

# LalCheetah ICPC Team Notebook (2016-17)

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## 1 Combinatorial optimization

### 1.1 Sparse max-flow(aka Modified Ford Fulkerson)

```
// Adjacency list implementation of Dinic's blocking flow
// algorithm.
// This is very fast in practice, and only loses to push-
// relabel flow.
//
// Running time:
// O(|V|^2 |E|)
//
// INPUT:
// - graph, constructed using AddEdge()
// - source and sink
//
// OUTPUT:
// - maximum flow value
// - To obtain actual flow values, look at edges with
//   capacity > 0
//   (zero capacity edges are residual edges).
//
#include<cstdio>
#include<vector>
#include<queue>
using namespace std;
```

```
typedef long long LL;

struct Edge {
    int u, v;
    LL cap, flow;
    Edge() {}
    Edge(int u, int v, LL cap): u(u), v(v), cap(cap), flow
        (0) {}
};

struct Dinic {
    int N;
    vector<Edge> E;
    vector<vector<int>> g;
    vector<int> d, pt;

    Dinic(int N): N(N), E(0), g(N), d(N), pt(N) {}

    void AddEdge(int u, int v, LL cap) {
        if (u != v) {
            E.emplace_back(Edge(u, v, cap));
            g[u].emplace_back(E.size() - 1);
            E.emplace_back(Edge(v, u, 0));
            g[v].emplace_back(E.size() - 1);
        }
    }

    bool BFS(int S, int T) {
        queue<int> q({S});
        fill(d.begin(), d.end(), N + 1);
        d[S] = 0;
        while (!q.empty()) {
            int u = q.front(); q.pop();
            if (u == T) break;
            for (int k: g[u]) {
                Edge &e = E[k];
                if (e.flow < e.cap && d[e.v] > d[e.u] + 1) {
                    d[e.v] = d[e.u] + 1;
                    q.emplace(e.v);
                }
            }
        }
        return d[T] != N + 1;
    }

    LL DFS(int u, int T, LL flow = -1) {
        if (u == T || flow == 0) return flow;
        for (int &i = pt[u]; i < g[u].size(); ++i) {
            Edge &e = E[g[u][i]];
            Edge &oe = E[g[u][i]^1];
            if (d[e.v] == d[e.u] + 1) {
                LL amt = e.cap - e.flow;
                if (flow != -1 && amt > flow) amt = flow;
                if (LL pushed = DFS(e.v, T, amt)) {
                    e.flow += pushed;
                    oe.flow -= pushed;
                    return pushed;
                }
            }
        }
        return 0;
    }

    LL MaxFlow(int S, int T) {
        LL total = 0;
        while (BFS(S, T)) {
            fill(pt.begin(), pt.end(), 0);
            while (LL flow = DFS(S, T))
                total += flow;
        }
        return total;
    }
};

// BEGIN CUT
// The following code solves SPOJ problem #4110: Fast
// Maximum Flow (FASTFLOW)

int main()
{
    int N, E;
    scanf("%d%d", &N, &E);
    Dinic dinic(N);
    for(int i = 0; i < E; i++)
    {
```

```
        int u, v;
        LL cap;
        scanf("%d%d%d", &u, &v, &cap);
        dinic.AddEdge(u - 1, v - 1, cap);
        dinic.AddEdge(v - 1, u - 1, cap);
    }
    printf("%lld\n", dinic.MaxFlow(0, N - 1));
    return 0;
}

// END CUT

1.2 Global min-cut

// Adjacency matrix implementation of Stoer-Wagner min
// cut algorithm.
//
// Running time:
// O(|V|^3)
//
// INPUT:
// - graph, constructed using AddEdge()
//
// OUTPUT:
// - (min cut value, nodes in half of min cut)
//
#include <cmath>
#include <vector>
#include <iostream>

using namespace std;

typedef vector<int> VI;
typedef vector<VI> VVI;

const int INF = 1000000000;

pair<int, VI> GetMinCut(VVI &weights) {
    int N = weights.size();
    VI used(N), cut, best_cut;
    int best_weight = -1;

    for (int phase = N-1; phase >= 0; phase--) {
        VI w = weights[0];
        VI added = used;
        int prev, last = 0;
        for (int i = 0; i < phase; i++) {
            prev = last;
            last = -1;
            for (int j = 1; j < N; j++)
                if (!added[j] && (last == -1 || w[j] > w[last]))
                    last = j;
            if (i == phase-1) {
                for (int j = 0; j < N; j++) weights[prev][j] +=
                    weights[last][j];
                for (int j = 0; j < N; j++) weights[j][prev] =
                    weights[prev][j];
                used[last] = true;
                cut.push_back(last);
                if (best_weight == -1 || w[last] < best_weight) {
                    best_cut = cut;
                    best_weight = w[last];
                }
            } else {
                for (int j = 0; j < N; j++)
                    w[j] += weights[last][j];
                added[last] = true;
            }
        }
        return make_pair(best_weight, best_cut);
    }
}

// BEGIN CUT
// The following code solves UVA problem #10989: Bomb,
// Divide and Conquer

int main() {
    int N;
    cin >> N;
    for (int i = 0; i < N; i++) {
```

```

int n, m;
cin >> n >> m;
VVI weights(n, VI(n));
for (int j = 0; j < m; j++) {
    int a, b, c;
    cin >> a >> b >> c;
    weights[a-1][b-1] = weights[b-1][a-1] = c;
}
pair<int, VI> res = GetMinCut(weights);
cout << "Case #" << i+1 << ": " << res.first << endl;
}
// END CUT

```

## 2 Geometry

### 2.1 Convex hull

```

// Compute the 2D convex hull of a set of points using
// the monotone chain
// algorithm. Eliminate redundant points from the hull
// if REMOVE_REDUNDANT is
// #defined.
//
// Running time: O(n log n)
//
// INPUT: a vector of input points, unordered.
// OUTPUT: a vector of points in the convex hull,
// counterclockwise, starting
// with bottommost/leftmost point

#include <cstdio>
#include <cassert>
#include <vector>
#include <algorithm>
#include <cmath>
// BEGIN CUT
#include <map>
// END CUT

using namespace std;

#define REMOVE_REDUNDANT

typedef double T;
const T EPS = 1e-7;
struct PT {
    T x, y;
    PT() {}
    PT(T x, T y) : x(x), y(y) {}
    bool operator<(const PT &rhs) const { return make_pair(
        y, x) < make_pair(rhs.y, rhs.x); }
    bool operator==(const PT &rhs) const { return make_pair(
        y, x) == make_pair(rhs.y, rhs.x); }
};

T cross(PT p, PT q) { return p.x*q.y-p.y*q.x; }
T area2(PT a, PT b, PT c) { return cross(a,b) + cross(b,c)
    + cross(c,a); }

#ifdef REMOVE_REDUNDANT
bool between(const PT &a, const PT &b, const PT &c) {
    return (fabs(area2(a,b,c)) < EPS && (a.x-b.x)*(c.x-b.x)
        <= 0 && (a.y-b.y)*(c.y-b.y) <= 0);
}
#endif

void ConvexHull(vector<PT> &pts) {
    sort(pts.begin(), pts.end());
    pts.erase(unique(pts.begin(), pts.end(), pts.end()), pts.end());
    vector<PT> up, dn;
    for (int i = 0; i < pts.size(); i++) {
        while (up.size() > 1 && area2(up[up.size()-2], up.
            back(), pts[i]) >= 0) up.pop_back();
        while (dn.size() > 1 && area2(dn[dn.size()-2], dn.
            back(), pts[i]) <= 0) dn.pop_back();
        up.push_back(pts[i]);
    }

