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```

    }
}
void add_edge(int u, int v, int c) {
    G[u].push_back(Edge(v, c, SZ(G[v])));
    G[v].push_back(Edge(u, 0, SZ(G[u]) - 1));
}
int DFS(int p, int flow) {
    if(p == t) return flow;
    for(int &i = iter[p]; i < SZ(G[p]); i++) {
        Edge &e = G[p][i];
        if(e.c > 0 && d[p] == d[e.v]+1) {
            int f = DFS(e.v, min(flow, e.c));
            if(f) {
                e.c -= f;
                G[e.v][e.r].c += f;
                return f;
            }
        }
    }
}
if( (--gap[d[p]]) == 0) d[s] = tot;
else {
    d[p]++;
    iter[p] = 0;
    ++gap[d[p]];
}
return 0;
}
int flow() {
    int res = 0;
    gap[0] = tot;
    for(res = 0; d[s] < tot; res += DFS(s, INF));
    return res;
}
} flow;

```

2.2 MinCostFlow c72a7d

```

struct zkwflow {
    static const int maxN = 10000;
    struct Edge { int v, f, re; ll w; };
    int n, s, t, ptr[maxN];
    bool vis[maxN]; ll dis[maxN];
    vector<Edge> E[maxN];

    void init(int _n, int _s, int _t) {
        n = _n, s = _s, t = _t;
        for (int i = 0; i < n; i++) E[i].clear();
    }
    void add_edge(int u, int v, int f, ll w) {
        E[u].push_back({v, f, (int)E[v].size(), w});
        E[v].push_back({u, 0, (int)E[u].size()-1, -w});
    }
    bool SPFA() {
        fill_n(dis, n, LLONG_MAX);
        fill_n(vis, n, false);

        dis[s] = 0;
        queue<int> q; q.push(s);

        while (!q.empty()) {
            int u = q.front(); q.pop();
            vis[u] = false;

            for (auto &it : E[u]) {
                if (it.f > 0 && dis[it.v] > dis[u] + it.w) {
                    dis[it.v] = dis[u] + it.w;
                    if (!vis[it.v]) {
                        vis[it.v] = true;
                        q.push(it.v);
                    }
                }
            }
        }

        return dis[t] != LLONG_MAX;
    }
    int DFS(int u, int nf) {
        if (u == t) return nf;
        int res = 0; vis[u] = true;
        for (int &i = ptr[u]; i < (int)E[u].size(); i++) {
            auto &it = E[u][i];

```

```

            if (it.f > 0 && dis[it.v] == dis[u] + it.w && !vis[it.v]) {
                int tf = DFS(it.v, min(nf, it.f));
                res += tf, nf -= tf, it.f -= tf;
                E[it.v][it.re].f += tf;
                if (nf == 0) {
                    vis[u] = false;
                    break;
                }
            }
        }
        return res;
    }
    pair<int, ll> flow() {
        int flow = 0; ll cost = 0;

        while (SPFA()) {
            fill_n(ptr, n, 0);
            int f = DFS(s, INT_MAX);
            flow += f;
            cost += dis[t] * f;
        }

        return { flow, cost };
    }
} flow;

```

2.3 Dinic aa63d9

```

struct Dinic{
    static const int MXN = 10000;
    struct Edge{ int v,f,re; };
    int n,s,t,level[MXN];
    vector<Edge> E[MXN];
    void init(int _n, int _s, int _t){
        n = _n; s = _s; t = _t;
        for (int i=0; i<n; i++) E[i].clear();
    }
    void add_edge(int u, int v, int f){
        E[u].push_back({v,f,(int)E[v].size()});
        E[v].push_back({u,0,(int)E[u].size()-1});
    }
    bool BFS(){
        for (int i=0; i<n; i++) level[i] = -1;
        queue<int> que;
        que.push(s);
        level[s] = 0;
        while (!que.empty()){
            int u = que.front(); que.pop();
            for (auto &it : E[u]){
                if (it.f > 0 && level[it.v] == -1){
                    level[it.v] = level[u]+1;
                    que.push(it.v);
                }
            }
        }
        return level[t] != -1;
    }
    int DFS(int u, int nf){
        if (u == t) return nf;
        int res = 0;
        for (auto &it : E[u]){
            if (it.f > 0 && level[it.v] == level[u]+1){
                int tf = DFS(it.v, min(nf,it.f));
                res += tf; nf -= tf; it.f -= tf;
                E[it.v][it.re].f += tf;
                if (nf == 0) return res;
            }
        }
        if (!res) level[u] = -1;
        return res;
    }
    int flow(int res=0){
        while ( BFS() )
            res += DFS(s,2147483647);
        return res;
    }
}flow;

```

2.4 Kuhn Munkres 7b81b8

```

struct KM{ // max weight, for min negate the weights
    static const int MXN = 2001; // 1-based
    static const ll INF = 0x3f3f3f3f;
    int n, mx[MXN], my[MXN], pa[MXN];
    ll g[MXN][MXN], lx[MXN], ly[MXN], sy[MXN];
    bool vx[MXN], vy[MXN];
    void init(int _n) {
        n = _n;
        for(int i=1; i<=n; i++) fill(g[i], g[i]+n+1, 0);
    }
    void addEdge(int x, int y, ll w) {g[x][y] = w;}
    void augment(int y) {
        for(int x, z; y; y = z)
            x=pa[y], z=mx[x], my[y]=x, mx[x]=y;
    }
    void bfs(int st) {
        for(int i=1; i<=n; ++i) sy[i]=INF, vx[i]=vy[i]=0;
        queue<int> q; q.push(st);
        for(;;) {
            while(q.size()) {
                int x=q.front(); q.pop(); vx[x]=1;
                for(int y=1; y<=n; ++y) if(!vy[y]){
                    ll t = lx[x]+ly[y]-g[x][y];
                    if(t==0){
                        pa[y]=x;
                        if(!my[y]){augment(y);return;}
                        vy[y]=1, q.push(my[y]);
                    }else if(sy[y]>t) pa[y]=x, sy[y]=t;
                }
            }
            ll cut = INF;
            for(int y=1; y<=n; ++y)
                if(!vy[y]&&cut>sy[y]) cut=sy[y];
            for(int j=1; j<=n; ++j){
                if(vx[j]) lx[j] -= cut;
                if(vy[j]) ly[j] += cut;
                else sy[j] -= cut;
            }
            for(int y=1; y<=n; ++y) if(!vy[y]&&sy[y]==0){
                if(!my[y]){augment(y);return;}
                vy[y]=1, q.push(my[y]);
            }
        }
    }
    ll solve(){
        fill(mx, mx+n+1, 0); fill(my, my+n+1, 0);
        fill(ly, ly+n+1, 0); fill(lx, lx+n+1, -INF);
        for(int x=1; x<=n; ++x) for(int y=1; y<=n; ++y)
            lx[x] = max(lx[x], g[x][y]);
        for(int x=1; x<=n; ++x) bfs(x);
        ll ans = 0;
        for(int y=1; y<=n; ++y) ans += g[my[y]][y];
        return ans;
    }
}graph;

```

2.5 SW min-cut 9beb62

```

const int INF=0x3f3f3f3f;
template<typename T>
struct stoer_wagner{// 0-base
    static const int MAXN=501;
    T g[MAXN][MAXN],dis[MAXN];
    int nd[MAXN],n,s,t;
    void init(int _n){
        n=_n;
        for(int i=0;i<n;++i)
            for(int j=0;j<n;++j)g[i][j]=0;
    }
    void add_edge(int u,int v,T w){
        g[u][v]=g[v][u]+=w;
    }
    T min_cut(){
        T ans=INF;
        for(int i=0;i<n;++i)nd[i]=i;
        for(int ind,tn=n;tn>1;--tn){
            for(int i=1;i<tn;++i)dis[nd[i]]=0;
            for(int i=1;i<tn;++i){
                ind=i;
                for(int j=i;j<tn;++j){
                    dis[nd[j]]+=g[nd[i-1]][nd[j]];
                    if(dis[nd[ind]]<dis[nd[j]])ind=j;
                }
            }
        }
    }
}

```

