2 = b.second - b.first;
                if (cross(v1, v2) == 0)
                        return cross(b.second - b.first, a.first - b.
                            first) > 0;
                else
                        return cross(v1, v2) > 0;
        }
        else
                return aa;
}

bool parallel(line a, line b)
{
        return cross(a.second - a.first, b.second - b.first) == 0;
}

pair<T2, T2> alpha(line a, line b)
{
        return pair<T2, T2>(cross(b.first - a.first, b.second - b.
            first),
                                                cross(a.second - a.
                                                    first, b.second -
                                                    b.first));
}

bool fcmp(T4 f1t, T4 f1b, T4 f2t, T4 f2b)
{
        if (f1b < 0)
        {
                f1t *= -1;
                f1b *= -1;
        }
        if (f2b < 0)
        {
                f2t *= -1;
                f2b *= -1;
        }
        return f1t * f2b < f2t * f1b; // check with eps
}
```

```
bool check(line a, line b, line c)
{
        bool crs = cross(c.second - c.first, a.second - a.first) > 0;
        pair<T2, T2> a1 = alpha(a, b);
        pair<T2, T2> a2 = alpha(a, c);
        bool alp = fcmp(a1.first, a1.second, a2.first, a2.second);
        return (crs ^ alp);
}

bool notin(line a, line b, line c) // is intersection of a and b in
    ccw direction of c?
{
        if (parallel(a, b))
                return false;
        if (parallel(a, c))
                return cross(c.second - c.first, a.first - c.first) <
                    0;
        if (parallel(b, c))
                return cross(c.second - c.first, b.first - c.first) <
                    0;
        return !(check(a, b, c) && check(b, a, c));
}

void print(vector<line> lines)
{
        cerr << "    " << endl;for (int i = 0; i < lines.size();
            i++)cerr << lines[i].first.first << " " <<
            lines[i].first.second << " -> " << lines[i].second.first
            << " " << lines[i].second.second << endl;cerr << "    "


 << endl<< endl;
}

line dq[MAXLINES];

vector<line> half_plane(vector<line> lines)
{
        lines.push_back(line(point(INF, -INF), point(INF, INF)));
        lines.push_back(line(point(-INF, INF), point(-INF, -INF)));
        lines.push_back(line(point(-INF, -INF), point(INF, -INF)));
        lines.push_back(line(point(INF, INF), point(-INF, INF)));
        sort(lines.begin(), lines.end(), cmp);
        int ptr = 0;
        for (int i = 0; i < lines.size(); i++)
                if (i > 0 &&
                        (lines[i - 1].first < lines[i - 1].second) ==
                            (lines[i].first < lines[i].second) &&
                        parallel(lines[i - 1], lines[i]))
                        continue;
                else
                        lines[ptr++] = lines[i];
        lines.resize(ptr);
        if (lines.size() < 2)
                return lines;
        //print(lines);
        int f = 0, e = 0;
        dq[e++] = lines[0];
        dq[e++] = lines[1];
        for (int i = 2; i < lines.size(); i++)
        {
```

```
                while (f < e - 1 && notin(dq[e - 2], dq[e - 1], lines[
                    i]))
                        e--;
                //print(vector<line>(dq + f, dq + e));
                if (e == f + 1)
                {
                        T2 crs = cross(dq[f].second - dq[f].first,
                            lines[i].second - lines[i].first) ;
                        if (crs < 0)
                                return vector<line>();
                        else if (crs == 0 && cross(lines[i].second -
                            lines[i].first, dq[f].second - lines[i].
                            first) < 0)
                                return vector<line>();
                }
                while (f < e - 1 && notin(dq[f], dq[f + 1], lines[i]))
                        f++;
                dq[e++] = lines[i];
        }
        while (f < e - 1 && notin(dq[e - 2], dq[e - 1], dq[f]))
                e--;
        while (f < e - 1 && notin(dq[f], dq[f + 1], dq[e - 1]))
                f++;
        vector<line> res;
        res.resize(e - f);
        for (int i = f; i < e; i++)
                res[i - f] = dq[i];
        return res;
}


int main()
{
        int n;
        cin >> n;
        vector<line> lines;
        for (int i = 0; i < n; i++)
        {
                int x1, y1, x2, y2;
                cin >> x1 >> y1 >> x2 >> y2;
                lines.push_back(line(point(x1, y1), point(x2, y2)));
        }
        lines = half_plane(lines);
        cout << lines.size() << endl;
        for (int i = 0; i < lines.size(); i++)
                cout << lines[i].first.first << " " << lines[i].first.
                    second << " " << lines[i].second.first << " " <<
                    lines[i].second.second << endl;
}
```

1.7 Is this point in circle of other 3 points?

```
#include <iostream>
#include <algorithm>

using namespace std;

typedef pair<int, int> point;

// returns positive if d is outside circle abc,
// positive if d is inside it and 0 if it's on border
int inCircle (point a, point b, point c, point d)
{
        if (cross(b - a, c - a) < 0)
                swap(b, c);
        int x[4][4] = {
                1, a.first, a.second, a.first * a.first + a.second * a
                    .second,
                1, b.first, b.second, b.first * b.first + b.second * b
                    .second,
                1, c.first, c.second, c.first * c.first + c.second * c
                    .second,
                1, d.first, d.second, d.first * d.first + d.second * d
                    .second
        };
        // you can replace the following with any faster way
        // of calculating determinant.
        int y[] = {0, 1, 2, 3};
        int ans = 0;
        do {
                int mul = 1;
                for (int i = 0; i < 4; i++)
                        for (int j = i + 1; j < 4; j++)
                                if (y[i] > y[j])
                                        mul *= -1;
                for (int i = 0; i < 4; i++)
                        mul *= x[i][y[i]];
                ans += mul;
        } while (next_permutation(y, y + 4));
        return ans;
}
```

1.8 Rotating Caliper

```
#include <iostream>
#include <algorithm>
#include <complex>
#include <vector>

using namespace std;

typedef pair<int, int> Point;
typedef pair<vector<Point>, vector<Point> > pvv;

int cross(Point a, Point b)
{
        return a.first * b.second - a.second * b.first;
}

int norm(Point a)
{
        return a.first * a.first + a.second * a.second;
}

Point operator - (Point a, Point b)
{
        return Point(a.first - b.first, a.second - b.second);
}

Point org;
```

```
bool cmp(Point a, Point b)
{
	a = a - org;
	b = b - org;
	if (cross(a, b) == 0)
		return norm(a) < norm(b);
	else
		return cross(a, b) > 0;
}

pvv convex_hull(vector<Point> v)
{
	org = v[0];
	for (int i = 0; i < v.size(); i++)
		org = min(org, v[i]);
	sort(v.begin(), v.end(), cmp);
	/*
	for (int i = 0; i < v.size(); i++)
		cout << v[i].first << ", " << v[i].second << endl;
	cout << endl;*/
	vector<Point> cv;
	cv.push_back(v[0]);
	cv.push_back(v[1]);
	for (int i = 2; i < v.size(); i++)
	{
		while (cv.size() >= 2 && cross(v[i] - cv[cv.size() -
		    2], cv[cv.size() - 1] - cv[cv.size() - 2]) > 0)
			cv.pop_back();
		cv.push_back(v[i]);
	}
	vector<Point> uh, lh;
	int mn = 0, mx = 0;
	for (int i = 0; i < cv.size(); i++)
	{
		if (cv[i] < cv[mn])
			mn = i;
		if (cv[i] > cv[mx])
			mx = i;
	}
	for (int i = mn; i != mx; i = (i + 1) % cv.size())
		lh.push_back(cv[i]);
	lh.push_back(cv[mx]);
	for (int i = mx; i != mn; i = (i + 1) % cv.size())
		uh.push_back(cv[i]);
	uh.push_back(cv[mn]);
	reverse(uh.begin(), uh.end());
	reverse(lh.begin(), lh.end());
	return pvv(uh, lh);

}

int findMax(vector<Point> a, vector<Point> b)
{
	int p1 = 0, p2 = 0;
	int res = 0;
	while (p1 < a.size() && p2 < b.size())
	{
		//cerr << a[p1].first << " " << a[p1].second << "
		    ----- " << b[p2].first << " " << b[p2].second <<
		    endl;
		res = max(res, norm(b[p2] - a[p1]));
		if (p1 + 1 == a.size())
			p2++;
		else if (p2 + 1 == b.size())
			p1++;
		else
		{
			Point v1, v2;
			if (a[p1] < a[p1 + 1])
				v1 = a[p1 + 1] - a[p1];
			else
				v1 = a[p1] - a[p1 + 1];

			if (b[p2] <  b[p2 + 1])
				v2 = b[p2 + 1] - b[p2];
			else
				v2 = b[p2] - b[p2 + 1];