```

```

        dn.push_back(pts[i]);
    }
    pts = dn;
    for (int i = (int) up.size() - 2; i >= 1; i--) pts.
        push_back(up[i]);
#ifdef REMOVE_REDUNDANT
    if (pts.size() <= 2) return;
    dn.clear();
    dn.push_back(pts[0]);
    dn.push_back(pts[1]);
    for (int i = 2; i < pts.size(); i++) {
        if (between(dn[dn.size()-2], dn[dn.size()-1], pts[i])
            ) dn.pop_back();
        dn.push_back(pts[i]);
    }
    if (dn.size() >= 3 && between(dn.back(), dn[0], dn[1]))
        {
            dn[0] = dn.back();
            dn.pop_back();
        }
    pts = dn;
#endif
}

// BEGIN CUT
// The following code solves SPOJ problem #26: Build the
// Fence (BSHEEP)

int main() {
    int t;
    scanf("%d", &t);
    for (int caseno = 0; caseno < t; caseno++) {
        int n;
        scanf("%d", &n);
        vector<PT> v(n);
        for (int i = 0; i < n; i++) scanf("%lf%lf", &v[i].x,
            &v[i].y);
        vector<PT> h(v);
        map<PT,int> index;
        for (int i = n-1; i >= 0; i--) index[v[i]] = i+1;
        ConvexHull(h);

        double len = 0;
        for (int i = 0; i < h.size(); i++) {
            double dx = h[i].x - h[(i+1)%h.size()].x;
            double dy = h[i].y - h[(i+1)%h.size()].y;
            len += sqrt(dx*dx+dy*dy);
        }

        if (caseno > 0) printf("\n");
        printf("%.2f\n", len);
        for (int i = 0; i < h.size(); i++) {
            if (i > 0) printf(" ");
            printf("%d", index[h[i]]);
        }
        printf("\n");
    }
}

// END CUT

```

### 2.2 Miscellaneous geometry

```

// C++ routines for computational geometry.

#include <iostream>
#include <vector>
#include <cmath>
#include <cassert>

using namespace std;

double INF = 1e100;
double EPS = 1e-12;

struct PT {
    double x, y;
    PT() {}
    PT(double x, double y) : x(x), y(y) {}
    PT(const PT &p) : x(p.x), y(p.y) {}

```

```

    PT operator + (const PT &p) const { return PT(x+p.x, y
        +p.y); }
    PT operator - (const PT &p) const { return PT(x-p.x, y
        -p.y); }
    PT operator * (double c) const { return PT(x*c, y
        *c); }
    PT operator / (double c) const { return PT(x/c, y
        /c); }
};

double dot(PT p, PT q) { return p.x*q.x+p.y*q.y; }
double dist2(PT p, PT q) { return dot(p-q,p-q); }
double cross(PT p, PT q) { return p.x*q.y-p.y*q.x; }
ostream &operator<<(ostream &os, const PT &p) {
    os << "(" << p.x << ", " << p.y << ")";
}

// rotate a point CCW or CW around the origin
PT RotateCCW90(PT p) { return PT(-p.y,p.x); }
PT RotateCW90(PT p) { return PT(p.y,-p.x); }
PT RotateCCW(PT p, double t) {
    return PT(p.x*cos(t)-p.y*sin(t), p.x*sin(t)+p.y*cos(t))
    ;
}

// project point c onto line through a and b
// assuming a != b
PT ProjectPointLine(PT a, PT b, PT c) {
    return a + (b-a)*dot(c-a, b-a)/dot(b-a, b-a);
}

// project point c onto line segment through a and b
PT ProjectPointSegment(PT a, PT b, PT c) {
    double r = dot(b-a,b-a);
    if (fabs(r) < EPS) return a;
    r = dot(c-a, b-a)/r;
    if (r < 0) return a;
    if (r > 1) return b;
    return a + (b-a)*r;
}

// compute distance from c to segment between a and b
double DistancePointSegment(PT a, PT b, PT c) {
    return sqrt(dist2(c, ProjectPointSegment(a, b, c)));
}

// compute distance between point (x,y,z) and plane ax+by
// +cz=d
double DistancePointPlane(double x, double y, double z,
    double a, double b, double c,
    double d)
{
    return fabs(a*x+b*y+c*z-d)/sqrt(a*a+b*b+c*c);
}

// determine if lines from a to b and c to d are parallel
// or collinear
bool LinesParallel(PT a, PT b, PT c, PT d) {
    return fabs(cross(b-a, c-d)) < EPS;
}

bool LinesCollinear(PT a, PT b, PT c, PT d) {
    return LinesParallel(a, b, c, d)
        && fabs(cross(a-b, a-c)) < EPS
        && fabs(cross(c-d, c-a)) < EPS;
}

// determine if line segment from a to b intersects with
// line segment from c to d
bool SegmentsIntersect(PT a, PT b, PT c, PT d) {
    if (LinesCollinear(a, b, c, d)) {
        if (dist2(a, c) < EPS || dist2(a, d) < EPS ||
            dist2(b, c) < EPS || dist2(b, d) < EPS) return true
            ;
        if (dot(c-a, c-b) > 0 && dot(d-a, d-b) > 0 && dot(c-b
            , d-b) > 0)
            return false;
        return true;
    }
    if (cross(d-a, b-a) * cross(c-a, b-a) > 0) return false
        ;
    if (cross(a-c, d-c) * cross(b-c, d-c) > 0) return false
        ;
    return true;
}