```

    }
    swap(nd[ind],nd[i]);
}
if(ans>dis[nd[ind]])
    ans=dis[t=nd[ind]],s=nd[ind-1];
for(int i=0;i<tn;++i)
    g[nd[ind-1]][nd[i]]=g[nd[i]][nd[ind-1]]
    +=g[nd[i]][nd[ind]];
}
return ans;
}
};

```

2.6 Max Cost Circulation 575920

```

struct MaxCostCirc {
    static const int MAXN = 33;
    int n, m;
    struct Edge { int v, w, c, r; };
    vector<Edge> g[ MAXN ];
    int dis[ MAXN ], prv[ MAXN ], prve[ MAXN ];
    bool vis[ MAXN ];
    int ans;
    void init( int _n, int _m ): n(_n), m(_m) {}
    void adde( int u, int v, int w, int c ) {
        g[ u ].push_back( { v, w, c, SZ( g[ v ] ) } );
        g[ v ].push_back( { u, -w, 0, SZ( g[ u ] )-1 } );
    }
    bool poscyc() {
        fill( dis, dis+n+1, 0 );
        fill( prv, prv+n+1, 0 );
        fill( vis, vis+n+1, 0 );
        int tmp = -1;
        FOR( t, n+1 ) {
            REP( i, 1, n ) {
                FOR( j, SZ( g[ i ] ) ) {
                    Edge& e = g[ i ][ j ];
                    if( e.c && dis[ e.v ] < dis[ i ]+e.w ) {
                        dis[ e.v ] = dis[ i ]+e.w;
                        prv[ e.v ] = i;
                        prve[ e.v ] = j;
                        if( t == n ) {
                            tmp = i;
                            break;
                        }
                    }
                }
            }
        }
        if( tmp == -1 ) return 0;
        int cur = tmp;
        while( !vis[ cur ] ) {
            vis[ cur ] = 1;
            cur = prv[ cur ];
        }
        int now = cur, cost = 0, df = 100000;
        do{
            Edge &e = g[ prv[ now ] ][ prve[ now ] ];
            df = min( df, e.c );
            cost += e.w;
            now = prv[ now ];
        }while( now != cur );
        ans += df*cost; now = cur;
        do{
            Edge &e = g[ prv[ now ] ][ prve[ now ] ];
            Edge &re = g[ now ][ e.r ];
            e.c -= df;
            re.c += df;
            now = prv[ now ];
        }while( now != cur );
        return 1;
    }
} circ;

```

2.7 Gomory-Hu Tree 796cf8

```

//n,Dinic::flow must be filled
//result:e[u][v]=u-v mincut;p[u]:u's parent on cut tree
int n,e[MXN][MXN],p[MXN];
void gomory_hu(){
    fill(p, p+n, 0);
    fill(e[0], e[n], INF);
    for(int s = 1; s < n; s++){
        int t = p[s];
        Dinic F; F.init(n,s,t);
        copy(flow.E, flow.E+MXN, F.E);
    }
}

```

```

    int tmp = F.flow();
    for( int i = 0 ; i < s ; i++ )
        e[s][i] = e[i][s] = min(tmp, e[t][i]);
    for( int i = s+1 ; i < n ; i++ )
        if ( p[i] == t && F.level[i] != -1 ) p[i] = s;
}

```

2.8 Max flow with lower/upper bound b5002a

```

// Max flow with lower/upper bound on edges
// use with ISAP
int in[ N ], out[ N ];
int l[ M ], r[ M ], a[ M ], b[ M ];
int solve(int n, int m, int s, int t){
    flow.init( n );
    for( int i = 0 ; i < m ; i ++ ){
        in[ r[ i ] ] += a[ i ];
        out[ l[ i ] ] += a[ i ];
        flow.addEdge( l[ i ], r[ i ], b[ i ] - a[ i ] );
        // flow from l[i] to r[i] must in [a[i], b[i]]
    }
    int nd = 0;
    for( int i = 0 ; i <= n ; i ++ ){
        if( in[ i ] < out[ i ] ){
            flow.addEdge( i, flow.t, out[ i ] - in[ i ] );
            nd += out[ i ] - in[ i ];
        }
        if( out[ i ] < in[ i ] )
            flow.addEdge( flow.s, i, in[ i ] - out[ i ] );
    }
    // original sink to source
    flow.addEdge( t, s, INF );
    if( flow.solve() != nd )
        // no solution
        return -1;
    int ans = flow.G[ s ].back().c; // source to sink
    flow.G[ s ].back().c = flow.G[ t ].back().c = 0;
    // take out super source and super sink
    for( size_t i = 0 ; i < flow.G[ flow.s ].size() ; i ++ )
        flow.G[ flow.s ][ i ].c = 0;
    Maxflow::Edge &e = flow.G[ flow.s ][ i ];
    flow.G[ e.v ][ e.r ].c = 0;
}
for( size_t i = 0 ; i < flow.G[ flow.t ].size() ; i ++ )
    flow.G[ flow.t ][ i ].c = 0;
Maxflow::Edge &e = flow.G[ flow.t ][ i ];
flow.G[ e.v ][ e.r ].c = 0;
}
flow.addEdge( flow.s, s, INF );
flow.addEdge( t, flow.t, INF );
flow.reset(); // set iter,d,gap to 0
return ans + flow.solve();
}

```

2.9 HLPPA 3c7c91

```

template <int MAXN, class T = int>
struct HLPP {
    const T INF = numeric_limits<T>::max();
    struct Edge {
        int to, rev; T f;
    };
    int n, s, t;
    vector<Edge> adj[MAXN];
    deque<int> lst[MAXN];
    vector<int> gap[MAXN];
    int ptr[MAXN];
    T ef[MAXN];
    int h[MAXN], cnt[MAXN], work, hst=0; // highest
    void init(int _n, int _s, int _t) {
        n=_n+1; s=_s; t=_t;
        for(int i=0;i<n;i++) adj[i].clear();
    }
    void add_edge(int u,int v,T f,bool isDir = true){
        adj[u].push_back({v,adj[v].size(),f});
        adj[v].push_back({u,adj[u].size()-1,isDir?f:0});
    }
    void updHeight(int v, int nh) {

```