			//cerr << v1.first << " " << v1.second << "
			    ### " << v2.first << " " << v2.second <<
			    endl;
			if (cross(v1, v2) > 0)
				p2++;
			else
				p1++;
		}
	}
	return res;
}

vector<Point> v1, v2;

int main()
{
	int n;
	cin >> n;
	for (int i = 0; i < n; i++)
	{
		int x, y;
		cin >> x >> y;
		v1.push_back(Point(x, y));
	}
	sort(v1.begin(), v1.end());
	v1.resize(unique(v1.begin(), v1.end()) - v1.begin());
	int m;
	cin >> m;
	for (int i = 0; i < m; i++)
	{
		int x, y;
		cin >> x >> y;
		v2.push_back(Point(x, y));
	}
	sort(v2.begin(), v2.end());
	v2.resize(unique(v2.begin(), v2.end()) - v2.begin());


	pvv h1 = convex_hull(v1);
	pvv h2 = convex_hull(v2);
	cout << max(max(findMax(h1.first, h2.second), findMax(h1.
	    second, h2.first)), max(findMax(h1.first, h2.first),
	    findMax(h1.second, h2.second))) << endl;
```

```
}
```

1.9 Duality and properties

duality of point (a, b) is y = ax - b and duality of line y = ax + b is (a, -b)
Properties:

1. p is on l iff l* is in p*
2. p is in intersection of l1 and l2 iff l1* and l2* lie on p*
3. Duality preserve vertical distance
4. Translating a line in primal to moving vertically in dual
5. Rotating a line in primal to moving a point along a non-vertical line
6. $li \cap lj$ is a vertex of lower envelope $\iff$ (li*, lj*) is an edge of upper hull in dual

1.10 Delaunay(nlg^2n)

```
#include <iostream>
#include <cmath>
#include <set>
#include <algorithm>
#include <vector>

using namespace std;

const int MAXN = 100 * 1000 + 10;
const int MAXLG = 20;
const int INF = 100 * 1000 * 1000 + 10;

const int MAXPOINTS = MAXN * MAXLG;

typedef pair<int ,int> point;

point operator - (point a, point b)
{
        return point(a.first - b.first, a.second - b.second);
}

struct tria
{
        int a, b, c;
        tria(int _a, int _b, int _c)
        {
                a = _a;
                b = _b;
                c = _c;
        }
        tria()
        {
                a = b = c = 0;
        }
};
long long cross(point a, point b)
{
        return ((long long)a.first * b.second - (long long)a.second *
            b.first);
}

long long dot(point a, point b)
{
        return ((long long)a.first * b.first + (long long)a.second * b
            .second);
}
__int128 inCircle (point a, point b, point c, point d)
{
        if (cross(b - a, c - a) < 0)
                swap(b, c);

        __int128 x1 = b.first - a.first;
        __int128 y1 = b.second - a.second;
        __int128 z1 = dot(b, b) - dot(a, a);

        __int128 x2 = c.first - a.first;
        __int128 y2 = c.second - a.second;
        __int128 z2 = dot(c, c) - dot(a, a);
        // (ai + bj + ck) (di + ej + fk) = (ae - bd)k + (cd - af)j + (
            bf - ce)i
        __int128 cx = y1 * z2 - z1 * y2;
        __int128 cy = z1 * x2 - x1 * z2;
        __int128 cz = x1 * y2 - y1 * x2;

        __int128 res =  cx * (d.first - a.first) + cy * (d.second - a.
            second) + cz * (dot(d, d) - dot(a, a));
        return res;

}



struct Delaunay
{

        typedef pair<point, int> ppi;
        typedef pair<int, int> pii;
        typedef pair<pii, int> pip;
        tria t[MAXPOINTS];
        bool mrk[MAXPOINTS];
        int last[MAXPOINTS];
        int childs[MAXPOINTS][3];
        int cnt;
        vector<ppi> points;
        set<pip> edges;
        vector<tria> res;
        int n;

        inline void add_edge(int a, int b, int c)
        {
```

```
        edges.insert(pip(pii(min(a, b), max(a, b)), c));
}

inline void remove_edge(int a, int b, int c)
{
        edges.erase(pip(pii(min(a, b), max(a, b)), c));
}


int add_triangle(int a, int b, int c)
{
        if (cross(points[b].first - points[a].first, points[c
            ].first - points[a].first) == 0)
                return -1;
        if (cross(points[b].first - points[a].first, points[c
            ].first - points[a].first) < 0)
                swap(b, c);

        add_edge(a, b, cnt);
        add_edge(b, c, cnt);
        add_edge(c, a, cnt);
        t[cnt] = tria(a, b, c);
        childs[cnt][0] = childs[cnt][1] = childs[cnt][2] = -1;
        mrk[cnt] = false;
        last[cnt] = -1;

        cnt++;
        return cnt - 1;
}

inline void remove_triangle(int v)
{
        childs[v][0] = childs[v][1] = childs[v][2] = -1;
        remove_edge(t[v].a, t[v].b, v);
        remove_edge(t[v].b, t[v].c, v);
        remove_edge(t[v].c, t[v].a, v);
}

inline void relax_edge(const int &a, const int &b)
{
        pii key(min(a, b), max(a, b));
        set<pip>::iterator it = edges.lower_bound(pip(key, -1)
            );
        if (it == edges.end() || it->first != key)
                return;
        set<pip>::iterator it2 = it;
        it2++;
        if (it2 == edges.end() || it2->first != key)
                return;
        int c1 = t[it->second].a + t[it->second].b + t[it->
            second].c - a - b;
        int c2 = t[it2->second].a + t[it2->second].b + t[it2->
            second].c - a - b;
        if (c1 > n || c2 > n)
                return;
        if (inCircle(points[a].first, points[b].first, points[
            c1].first, points[c2].first) < 0 ||
                        inCircle(points[a].first, points[b].
                            first, points[c2].first, points[c1
                            ].first) < 0)
        {
                int v1 = it->second;
                int v2 = it2->second;
                remove_triangle(v1);
                remove_triangle(v2);
                mrk[v1] = mrk[v2] = true;
                childs[v1][0] = childs[v2][0] = add_triangle(a
                    , c1, c2);
                childs[v1][1] = childs[v2][1] = add_triangle(b
                    , c1, c2);
                relax(childs[v1][0]);
                relax(childs[v1][1]);
        }
}

inline void relax(int v)
{
        relax_edge(t[v].a, t[v].b);
        relax_edge(t[v].b, t[v].c);
        relax_edge(t[v].c, t[v].a);
}


inline bool inLine(int a, int b, int c)
{
        return cross(points[b].first - points[a].first, points
            [c].first - points[a].first) >= 0;
}

inline bool inTriangle(int a, int b, int c, int d)
{
        return inLine(a, b, d) && inLine(b, c, d) && inLine(c,
             a, d);
}

void find(int v, int p, int cl)
{
        if (last[v] == cl)
                return;
        bool reached = false;
        last[v] = cl;
        for (int i = 0; i < 3; i++)
        {
                int u = childs[v][i];
                if (u == -1)
                        continue;
                reached = true;
                if (mrk[u] || inTriangle(t[u].a, t[u].b, t[u].
                    c, p))
                        find(u, p, cl);
        }
        if (reached)
                return ;
        remove_triangle(v);
        childs[v][0] = add_triangle(p, t[v].a, t[v].b);
        childs[v][1] = add_triangle(p, t[v].b, t[v].c);
        childs[v][2] = add_triangle(p, t[v].c, t[v].a);
        relax(childs[v][0]);
        relax(childs[v][1]);
        relax(childs[v][2]);

}
```

```
        void getRes(int v, int cl)
        {
                if (last[v] == cl)
                        return;
                last[v] = cl;
                bool reached = false;
                for (int i = 0; i < 3; i++)
                {
                        int u = childs[v][i];
                        if (u == -1)
                                continue;
                        reached = true;
                        getRes(u, cl);
                }
                if (!reached && t[v].a < n && t[v].b < n && t[v].c < n
                    )
                        res.push_back(t[v]);
        }

        vector<tria> delaunay(vector<point> v)
        {
                cnt = 0;
                int cl = 0;
                points.clear();
                for (int i = 0; i < v.size(); i++)
                        points.push_back(ppi(v[i], i));
                random_shuffle(points.begin(), points.end());
                n = points.size();
                points.push_back(ppi(point(INF, INF), n));
                points.push_back(ppi(point(-INF * 3, INF), n + 1));
                points.push_back(ppi(point(INF, -INF * 3), n + 2));
                int root = add_triangle(n, n + 1, n + 2);
                for (int i = 0; i < n; i++)
                {