```

```

// compute intersection of line passing through a and b
// with line passing through c and d, assuming that
// unique
// intersection exists; for segment intersection, check
// if
// segments intersect first
PT ComputeLineIntersection(PT a, PT b, PT c, PT d) {
    b=b-a; d=d-c; c=c-a;
    assert(dot(b, b) > EPS && dot(d, d) > EPS);
    return a + b*cross(c, d)/cross(b, d);
}

// compute center of circle given three points
PT ComputeCircleCenter(PT a, PT b, PT c) {
    b=(a+b)/2;
    c=(a+c)/2;
    return ComputeLineIntersection(b, b+RotateCW90(a-b), c,
    c+RotateCW90(a-c));
}

// determine if point is in a possibly non-convex polygon
// (by William
// Randolph Franklin); returns 1 for strictly interior
// points, 0 for
// strictly exterior points, and 0 or 1 for the remaining
// points.
// Note that it is possible to convert this into an *
// exact* test using
// integer arithmetic by taking care of the division
// appropriately
// (making sure to deal with signs properly) and then by
// writing exact
// tests for checking point on polygon boundary
bool PointInPolygon(const vector<PT> &p, PT q) {
    bool c = 0;
    for (int i = 0; i < p.size(); i++) {
        int j = (i+1) % p.size();
        if ((p[i].y <= q.y && q.y < p[j].y ||
            p[j].y <= q.y && q.y < p[i].y) &&
            q.x < p[i].x + (p[j].x - p[i].x) * (q.y - p[i].y) /
            (p[j].y - p[i].y))
            c = !c;
    }
    return c;
}

// determine if point is on the boundary of a polygon
bool PointOnPolygon(const vector<PT> &p, PT q) {
    for (int i = 0; i < p.size(); i++)
        if (dist2(ProjectPointSegment(p[i], p[(i+1)%p.size()]
        ), q), q) < EPS)
            return true;
    return false;
}

// compute intersection of line through points a and b
// with
// circle centered at c with radius r > 0
vector<PT> CircleLineIntersection(PT a, PT b, PT c,
    double r) {
    vector<PT> ret;
    b = b-a;
    a = a-c;
    double A = dot(b, b);
    double B = dot(a, b);
    double C = dot(a, a) - r*r;
    double D = B*B - A*C;
    if (D < -EPS) return ret;
    ret.push_back(c+a+b*(-B+sqrt(D+EPS))/A);
    if (D > EPS)
        ret.push_back(c+a+b*(-B-sqrt(D))/A);
    return ret;
}

// compute intersection of circle centered at a with
// radius r
// with circle centered at b with radius R
vector<PT> CircleCircleIntersection(PT a, PT b, double r,
    double R) {
    vector<PT> ret;
    double d = sqrt(dist2(a, b));
    if (d > r+R || d+min(r, R) < max(r, R)) return ret;
    double x = (d*d-R*R+r*r)/(2*d);
    double y = sqrt(r*r-x*x);
    PT v = (b-a)/d;
    ret.push_back(a+v*x + RotateCCW90(v)*y);
    if (y > 0)
        ret.push_back(a+v*x - RotateCCW90(v)*y);
    return ret;
}

// This code computes the area or centroid of a (possibly
// nonconvex)
// polygon, assuming that the coordinates are listed in a
// clockwise or
// counterclockwise fashion. Note that the centroid is
// often known as
// the "center of gravity" or "center of mass".
double ComputeSignedArea(const vector<PT> &p) {
    double area = 0;
    for(int i = 0; i < p.size(); i++) {
        int j = (i+1) % p.size();
        area += p[i].x*p[j].y - p[j].x*p[i].y;
    }
    return area / 2.0;
}

double ComputeArea(const vector<PT> &p) {
    return fabs(ComputeSignedArea(p));
}

PT ComputeCentroid(const vector<PT> &p) {
    PT c(0,0);
    double scale = 6.0 * ComputeSignedArea(p);
    for (int i = 0; i < p.size(); i++) {
        int j = (i+1) % p.size();
        c = c + (p[i]+p[j])*(p[i].x*p[j].y - p[j].x*p[i].y);
    }
    return c / scale;
}

// tests whether or not a given polygon (in CW or C CW
// order) is simple
bool IsSimple(const vector<PT> &p) {
    for (int i = 0; i < p.size(); i++) {
        for (int k = i+1; k < p.size(); k++) {
            int j = (i+1) % p.size();
            int l = (k+1) % p.size();
            if (i == l || j == k) continue;
            if (SegmentsIntersect(p[i], p[j], p[k], p[l]))
                return false;
        }
    }
    return true;
}

int main() {
    // expected: (-5,2)
    cerr << RotateCCW90(PT(2,5)) << endl;

    // expected: (5,-2)
    cerr << RotateCW90(PT(2,5)) << endl;

    // expected: (-5,2)
    cerr << RotateCCW(PT(2,5),M_PI/2) << endl;

    // expected: (5,2)
    cerr << ProjectPointLine(PT(-5,-2), PT(10,4), PT(3,7))
    << endl;

    // expected: (5,2) (7.5,3) (2.5,1)
    cerr << ProjectPointSegment(PT(-5,-2), PT(10,4), PT
    (3,7)) << " "
    << ProjectPointSegment(PT(7.5,3), PT(10,4), PT
    (3,7)) << " "
    << ProjectPointSegment(PT(-5,-2), PT(2.5,1), PT
    (3,7)) << endl;

    // expected: 6.78903
    cerr << DistancePointPlane(4,-4,3,2,-2,5,-8) << endl;

    // expected: 1 0 1
    cerr << LinesParallel(PT(1,1), PT(3,5), PT(2,1), PT
    (4,5)) << " "
    << LinesParallel(PT(1,1), PT(3,5), PT(2,0), PT
    (4,5)) << " "
    << LinesParallel(PT(1,1), PT(3,5), PT(5,9), PT
    (7,13)) << endl;

    // expected: 0 0 1
    cerr << LinesCollinear(PT(1,1), PT(3,5), PT(2,1), PT
    (4,5)) << " "
    << LinesCollinear(PT(1,1), PT(3,5), PT(2,0), PT
    (4,5)) << " "
    << LinesCollinear(PT(1,1), PT(3,5), PT(5,9), PT
    (7,13)) << endl;

    // expected: 1 1 1 0
    cerr << SegmentsIntersect(PT(0,0), PT(2,4), PT(3,1), PT
    (-1,3)) << " "
    << SegmentsIntersect(PT(0,0), PT(2,4), PT(4,3), PT
    (0,5)) << " "
    << SegmentsIntersect(PT(0,0), PT(2,4), PT(2,-1),
    PT(-2,1)) << " "
    << SegmentsIntersect(PT(0,0), PT(2,4), PT(5,5), PT
    (1,7)) << endl;

    // expected: (1,2)
    cerr << ComputeLineIntersection(PT(0,0), PT(2,4), PT
    (3,1), PT(-1,3)) << endl;

    // expected: (1,1)
    cerr << ComputeCircleCenter(PT(-3,4), PT(6,1), PT(4,5))
    << endl;

    vector<PT> v;
    v.push_back(PT(0,0));
    v.push_back(PT(5,0));
    v.push_back(PT(5,5));
    v.push_back(PT(0,5));

    // expected: 1 1 1 0 0
    cerr << PointInPolygon(v, PT(2,2)) << " "
    << PointInPolygon(v, PT(2,0)) << " "
    << PointInPolygon(v, PT(0,2)) << " "
    << PointInPolygon(v, PT(5,2)) << " "
    << PointInPolygon(v, PT(2,5)) << endl;

    // expected: 0 1 1 1 1
    cerr << PointOnPolygon(v, PT(2,2)) << " "
    << PointOnPolygon(v, PT(2,0)) << " "
    << PointOnPolygon(v, PT(0,2)) << " "
    << PointOnPolygon(v, PT(5,2)) << " "
    << PointOnPolygon(v, PT(2,5)) << endl;

    // expected: (1,6)
    // (5,4) (4,5)
    // blank line
    // (4,5) (5,4)
    // blank line
    // (4,5) (5,4)
    vector<PT> u = CircleLineIntersection(PT(0,6), PT(2,6),
    PT(1,1), 5);
    for (int i = 0; i < u.size(); i++) cerr << u[i] << " ";
    cerr << endl;
    u = CircleLineIntersection(PT(0,9), PT(9,0), PT(1,1),
    5);
    for (int i = 0; i < u.size(); i++) cerr << u[i] << " ";
    cerr << endl;
    u = CircleCircleIntersection(PT(1,1), PT(10,10), 5, 5);
    for (int i = 0; i < u.size(); i++) cerr << u[i] << " ";
    cerr << endl;
    u = CircleCircleIntersection(PT(1,1), PT(8,8), 5, 5);
    for (int i = 0; i < u.size(); i++) cerr << u[i] << " ";
    cerr << endl;
    u = CircleCircleIntersection(PT(1,1), PT(4.5,4.5), 10,
    sqrt(2.0)/2.0);
    for (int i = 0; i < u.size(); i++) cerr << u[i] << " ";
    cerr << endl;
    u = CircleCircleIntersection(PT(1,1), PT(4.5,4.5), 5,
    sqrt(2.0)/2.0);
    for (int i = 0; i < u.size(); i++) cerr << u[i] << " ";
    cerr << endl;

    // area should be 5.0
    // centroid should be (1.1666666, 1.1666666)
    PT pa[] = { PT(0,0), PT(5,0), PT(1,1), PT(0,5) };
    vector<PT> p(pa, pa+4);
    PT c = ComputeCentroid(p);
    cerr << "Area: " << ComputeArea(p) << endl;
    cerr << "Centroid: " << c << endl;

    return 0;
}