```

        work++;
        if(h[v] != n) cnt[h[v]]--;
        h[v] = nh;
        if(nh == n) return;
        cnt[nh]++, hst = nh; gap[nh].push_back(v);
        if(ef[v]>0) lst[nh].push_back(v), ptr[nh]++;
    }
    void globalRelabel() {
        work = 0;
        fill(h, h+n, n);
        fill(cnt, cnt+n, 0);
        for(int i=0; i<=hst; i++)
            lst[i].clear(), gap[i].clear(), ptr[i] = 0;
        queue<int> q({t}); h[t] = 0;
        while(!q.empty()) {
            int v = q.front(); q.pop();
            for(auto &e : adj[v])
                if(h[e.to] == n && adj[e.to][e.rev].f > 0)
                    q.push(e.to), updHeight(e.to, h[v] + 1);
            hst = h[v];
        }
    }
    void push(int v, Edge &e) {
        if(ef[e.to] == 0)
            lst[h[e.to]].push_back(e.to), ptr[h[e.to]]++;
        T df = min(ef[v], e.f);
        e.f -= df, adj[e.to][e.rev].f += df;
        ef[v] -= df, ef[e.to] += df;
    }
    void discharge(int v) {
        int nh = n;
        for(auto &e : adj[v]) {
            if(e.f > 0) {
                if(h[v] == h[e.to] + 1) {
                    push(v, e);
                    if(ef[v] <= 0) return;
                }
                else nh = min(nh, h[e.to] + 1);
            }
        }
        if(cnt[h[v]] > 1) updHeight(v, nh);
        else {
            for(int i = h[v]; i < n; i++) {
                for(auto j : gap[i]) updHeight(j, n);
                gap[i].clear(), ptr[i] = 0;
            }
        }
    }
    T flow() {
        fill(ef, ef+n, 0);
        ef[s] = INF, ef[t] = -INF;
        globalRelabel();
        for(auto &e : adj[s]) push(s, e);
        for(; hst >= 0; hst--) {
            while(!lst[hst].empty()) {
                int v=lst[hst].back(); lst[hst].pop_back();
                discharge(v);
                if(work > 4 * n) globalRelabel();
            }
        }
        return ef[t] + INF;
    }
};

```

2.10 Flow Method

Maximize $c^T x$ subject to $Ax \leq b, x \geq 0$;
with the corresponding symmetric dual problem,
Minimize $b^T y$ subject to $A^T y \geq c, y \geq 0$.

Maximize $c^T x$ subject to $Ax \leq b$;
with the corresponding asymmetric dual problem,
Minimize $b^T y$ subject to $A^T y = c, y \geq 0$.

General Graph:

$|Max\ Ind.\ Set| + |Min\ Vertex\ Cover| = |V|$

$|Max\ Ind.\ Edge\ Set| + |Min\ Edge\ Cover| = |V|$

Bipartite Graph:

$|Max\ Ind.\ Set| = |Min\ Edge\ Cover|$

$|Max\ Ind.\ Edge\ Set| = |Min\ Vertex\ Cover|$

To reconstruct the minimum vertex cover, dfs from each

unmatched vertex on the left side **and** with unused edges only. Equivalently, dfs from source with unused edges only **and** without visiting sink. Then, a vertex is chosen iff. it is on the left side **and** without visited **or** on the right side **and** visited through dfs.

Minimum Weighted Bipartite Edge Cover:

Construct **new** bipartite graph with $n+m$ vertices on each side:

for each vertex u , duplicate a vertex u' on the other side
for each edge (u,v,w) , add edges (u,v,w) and (v',u',w)
for each vertex u , add edge $(u,u',2w)$ where w is min edge connects to u
then the answer is the minimum perfect matching of the **new** graph (KM)

Maximum density subgraph ($\sum W_e + \sum W_v$) / IVI
Binary search on answer:

For a fixed D , construct a Max flow model as follow:

Let S be Sum of all weight(**or** inf)

1. from source to each node with cap = S
2. For each (u,v,w) in E , $(u \rightarrow v, \text{cap}=w)$, $(v \rightarrow u, \text{cap}=w)$
3. For each node v , from v to sink with cap = $S + 2 * D - \text{deg}[v] - 2 * (W \text{ of } v)$

where $\text{deg}[v] = \sum \text{weight of edge associated with } v$
If $\text{maxflow} < S * IVI$, D is an answer.

Requiring subgraph: all vertex can be reached from source with edge whose cap > 0 .

Maximum closed subgraph

1. connect source with positive weighted vertex(capacity = weight)
2. connect sink with negative weighted vertex(capacity = -weight)
3. make capacity of the original edges = inf
4. ans = sum(positive weighted vertex weight) - (max flow)

Minimum Path Cover of DAG

1. For each vertex v , split it to v_{in} **and** v_{out} .
2. For each edge $(u \rightarrow v)$, add an edge between u_{out} **and** v_{in}
3. |Minimum Path Cover| = $IVI - |\text{Maximum Matching}|$ of the **new** bipartite graph

3 Math

3.1 FFT 9ed6b5

```
const int MAXN = 262144;
// (must be 2^k)
// before any usage, run pre_fft() first
typedef long double ld;
typedef complex<ld> cplx;
const ld PI = acos(-1);
const cplx I(0, 1);
cplx omega[MAXN+1];
void pre_fft(){
    for(int i=0; i<=MAXN; i++){
        omega[i] = exp(i * 2 * PI / MAXN * I);
    }
}
// n must be 2^k
void fft(int n, vector<cplx> &a, bool inv=false){
    int basic = MAXN / n;
    int theta = basic;
    for (int m = n; m >= 2; m >= 1) {
        int mh = m >> 1;
        for (int i = 0; i < mh; i++) {
            cplx w = omega[inv ? MAXN-(i*theta%MAXN) : i*theta%MAXN];
            for (int j = i; j < n; j += m) {
                int k = j + mh;
                cplx x = a[j] - a[k];
                a[j] += a[k];
                a[k] = w * x;
            }
        }
        theta = (theta * 2) % MAXN;
    }
}
```

```
int i = 0;
for (int j = 1; j < n - 1; j++) {
    for (int k = n >> 1; k > (i ^ k); k >= 1);
    if (j < i) swap(a[i], a[j]);
}
if(inv) for (i = 0; i < n; i++) a[i] /= n;
```

3.2 NTT 842b2b

```
/* p=a*2^k+1
p          a      k      root
998244353  119    23      3
2013265921 15     27     31
2061584302081 15    37      7
2748779069441 5     39      3
1945555039024054273 27 56    5 */
template<ll P,ll root,int MAXK,int MAXN>
struct NTT{
    static ll powi(ll a,ll b){
        ll ret=1;
        for(;b>=1;a=mul(a, a, P)){
            if(b&1) ret=mul(ret, a, P);
        }
        return ret;
    }
    static ll inv(ll a,ll b){
        if(a==1) return 1;
        return (((a-inv(b*a,a))*b+1)/a)%b; // overflow
    }
    ll omega[MAXK+1], inv_omega[MAXK+1];
    NTT(){
        omega[MAXK]=powi(root,(P-1)>>MAXK);
        for(int i=MAXK-1;i>=0;i--){
            omega[i]=mul(omega[i+1], omega[i+1], P);
        }
        for(int i=0;i<=MAXK;i++){
            inv_omega[i]=inv(omega[i],P);
        }
    }
    void tran(int n,ll a[],bool inv_ntt=false){//n=2^i
        for(int i=1,j=0;i<n;i++){
            for(int k=n>>1;!(j^k)&k;k>=1);
            if(i<j) swap(a[i],a[j]);
        }
        ll *G=(inv_ntt?inv_omega:omega);
        for(int k=2,t=1;k<=n;k<=1){
            int k2=k>>1;ll dw=G[t++];
            for(int j=0;j<n;j+=k){
                ll w=1;
                for(int i=j;i<j+k2;i++){
                    ll x=a[i],y=mul(a[i+k2], w, P);
                    a[i]=x+y; if(a[i]>=P) a[i]-=P;
                    a[i+k2]=x-y; if(a[i+k2]<0) a[i+k2]+=P;
                    w=mul(w, dw, P);
                }
            }
        }
        if(inv_ntt){
            ll inv_n=inv(n,P);
            for(int i=0;i<n;i++) a[i]=mul(a[i], inv_n, P);
        }
    }
};
const ll P=2013265921,root=31;
const int MAXN=4194304,MAXK=22; //MAXN=2^k
NTT<P,root,MAXK,MAXN> ntt;
```

3.3 Fast Walsh Transform c05f81

```
/* xor convolution:
* x = (x0,x1) , y = (y0,y1)
* z = ( x0y0 + x1y1 , x0y1 + x1y0 )
* =>
* x' = ( x0+x1 , x0-x1 ) , y' = ( y0+y1 , y0-y1 )
* z' = ( ( x0+x1 )( y0+y1 ) , ( x0-x1 )( y0-y1 ) )
* z = (1/2) * z''
* or convolution:
* x = (x0, x0+x1), inv = (x0, x1-x0) w/o final div
* and convolution:
* x = (x0+x1, x1), inv = (x0-x1, x1) w/o final div
* ternary xor convolution:
* x = (x0+x1+x2,x0+x1w+x2w^2,x0+x1w^2+x2w)
* inv = (1/3) * (x0+x1+x2,x0+x1w^2+x2w,x0+x1w+x2w^2)
```



```

* where w^3=1 and w^2=-w-1 */
typedef long long LL;
const int MAXN = (1<<20)+10;
const LL MOD = 1e9+7;
inline LL pw( LL x , LL k ) {
    LL res = 1;
    for( LL bs = x ; k ; k >= 1, bs = (bs * bs)%MOD )
        if( k&1 ) res = ( res * bs ) % MOD;
    return res;
}
inline LL invf( LL x ) {
    return pw( x , MOD-2 );
}
inline void fwt( LL x[ MAXN ] , int N , bool inv=0 ) {
    for( int d = 1 ; d < N ; d <= 1 ) {
        int d2 = d<<1;
        for( int s = 0 ; s < N ; s += d2 )
            for( int i = s , j = s+d ; i < s+d ; i++, j++ ){
                LL ta = x[ i ] , tb = x[ j ];
                x[ i ] = ta+tb;
                x[ j ] = ta-tb;
                if( x[ i ] >= MOD ) x[ i ] -= MOD;
                if( x[ j ] < 0 ) x[ j ] += MOD;
            }
    }
    LL invN = invf( N );
    if( inv )
        for( int i = 0 ; i < N ; i++ ) {
            x[ i ] *= invN;
            x[ i ] %= MOD;
        }
}

```

3.4 Poly operator 782280