                        //      cout << "" << inTriangle(n,n+1, n+2, i
                            ) << endl;
                        find(root, i, cl++);
                }
                res.clear();
                getRes(root, cl++);
                for (int i = 0; i < res.size(); i++)
                {
                        res[i].a = points[res[i].a].second;
                        res[i].b = points[res[i].b].second;
                        res[i].c = points[res[i].c].second;
                }
                return res;
        }
};


typedef pair<long double, long double> pointD;


long double crossD(pointD a, pointD b)
{
        return a.first * b.second - a.second * b.first;
}

pointD operator + (pointD a, pointD b)
{
        return pointD(a.first + b.first, a.second + b.second);
}
pointD operator - (pointD a, pointD b)
{
        return pointD(a.first - b.first, a.second - b.second);
}
pointD operator * (pointD a, long double b)
{
        return pointD(a.first * b, a.second * b);
}
pointD operator / (pointD a, long double b)
{
        return pointD(a.first / b, a.second / b);
}

pointD intersect(pointD a, pointD b, pointD c, pointD d)
{
        long double alpha = crossD(c - a, d - c) / crossD(b - a, d - c
            );
        return a + (b - a) * alpha;
}

pointD norm(pointD a)
{
        return pointD(-a.second, a.first);
}

long double dot(pointD a, pointD b)
{
        return a.first * b.first + a.second * b.second;
}

long double getRadius(pointD a, pointD b, pointD c)
{
        pointD v1 = norm(b - a) + ((a + b) / 2);
        pointD v2 = norm(c - b) + ((b + c) / 2);
        pointD center =  intersect((a + b) / 2, v1, (b + c) / 2, v2);
        pointD ret = a - center;
        return sqrt(dot(ret, ret));
}

Delaunay d;
int main()
{
        srand(2018);
        ios::sync_with_stdio(false);
        cin.tie(0);
        int n;
        cin >> n;
        vector<point> v;
        for (int i = 0; i < n; i++)
        {
                int x, y;
                cin >> x >> y;
                v.push_back(point(x, y));
        }
        vector<tria> ans = d.delaunay(v);
        long double res = 0;
        for (int i = 0; i < ans.size(); i++)
                res = max(res, getRadius(v[ans[i].a], v[ans[i].b], v[
```

```
                    ans[i].c]));
        cout.precision(6);
        cout << fixed << res << endl;
}
```

1.11 Stupid Delaunay(n^4)

```
// Slow but simple Delaunay triangulation. Does not handle
// degenerate cases (from O'Rourke, Computational Geometry in C)
//
// Running time: O(n^4)
//
// INPUT:    x[] = x-coordinates
//           y[] = y-coordinates
//
// OUTPUT:   triples = a vector containing m triples of indices
//                     corresponding to triangle vertices

#include<vector>
using namespace std;

typedef double T;

struct triple {
    int i, j, k;
    triple() {}
    triple(int i, int j, int k) : i(i), j(j), k(k) {}
};

vector<triple> delaunayTriangulation(vector<T>& x, vector<T>& y) {
        int n = x.size();
        vector<T> z(n);
        vector<triple> ret;

        for (int i = 0; i < n; i++)
            z[i] = x[i] * x[i] + y[i] * y[i];

        for (int i = 0; i < n-2; i++) {
            for (int j = i+1; j < n; j++) {
                for (int k = i+1; k < n; k++) {
                    if (j == k) continue;
                    double xn = (y[j]-y[i])*(z[k]-z[i]) - (y[k]-y[i])
                        *(z[j]-z[i]);
                    double yn = (x[k]-x[i])*(z[j]-z[i]) - (x[j]-x[i])
                        *(z[k]-z[i]);
                    double zn = (x[j]-x[i])*(y[k]-y[i]) - (x[k]-x[i])
                        *(y[j]-y[i]);
                    bool flag = zn < 0;
                    for (int m = 0; flag && m < n; m++)
                        flag = flag && ((x[m]-x[i])*xn +
                                        (y[m]-y[i])*yn +
                                        (z[m]-z[i])*zn <= 0);
                    if (flag) ret.push_back(triple(i, j, k));
                }
            }
        }
        return ret;
}

int main()
{
    T xs[]={0, 0, 1, 0.9};
    T ys[]={0, 1, 0, 0.9};
    vector<T> x(&xs[0], &xs[4]), y(&ys[0], &ys[4]);
    vector<triple> tri = delaunayTriangulation(x, y);

    //expected: 0 1 3
    //          0 3 2

    int i;
    for(i = 0; i < tri.size(); i++)
        printf("%d %d %d\n", tri[i].i, tri[i].j, tri[i].k);
    return 0;
}
```

2 Graph

2.1 Maximum matching - Edmond's blossom

```
/*
  GETS:
  n->number of vertices
  you should use add_edge(u,v) and
  add pair of vertices as edges (vertices are 0..n-1)
  (note: please don't add multiple edge)

  GIVES:
  output of edmonds() is the maximum matching in general graph
  match[i] is matched pair of i (-1 if there isn't a matched pair)

  O(mn^2)
*/

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

struct struct_edge{int v;struct_edge* nxt;};
typedef struct_edge* edge;
const int MAXN=500;

struct Edmonds
{
  struct_edge pool[MAXN*MAXN*2];
  edge top=pool,adj[MAXN];
  int n,match[MAXN],qh,qt,q[MAXN],father[MAXN],base[MAXN];
  bool inq[MAXN],inb[MAXN];

  void add_edge(int u,int v)
  {
    top->v=v,top->nxt=adj[u],adj[u]=top++;
    top->v=u,top->nxt=adj[v],adj[v]=top++;
  }
  int LCA(int root,int u,int v)
  {
    static bool inp[MAXN];
    memset(inp,0,sizeof(inp));
    while(1)
      {
```

```
      inp[u=base[u]]=true;
      if (u==root) break;
      u=father[match[u]];
    }
  while(1)
    {
      if (inp[v=base[v]]) return v;
      else v=father[match[v]];
    }
}

void mark_blossom(int lca,int u)
{
  while (base[u]!=lca)
    {
      int v=match[u];
      inb[base[u]]=inb[base[v]]=true;
      u=father[v];
      if (base[u]!=lca) father[u]=v;
    }
}

void blossom_contraction(int s,int u,int v)
{
  int lca=LCA(s,u,v);
  memset(inb,0,sizeof(inb));
  mark_blossom(lca,u);
  mark_blossom(lca,v);
  if (base[u]!=lca)
    father[u]=v;
  if (base[v]!=lca)
    father[v]=u;
  for (int u=0;u<n;u++)
    if (inb[base[u]])
      {
        base[u]=lca;
        if (!inq[u])
          inq[q[++qt]=u]=true;
      }
}

int find_augmenting_path(int s)
{
  memset(inq,0,sizeof(inq));
  memset(father,-1,sizeof(father));
  for (int i=0;i<n;i++) base[i]=i;
  inq[q[qh=qt=0]=s]=true;
  while (qh<=qt)
    {
      int u=q[qh++];
      for (edge e=adj[u];e;e=e->nxt)
        {
          int v=e->v;
          if (base[u]!=base[v] && match[u]!=v)
            {
              if (v==s || (match[v]!=-1 && father[match[v]]!=-1))
                blossom_contraction(s,u,v);
              else if (father[v]==-1)
                {
                  father[v]=u;
                  if (match[v]==-1)
                    return v;
                  else if (!inq[match[v]])
                    inq[q[++qt]=match[v]]=true;
                }
            }
        }
    }
  return -1;
}

  int augment_path(int s,int t)
  {
    int u=t,v,w;
    while (u!=-1)
      {
        v=father[u];
        w=match[v];
        match[v]=u;
        match[u]=v;
        u=w;
      }
    return t!=-1;
  }

  int edmonds()
  {
    int matchc=0;
    memset(match,-1,sizeof(match));
    for (int u=0;u<n;u++)
      if (match[u]==-1)
        matchc+=augment_path(u,find_augmenting_path(u));
    return matchc;
  }
};
```

2.2 Biconnected components