```

```
}
```

## 3 Numerical algorithms

### 3.1 Fast Fourier transform

```
#include <cassert>
#include <cstdio>
#include <cmath>

struct cpx
{
    cpx() {}
    cpx(double aa):a(aa),b(0) {}
    cpx(double aa, double bb):a(aa),b(bb) {}
    double a;
    double b;
    double modsq(void) const
    {
        return a * a + b * b;
    }
    cpx bar(void) const
    {
        return cpx(a, -b);
    }
};

cpx operator +(cpx a, cpx b)
{
    return cpx(a.a + b.a, a.b + b.b);
}

cpx operator *(cpx a, cpx b)
{
    return cpx(a.a * b.a - a.b * b.b, a.a * b.b + a.b * b.a);
}

cpx operator /(cpx a, cpx b)
{
    cpx r = a * b.bar();
    return cpx(r.a / b.modsq(), r.b / b.modsq());
}

cpx EXP(double theta)
{
    return cpx(cos(theta), sin(theta));
}

const double two_pi = 4 * acos(0);

// in:    input array
// out:    output array
// step:  {SET TO 1} (used internally)
// size:   length of the input/output (MUST BE A POWER OF
//         2)
// dir:    either plus or minus one (direction of the FFT)
// RESULT: out[k] = \sum_{j=0}^{size-1} in[j] * exp(dir
//         * 2pi * i * j * k / size)
void FFT(cpx *in, cpx *out, int step, int size, int dir)
{
    if(size < 1) return;
    if(size == 1)
    {
        out[0] = in[0];
        return;
    }
    FFT(in, out, step * 2, size / 2, dir);
    FFT(in + step, out + size / 2, step * 2, size / 2, dir);
    for(int i = 0; i < size / 2; i++)
    {
        cpx even = out[i];
        cpx odd = out[i + size / 2];
        out[i] = even + EXP(dir * two_pi * i / size) * odd;
        out[i + size / 2] = even + EXP(dir * two_pi * (i +
            size / 2) / size) * odd;
    }
}
```

```
// Usage:
// f[0..N-1] and g[0..N-1] are numbers
// Want to compute the convolution h, defined by
// h[n] = sum of f[k]g[n-k] (k = 0, ..., N-1).
// Here, the index is cyclic; f[-1] = f[N-1], f[-2] = f[N-2], etc.
// Let F[0..N-1] be FFT(f), and similarly, define G and H.
// The convolution theorem says H[n] = F[n]G[n] (element-wise product).
// To compute h[] in O(N log N) time, do the following:
// 1. Compute F and G (pass dir = 1 as the argument).
// 2. Get H by element-wise multiplying F and G.
// 3. Get h by taking the inverse FFT (use dir = -1 as the argument)
// and *dividing by N*. DO NOT FORGET THIS SCALING FACTOR.

int main(void)
{
    printf("If rows come in identical pairs, then everything works.\n");

    cpx a[8] = {0, 1, cpx(1,3), cpx(0,5), 1, 0, 2, 0};
    cpx b[8] = {1, cpx(0,-2), cpx(0,1), 3, -1, -3, 1, -2};
    cpx A[8];
    cpx B[8];
    FFT(a, A, 1, 8, 1);
    FFT(b, B, 1, 8, 1);

    for(int i = 0; i < 8; i++)
    {
        printf("%7.2lf%7.2lf", A[i].a, A[i].b);
    }
    printf("\n");
    for(int i = 0; i < 8; i++)
    {
        cpx Ai(0,0);
        for(int j = 0; j < 8; j++)
        {
            Ai = Ai + a[j] * EXP(j * i * two_pi / 8);
        }
        printf("%7.2lf%7.2lf", Ai.a, Ai.b);
    }
    printf("\n");
    cpx AB[8];
    for(int i = 0; i < 8; i++)
    {
        AB[i] = A[i] * B[i];
    }
    cpx aconvb[8];
    FFT(AB, aconvb, 1, 8, -1);
    for(int i = 0; i < 8; i++)
    {
        aconvb[i] = aconvb[i] / 8;
    }
    for(int i = 0; i < 8; i++)
    {
        printf("%7.2lf%7.2lf", aconvb[i].a, aconvb[i].b);
    }
    printf("\n");
    for(int i = 0; i < 8; i++)
    {
        cpx aconvbi(0,0);
        for(int j = 0; j < 8; j++)
        {
            aconvbi = aconvbi + a[j] * b[(8 + i - j) % 8];
        }
        printf("%7.2lf%7.2lf", aconvbi.a, aconvbi.b);
    }
    printf("\n");
    return 0;
}
```