```

struct PolyOp {
#define FOR(i, c) for( int i = 0; i < (c); ++i)
    NTT<P, root, MAXN> ntt;
    static int nxt2k(int x) {
        int i = 1; for( ; i < x; i <= 1); return i;
    }
    void Mul(int n, LL a[], int m, LL b[], LL c[]) {
        static LL aa[MAXN], bb[MAXN];
        int N = nxt2k(n+m);
        copy(a, a+n, aa); fill(aa+n, aa+N, 0);
        copy(b, b+m, bb); fill(bb+m, bb+N, 0);
        ntt.tran(N, aa); ntt.tran(N, bb);
        FOR(i, N) c[i] = aa[i] * bb[i] % P;
        ntt.tran(N, c, 1);
    }
    void Inv(int n, LL a[], LL b[]) {
        // ab = aa^-1 = 1 mod x^(n/2)
        // (b - a^-1)^2 = 0 mod x^n
        // bb + a^-2 - 2 ba^-1 = 0
        // bba + a^-1 - 2b = 0
        // a^-1 = 2b - bba
        static LL tmp[MAXN];
        if( n == 1 ) {b[0] = ntt.inv(a[0], P); return;}
        Inv((n+1)/2, a, b);
        int N = nxt2k(n*2);
        copy(a, a+n, tmp);
        fill(tmp+n, tmp+N, 0);
        fill(b+n, b+N, 0);
        ntt.tran(N, tmp); ntt.tran(N, b);
        FOR(i, N) {
            LL t1 = (2 - b[i] * tmp[i]) % P;
            if( t1 < 0 ) t1 += P;
            b[i] = b[i] * t1 % P;
        }
        ntt.tran(N, b, 1);
        fill(b+n, b+N, 0);
    }
    void Div(int n, LL a[], int m, LL b[], LL d[], LL r[]) {
        // Ra = Rb * Rd mod x^(n-m+1)
        // Rd = Ra * Rb^-1 mod
        static LL aa[MAXN], bb[MAXN], ta[MAXN], tb[MAXN];
        if( n < m ) {copy(a, a+n, r); fill(r+n, r+m, 0);
            return;}
        // d: n-1 - (m-1) = n-m (n-m+1 terms)
        copy(a, a+n, aa); copy(b, b+m, bb);
        reverse(aa, aa+n); reverse(bb, bb+m);

```

```

    Inv(n-m+1, bb, tb);
    Mul(n-m+1, ta, n-m+1, tb, d);
    fill(d+n-m+1, d+n, 0); reverse(d, d+n-m+1);
    // r: m-1 - 1 = m-2 (m-1 terms)
    Mul(m, b, n-m+1, d, ta);
    FOR(i, n) { r[i] = a[i] - ta[i]; if( r[i] < 0 ) r[i]
        += P; }
}
void dx(int n, LL a[], LL b[]) { REP(i, 1, n-1) b[i-1]
    = i * a[i] % P; }
void Sx(int n, LL a[], LL b[]) {
    b[0] = 0;
    FOR(i, n) b[i+1] = a[i] * ntt.inv(i+1, P) % P;
}
void Ln(int n, LL a[], LL b[]) {
    // Integral a' a^-1 dx
    static LL a1[MAXN], a2[MAXN], b1[MAXN];
    int N = nxt2k(n*2);
    dx(n, a, a1); Inv(n, a, a2);
    Mul(n-1, a1, n, a2, b1);
    Sx(n+n-1-1, b1, b);
    fill(b+n, b+N, 0);
}
void Exp(int n, LL a[], LL b[]) {
    // Newton method to solve g(a(x)) = ln b(x) - a(x) =
    // 0
    // b' = b - g(b(x)) / g'(b(x))
    // b' = b (1 - lnb + a)
    static LL lnb[MAXN], c[MAXN], tmp[MAXN];
    assert(a[0] == 0); // dont know exp(a[0]) mod P
    if( n == 1 ) {b[0] = 1; return;}
    Exp((n+1)/2, a, b);
    fill(b+(n+1)/2, b+n, 0);
    Ln(n, b, lnb);
    fill(c, c+n, 0); c[0] = 1;
    FOR(i, n) {
        c[i] += a[i] - lnb[i];
        if( c[i] < 0 ) c[i] += P;
        if( c[i] >= P ) c[i] -= P;
    }
    Mul(n, b, n, c, tmp);
    copy(tmp, tmp+n, b);
}
bool Sqrt(int n, LL a[], LL b[]) {
    // Square root of a : b * b = a ( mod x^n )
    // bb = a mod x^(n/2)
    // ( bb - a )^2 = 0 mod x^n
    // ( bb + a )^2 = 4 bba
    // ( ( bb + a ) / 2b )^2 = a
    // sqrt(a) = b / 2 + a / 2b
    static LL c[MAXN];
    int ind=0, x, y, p=1;
    while(a[ind]==0) ind++;
    for(int i=0; i<n; i++) a[i]=a[i+ind];
    if((ind&1) || !solve(a[0], mod, x, y)) // discrete sqrt
        return 0;
    b[0]=min(x, y);
    while(p<n) p<=1;
    for(int t=2; t<=p; t<=1){
        Inv(t, b, c); Mul(t, a, t, c);
        for(int i=0; i<t; i++)
            b[i]=(b[i]+c[i])*inv(2)%mod;
    }
    if(ind){
        for(int i=p-1; i>=ind/2; i--) b[i]=b[i-ind/2];
        for(int i=0; i<ind/2; i++) b[i]=0;
        for(int i=p-1; i>=ind; i--) a[i]=a[i-ind];
        for(int i=0; i<ind; i++) a[i]=0;
    }
}
}
polyop;

```

3.5 Linear Recurrence 29d614

```

// Usage: linearRec({0, 1}, {1, 1}, k) //k'th fib
typedef vector<ll> Poly;
ll linearRec(Poly&& S, Poly&& tr, ll k) {
    int n=tr.size();
    auto combine=[&](Poly& a, Poly& b) {
        Poly res(n*2+1);
        for(int i=0; i<=n; i++) for(int j=0; j<=n; j++)
            res[i+j]=(res[i+j]+a[i]*b[j])%mod;
    }
}

```

```

for(int i=2*n;i>n;--i) for(int j=0;j<n;j++)
    res[i-1-j]=(res[i-1-j]+res[i]*tr[j])%mod;
res.resize(n+1);
return res;
}; // a * b mod (x^n-tr)
Poly pol(n+1), e(pol);
pol[0]=e[1]=1;
for (++k;k/2) {
    if(k%2) pol=combine(pol,e);
    e=combine(e,e);
}
ll res=0;
for(int i=0;i<n;i++) res=(res+pol[i+1]*S[i])%mod;
return res;
}

```

3.6 BerlekampMassey 868031

```

// find shortest linear recurrence relation O(n^2)
// example: BM({1,1,2,3,5,8,13,21})
// 2*len terms for uniqueness
inline vector<ll> BM(const vector<ll> &x) {
    vector<ll> ls, cur;
    int lf; ll ld;
    for(int i=0;i<x.size();++i) {
        ll t=0;
        for(int j=0;j<cur.size();++j)
            t=(t+x[i-j]*cur[j])%mod;
        if((t-x[i])%mod==0) continue;
        if(!cur.size()) {
            cur.resize(i+1); lf=i; ld=(t-x[i])%mod; continue;
        }
        ll k=-(x[i]-t)*inv(ld, mod)%mod;
        vector<ll> c(i-lf-1); c.push_back(k);
        for(auto j:ls) c.push_back(-j*k%mod);
        if(c.size()<cur.size()) c.resize(cur.size());
        for(int j=0;j<cur.size();++j)
            c[j]=(c[j]+cur[j])%mod;
        if(i-lf+(int)ls.size()>=(int)cur.size())
            ls=cur, lf=i, ld=(t-x[i])%mod;
        cur=move(c);
    }
    for(auto& xx:cur) xx=(xx%mod+mod)%mod;
    return cur;
}

```

3.7 Miller Rabin 3f91d2