```
vector<int> adj[maxn];
bool vis[maxn];
int dep[maxn], par[maxn], lowlink[maxn];
vector<vector<int> > comp;
stack<int> st;
void dfs(int u, int depth = 0, int parent = -1)
{
        vis[u] = true;
        dep[u] = depth;
        par[u] = parent;
        lowlink[u] = depth;
        st.push(u);
        for (int i = 0; i < adj[u].size(); i++)
        {
                int v = adj[u][i];
                if (!vis[v])
                {
                        dfs(v, depth + 1, u);
                        lowlink[u] = min(lowlink[u], lowlink[v]);
                }
                else
                        lowlink[u] = min(lowlink[u], dep[v]);
        }
```

```
        if (lowlink[u] == dep[u] - 1)
        {
                comp.push_back(vector<int>());
                while (st.top() != u)
                {
                        comp.back().push_back(st.top());
                        st.pop();
                }
                comp.back().push_back(u);
                st.pop();
                comp.back().push_back(par[u]);
        }
}
void bicon(int n)
{
        for (int i = 0; i < n; i++)
                if (!vis[i])
                        dfs(i);
}
```

2.3 Gomory-hu

```
struct GomoryHu
{
        int par[MAXN], ans[MAXN][MAXN]; // SET MAXIMUM NUMBER OF NODES
        int edges[4 * MAXE]; // SET MAXIMUM NUMBER OF EDGES
        int ecnt;
        void clear()
        {
                ecnt = 0;
        }
        void add_edge(int u, int v, int uv, int vu = 0)
        {
                edges[ecnt++] = u;
                edges[ecnt++] = v;
                edges[ecnt++] = uv;
                edges[ecnt++] = vu;
        }
        Flow graph; // USE flow.cpp
        void build(int n)
        {
                for (int i = 0; i < n; i++)
                {
                        par[i] = 0;
                        for (int j = 0; j < n; j++)
                                ans[i][j] = 1e9; // SET YOUR INFINITY
                }
                for (int v = 1; v < n; v++)
                {
                        graph.clear();
                        for (int i = 0; i < ecnt; i += 4)
                                graph.add_edge(edges[i], edges[i + 1],
                                     edges[i + 2], edges[i + 3]);
                        int f = graph.max_flow(v, par[v]);
                        for (int u = v + 1; u < n; u++)
                                if (graph.d[u] != -1 && par[u] == par[
                                    v])
                                        par[u] = v;
                        ans[v][par[v]] = ans[par[v]][v] = f;
                        for (int u = 0; u < v; u++)
                                ans[u][v] = ans[v][u] = min(f, ans[par
                                    [v]][u]);
                }
        }
        GomoryHu()
        {
                clear();
        }
};
```

2.4 Directed minimum spanning tree (mlogn)

```
/*
  GETS:
  call make_graph(n) at first
  you should use add_edge(u,v,w) and
  add pair of vertices as edges (vertices are 0..n-1)

  GIVES:
  output of dmst(v) is the minimum arborescence with root v in
      directed graph
  (INF if it hasn't a spanning arborescence with root v)

  O(mlogn)
*/

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

const int INF = 2e7;

struct MinimumAborescense
{
  struct edge {
    int src, dst, weight;
  };

  struct union_find {
    vector<int> p;
    union_find(int n) : p(n, -1) { };
    bool unite(int u, int v) {
      if ((u = root(u)) == (v = root(v))) return false;
      if (p[u] > p[v]) swap(u, v);
      p[u] += p[v]; p[v] = u;
      return true;
    }
    bool find(int u, int v) { return root(u) == root(v); }
    int root(int u) { return p[u] < 0 ? u : p[u] = root(p[u]); }
    int size(int u) { return -p[root(u)]; }
  };

  struct skew_heap {
    struct node {
      node *ch[2];
      edge key;
      int delta;
    } *root;
    skew_heap() : root(0) { }
    void propagate(node *a) {
      a->key.weight += a->delta;
```

```
    if (a->ch[0]) a->ch[0]->delta += a->delta;
    if (a->ch[1]) a->ch[1]->delta += a->delta;
    a->delta = 0;
  }
  node *merge(node *a, node *b) {
    if (!a || !b) return a ? a : b;
    propagate(a); propagate(b);
    if (a->key.weight > b->key.weight) swap(a, b);
    a->ch[1] = merge(b, a->ch[1]);
    swap(a->ch[0], a->ch[1]);
    return a;
  }
  void push(edge key) {
    node *n = new node();
    n->ch[0] = n->ch[1] = 0;
    n->key = key; n->delta = 0;
    root = merge(root, n);
  }
  void pop() {
    propagate(root);
    node *temp = root;
    root = merge(root->ch[0], root->ch[1]);
  }
  edge top() {
    propagate(root);
    return root->key;
  }
  bool empty() {
    return !root;
  }
  void add(int delta) {
    root->delta += delta;
  }
  void merge(skew_heap x) {
    root = merge(root, x.root);
  }
};

vector<edge> edges;
void add_edge(int src, int dst, int weight) {
  edges.push_back({src, dst, weight});
}
int n;
void make_graph(int _n) {
  n = _n;
  edges.clear();
}

int dmst(int r) {
  union_find uf(n);
  vector<skew_heap> heap(n);
  for (auto e: edges)
    heap[e.dst].push(e);

  double score = 0;
  vector<int> seen(n, -1);
  seen[r] = r;
  for (int s = 0; s < n; ++s) {
    vector<int> path;
    for (int u = s; seen[u] < 0;) {
      path.push_back(u);
      seen[u] = s;
      if (heap[u].empty()) return INF;

      edge min_e = heap[u].top();
      score += min_e.weight;
      heap[u].add(-min_e.weight);
      heap[u].pop();

      int v = uf.root(min_e.src);
      if (seen[v] == s) {
        skew_heap new_heap;
        while (1) {
          int w = path.back();
          path.pop_back();
          new_heap.merge(heap[w]);
          if (!uf.unite(v, w)) break;
        }
        heap[uf.root(v)] = new_heap;
        seen[uf.root(v)] = -1;
      }
      u = uf.root(v);
    }
  }
  return score;
 }
};
```

2.5 Directed minimum spanning tree (nm)

```
/*
  GETS:
  call make_graph(n) at first
  you should use add_edge(u,v,w) and
  add pair of vertices as edges (vertices are 0..n-1)

  GIVES:
  output of dmst(v) is the minimum arborescence with root v in
      directed graph
  (-1 if it hasn't a spanning arborescence with root v)

  O(mn)
*/

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

const int INF = 2e7;

struct MinimumAborescense
{
  int n;
  struct edge {
    int src, dst;
    int weight;
  };
  vector<edge> edges;

  void make_graph(int _n) {
    n=_n;
    edges.clear();
```

```
  }

  void add_edge(int u, int v, int w) {
    edges.push_back({u, v, w});
  }

  int dmst(int r) {
    int N = n;
    for (int res = 0; ;) {
      vector<edge> in(N, {-1,-1,(int)INF});
      vector<int> C(N, -1);
      for (auto e: edges)
        if (in[e.dst].weight > e.weight)
          in[e.dst] = e;
      in[r] = {r, r, 0};

      for (int u = 0; u < N; ++u) { // no comming edge ==> no
          aborescense
        if (in[u].src < 0) return -1;
        res += in[u].weight;
      }
      vector<int> mark(N, -1); // contract cycles
      int index = 0;
      for (int i = 0; i < N; ++i) {
        if (mark[i] != -1) continue;
        int u = i;
        while (mark[u] == -1) {
          mark[u] = i;
          u = in[u].src;
        }
        if (mark[u] != i || u == r) continue;
        for (int v = in[u].src; u != v; v = in[v].src) C[v] = index;
        C[u] = index++;
      }
      if (index == 0) return res; // found arborescence
      for (int i = 0; i < N; ++i) // contract
        if (C[i] == -1) C[i] = index++;

      vector<edge> next;
      for (auto &e: edges)
        if (C[e.src] != C[e.dst] && C[e.dst] != C[r])
          next.push_back({C[e.src], C[e.dst], e.weight - in[e.dst].
              weight});
      edges.swap(next);
      N = index; r = C[r];
    }
  }
};
```

2.6 Dominator tree