## 4 Graph algorithms

### 4.1 Fast Dijkstra's algorithm

```
// Implementation of Dijkstra's algorithm using adjacency
```

```
lists
// and priority queue for efficiency.
//
// Running time: O(|E| log |V|)

#include <queue>
#include <cstdio>

using namespace std;
const int INF = 2000000000;
typedef pair<int, int> PII;

int main() {
    int N, s, t;
    scanf("%d%d%d", &N, &s, &t);
    vector<vector<PII>> edges(N);
    for (int i = 0; i < N; i++) {
        int M;
        scanf("%d", &M);
        for (int j = 0; j < M; j++) {
            int vertex, dist;
            scanf("%d%d", &vertex, &dist);
            edges[i].push_back(make_pair(dist, vertex)); // note order of arguments here
        }
    }

    // use priority queue in which top element has the "smallest" priority
    priority_queue<PII, vector<PII>, greater<PII>> Q;
    vector<int> dist(N, INF), dad(N, -1);
    Q.push(make_pair(0, s));
    dist[s] = 0;
    while (!Q.empty()) {
        PII p = Q.top();
        Q.pop();
        int here = p.second;
        if (here == t) break;
        if (dist[here] != p.first) continue;
        for (vector<PII>::iterator it = edges[here].begin(); it != edges[here].end(); it++) {
            if (dist[here] + it->first < dist[it->second]) {
                dist[it->second] = dist[here] + it->first;
                dad[it->second] = here;
                Q.push(make_pair(dist[it->second], it->second));
            }
        }
    }
    printf("%d\n", dist[t]);
    if (dist[t] < INF)
        for (int i = t; i != -1; i = dad[i])
            printf("%d%c", i, (i == s ? '\n' : ' '));
    return 0;
}

/*
Sample input:
5 0 4
2 1 2 3 1
2 2 4 4 5
3 1 4 3 3 4 1
2 0 1 2 3
2 1 5 2 1

Expected:
5
4 2 3 0
*/
```

## 4.2 Strongly connected components

```
#include<memory.h>
struct edge{int e, nxt;};
int V, E;
edge e[MAXE], er[MAXE];
int sp[MAXV], spr[MAXV];
int group_cnt, group_num[MAXV];
bool v[MAXV];
int stk[MAXV];
void fill_forward(int x)
{
    int i;
    v[x]=true;
    for(i=sp[x];i;i=e[i].nxt) if(!v[e[i].e]) fill_forward(e[i].e);
    stk[++stk[0]]=x;
}
void fill_backward(int x)
{
    int i;
    v[x]=false;
    group_num[x]=group_cnt;
    for(i=spr[x];i;i=er[i].nxt) if(v[er[i].e])
        fill_backward(er[i].e);
}
void add_edge(int v1, int v2) //add edge v1->v2
{
    e[++E].e=v2; e[E].nxt=sp[v1]; sp[v1]=E;
    er[E].e=v1; er[E].nxt=spr[v2]; spr[v2]=E;
}
void SCC()
{
    int i;
    stk[0]=0;
    memset(v, false, sizeof(v));
    for(i=1;i<=V;i++) if(!v[i]) fill_forward(i);
    group_cnt=0;
    for(i=stk[0];i>=1;i--) if(v[stk[i]]){group_cnt++;
        fill_backward(stk[i]);}
}
```

## 4.3 Bellman Ford's algorithm

```
// This function runs the Bellman-Ford algorithm for
// single source
// shortest paths with negative edge weights. The
// function returns
// false if a negative weight cycle is detected.
// Otherwise, the
// function returns true and dist[i] is the length of the
// shortest
// path from start to i.
//
// Running time: O(|V|^3)
//
// INPUT: start, w[i][j] = cost of edge from i to j
// OUTPUT: dist[i] = min weight path from start to i
// prev[i] = previous node on the best path
// from the start node

#include <iostream>
#include <queue>
#include <cmath>
#include <vector>

using namespace std;

typedef double T;
typedef vector<T> VT;
typedef vector<VT> VVT;

typedef vector<int> VI;
typedef vector<VI> VVI;
```

```
bool BellmanFord (const VVT &w, VT &dist, VI &prev, int
start){
    int n = w.size();
    prev = VI(n, -1);
    dist = VT(n, 1000000000);
    dist[start] = 0;

    for (int k = 0; k < n; k++){
        for (int i = 0; i < n; i++){
            for (int j = 0; j < n; j++){
                if (dist[j] > dist[i] + w[i][j]){
                    if (k == n-1) return false;
                    dist[j] = dist[i] + w[i][j];
                    prev[j] = i;
                }
            }
        }
    }

    return true;
}
```

## 5 Miscellaneous

### 5.1 C++ template

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

const long long Mod = 1e9 + 7;
const long long Inf = 1e18;
const long long Lim = 1e5 + 1e3;
const double eps = 1e-10;

typedef long long ll;
typedef vector<int> vi;
typedef vector<ll> vll;
typedef pair<int, int> pii;
typedef pair<ll, ll> pll;
typedef vector<pll> vll;

#define F first
#define S second
#define uint unsigned int
#define mp make_pair
#define pb push_back
#define pi 2*acos(0.0)
#define rep2(i,b,a) for(ll i = (ll)b, _a = (ll)a; i >= _a
; i--)
#define repl(i,a,b) for(ll i = (ll)a, _b = (ll)b; i <= _b
; i++)
#define rep(i,n) for(ll i = 0, _n = (ll)n ; i < _n ; i++)
#define mem(a,val) memset(a,val,sizeof(a))
#define fast ios_base::sync_with_stdio(false),cin.tie(0),
cout.tie(0);
```

### 5.2 C++ input/output

```
#include <iostream>
#include <iomanip>

using namespace std;

int main()
{
    // Ouput a specific number of digits past the decimal
    // point,
    // in this case 5
    cout.setf(ios::fixed); cout << setprecision(5);
    cout << 100.0/7.0 << endl;
    cout.unsetf(ios::fixed);

    // Output the decimal point and trailing zeros
```

```
cout.setf(ios::showpoint);
cout << 100.0 << endl;
cout.unsetf(ios::showpoint);

// Output a '+' before positive values
cout.setf(ios::showpos);
cout << 100 << " " << -100 << endl;
cout.unsetf(ios::showpos);