```

// n < 4,759,123,141      3 : 2, 7, 61
// n < 1,122,004,669,633  4 : 2, 13, 23, 1662803
// n < 3,474,749,660,383  6 : pirmes <= 13
// n < 2^64              7 :
// 2, 325, 9375, 28178, 450775, 9780504, 1795265022
bool witness(LL a, LL n, LL u, int t) {
    if(!a) return 0;
    LL x=mypow(a,u,n);
    for(int i=0;i<t;i++) {
        LL nx=mul(x,x,n);
        if(nx==1&&x!=1&&x!=n-1) return 1;
        x=nx;
    }
    return x!=1;
}
bool miller_rabin(LL n, int s=100) {
    // iterate s times of witness on n
    // return 1 if prime, 0 otherwise
    if(n<2) return 0;
    if(!(n&1)) return n == 2;
    LL u=n-1; int t=0;
    while(!(u&1)) u>>=1, t++;
    while(s--){
        LL a=randll()%(n-1)+1;
        if(witness(a,n,u,t)) return 0;
    }
    return 1;
}

```

3.8 Simplex c2c23c

```

/*target:
    max \sum_{j=1}^n A_{0,j}*x_j
condition:

```

```

\sum_{j=1}^n A_{i,j}*x_j <= A_{i,0} li=1~m
x_j >= 0 lj=1~n
VDB = vector<double>*/
template<class VDB>
VDB simplex(int m,int n,vector<VDB> a){
    vector<int> left(m+1), up(n+1);
    iota(left.begin(), left.end(), n);
    iota(up.begin(), up.end(), 0);
    auto pivot = [&](int x, int y){
        swap(left[x], up[y]);
        auto k = a[x][y]; a[x][y] = 1;
        vector<int> pos;
        for(int j = 0; j <= n; ++j){
            a[x][j] /= k;
            if(a[x][j] != 0) pos.push_back(j);
        }
        for(int i = 0; i <= m; ++i){
            if(a[i][y]==0 || i == x) continue;
            k = a[i][y], a[i][y] = 0;
            for(int j : pos) a[i][j] -= k*a[x][j];
        }
    };
    for(int x,y;;){
        for(int i=x+1; i <= m; ++i)
            if(a[i][0]<a[x][0]) x = i;
        if(a[x][0]>=0) break;
        for(int j=y+1; j <= n; ++j)
            if(a[x][j]<a[x][y]) y = j;
        if(a[x][y]>=0) return VDB(); //infeasible
        pivot(x, y);
    }
    for(int x,y;;){
        for(int j=y+1; j <= n; ++j)
            if(a[0][j] > a[0][y]) y = j;
        if(a[0][y]<=0) break;
        x = -1;
        for(int i=1; i<=m; ++i) if(a[i][y] > 0)
            if(x == -1 || a[i][0]/a[i][y]
                < a[x][0]/a[x][y]) x = i;
        if(x == -1) return VDB(); //unbounded
        pivot(x, y);
    }
    VDB ans(n + 1);
    for(int i = 1; i <= m; ++i)
        if(left[i] <= n) ans[left[i]] = a[i][0];
    ans[0] = -a[0][0];
    return ans;
}

```

3.9 Faulhaber df817f

```

/* faulhaber' s formula -
    * cal power sum formula of all p=1~k in O(k^2) */
#define MAXK 2500
const int mod = 1000000007;
int b[MAXK]; // bernoulli number
int inv[MAXK+1]; // inverse
int cm[MAXK+1][MAXK+1]; // combinatorics
int co[MAXK][MAXK+2]; // coeeficient of x^j when p=i
inline int getinv(int x) {
    int a=x, b=mod, a0=1, a1=0, b0=0, b1=1;
    while(b) {
        int q,t;
        q=a/b; t=b; b=a-b*q; a=t;
        t=b0; b0=a0-b0*q; a0=t;
        t=b1; b1=a1-b1*q; a1=t;
    }
    return a0<0?a0+mod:a0;
}
inline void pre() {
    /* combinational */
    for(int i=0;i<=MAXK;i++) {
        cm[i][0]=cm[i][i]=1;
        for(int j=1;j<i;j++)
            cm[i][j]=add(cm[i-1][j-1], cm[i-1][j]);
    }
    /* inverse */
    for(int i=1;i<=MAXK;i++) inv[i]=getinv(i);
    /* bernoulli */
    b[0]=1; b[1]=getinv(2); // with b[1] = 1/2
    for(int i=2;i<=MAXK;i++) {
        if(i&1) { b[i]=0; continue; }
    }
}

```

```

    b[i]=1;
    for(int j=0;j<i;j++)
        b[i]=sub(b[i], mul(cm[i][j],mul(b[j], inv[i-j+1])))
    };
}
/* faulhaber */
// sigma_x=1~n {x^p} =
// 1/(p+1) * sigma_j=0~p {C(p+1,j)*B_j*n^(p-j+1)}
for(int i=1;i<MAXK;i++) {
    co[i][0]=0;
    for(int j=0;j<=i;j++)
        co[i][i-j+1]=mul(inv[i+1], mul(cm[i+1][j], b[j]));
}
}
/* sample usage: return f(n,p) = sigma_x=1~n (x^p) */
inline int solve(int n,int p) {
    int sol=0,m=n;
    for(int i=1;i<=p+1;i++) {
        sol=add(sol,mul(co[p][i],m));
        m = mul(m, n);
    }
    return sol;
}

```

3.10 Chinese Remainder 6fe08b

```

ll solve(ll x1, ll m1, ll x2, ll m2) {
    ll g = __gcd(m1, m2);
    if((x2 - x1) % g) return -1; // no sol
    m1 /= g; m2 /= g;
    pair<ll,ll> p = gcd(m1, m2);
    ll lcm = m1 * m2 * g;
    ll res = p.first * (x2 - x1) % lcm * m1 % lcm + x1; //
    overflow
    return (res % lcm + lcm) % lcm;
}

```

3.11 Pollard Rho 2f8c41

```

// does not work when n is prime
LL f(LL x, LL mod){ return add(mul(x,x,mod),1,mod); }
LL pollard_rho(LL n) {
    if(!n&1) return 2;
    while(true){
        LL y=2, x=rand()%(n-1)+1, res=1;
        for(int sz=2; res==1; sz*=2) {
            for(int i=0; i<sz && res<=1; i++) {
                x = f(x, n);
                res = __gcd(abs(x-y), n);
            }
            y = x;
        }
        if (res!=0 && res!=n) return res;
    }
}

```

3.12 ax+by=gcd 5a651f

```

pair<ll,ll> gcd(ll a, ll b){
    if(b == 0) return {1, 0};
    pair<ll,ll> q = gcd(b, a % b);
    return {q.second, q.first - q.second * (a / b)};
}

```

3.13 Discrete sqrt 9c4c8a

```

void calch(int &t, int &h, const int p) {
    int tmp=p-1; for(t=0;(tmp&1)==0;tmp/=2) t++; h=tmp;
}
// solve equation x^2 mod p = a where p is a prime
bool solve(int a, int p, int &x, int &y) {
    if(p == 2) { x = y = 1; return true; }
    int p2 = p / 2, tmp = mypow(a, p2, p);
    if (tmp == p - 1) return false;
    if ((p + 1) % 4 == 0) {
        x=mypow(a,(p+1)/4,p); y=p-x; return true;
    } else {
        int t, h, b, pb; calch(t, h, p);
        if (t >= 2) {
            do {b = rand() % (p - 2) + 2;
            } while (mypow(b, p / 2, p) != p - 1);
            pb = mypow(b, h, p);

```

```

    } int s = mypow(a, h / 2, p);
    for (int step = 2; step <= t; step++) {
        int ss = (((LL)(s * s) % p) * a) % p;
        for(int i=0;i<t-step;i++) ss=mul(ss,ss,p);
        if (ss + 1 == p) s = (s * pb) % p;
        pb = ((LL)pb * pb) % p;
    } x = ((LL)s * a) % p; y = p - x;
} return true;
}

```

3.14 Romberg 6dc94c