```
struct DominatorTree
{
        vector<int> adj[MAXN], radj[MAXN], tree[MAXN], bucket[MAXN];
            // SET MAXIMUM NUMBER OF NODES
        int sdom[MAXN], par[MAXN], idom[MAXN], dsu[MAXN], label[MAXN];
        int arr[MAXN], rev[MAXN], cnt;
        void clear()
        {
                for (int i = 0; i < MAXN; i++)
                {
                        adj[i].clear();
                        radj[i].clear();
                        tree[i].clear();
                        sdom[i] = idom[i] = dsu[i] = label[i] = i;
                        arr[i] = -1;
                }
                cnt = 0;
        }
        void add_edge(int u, int v)
        {
                adj[u].push_back(v);
        }
        void dfs(int v)
        {
                arr[v] = cnt;
                rev[cnt] = v;
                cnt++;
                for (int i = 0; i < adj[v].size(); i++)
                {
                        int u = adj[v][i];
                        if (arr[u] == -1)
                        {
                                dfs(u);
                                par[arr[u]] = arr[v];
                        }
                        radj[arr[u]].push_back(arr[v]);
                }
        }
        int find(int v, int x = 0)
        {
                if (dsu[v] == v)
                        return (x ? -1 : v);
                int u = find(dsu[v], x + 1);
                if (u < 0)
                        return v;
                if (sdom[label[dsu[v]]] < sdom[label[v]])
                        label[v] = label[dsu[v]];
                dsu[v] = u;
                return (x ? u : label[v]);
        }
        void merge(int u, int v)
        {
                dsu[v] = u;
        }
        void build(int root)
        {
                dfs(root);
                int n = cnt;
                for (int v = n - 1; v >= 0; v--)
                {
                        for (int i = 0; i < radj[v].size(); i++)
                        {
                                int u = radj[v][i];
                                sdom[v] = min(sdom[v], sdom[find(u)]);
                        }
                        if (v > 0)
                                bucket[sdom[v]].push_back(v);
                        for (int i = 0; i < bucket[v].size(); i++)
                        {
                                int u = bucket[v][i];
```

```
                int w = find(u);
                if (sdom[u] == sdom[w])
                        idom[u] = sdom[u];
                else
                        idom[u] = w;
            }
            if (v > 0)
                merge(par[v], v);
        }
        for (int v = 1; v < n; v++)
        {
            if (idom[v] != sdom[v])
                idom[v] = idom[idom[v]];
            tree[rev[v]].push_back(rev[idom[v]]);
            tree[rev[idom[v]]].push_back(rev[v]);
        }
    }
    DominatorTree()
    {
        clear();
    }
};
```

2.7 Flow - Dinic

```
struct Flow
{
    int head[MAXN], q[MAXN], d[MAXN], ptr[MAXN]; // SET MAXIMUM
        NUMBER OF NODES
    int from[2 * MAXE], to[2 * MAXE], cap[2 * MAXE], prv[2 * MAXE
        ]; // SET MAXIMUM NUMBER OF EDGES
    int ecnt;
    void clear()
    {
        memset(head, -1, sizeof(head));
        ecnt = 0;
    }
    void add_edge(int u, int v, int uv, int vu = 0)
    {
        from[ecnt] = u, to[ecnt] = v, cap[ecnt] = uv, prv[ecnt
            ] = head[u]; head[u] = ecnt++;
        from[ecnt] = v, to[ecnt] = u, cap[ecnt] = vu, prv[ecnt
            ] = head[v]; head[v] = ecnt++;
    }
    bool bfs(int source, int sink)
    {
        int h = 0, t = 0;
        memset(d, -1, sizeof(d));
        d[source] = 0;
        q[t++] = source;
        while (h < t)
        {
            int v = q[h++];
            for (int i = head[v]; i != -1; i = prv[i])
                if (cap[i] && d[to[i]] == -1)
                {
                    d[to[i]] = d[v] + 1;
                    q[t++] = to[i];
                }
        }
        return (d[sink] != -1);
    }
    int dfs(int v, int sink, int f = 1e9) // SET YOUR INFINITY
    {
        if (!f || v == sink)
            return f;
        int ans = 0;
        for (int &i = ptr[v]; i != -1; i = prv[i])
            if (d[to[i]] == d[v] + 1)
            {
                int x = dfs(to[i], sink, min(f, cap[i
                    ]));
                cap[i] -= x;
                cap[i ^ 1] += x;
                f -= x;
                ans += x;
                if (!f)
                    break;
            }
        return ans;
    }
    int max_flow(int source, int sink)
    {
        int f = 0;
        while (bfs(source, sink))
        {
            int x;
            memcpy(ptr, head, sizeof(head));
            while (x = dfs(source, sink))
                f += x;
        }
        return f;
    }
    Flow()
    {
        clear();
    }
};
```

2.8 Maximum weighted matching - Hungarian

```
/*
  GETS:
  n->number of vertices in each part
  cost[i][j]->weight of edge between i,j
  (vertices in each part are 0..n-1)

  GIVES:
  output of hungarian() is the maximum weighted matching
  xy[v] is matched pair of v if v is in X
  and yx[v] is matched pair of v if v is in Y
  (-1 if there isn't a matched pair)

  O(n^3)
*/

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

const int MAXN = 505;
```

```
const int inf = 1e8;

struct Hungarian
{
  int cost[MAXN][MAXN];
  int n, max_match;
  int lx[MAXN], ly[MAXN];
  int xy[MAXN];
  int yx[MAXN];
  bool S[MAXN], T[MAXN];
  int slack[MAXN];
  int slackx[MAXN];
  int prev[MAXN];

  void init_labels()
  {
    memset(lx, 0, sizeof(lx));
    memset(ly, 0, sizeof(ly));
    for (int x = 0; x < n; x++)
      for (int y = 0; y < n; y++)
        lx[x] = max(lx[x], cost[x][y]);
  }

  void add_to_tree(int x, int prevx)
  {
    S[x] = true;
    prev[x] = prevx;
    for (int y = 0; y < n; y++)
      if (lx[x] + ly[y] - cost[x][y] < slack[y])
        {
          slack[y] = lx[x] + ly[y] - cost[x][y];
          slackx[y] = x;
        }
  }

  void update_labels()
  {
    int x, y, delta = inf;
    for (y = 0; y < n; y++)
      if (!T[y])
        delta = min(delta, slack[y]);
    for (x = 0; x < n; x++)
      if (S[x]) lx[x] -= delta;
    for (y = 0; y < n; y++)
      if (T[y]) ly[y] += delta;
    for (y = 0; y < n; y++)
      if (!T[y])
        slack[y] -= delta;
  }

  void augment()
  {
    if (max_match == n) return;
    int x, y, root;
    int q[MAXN], wr = 0, rd = 0;
    memset(S, false, sizeof(S));
    memset(T, false, sizeof(T));
    memset(prev, -1, sizeof(prev));
    for (x = 0; x < n; x++)
      if (xy[x] == -1)
        {
          q[wr++] = root = x;
          prev[x] = -2;
          S[x] = true;
          break;
        }
    for (y = 0; y < n; y++)
      {
        slack[y] = lx[root] + ly[y] - cost[root][y];
        slackx[y] = root;
      }


    while (true)
      {
        while (rd < wr)
          {
            x = q[rd++];
            for (y = 0; y < n; y++)
              if (cost[x][y] == lx[x] + ly[y] && !T[y])
                {
                  if (yx[y] == -1) break;
                  T[y] = true;
                  q[wr++] = yx[y];
                  add_to_tree(yx[y], x);
                }
            if (y < n) break;
          }
        if (y < n) break;

        update_labels();
        wr = rd = 0;
        for (y = 0; y < n; y++)
          if (!T[y] && slack[y] == 0)
            {
              if (yx[y] == -1)
                {
                  x = slackx[y];
                  break;
                }
              else
                {
                  T[y] = true;
                  if (!S[yx[y]])
                    {
                      q[wr++] = yx[y];
                      add_to_tree(yx[y], slackx[y]);
                    }
                }
            }
        if (y < n) break;
      }


    if (y < n)
      {
        max_match++;
        for (int cx = x, cy = y, ty; cx != -2; cx = prev[cx], cy = ty)
          {
            ty = xy[cx];
            yx[cy] = cx;
            xy[cx] = cy;
```

```
            }
          augment();
        }
    }

    int hungarian()
    {
      int ret = 0;
      max_match = 0;
      memset(xy, -1, sizeof(xy));
      memset(yx, -1, sizeof(yx));
      init_labels();
      augment();
      for (int x = 0; x < n; x++)
        ret += cost[x][xy[x]];
      return ret;
    }
};
```

2.9 Ear decomposition