// Output numerical values in hexadecimal
cout << hex << 100 << " " << 1000 << " " << 10000 <<
dec << endl;
}
```

### 5.3 Longest increasing subsequence

```
// Given a list of numbers of length n, this routine
// extracts a
// longest increasing subsequence.
//
// Running time: O(n log n)
//
// INPUT: a vector of integers
// OUTPUT: a vector containing the longest increasing
// subsequence
```

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

using namespace std;

typedef vector<int> VI;
typedef pair<int,int> PII;
typedef vector<PII> VPII;

#define STRICTLY_INCREASNG

VI LongestIncreasingSubsequence(VI v) {
    VPII best;
    VI dad(v.size(), -1);

    for (int i = 0; i < v.size(); i++) {
#ifdef STRICTLY_INCREASNG
        PII item = make_pair(v[i], 0);
        VPII::iterator it = lower_bound(best.begin(), best.
            end(), item);
        item.second = i;
#else
        PII item = make_pair(v[i], i);
        VPII::iterator it = upper_bound(best.begin(), best.
            end(), item);
#endif
        if (it == best.end()) {
            dad[i] = (best.size() == 0 ? -1 : best.back().
                second);
            best.push_back(item);
        } else {
            dad[i] = dad[it->second];
            *it = item;
        }
    }

    VI ret;
    for (int i = best.back().second; i >= 0; i = dad[i])
        ret.push_back(v[i]);
    reverse(ret.begin(), ret.end());
    return ret;
}
```

### 5.4 Knuth-Morris-Pratt

```
/*
Searches for the string w in the string s (of length k).
Returns the
```

```

0-based index of the first match (k if no match is found)
. Algorithm
runs in O(k) time.
*/

#include <iostream>
#include <string>
#include <vector>

using namespace std;

typedef vector<int> VI;

void buildTable(string& w, VI& t)
{
    t = VI(w.length());
    int i = 2, j = 0;
    t[0] = -1; t[1] = 0;

    while(i < w.length())
    {
        if(w[i-1] == w[j]) { t[i] = j+1; i++; j++; }
        else if(j > 0) j = t[j];
        else { t[i] = 0; i++; }
    }
}

int KMP(string& s, string& w)
{
    int m = 0, i = 0;
    VI t;

    buildTable(w, t);
    while(m+i < s.length())
    {
        if(w[i] == s[m+i])
        {
            i++;
            if(i == w.length()) return m;
        }
        else
        {
            m += i-t[i];
            if(i > 0) i = t[i];
        }
    }
    return s.length();
}

int main()
{
    string a = (string) "The example above illustrates the
        general technique for assembling "+
        "the table with a minimum of fuss. The principle is
        that of the overall search: "+
        "most of the work was already done in getting to the
        current position, so very "+
        "little needs to be done in leaving it. The only
        minor complication is that the "+
        "logic which is correct late in the string
        erroneously gives non-proper "+
        "substrings at the beginning. This necessitates some
        initialization code.";

    string b = "table";

    int p = KMP(a, b);
    cout << p << ": " << a.substr(p, b.length()) << " " <<
        b << endl;
}

```

## 5.5 Topological sort (C++)

```

// This function uses performs a non-recursive
// topological sort.
//
// Running time: O(|V|^2). If you use adjacency lists (
// vector<map<int>> >),
// the running time is reduced to O(|E|).
//

```

```

// INPUT: w[i][j] = 1 if i should come before j, 0
// otherwise
// OUTPUT: a permutation of 0,...,n-1 (stored in a
// vector)
// which represents an ordering of the nodes
// which is consistent with w
//
// If no ordering is possible, false is returned.

#include <iostream>
#include <queue>
#include <cmath>
#include <vector>

using namespace std;

typedef double T;
typedef vector<T> VT;
typedef vector<VT> VVT;

typedef vector<int> VI;
typedef vector<VI> VVI;

bool TopologicalSort (const VVI &w, VI &order){
    int n = w.size();
    VI parents (n);
    queue<int> q;
    order.clear();

    for (int i = 0; i < n; i++){
        for (int j = 0; j < n; j++){
            if (w[j][i]) parents[i]++;
            if (parents[i] == 0) q.push (i);
        }

        while (q.size() > 0){
            int i = q.front();
            q.pop();
            order.push_back (i);
            for (int j = 0; j < n; j++) if (w[i][j]){
                parents[j]--;
                if (parents[j] == 0) q.push (j);
            }
        }

        return (order.size() == n);
    }
}

```

## 5.6 Fast exponentiation

```

/*
Uses powers of two to exponentiate numbers and matrices.
Calculates
n^k in O(log(k)) time when n is a number. If A is an n x
n matrix,
calculates A^k in O(n^3*log(k)) time.
*/

#include <iostream>
#include <vector>

using namespace std;

typedef double T;
typedef vector<T> VT;
typedef vector<VT> VVT;

T power(T x, int k) {
    T ret = 1;

    while(k) {
        if(k & 1) ret *= x;
        k >>= 1; x *= x;
    }
    return ret;
}

VVT multiply(VVT& A, VVT& B) {
    int n = A.size(), m = A[0].size(), k = B[0].size();
}

```

```

VVT C(n, VT(k, 0));

for(int i = 0; i < n; i++)
    for(int j = 0; j < k; j++)
        for(int l = 0; l < m; l++)
            C[i][j] += A[i][l] * B[l][j];

return C;
}

VVT power(VVT& A, int k) {
    int n = A.size();
    VVT ret(n, VT(n)), B = A;
    for(int i = 0; i < n; i++) ret[i][i]=1;

    while(k) {
        if(k & 1) ret = multiply(ret, B);
        k >>= 1; B = multiply(B, B);
    }
    return ret;
}

int main()
{
    /* Expected Output:
    2.37^48 = 9.72569e+17

    376 264 285 220 265
    550 376 529 285 484
    484 265 376 264 285
    285 220 265 156 264
    529 285 484 265 376 */
    double n = 2.37;
    int k = 48;

    cout << n << "^" << k << " = " << power(n, k) << endl;

    double At[5][5] = {
        { 0, 0, 1, 0, 0 },
        { 1, 0, 0, 1, 0 },
        { 0, 0, 0, 0, 1 },
        { 1, 0, 0, 0, 0 },
        { 0, 1, 0, 0, 0 } };

    vector <vector <double>> > A(5, vector <double>(5));
    for(int i = 0; i < 5; i++)
        for(int j = 0; j < 5; j++)
            A[i][j] = At[i][j];

    vector <vector <double>> > Ap = power(A, k);

    cout << endl;
    for(int i = 0; i < 5; i++) {
        for(int j = 0; j < 5; j++)
            cout << Ap[i][j] << " ";
        cout << endl;
    }
}