```

// Estimates the definite integral of
// \int_a^b f(x) dx
template<class T>
double romberg( T& f, double a, double b, double eps=1e
-8){
    vector<double>t; double h=b-a,last,curr; int k=1,i=1;
    t.push_back(h*(f(a)+f(b))/2);
    do{ last=t.back(); curr=0; double x=a+h/2;
        for(int j=0;j<k;j++) curr+=f(x), x+=h;
        curr=(t[0] + h*curr)/2; double k1=4.0/3.0,k2
        =1.0/3.0;
        for(int j=0;j<i;j++){ double temp=k1*curr-k2*t[j];
            t[j]=curr; curr=temp; k2/=4*k1-k2; k1=k2+1;
        } t.push_back(curr); k*=2; h/=2; i++;
    }while( fabs(last-curr) > eps);
    return t.back();
}

```

3.15 Prefix Inverse 230130

```

void solve( int m ){
    inv[ 1 ] = 1;
    for( int i = 2 ; i < m ; i ++ )
        inv[ i ] = ((LL)(m - m / i) * inv[m % i]) % m;
}

```

3.16 Roots of Polynomial adb2af

```

const double eps = 1e-12;
const double inf = 1e+12;
double a[ 10 ], x[ 10 ]; // a[0..n](coef) must be filled
int n; // degree of polynomial must be filled
int sign( double x ){return (x < -eps)?(-1):(x>eps);}
double f(double a[], int n, double x){
    double tmp=1,sum=0;
    for(int i=0;i<=n;i++){
        sum=sum+a[i]*tmp; tmp=tmp*x; }
    return sum;
}
double binary(double l,double r,double a[],int n){
    int sl=sign(f(a,n,l)),sr=sign(f(a,n,r));
    if(sl==0) return l; if(sr==0) return r;
    if(sl*sr>0) return inf;
    while(r-l>eps){
        double mid=(l+r)/2;
        int ss=sign(f(a,n,mid));
        if(ss==0) return mid;
        if(ss*sl>0) l=mid; else r=mid;
    }
    return l;
}
void solve(int n,double a[],double x[],int &nx){
    if(n==1){ x[1]=-a[0]/a[1]; nx=1; return; }
    double da[10], dx[10]; int ndx;
    for(int i=n;i>=1;i--) da[i-1]=a[i]*i;
    solve(n-1,da,dx,ndx);
    nx=0;
    if(ndx==0){
        double tmp=binary(-inf,inf,a,n);
        if (tmp<inf) x[++nx]=tmp;
        return;
    }
    double tmp;
    tmp=binary(-inf,dx[1],a,n);
    if(tmp<inf) x[++nx]=tmp;
    for(int i=1;i<=ndx-1;i++){
        tmp=binary(dx[i],dx[i+1],a,n);
        if(tmp<inf) x[++nx]=tmp;
    }
    tmp=binary(dx[ndx],inf,a,n);

```



```

    if(tmp<inf) x[+nx]=tmp;
} // roots are stored in x[1..nx]

```

3.17 Primes and μ function 1350a0

```

/* 12721, 13331, 14341, 75577, 123457, 222557, 556679
* 999983, 1097774749, 1076767633, 100102021, 999997771
* 1001010013, 1000512343, 987654361, 999991231
* 999888733, 98789101, 987777733, 999991921, 1010101333
* 1010102101, 1000000000039, 100000000000037
* 2305843009213693951, 4611686018427387847
* 9223372036854775783, 18446744073709551557 */
int mu[ N ], p_tbl[ N ]; // multiplicative function f
vector<int> primes;
void sieve() {
    mu[ 1 ] = p_tbl[ 1 ] = 1;
    for( int i = 2 ; i < N ; i ++ ){
        if( !p_tbl[ i ] ){
            p_tbl[ i ] = i;
            primes.push_back( i );
            mu[ i ] = -1; // f(i)=... where i is prime
        }
        for( int p : primes ){
            int x = i * p;
            if( x >= N ) break;
            p_tbl[ x ] = p;
            mu[ x ] = -mu[ i ];
            if( i % p == 0 ){ // f(x)=f(i)/f(p^(k-1))*f(p^k)
                mu[ x ] = 0;
                break;
            } // else f(x)=f(i)*f(p)
        }
    }
}
vector<int> factor( int x ){
    vector<int> fac{ 1 };
    while( x > 1 ){
        int fn = fac.size(), p = p_tbl[ x ], pos = 0;
        while( x % p == 0 ){
            x /= p;
            for( int i = 0 ; i < fn ; i ++ )
                fac.PB( fac[ pos ++ ] * p );
        }
    }
    return fac;
}

```

3.18 Subset Convolution 53a5f7

```

// h(s)=\sum_{s'} \subseteq s f(s')g(s\backslash s')
vector<int> SubsetConv(int n, const vector<int> &f,
    const vector<int> &g) {
    const int m = 1 << n;
    vector<vector<int>> a(n + 1, vector<int>(m)), b(n + 1,
        vector<int>(m));
    for( int i = 0; i < m; ++i ) {
        a[__builtin_popcount(i)][i] = f[i];
        b[__builtin_popcount(i)][i] = g[i];
    }
    for( int i = 0; i <= n; ++i ) {
        for( int j = 0; j < n; ++j ) {
            for( int s = 0; s < m; ++s ) {
                if( s >> j & 1 ) {
                    a[i][s] += a[i][s ^ (1 << j)];
                    b[i][s] += b[i][s ^ (1 << j)];
                }
            }
        }
    }
    vector<vector<int>> c(n + 1, vector<int>(m));
    for( int s = 0; s < m; ++s ) {
        for( int i = 0; i <= n; ++i ) {
            for( int j = 0; j <= i; ++j ) c[i][s] += a[j][s] *
                b[i - j][s];
        }
    }
    for( int i = 0; i <= n; ++i ) {
        for( int j = 0; j < n; ++j ) {
            for( int s = 0; s < m; ++s ) {
                if( s >> j & 1 ) c[i][s] -= c[i][s ^ (1 << j)];
            }
        }
    }
    vector<int> res(m);
    for( int i = 0; i < m; ++i ) res[i] = c[
        __builtin_popcount(i)][i];
    return res;
}

```