```
1- Find a spanning tree of the given graph and choose a root for the
    tree.
2- Determine, for each edge uv that is not part of the tree, the
    distance between the root and the lowest common ancestor of u and
    v.
3- For each edge uv that is part of the tree, find the corresponding "
    master edge", a non-tree edge wx such that the cycle formed by
    adding wx to the tree passes through uv and such that, among such
    edges, w and x have a lowest common ancestor that is as close to
    the root as possible (with ties broken by edge identifiers).
4- Form an ear for each non-tree edge, consisting of it and the tree
    edges for which it is the master, and order the ears by their
    master edges' distance from the root (with the same tie-breaking
    rule).
```

3 Combinatorics

3.1 LP simplex

```
#include <cmath>
#include <cstdio>
#include <memory.h>

const int MAXEQ = 310;
const int MAXVAR = 310;
const long double eps = 1e-8; // 1e-6?

struct Simplex {
        long double A[MAXEQ][MAXVAR+1];
        long double obj[MAXVAR+1];
        int ones[MAXEQ];

        long double saved[MAXVAR+1];
        long double sol[MAXVAR+1];

        int n_r, n_col;

void mult_row(long double* row, long double k) {
        for (int j = 0; j <= n_col; j++)
                row[j] *= k;
}
void add_row_mult(long double* row_b, long double* row_a, long
     double mult) {
        for (int j = 0; j <= n_col; j++)
                row_b[j] += row_a[j]*mult;
}
void pivot(int r, int c) {
        mult_row(A[r], 1.0 / A[r][c]);
        ones[r] = c;
        for (int i = 0; i <= n_r; i++) {
                if (i != r && A[i][c] != 0)
                        add_row_mult(A[i], A[r], -A[i][c]);
        }
        add_row_mult(obj, A[r], -obj[c]);
        add_row_mult(saved, A[r], -saved[c]);
}
void move_col(int c2, int c1) {
        for (int i = 0; i < n_r; i++)
        {
                A[i][c2] = A[i][c1];
                A[i][c1] = 0;
        }
        obj[c2] = obj[c1];
        obj[c1] = 0;
        saved[c2] = saved[c1];
        saved[c1] = 0;
}

long double solve_feasible() {
        while (true) {
                int new_one = -1;
                for (int j = 0; j < n_col; j++)
                        if (obj[j] < -eps)
                        {
                                new_one = j;
                                break;
                        }
                if (new_one == -1)
                        break;

                int row = -1;
                long double lim = 1e100;
                for (int i = 0; i < n_r; i++) {
                        if (A[i][new_one] > eps) {
                                long double val = A[i][n_col]
                                    / A[i][new_one];
                                if (val < lim) {
                                        lim = val;
                                        row = i;
                                }
                        }
                }
                if (row == -1)
                        return -1e100; // unbounded // !!
                            promjena
                pivot(row, new_one);
        }
```

```
                memset(sol, 0, sizeof sol);
                for (int i = 0; i < n_r; i++) sol[ones[i]] = A[i][
                    n_col];
                return obj[n_col];
        }

        bool get_feasibile() {
                int min_row = -1;
                for (int i = 0; i < n_r; i++)
                        if (min_row == -1 || A[i][n_col] < A[min_row][
                            n_col])
                                min_row = i;
                if (A[min_row][n_col] > eps)
                        return true; // basic feasible

                ++n_col;
                for (int i = 0; i < n_col; i++)
                        saved[i] = obj[i];
                move_col(n_col, n_col-1);

                memset(obj, 0, sizeof obj);
                obj[n_col - 1] = 1;
                for (int i = 0; i < n_r; i++)
                        A[i][n_col - 1] = -1;

                pivot(min_row, n_col - 1);
                long double val = solve_feasible();
                if (val < -eps)
                        return false; // infeasible // !!!! promjena
                for (int i = 0; i < n_r; i++) {
                        if (ones[i] == n_col - 1) {
                                int maxj = -1;
                                for (int j = 0; j < n_col; j++)
                                        if (maxj == -1 || fabs(A[i][j
                                            ]) > fabs(A[i][maxj]))
                                                maxj = j;
                                pivot(i, maxj);
                        }
                }

                move_col(n_col-1, n_col);
                for (int i = 0; i < n_col; i++)
                        obj[i] = saved[i];
                --n_col;
                return true;
        }

        long double solve_all() {
                if (!get_feasibile()) return 1e100; // impossible
                return - solve_feasible(); // !!! promjena
        }
};
```

3.2 FFT

```
const int LG = 20; // IF YOU WANT TO CONVOLVE TWO ARRAYS OF LENGTH N
    AND M CHOOSE LG IN SUCH A WAY THAT 2^LG > n + m
const int MAX = 1 << LG;

struct point
{
        double real, imag;
        point(double _real = 0.0, double _imag = 0.0)
        {
                real = _real;
                imag = _imag;
        }
};
point operator + (point a, point b)
{
        return point(a.real + b.real, a.imag + b.imag);
}
point operator - (point a, point b)
{
        return point(a.real - b.real, a.imag - b.imag);
}
point operator * (point a, point b)
{
        return point(a.real * b.real - a.imag * b.imag, a.real * b.
            imag + a.imag * b.real);
}

void fft(point *a, bool inv)
{
        for (int mask = 0; mask < MAX; mask++)
        {
                int rev = 0;
                for (int i = 0; i < LG; i++)
                        if ((1 << i) & mask)
                                rev |= (1 << (LG - 1 - i));
                if (mask < rev)
                        swap(a[mask], a[rev]);
        }
        for (int len = 2; len <= MAX; len *= 2)
        {
                double ang = 2.0 * M_PI / len;
                if (inv)
                        ang *= -1.0;
                point wn(cos(ang), sin(ang));
                for (int i = 0; i < MAX; i += len)
                {
                        point w(1.0, 0.0);
                        for (int j = 0; j < len / 2; j++)
                        {
                                point t1 = a[i + j] + w * a[i + j +
                                    len / 2];
                                point t2 = a[i + j] - w * a[i + j +
                                    len / 2];
                                a[i + j] = t1;
                                a[i + j + len / 2] = t2;
                                w = w * wn;
                        }
                }
        }
        if (inv)
                for (int i = 0; i < MAX; i++)
                {
                        a[i].real /= MAX;
                        a[i].imag /= MAX;
                }
}
```

3.3 NTT

```
const int MOD = 998244353;
const int LG = 16; // IF YOU WANT TO CONVOLVE TWO ARRAYS OF LENGTH N
    AND M CHOOSE LG IN SUCH A WAY THAT 2^LG > n + m
const int MAX = (1 << LG);
const int ROOT = 44759; // ENSURE THAT ROOT^2^(LG - 1) = MOD - 1
int bpow(int a, int b)
{
        int ans = 1;
        while (b)
        {
                if (b & 1)
                        ans = 1LL * ans * a % MOD;
                b >>= 1;
                a = 1LL * a * a % MOD;
        }
        return ans;
}
void ntt(int *a, bool inv)
{
        for (int mask = 0; mask < MAX; mask++)
        {
                int rev = 0;
                for (int i = 0; i < LG; i++)
                        if ((1 << i) & mask)
                                rev |= (1 << (LG - 1 - i));
                if (mask < rev)
                        swap(a[mask], a[rev]);
        }
        for (int len = 2; len <= MAX; len *= 2)
        {
                int wn = bpow(ROOT, MAX / len);
                if (inv)
                        wn = bpow(wn, MOD - 2);
                for (int i = 0; i < MAX; i += len)
                {
                        int w = 1;
                        for (int j = 0; j < len / 2; j++)
                        {
                                int l = a[i + j];
                                int r = 1LL * w * a[i + j + len / 2] %
                                     MOD;
                                a[i + j] = (l + r);
                                a[i + j + len / 2] = l - r + MOD;
                                if (a[i + j] >= MOD)
                                        a[i + j] -= MOD;
                                if (a[i + j + len / 2] >= MOD)
                                        a[i + j + len / 2] -= MOD;
                                w = 1LL * w * wn % MOD;
                        }
                }
        }
        if (inv)
        {
                int x = bpow(MAX, MOD - 2);
                for (int i = 0; i < MAX; i++)
                        a[i] = 1LL * a[i] * x % MOD;
        }
}
```

3.4 Stirling 1

