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## 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 two circles

```

#include <iomanip>
#include <iostream>
#define _USE_MATH_DEFINES
#include <cmath>
#include <vector>
using namespace std;
typedef long long ll;
typedef long double ld;

```

```

const int MAX_N = 2e5+10;
const int INF = 1e9;
const ld eps = 1e-8;

bool is_zero(ld x) {
    if(abs(x) <= eps)
        return true;
    return false;
}

struct point {
public:
    ld x, y;
    point() {}
    point(ld xx, ld yy) {
        x = xx;
        y = yy;
    }
};

struct circle {
public:
    ld r;
    point o;
    circle(ld rr, ld x, ld y) {
        r = rr;
        o.x = x;
        o.y = y;
    }
    ld S() {
        return M_PI*r*r;
    }
    ld distance(point p1, point p2) { return hypot(p2.x-p1.x,p2.y-p1.y);
    }
    /*
    0 = other is inside this, zero point
    1 = other is tangent inside of this, one point
    2 = other is intersect with this, two point
    3 = other is tangent outside of this, one point
    4 = other is outside of this, zero point
    */
    pair<int, vector<point>> > intersect(circle other) {
        vector<point> v;
        ld sumr = other.r + r;
        ld rr = r - other.r;
        ld dis = distance(o, other.o);

        ld a = (r*r - other.r*other.r + dis*dis)/(2*dis);
        ld h = sqrt(r*r-a*a);
        point p2(o.x, o.y);
        p2.x = a*(other.o.x - o.x)/dis;
        p2.y = a*(other.o.y - o.y)/dis;

        if(is_zero(sumr-dis)) {
            v.push_back(p2);
            return make_pair(3, v);
        }
        if(is_zero(rr - dis)) {
            v.push_back(p2);

```

```

        return make_pair(1, v);
    }
    if(dis <= rr)
        return make_pair(0, v);
    if(dis >= sumr)
        return make_pair(4, v);

    point p3(p2.x + h*(other.o.y - o.y)/dis, p2.y - h*(other.o.x - o.x)/dis);
    point p4(p2.x - h*(other.o.y - o.y)/dis, p2.y + h*(other.o.x - o.x)/dis);
    v.push_back(p3);
    v.push_back(p4);
    return make_pair(2, v);
}

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

ld intersection_area(circle c2) {
    ld l = distance(o, c2.o);
    if(l >= r + c2.r) return 0;
    else if(c2.r >= l + r) return S();
    else if(r >= l + c2.r) return c2.S();
    return f(l, r, c2.r) + f(l, c2.r, r);
}
};

```

## 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  $l_1$  and  $l_2$  iff  $l_1^*$  and  $l_2^*$  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.  $l_i \cap l_j$  is a vertex of lower envelope  $\iff (l_i^*, l_j^*)$  is an edge of upper hull in dual

## 1.10 Delaunay $O(n \log^2 n)$

```

#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<pii>::iterator it = edges.lower_bound(pii(key, -1));
    if (it == edges.end() || it->first != key)
        return;
    set<pii>::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(pii(v[i], i));
    random_shuffle(points.begin(), points.end());
    n = points.size();
    points.push_back(pii(point(INF, INF), n));
    points.push_back(pii(point(-INF * 3, INF), n + 1));
    points.push_back(pii(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 $O(n^4)$

```

// 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[u]][v]);
        }
    }
    GomoryHu()
    {
        clear();
    }
};

```

## 2.4 Directed minimum spanning tree $O(m \log n)$

```

/*
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(m log n)
*/

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

```

```

const int INF = 2e7;

struct MinimumAborescence
{
    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;
}
};

```

```

/*
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 MinimumAborescence
{
    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
                aborescence
                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;
                }
            }

```

## 2.5 Directed minimum spanning tree $O(nm)$

```

    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 sdом[MAXN], par[MAXN], idом[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();
            sdом[i] = idом[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 (sdом[label[dsu[v]]] < sdом[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];
            sdом[v] = min(sdом[v], sdом[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 (sdом[u] == sdом[w])
                idом[u] = sdом[u];
            else
                idом[u] = w;
        }
        if (v > 0)
            merge(par[v], v);
    }
    for (int v = 1; v < n; v++)
    {
        if (idом[v] != sdом[v])
            idом[v] = idом[idом[v]];
        tree[rev[v]].push_back(rev[idом[v]]);
        tree[rev[idом[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_feasible()) 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

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

### 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 each edge  $(v \rightarrow u)$  and weight  $w$ :

$X_u - X_v \leq w$

Flow:

maximize  $\Sigma f_{out}$  (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 each edge  $(v \rightarrow u)$  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 Duality of LP

primal: Maximize  $c^T x$  subject to  $Ax \leq b, x \geq 0$

dual: Minimize  $b^T y$  subject to  $A^T y \geq c, y \geq 0$

### 3.9 Extended catalan

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

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

### 3.10 Find polynomial from it's points

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

### 3.11 Number of primes

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

### 3.12 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

### 3.13 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

### 3.14 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

### 3.15 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

$[n]$  — Stirling numbers of the first kind; number of permutations of  $n$  elements with  $k$  cycles

$$[n+1] = n[n] + [n-1]$$

$$(x)_n = x(x-1) \cdots x-n+1 = \sum_{k=0}^n (-1)^{n-k} [k] x^k$$

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

$$\{n+1\} = k\{n\} + \{n-1\}$$

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

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

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

## Binomial transform

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

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

## 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

$$a_0, a_1, \dots, a_n, \dots \text{ is } A(x) = \sum_{n=0}^{\infty} a_n x^n$$

Exponential generating function (e.g.f.) for

$$\text{sequence } a_0, a_1, \dots, a_n, \dots \text{ is } A(x) = \sum_{n=0}^{\infty} a_n x^n$$

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

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

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

## 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

$$B_{k+1}(x) = (-B_k(x)^2 A(x) + 2B_k(x)) \bmod x^{2^{k+1}}$$

## 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  $k$ -dimensional 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
```