```

}

```

3.19 Result fd0b69

- Lucas' Theorem :
For $n, m \in \mathbb{Z}^*$ and prime P , $C(m, n) \bmod P = \prod C(m_i, n_i)$ where m_i is the i -th digit of m in base P .
- 1st Stirling Numbers(permutation $|P| = n$ with k cycles):
 $S(n, k) = \text{coefficient of } x^k \text{ in } \sum_{i=0}^{n-1} (x+i)$
 $S(n+1, k) = nS(n, k) + S(n, k-1)$
- 2nd Stirling Numbers(Partition n elements into k non-empty set):

$$S(n, k) = \frac{1}{k!} \sum_{j=0}^k (-1)^{k-j} \binom{k}{j} j^n$$

$$S(n+1, k) = kS(n, k) + S(n, k-1)$$
- Calculate $f(x+n)$ where $f(x) = \sum_{i=0}^{n-1} a_i x^i$:

$$f(x+n) = \sum_{i=0}^{n-1} a_i (x+n)^i = \sum_{i=0}^{n-1} x^i \cdot \frac{1}{i!} \sum_{j=i}^{n-1} \frac{a_j}{j!} \cdot \frac{n^{j-i}}{(j-i)!}$$
- Calculate $c[i-j] + a[i] \times b[j]$ for $a[n], b[m]$
 1. $a = \text{reverse}(a)$; $c = \text{mul}(a, b)$; $c = \text{reverse}(c[1:n])$;
 2. $b = \text{reverse}(b)$; $c = \text{mul}(a, b)$; $c = \text{rshift}(c, m-1)$;
- Eulerian number(permutation $1 \sim n$ with m $a[i] > a[i-1]$):

$$A(n, m) = \sum_{i=0}^m (-1)^i \binom{n+1}{i} (m+1-i)^n$$

$$A(n, m) = (n-m)A(n-1, m-1) + (m+1)A(n-1, m)$$
- Derangement:

$$D(n) = (n-1)(D(n-1) + D(n-2)) = nD(n-1) + (-1)^n$$
- Pick's Theorem : $A = i + b/2 - 1$
- Euler Characteristic:
 planar graph: $V - E + F - C = 1$
 convex polyhedron: $V - E + F = 2$
 V, E, F, C : number of vertices, edges, faces(regions), and components
- Kirchhoff's theorem :
 - number of spanning tree of undirected graph:
 degree matrix $D_{ii} = \deg(i)$, $D_{ij} = 0$
 adjacency matrix $G_{ij} = \# \text{ of } (i, j) \in E$, $G_{ii} = 0$,
 let $A = D - G$, delete any one row, one column, and cal $\det(A')$
 - number of spanning tree of directed graph:
 in-degree matrix $D_{ii}^{\text{in}} = \text{indeg}(i)$, $D_{ij}^{\text{in}} = 0$
 out-degree matrix $D_{ii}^{\text{out}} = \text{outdeg}(i)$, $D_{ij}^{\text{out}} = 0$
 let $L^{\text{in}} = D^{\text{in}} - G$, $L^{\text{out}} = D^{\text{out}} - G$, delete the i -th row and column
 $\det(L_i^{\text{in}})$ and $\det(L_i^{\text{out}})$ is the number of spanning tree from/to root i
- Burnside Lemma: $|X/G| = \frac{1}{|G|} \sum_{g \in G} |X^g|$
- Polya theorem: $|Y^x/G| = \frac{1}{|G|} \sum_{g \in G} m^{c(g)}$
 $m = |Y|$: num of colors, $c(g)$: num of cycle
- Anti SG (the person who has no strategy wins) :
 first player wins iff either
 1. SG value of ALL subgame ≤ 1 and SG value of the game $= 0$
 2. SG value of some subgame > 1 and SG value of the game $\neq 0$
- Möbius inversion formula :

$$g(n) = \sum_{d|n} f(d) \text{ for every integer } n \geq 1, \text{ then}$$

$$f(n) = \sum_{d|n} \mu(d) g\left(\frac{n}{d}\right) = \sum_{d|n} \mu\left(\frac{n}{d}\right) g(d) \text{ for every integer } n \geq 1$$
 Dirichlet convolution : $f * g = g * f = \sum_{d|n} f(d) g\left(\frac{n}{d}\right) = \sum_{d|n} f\left(\frac{n}{d}\right) g(d)$
 $g = f * 1 \Leftrightarrow f = g * \mu$, $\epsilon = \mu * 1$, $Id = \phi * 1$, $d = 1 * 1$, $\sigma = Id * 1 = \phi * d$,
 $\sigma_k = Id_k * 1$ where $\epsilon(n) = [n=1]$, $1(n) = 1$, $Id(n) = n$, $Id_k(n) = n^k$,
 $d(n) = \#(\text{divisor})$, $\sigma(n) = \sum \text{divisor}$, $\sigma_k(n) = \sum \text{divisor}^k$
- Find a Primitive Root of n :
 n has primitive roots iff $n = 2, 4, p^k, 2p^k$ where p is an odd prime.
 1. Find $\phi(n)$ and all prime factors of $\phi(n)$, says $P = \{p_1, \dots, p_m\}$
 2. $\forall g \in [2, n]$, if $g^{\frac{\phi(n)}{p_i}} \neq 1, \forall p_i \in P$, then g is a primitive root.
 3. Since the smallest one isn't too big, the algorithm runs fast.
 4. n has exactly $\phi(\phi(n))$ primitive roots.
- Sum of Two Squares Thm (Legendre):
 For a given positive integer N , let
 $D1 = (\# \text{ of } d \in N \text{ dividing } N \text{ that } d \equiv 1 \pmod{4})$
 $D3 = (\# \text{ of } d \in N \text{ dividing } N \text{ that } d \equiv 3 \pmod{4})$
 then N can be written as a sum of two squares in exactly $R(N) = 4(D1 - D3)$ ways.
- Difference of $D1 - D3$ Thm:
 let $N = 2^t \times [p_1^{e_1} \times \dots \times p_r^{e_r}] \times [q_1^{f_1} \times \dots \times q_s^{f_s}]$
 where $p_i \in \text{mod } 4 = 1 \text{ prime}$, $q_i \in \text{mod } 4 = 3 \text{ prime}$
 then $D1 - D3 = \begin{cases} (e_1+1)(e_2+1)\dots(er+1) & \text{if } f_i \text{ all even} \\ 0 & \text{if any } f_i \text{ is odd} \end{cases}$
- Sherman-Morrison formula:
 suppose $A \in \mathbb{R}^{n \times n}$ is invertible and $u, v \in \mathbb{R}^n$
 $A + uv^T$ is invertible if and only if $1 + v^T A^{-1} u \neq 0$

$$(A + uv^T)^{-1} = A^{-1} - \frac{A^{-1} u v^T A^{-1}}{1 + v^T A^{-1} u}$$

4 Geometry

4.1 Intersection of 2 lines 3db65e

```
Pt LLIntersect(Line a, Line b) {
    Pt p1 = a.s, p2 = a.e, q1 = b.s, q2 = b.e;
    ld f1 = (p2-p1)^(q1-p1), f2 = (p2-p1)^(p1-q2), f;
    if(dcmp(f=f1+f2) == 0)
        return dcmp(f1)?Pt(NAN,NAN):Pt(INFINITY,INFINITY);
    return q1*(f2/f) + q2*(f1/f);
}
```

4.2 halfPlaneIntersection 8fb188

```
// for point or line solution, change > to >=
bool onleft(Line L, Pt p) {
    return dcmp(L.v^(p-L.s)) > 0;
}
// assume that Lines intersect
vector<Pt> HPI(vector<Line>& L) {
    sort(L.begin(), L.end()); // sort by angle
    int n = L.size(), fir, las;
    Pt *p = new Pt[n];
    Line *q = new Line[n];
    q[fir=las=0] = L[0];
    for(int i = 1; i < n; i++) {
        while(fir < las && !onleft(L[i], p[las-1])) las--;
        while(fir < las && !onleft(L[i], p[fir])) fir++;
        q[++las] = L[i];
        if(dcmp(q[las].v^q[las-1].v) == 0) {
            las--;
            if(onleft(q[las], L[i].s)) q[las] = L[i];
        }
        if(fir < las) p[las-1] = LLIntersect(q[las-1], q[las]);
    }
    while(fir < las && !onleft(q[fir], p[las-1])) las--;
    if(las-fir <= 1) return {};
    p[las] = LLIntersect(q[las], q[fir]);
    int m = 0;
    vector<Pt> ans(las-fir+1);
    for(int i = fir; i <= las; i++) ans[m++] = p[i];
    return ans;
}
```

4.3 Intersection of 2 segments b7e393

```
bool onseg(Pt p, Line L) {
    Pt x = L.s-p, y = L.e-p;
    return dcmp(x^y) == 0 && dcmp(x*y) <= 0; //inseg:dcmp(x*y)<0
}
// assume a.s != a.e != b.s != b.e
Pt SSIntersect(Line a, Line b) {
    Pt p = LLIntersect(a, b);
    if(isinf(p.x) && (onseg(a.s,b) || onseg(a.e,b) ||
        onseg(b.s, a) || onseg(b.e, a))) return p; //
        parallel
    if(isfinite(p.x) && onseg(p, a) && onseg(p, b)) return
        p; //not parallel
    return {NAN,NAN};
}
```

4.4 Banana de5c4e

```
int ori( const Pt& o , const Pt& a , const Pt& b ){
    ll ret = ( a - o ) ^ ( b - o );
    return (ret > 0) - (ret < 0);
}
// p1 == p2 || q1 == q2 need to be handled
bool banana( const Pt& p1 , const Pt& p2 ,
    const Pt& q1 , const Pt& q2 ){
    if( ( ( p2 - p1 ) ^ ( q2 - q1 ) ) == 0 ){ // parallel
        if( ori( p1 , p2 , q1 ) ) return false;
        return ( ( p1 - q1 ) * ( p2 - q1 ) ) <= 0 ||
            ( ( p1 - q2 ) * ( p2 - q2 ) ) <= 0 ||
            ( ( q1 - p1 ) * ( q2 - p1 ) ) <= 0 ||
            ( ( q1 - p2 ) * ( q2 - p2 ) ) <= 0;
    }
    return (ori( p1, p2, q1 ) * ori( p1, p2, q2 )<=0) &&
        (ori( q1, q2, p1 ) * ori( q1, q2, p2 )<=0);
}
```

4.5 Intersection of circle and line 73c7f5