```
#include <bits/stdc++.h>
using namespace std;
typedef long long ll;
#define pb push_back
const int mod = 998244353;
const int root = 15311432;
const int root_1 = 469870224;
const int root_pw = 1 << 23;
const int N = 400004;

vector<int> v[N];

ll modInv(ll a, ll mod = mod){
        ll x0 = 0, x1 = 1, r0 = mod, r1 = a;
        while(r1){
                ll q = r0 / r1;
                x0 -= q * x1; swap(x0, x1);
                r0 -= q * r1; swap(r0, r1);
        }
        return x0 < 0 ? x0 + mod : x0;
}

void fft (vector<int> &a, bool inv) {
        int n = (int) a.size();

        for (int i=1, j=0; i<n; ++i) {
                int bit = n >> 1;
                for (; j>=bit; bit>>=1)
                        j -= bit;
                j += bit;
                if (i < j)
                        swap (a[i], a[j]);
        }

        for (int len=2; len<=n; len<<=1) {
                int wlen = inv ? root_1 : root;
                for (int i=len; i<root_pw; i<<=1)
                        wlen = int (wlen * 1ll * wlen % mod);
                for (int i=0; i<n; i+=len) {
                        int w = 1;
                        for (int j=0; j<len/2; ++j) {
                                int u = a[i+j],  v = int (a[i+j+len/2]
                                     * 1ll * w % mod);
                                a[i+j] = u+v < mod ? u+v : u+v-mod;
                                a[i+j+len/2] = u-v >= 0 ? u-v : u-v+
                                    mod;
                                w = int (w * 1ll * wlen % mod);
                        }
                }
        }

        if(inv) {
                int nrev = modInv(n, mod);
                for (int i=0; i<n; ++i)
                        a[i] = int (a[i] * 1ll * nrev % mod);
        }
}
```

```
void pro(const vector<int> &a, const vector<int> &b, vector<int> &res)
     {
        vector<int> fa(a.begin(), a.end()),  fb(b.begin(), b.end());
        int n = 1;
        while (n < (int) max(a.size(), b.size()))  n <<= 1;
        n <<= 1;
        fa.resize (n),  fb.resize (n);

        fft(fa, false), fft (fb, false);
        for (int i = 0; i < n; ++i)
                fa[i] = 1LL * fa[i] * fb[i] % mod;
        fft (fa, true);
        res = fa;
}

int S(int n, int r) {

        int nn = 1;
        while(nn < n) nn <<= 1;

        for(int i = 0; i < n; ++i) {
                v[i].push_back(i);
                v[i].push_back(1);
        }
        for(int i = n; i < nn; ++i) {
                v[i].push_back(1);
        }

        for(int j = nn; j > 1; j >>= 1){
                int hn = j >> 1;
                for(int i = 0; i < hn; ++i){
                        pro(v[i], v[i + hn], v[i]);
                }
        }

        return v[0][r];
}

int fac[N], ifac[N], inv[N];

void prencr(){
        fac[0] = ifac[0] = inv[1] = 1;
        for(int i = 2; i < N; ++i)
                inv[i] = mod - 1LL * (mod / i) * inv[mod % i] % mod;
        for(int i = 1; i < N; ++i){
                fac[i] = 1LL * i * fac[i - 1] % mod;
                ifac[i] = 1LL * inv[i] * ifac[i - 1] % mod;
        }
}

int C(int n, int r){
        return (r >= 0 && n >= r) ? (1LL * fac[n] * ifac[n - r] % mod
            * ifac[r] % mod) : 0;
}

int main(){
        prencr();
        int n, p, q;
        cin >> n >> p >> q;
        ll ans = C(p + q - 2, p - 1);
        ans *= S(n - 1, p + q - 2);
        ans %= mod;
        cout << ans;
}
```

3.5 Stirling 2

$$\left\{ \begin{matrix} \mathrm{n} \\ \mathrm{k} \end{matrix} \right\} = \frac{1}{k!}\sum_{j=0}^{k}(-1)^{k-j}\binom{k}{j}j^n$$

3.6 Chinese remainder

```
// Find a number X such that X%a[i]==r[i] for all (0<=i<n) (-1 if it's
     not exist) O(nlogn)
#include<bits/stdc++.h>
using namespace std;

const int MAXN = 1000;
int n;
long long a[MAXN];
long long r[MAXN];

long long gcd(long long x,long long y,long long &c1,long long &c2) {
  if (y==0) {
    c1=1; c2=0;
    return x;
  }
  int r=x%y;
  long long ans=gcd(y,r,c2,c1);
  c2-=c1*(x/y);
  return ans;
}
int solve_pair(long long &c,long long &rr,long long a,long long r) {
  long long c1=1,a1=1;
  long long g=gcd(c,a,c1,a1);
  long long c2=c/g,a2=a/g;
  long long rr1=rr%g,r1=r%g;
  if(rr1 != r1) return rr=-1;
  rr=(c2*(r/g)*c1+a2*a1*(rr/g))*g+rr1;

  c=c2*a2*g;
  rr=(rr%c+c)%c;
  return 0;
}
long long chinese_remainder() {
  long long c=a[0],rr=r[0];
  for(int i=1;i<n;i++){
    solve_pair(c,rr,a[i],r[i]);
    if(rr==-1)return -1;
  }
  return rr;
}
```

3.7 Popular LP

BellmanFord:

maximize X_n
$X_1 = 0$
and for eache edge ($v- > u$ and weight w):
$X_u - X_v \leq w$

Flow:

maximize Σf_{out} (where *out* is output edges of vertex 1)
for each vertex (except 1 and n):
$\Sigma f_{in} - \Sigma f_{out} = 0$ (where *in* is input edges of v and *out* is output edges of v)

Dijkstra(IP):

minimize $\Sigma z_i * w_i$
for eache edge ($v- > u$ and weight w):
$0 \leq z_i \leq 1$
and for each ST-cut which vertex 1 is in S and vertex n is in T:
$\Sigma z_e \geq 1$ (for each edge e from S to T)

3.8 Extended catalan

number of ways for going from 0 to A with k moves without going to -B:

$$\binom{k}{\frac{A+k}{2}} - \binom{k}{\frac{2B+A+k}{2}}$$

3.9 Find polynomial from it's points

$P(x) = \sum_{i=1}^{n} y_i \prod_{j=1, j\neq i}^{n} \frac{x-x_j}{x_i-x_j}$

3.10 Number of primes

```
30: 10
60: 17
100: 25
1000: 168
10000: 1229
100000: 9592
1000000: 78498
10000000: 664579
```

3.11 Factorials

```
1: 1
2: 2
3: 6
4: 24
5: 120
6: 720
7: 5040
8: 40320
9: 362880
10: 3628800
11: 39916800
12: 479001600
13: 6227020800
14: 87178291200
15: 1307674368000
```

3.12 Powers of 3

```
1: 3
2: 9
3: 27
4: 81
5: 243
6: 729
7: 2187
8: 6561
9: 19683
10: 59049
11: 177147
12: 531441
13: 1594323
14: 4782969
15: 14348907
16: 43046721
17: 129140163
18: 387420489
19: 1162261467
20: 3486784401
```

3.13 C(2n,n)

```
1: 2
2: 6
3: 20
4: 70
5: 252
6: 924
7: 3432
8: 12870
9: 48620
10: 184756
11: 705432
12: 2704156
13: 10400600
14: 40116600
15: 155117520
```

3.14 Most divisor

```
<= 100: 60 with 12 divisors
<= 1000: 840 with 32 divisors
```

```
<= 10000: 7560 with 64 divisors
<= 100000: 83160 with 128 divisors
<= 1000000: 720720 with 240 divisors
<= 10000000: 8648640 with 448 divisors
<= 100000000: 73513440 with 768 divisors
<= 1000000000: 735134400 with 1344 divisors
<= 10000000000: 6983776800 with 2304 divisors
<= 100000000000: 97772875200 with 4032 divisors
<= 1000000000000: 963761198400 with 6720 divisors
<= 10000000000000: 9316358251200 with 10752 divisors
<= 100000000000000: 97821761637600 with 17280 divisors
<= 1000000000000000: 866421317361600 with 26880 divisors
<= 10000000000000000: 8086598962041600 with 41472 divisors
<= 100000000000000000: 74801040398884800 with 64512 divisors
<= 1000000000000000000: 897612484786617600 with 103680 divisors
```

4 String

4.1 Manacher

```
int m[MAXN]; // SET MAXIMUM LENGTH OF STRING
void build(string s)
{
        int n = s.size();
        int l = 0, r = 0;
        for (int i = 0; i < n; i++)
                if (r <= i)
                {
                        l = i, r = i + 1;
                        while (2 * l - r >= 0 && s[r] == s[2 * l - r])
                                r++;
                        m[i] = r - l;
                }
                else if (m[2 * l - i] < r - i)
                        m[i] = m[2 * l - i];
                else
                {
                        l = i;
                        while (2 * l - r >= 0 && s[r] == s[2 * l - r])
                                r++;
                        m[i] = r - l;
                }
}
```

4.2 Palindromic tree