```

## 5.7 Longest common subsequence

```

/*
Calculates the length of the longest common subsequence
of two vectors.
Backtracks to find a single subsequence or all
subsequences. Runs in
O(m*n) time except for finding all longest common
subsequences, which
may be slow depending on how many there are.
*/

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

using namespace std;

typedef int T;
typedef vector<T> VT;
typedef vector<VT> VVT;

```



```

typedef vector<int> VI;
typedef vector<VI> VVI;

void backtrack(VVI& dp, VT& res, VT& A, VT& B, int i, int j)
{
    if(!i || !j) return;
    if(A[i-1] == B[j-1]) { res.push_back(A[i-1]); backtrack(dp, res, A, B, i-1, j-1); }
    else
    {
        if(dp[i][j-1] >= dp[i-1][j]) backtrack(dp, res, A, B, i, j-1);
        else backtrack(dp, res, A, B, i-1, j);
    }
}

void backtrackall(VVI& dp, set<VT>& res, VT& A, VT& B, int i, int j)
{
    if(!i || !j) { res.insert(VI()); return; }
    if(A[i-1] == B[j-1])
    {
        set<VT> tempres;
        backtrackall(dp, tempres, A, B, i-1, j-1);
        for(set<VT>::iterator it=tempres.begin(); it!=tempres.end(); it++)
        {
            VT temp = *it;
            temp.push_back(A[i-1]);
            res.insert(temp);
        }
    }
    else
    {
        if(dp[i][j-1] >= dp[i-1][j]) backtrackall(dp, res, A, B, i, j-1);
        if(dp[i][j-1] <= dp[i-1][j]) backtrackall(dp, res, A, B, i-1, j);
    }
}

VT LCS(VT& A, VT& B)
{
    VVI dp;
    int n = A.size(), m = B.size();
    dp.resize(n+1);
    for(int i=0; i<=n; i++) dp[i].resize(m+1, 0);

    for(int i=1; i<=n; i++)
        for(int j=1; j<=m; j++)
        {
            if(A[i-1] == B[j-1]) dp[i][j] = dp[i-1][j-1]+1;
            else dp[i][j] = max(dp[i-1][j], dp[i][j-1]);
        }

    VT res;
    backtrack(dp, res, A, B, n, m);
    reverse(res.begin(), res.end());
    return res;
}

set<VT> LCSall(VT& A, VT& B)
{
    VVI dp;
    int n = A.size(), m = B.size();
    dp.resize(n+1);
    for(int i=0; i<=n; i++) dp[i].resize(m+1, 0);
    for(int i=1; i<=n; i++)
        for(int j=1; j<=m; j++)
        {
            if(A[i-1] == B[j-1]) dp[i][j] = dp[i-1][j-1]+1;
            else dp[i][j] = max(dp[i-1][j], dp[i][j-1]);
        }
    set<VT> res;
    backtrackall(dp, res, A, B, n, m);
    return res;
}

int main()
{
    int a[] = { 0, 5, 5, 2, 1, 4, 2, 3 }, b[] = { 5, 2, 4, 3, 2, 1, 2, 1, 3 };
    VI A = VI(a, a+8), B = VI(b, b+9);

```

```

VI C = LCS(A, B);

for(int i=0; i<C.size(); i++) cout << C[i] << " ";
cout << endl << endl;

set<VI> D = LCSall(A, B);
for(set<VI>::iterator it = D.begin(); it != D.end(); it++)
{
    for(int i=0; i<(*it).size(); i++) cout << (*it)[i] << " ";
    cout << endl;
}

```

## 5.8 Miller-Rabin Primality Test (C)

```

// Randomized Primality Test (Miller-Rabin):
// Error rate: 2^(-TRIAL)
// Almost constant time. srand is needed

#include <stdlib.h>
#define EPS 1e-7

typedef long long LL;

LL ModularMultiplication(LL a, LL b, LL m)
{
    LL ret=0, c=a;
    while(b)
    {
        if(b&1) ret=(ret+c)%m;
        b>>=1; c=(c+c)%m;
    }
    return ret;
}

LL ModularExponentiation(LL a, LL n, LL m)
{
    LL ret=1, c=a;
    while(n)
    {
        if(n&1) ret=ModularMultiplication(ret, c, m);
        n>>=1; c=ModularMultiplication(c, c, m);
    }
    return ret;
}

bool Witness(LL a, LL n)
{
    LL u=n-1;
    int t=0;
    while(!(u&1)){u>>=1; t++;}
    LL x0=ModularExponentiation(a, u, n), x1;
    for(int i=1; i<=t; i++)
    {
        x1=ModularMultiplication(x0, x0, n);
        if(x1==1 && x0!=1 && x0!=n-1) return true;
        x0=x1;
    }
    if(x0!=1) return true;
    return false;
}

LL Random(LL n)
{
    LL ret=rand(); ret*=32768;
    ret+=rand(); ret*=32768;
    ret+=rand(); ret*=32768;
    ret+=rand();
    return ret%n;
}

bool IsPrimeFast(LL n, int TRIAL)
{
    while(TRIAL-->0)
    {
        LL a=Random(n-2)+1;
        if(Witness(a, n)) return false;
    }
    return true;
}

```

## 6 Data structures

### 6.1 Suffix array

```

// Suffix array construction in O(L log^2 L) time.
// Routine for
// computing the length of the longest common prefix of
// any two
// suffixes in O(log L) time.
//
// INPUT: string s
//
// OUTPUT: array suffix[] such that suffix[i] = index (
//         from 0 to L-1)
//         of substring s[i...L-1] in the list of sorted
//         suffixes.
//         That is, if we take the inverse of the
//         permutation suffix[],
//         we get the actual suffix array.

#include <vector>
#include <iostream>
#include <string>

using namespace std;

struct SuffixArray {
    const int L;
    string s;
    vector<vector<int>> > P;
    vector<pair<pair<int,int>,int>> > M;

    SuffixArray(const string &s) : L(s.length()), s(s), P
    (1, vector<int>(L, 0)), M(L) {
        for (int i = 0; i < L; i++) P[0][i] = int(s[i]);
        for (int skip = 1, level = 1; skip < L; skip *= 2,
            level++) {
            P.push_back(vector<int>(L, 0));
            for (int i = 0; i < L; i++)
                M[i] = make_pair(make_pair(P[level-1][i], i +
                    skip < L ? P[level-1][i + skip] : -1000), i);
            sort(M.begin(), M.end());
            for (int i = 0; i < L; i++)
                P[level][M[i].second] = (i > 0 && M[i].first == M
                    [i-1].first) ? P[level][M[i-1].second] : i;
        }
    }

    vector<int> GetSuffixArray() { return P.back(); }

    // returns the length of the longest common prefix of s
    // [i...L-1] and s[j...L-1]
    int LongestCommonPrefix(int i, int j) {
        int len = 0;
        if (i == j) return L - i;
        for (int k = P.size() - 1; k >= 0 && i < L && j < L;
            k--) {
            if (P[k][i] == P[k][j]) {
                i += 1 << k;
                j += 1 << k;
                len += 1 << k;
            }
        }
        return len;
    }
};

// BEGIN CUT
// The following code solves UVA problem 11512: GATTACA.
#define TESTING
#ifdef TESTING
int main() {
    int T;
    cin >> T;
    for (int caseno = 0; caseno < T; caseno++) {
        string s;

```

```

cin >> s;
SuffixArray array(s);
vector<int> v = array.GetSuffixArray();
int bestlen = -1, bestpos = -1, bestcount = 0;
for (int i = 0; i < s.length(); i++) {
    int len = 0, count = 0;
    for (int j = i+1; j < s.length(); j++) {
        int l = array.LongestCommonPrefix(i, j);
        if (l >= len) {
            if (l > len) count = 2; else count++;
            len = l;
        }
    }
    if (len > bestlen || len == bestlen && s.substr(
        bestpos, bestlen) > s.substr(i, len)) {
        bestlen = len;
        bestcount = count;
        bestpos = i;
    }
    if (bestlen == 0) {
        cout << "No repetitions found!" << endl;
    } else {
        cout << s.substr(bestpos, bestlen) << " " <<
            bestcount << endl;
    }
}

#else
// END CUT
int main() {

    // bobocel is the 0'th suffix
    // obocel is the 5'th suffix
    // bocel is the 1'st suffix
    // ocel is the 6'th suffix
    // cel is the 2'nd suffix
    // el is the 3'rd suffix
    // l is the 4'th suffix
    SuffixArray suffix("bobocel");
    vector<int> v = suffix.GetSuffixArray();

    // Expected output: 0 5 1 6 2 3 4
    //
    for (int i = 0; i < v.size(); i++) cout << v[i] << " ";
    cout << endl;
    cout << suffix.LongestCommonPrefix(0, 2) << endl;
}
// BEGIN CUT
#endif
// END CUT

```

## 6.2 Binary Indexed Tree

```

#include <iostream>
using namespace std;

#define LOGSZ 17

int tree[(1<<LOGSZ)+1];
int N = (1<<LOGSZ);

// add v to value at x
void set(int x, int v) {
    while(x <= N) {
        tree[x] += v;
        x += (x & -x);
    }
}

// get cumulative sum up to and including x

```

```

int get(int x) {
    int res = 0;
    while(x) {
        res += tree[x];
        x -= (x & -x);
    }
    return res;
}

// get largest value with cumulative sum less than or
// equal to x;
// for smallest, pass x-1 and add 1 to result
int getind(int x) {
    int idx = 0, mask = N;
    while(mask && idx < N) {
        int t = idx + mask;
        if(x >= tree[t]) {
            idx = t;
            x -= tree[t];
        }
        mask >>= 1;
    }
    return idx;
}

#include <iostream>
#include <vector>
using namespace std;
int find(vector<int> &C, int x) { return (C[x] == x) ? x
    : C[x] = find(C, C[x]); }
void merge(vector<int> &C, int x, int y) { C[find(C, x)]
    = find(C, y); }
int main()
{
    int n = 5;
    vector<int> C(n);
    for (int i = 0; i < n; i++) C[i] = i;
    merge(C, 0, 2);
    merge(C, 1, 0);
    merge(C, 3, 4);
    for (int i = 0; i < n; i++) cout << i << " " <<
        find(C, i) << endl;
    return 0;
}

```

## 6.3 Union-find set(aka DSU)

```

#include <iostream>
#include <vector>
using namespace std;
int find(vector<int> &C, int x) { return (C[x] == x) ? x
    : C[x] = find(C, C[x]); }
void merge(vector<int> &C, int x, int y) { C[find(C, x)]
    = find(C, y); }
int main()
{
    int n = 5;
    vector<int> C(n);
    for (int i = 0; i < n; i++) C[i] = i;
    merge(C, 0, 2);
    merge(C, 1, 0);
    merge(C, 3, 4);
    for (int i = 0; i < n; i++) cout << i << " " <<
        find(C, i) << endl;
    return 0;
}

```

## 6.4 Lowest common ancestor

```

const int max_nodes, log_max_nodes;
int num_nodes, log_num_nodes, root;

vector<int> children[max_nodes]; // children[i]
    contains the children of node i
int A[max_nodes][log_max_nodes+1]; // A[i][j] is the
    2^j-th ancestor of node i, or -1 if that ancestor
    does not exist
int L[max_nodes]; // L[i] is the
    distance between node i and the root

// floor of the binary logarithm of n
int lb(unsigned int n)
{
    if(n==0)
        return -1;
    int p = 0;
    if (n >= 1<<16) { n >>= 16; p += 16; }
}

```

```

if (n >= 1<< 8) { n >>= 8; p += 8; }
if (n >= 1<< 4) { n >>= 4; p += 4; }
if (n >= 1<< 2) { n >>= 2; p += 2; }
if (n >= 1<< 1) { p += 1; }
return p;
}

void DFS(int i, int l)
{
    L[i] = l;
    for(int j = 0; j < children[i].size(); j++)
        DFS(children[i][j], l+1);
}

int LCA(int p, int q)
{
    // ensure node p is at least as deep as node q
    if(L[p] < L[q])
        swap(p, q);

    // "binary search" for the ancestor of node p
    // situated on the same level as q
    for(int i = log_num_nodes; i >= 0; i--)
        if(L[p] - (1<<i) >= L[q])
            p = A[p][i];

    if(p == q)
        return p;

    // "binary search" for the LCA
    for(int i = log_num_nodes; i >= 0; i--)
        if(A[p][i] != -1 && A[p][i] != A[q][i])
        {
            p = A[p][i];
            q = A[q][i];
        }

    return A[p][0];
}

int main(int argc, char* argv[])
{
    // read num_nodes, the total number of nodes
    log_num_nodes=lb(num_nodes);

    for(int i = 0; i < num_nodes; i++)
    {
        int p;
        // read p, the parent of node i or -1 if node i
        // is the root

        A[i][0] = p;
        if(p != -1)
            children[p].push_back(i);
        else
            root = i;
    }

    // precompute A using dynamic programming
    for(int j = 1; j <= log_num_nodes; j++)
        for(int i = 0; i < num_nodes; i++)
            if(A[i][j-1] != -1)
                A[i][j] = A[A[i][j-1]][j-1];
            else
                A[i][j] = -1;

    // precompute L
    DFS(root, 0);

    return 0;
}

```