```
struct PalindromicTree
{
        struct node
        {
                int to[SIGMA]; // SET MAXIMUM NUMBER OF CHARACTERS IN
                    ALPHABET
                int link, len;
                node()
                {
                        for (int i = 0; i < SIGMA; i++)
                                to[i] = -1;
                        link = len = 0;
                }
        } tree[MAXN]; // SET MAXIMUM LENGTH OF STRING
        int sz, suf;
        string s;
        void clear()
        {
                sz = 0;
                tree[sz++] = node();
                tree[sz++] = node();
                tree[0].len = -1;
                suf = 1;
                s = "";
        }
        bool add_letter(int c)
        {
                int pos = s.size();
                s += char(c);
                while (pos - tree[suf].len - 1 < 0 || s[pos] != s[pos
                    - tree[suf].len - 1])
                        suf = tree[suf].link;
                if (tree[suf].to[c] != -1)
                {
                        suf = tree[suf].to[c];
                        return false;
                }
                tree[sz] = node();
                tree[sz].len = tree[suf].len + 2;
                tree[suf].to[c] = sz++;
                int cur = suf;
                suf = sz - 1;
                if (tree[suf].len == 1)
                {
                        tree[suf].link = 1;
                        return true;
                }
                do
                {
                        cur = tree[cur].link;
                } while (pos - tree[cur].len - 1 < 0 || s[pos] != s[
                    pos - tree[cur].len - 1]);
                tree[suf].link = tree[cur].to[c];
                return true;
        }
        PalindromicTree()
        {
                clear();
        }
};
```

4.3 Z function

```
int z[MAXN]; // SET MAXIMUM LENGTH OF STRING
void build(string s)
{
        int n = s.size();
        z[0] = n;
        int l = 0, r = 0;
        for (int i = 1; i < n; i++)
                if (r < i)
```

```
                {
                        l = r = i;
                        while (r < n && s[r - l] == s[r])
                                r++;
                        z[i] = r - l;
                }
                else if (z[i - l] < r - i)
                        z[i] = z[i - l];
                else
                {
                        l = i;
                        while (r < n && s[r - l] == s[r])
                                r++;
                        z[i] = r - l;
                }
        }
```

5 Data structure

5.1 Treap

```
#include <iostream>
#include <vector>
#include <algorithm>

using namespace std;

typedef pair<int, int> pii;

struct Treap {
        typedef pii T;
        typedef struct _Node {
                T x;
                int y, cnt;
                _Node *l, *r;

                _Node(T _x) {
                        x = _x;
                        y = ((rand() & ((1 << 16) - 1)) << 16) ^ rand
                            ();
                        l = r = NULL;
                        cnt = 1;
                }
                ~_Node() { delete l; delete r; }
                void recalc() {
                        cnt = 0;
                        if (l)
                                cnt += l->cnt;
                        cnt++;
                        if (r)
                                cnt += r->cnt;
                }
                void debug() {
                        if (l)
                                l->debug();
                        if (r)
                                r->debug();
                        cerr << x.first << " " << x.second << " " << (
                            l ? l->x.first : -1) << " " << (r ? r->x.
                            first : -1) << " " << cnt << endl;
                }
        } *Node;

        Node merge(Node l, Node r) {
                if (!l || !r) return l ? l : r;
                if (l->y < r->y) {
                        l->r = merge(l->r, r);
                        l->recalc();
                        return l;
                } else {
                        r->l = merge(l, r->l);
                        r->recalc();
                        return r;
                }
        }

        void split(Node v, T x, Node &l, Node &r, bool eq=false) {
                l = r = NULL;
                if (!v) return;
                if (v->x < x || (eq && v->x == x)) {
                        split(v->r, x, v->r, r);
                        l = v;
                } else {
                        split(v->l, x, l, v->l);
                        r = v;
                }
                v->recalc();
        }

        Node root;
        Treap() : root(NULL) {}
        ~Treap() { delete root; }
        void insert(T x) {
                Node l, r;
                split(root, x, l, r);
                root = merge(merge(l, new _Node(x)), r);
        }
        void erase(T x) {
                Node l, m, r;
                split(root, x, l, m);
                split(m, x, m, r, true);
                // assert(m && m->cnt == 1 && m->x == x);
                delete m;
                root = merge(l, r);
        }
        int size() const { return root ? root->cnt : 0; }
};

Treap t;
```

Useful formulas

$\binom{n}{k} = \frac{n!}{k!(n-k)!}$ — number of ways to choose k objects out of n

$\binom{n+k-1}{k-1}$ — number of ways to choose k objects out of n with repetitions

$\begin{bmatrix} n \\ m \end{bmatrix}$ — Stirling numbers of the first kind; number of permutations of n elements with k cycles

$\begin{bmatrix} n+1 \\ m \end{bmatrix} = n\begin{bmatrix} n \\ m \end{bmatrix} + \begin{bmatrix} n \\ m-1 \end{bmatrix}$

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

$\begin{Bmatrix} n \\ m \end{Bmatrix}$ — Stirling numbers of the second kind; number of partitions of set $1, \dots, n$ into k disjoint subsets.

$\begin{Bmatrix} n+1 \\ m \end{Bmatrix} = k\begin{Bmatrix} n \\ k \end{Bmatrix} + \begin{Bmatrix} n \\ k-1 \end{Bmatrix}$

$\sum_{k=0}^{n} \begin{Bmatrix} n \\ k \end{Bmatrix} (x)_k = x^n$

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

$C(x) = \frac{1-\sqrt{1-4x}}{2x}$

Binomial transform

If $a_n = \sum_{k=0}^{n} \binom{n}{k} b_k$, then $b_n = \sum_{k=0}^{n} (-1)^{n-k} \binom{n}{k} a_k$

- $a = (1, x, x^2, \dots), b = (1, (x+1), (x+1)^2, \dots)$
- $a_i = i^k, b_i = \begin{Bmatrix} n \\ i \end{Bmatrix} i!$

Burnside's lemma

Let G be a group of *action* on set X (Ex.: cyclic shifts of array, rotations and symmetries of $n \times n$ matrix, ...)

Call two objects x and y *equivalent* if there is an action f that transforms x to y: $f(x) = y$.

The number of equivalence classes then can be calculated as follows: $C = \frac{1}{|G|} \sum_{f \in G} |X^f|$, where X^f is the set of *fixed points* of f: $X^f = \{x | f(x) = x\}$

Generating functions

Ordinary generating function (o.g.f.) for sequence $a_0, a_1, \dots, a_n, \dots$ is $A(x) = \sum_{n=0}^{\infty} a_i x^i$

Exponential generating function (e.g.f.) for sequence $a_0, a_1, \dots, a_n, \dots$ is $A(x) = \sum_{n=0}^{\infty} a_i x^i$

$B(x) = A'(x), b_{n-1} = n \cdot a_n$

$c_n = \sum_{k=0}^{n} a_k b_{n-k}$ (o.g.f. convolution)

$c_n = \sum_{k=0}^{n} \binom{n}{k} a_k b_{n-k}$ (e.g.f. convolution, compute with FFT using $\widetilde{a_n} = \frac{a_n}{n!}$)

General linear recurrences

If $a_n = \sum_{k=1}^{n} b_k a_{n-k}$, then $A(x) = \frac{a_0}{1-B(x)}$. We also can compute all a_n with Divide-and-Conquer algorithm in $O(n \log^2 n)$.

Inverse polynomial modulo x^l

Given $A(x)$, find $B(x)$ such that $A(x)B(x) = 1 + x^l \cdot Q(x)$ for some $Q(x)$

1. Start with $B_0(x) = \frac{1}{a_0}$
2. Double the length of $B(x)$: $B_{k+1}(x) = (-B_k(x)^2 A(x) + 2B_k(x)) \mod x^{2^{k+1}}$

Fast subset convolution

Given array a_i of size 2^k, calculate $b_i = \sum_{j \& i = i} b_j$

```
for b = 0..k-1
  for i = 0..2^k-1
    if (i & (1 << b)) != 0:
      a[i + (1 << b)] += a[i]
```

Hadamard transform

Treat array a of size 2^k as k-dimentional array of size $2 \times 2 \times \dots \times 2$, calculate FFT of that array:

```
for b = 0..k-1
  for i = 0..2^k-1
    if (i & (1 << b)) != 0:
      u = a[i], v = a[i + (1 << b)]
      a[i] = u + v
      a[i + (1 << b)] = u - v
```