```
vector<Pt> CLInter(const Line &a,const Circle &c){
    Pt p=a.s+(c.o-a.s)*a.v/norm2(a.v)*a.v;
    ld d=c.r*c.r-norm2(c.o-p);
    if(d<=-eps) return {};
    if(d<eps) return {p};
    Pt v=a.v/norm(a.v)*sqrt(d);
    return {p+v,p-v};
}
```

4.6 Intersection of polygon and circle 95d872

```
ld PCIntersect(vector<Pt> v, Circle cir) {
    for(int i = 0; i < (int)v.size(); ++i) v[i] = v[i] -
        cir.o;
    ld ans = 0, r = cir.r;
    int n = v.size();
    for(int i = 0; i < n; ++i) {
        Pt pa = v[i], pb = v[(i+1)%n];
        if(norm(pa) < norm(pb)) swap(pa, pb);
        if(dcmp(norm(pb)) == 0) continue;
        ld s, h, theta;
        ld a = norm(pb), b = norm(pa), c = norm(pb-pa);
        ld cosB = (pb*(pb-pa))/a/c, B = acos(cosB);
        if(cosB > 1) B = 0;
        else if(cosB < -1) B = PI;
        ld cosC = (pa*pb)/a/b, C = acos(cosC);
        if(cosC > 1) C = 0;
        else if(cosC < -1) C = PI;
        if(a > r) {
            s = (C/2)*r*r;
            h = a*b*sin(C)/c;
            if(h < r && B < PI/2) s -= (acos(h/r)*r*r - h*sqrt(
                r*r-h*h));
        }
        else if(b > r) {
            theta = PI - B - asin(sin(B)/r*a);
            s = 0.5*a*r*sin(theta) + (C-theta)/2*r*r;
        }
        else s = 0.5*sin(C)*a*b;
        ans += abs(s)*dcmp(v[i]^v[(i+1)%n]);
    }
    return abs(ans);
}
```

4.7 Intersection of 2 circles 57edf8

```
vector<Pt> CCinter(Circle& a, Circle& b){
    Pt o1=a.o,o2=b.o; ld r1=a.r,r2=b.r;
    if(norm(o1-o2)>r1+r2) return {};
    if(norm(o1-o2)<max(r1,r2)-min(r1,r2)) return {};
    ld d2=(o1-o2)*(o1-o2),d=sqrt(d2);
    if(d>r1+r2) return {};
    Pt u=(o1+o2)*0.5+(o1-o2)*((r2*r2-r1*r1)/(2*d2));
    ld A=sqrt((r1+r2+d)*(r1-r2+d)*(r1+r2-d)*(-r1+r2+d));
    Pt v=Pt(o1.y-o2.y,-o1.x+o2.x)*A/(2*d2);
    return {u+v,u-v};
}
```

4.8 Circle cover 635fba

```
#define N 1021
struct CircleCover{
    int C; Circle c[N];
    bool g[N][N], overlap[N][N];
    // Area[i] : area covered by at least i circles
    ld Area[N];
    void init(int _C){ C = _C; }
    struct Teve {
        Pt p; ld ang; int add;
        Teve() {}
        Teve(Pt _a, ld _b, int _c):p(_a), ang(_b), add(_c){}
        bool operator<(const Teve &a)const {
            return ang < a.ang;
        }
    }eve[N * 2];
    // strict: x = 0, otherwise x = -1
    bool disjunct(Circle& a, Circle& b, int x)
    {return sign(norm(a.o - b.o) - a.r - b.r) > x;}
```

```

bool contain(Circle& a, Circle& b, int x)
{return sign(a.r - b.r - norm(a.o - b.o)) > x;}
bool contain(int i, int j){
    /* c[j] is non-strictly in c[i]. */
    return (sign(c[i].r - c[j].r) > 0 ||
            (sign(c[i].r - c[j].r) == 0 && i < j)) &&
            contain(c[i], c[j], -1);
}
void solve(){
    for(int i = 0; i <= C + 1; i++) Area[i] = 0;
    for(int i = 0; i < C; i++){
        for(int j = 0; j < C; j++){
            overlap[i][j] = contain(i, j);
        }
        for(int i = 0; i < C; i++){
            for(int j = 0; j < C; j++){
                g[i][j] = !(overlap[i][j] || overlap[j][i] ||
                    disjunct(c[i], c[j], -1));
            }
        }
        for(int i = 0; i < C; i++){
            int E = 0, cnt = 1;
            for(int j = 0; j < C; j++){
                if(j != i && overlap[j][i])
                    cnt++;
            }
            for(int j = 0; j < C; j++){
                if(i != j && g[i][j]){
                    vector<Pt> v=CCinter(c[i], c[j]);
                    ld A=atan2(v[0].y - c[i].o.y, v[0].x - c[i].o.x);
                    ld B=atan2(v[1].y - c[i].o.y, v[1].x - c[i].o.x);
                    eve[E++] = Teve(v[1], B, 1);
                    eve[E++] = Teve(v[0], A, -1);
                    if(B > A) cnt++;
                }
            }
            if(E == 0) Area[cnt] += pi * c[i].r * c[i].r;
            else{
                sort(eve, eve + E);
                eve[E] = eve[0];
                for(int j = 0; j < E; j++){
                    cnt += eve[j].add;
                    Area[cnt] += (eve[j].p ^ eve[j + 1].p) * .5;
                    ld theta = eve[j + 1].ang - eve[j].ang;
                    if(theta < 0) theta += 2. * pi;
                    Area[cnt] +=
                        (theta - sin(theta)) * c[i].r * c[i].r * .5;
                }
            }
        }
    }
}

```

4.9 Li Chao Segment Tree 801fb6

```

struct LiChao_min{
    struct line{
        LL m, c;
        line(LL _m=0, LL _c=0) { m = _m; c = _c; }
        LL eval(LL x) { return m * x + c; }
    };
    struct node{
        node *l, *r; line f;
        node(line v) { f = v; l = r = NULL; }
    };
    typedef node* pnode;
    pnode root; int sz;
#define mid ((l+r)>>1)
    void insert(line &v, int l, int r, pnode &nd){
        if(!nd) { nd = new node(v); return; }
        LL trl = nd->f.eval(l), trr = nd->f.eval(r);
        LL vl = v.eval(l), vr = v.eval(r);
        if(trl <= vl && trr <= vr) return;
        if(trl > vl && trr > vr) { nd->f = v; return; }
        if(trl > vl) swap(nd->f, v);
        if(nd->f.eval(mid) < v.eval(mid)) insert(v, mid + 1,
            r, nd->r);
        else swap(nd->f, v), insert(v, l, mid, nd->l);
    }
    LL query(int x, int l, int r, pnode &nd){
        if(!nd) return LLONG_MAX;
        if(l == r) return nd->f.eval(x);
        if(mid >= x) return min(nd->f.eval(x), query(x, l,
            mid, nd->l));
        return min(nd->f.eval(x), query(x, mid + 1, r, nd->r));
    }
}
/* -sz <= query_x <= sz */
void init(int _sz){ sz = _sz + 1; root = NULL; }

```

```

void add_line(LL m, LL c){ line v(m, c); insert(v, -sz,
    sz, root); }
LL query(LL x) { return query(x, -sz, sz, root); }
};

```

4.10 Convex Hull trick 0b12ee

```

/* Given a convexhull, answer queries in O(\lg N)
CH should not contain identical points, the area should
be > 0, min pair(x, y) should be listed first */
double det( const Pt& p1, const Pt& p2 )
{ return p1.x * p2.y - p1.y * p2.x; }
struct Conv{
    int n;
    vector<Pt> a;
    vector<Pt> upper, lower;
    Conv(vector<Pt> _a) : a(_a){
        n = a.size();
        int ptr = 0;
        for(int i=1; i<n; ++i) if (a[ptr] < a[i]) ptr = i;
        for(int i=0; i<=ptr; ++i) lower.push_back(a[i]);
        for(int i=ptr; i<n; ++i) upper.push_back(a[i]);
        upper.push_back(a[0]);
    }
    int sign( LL x ){ // fixed when changed to double
        return x < 0 ? -1 : x > 0; }
    pair<LL,int> get_tang(vector<Pt> &conv, Pt vec){
        int l = 0, r = (int)conv.size() - 2;
        while(l + 1 < r){
            int mid = (l + r) / 2;
            if(sign(det(conv[mid+1]-conv[mid],vec))>0)r=mid;
            else l = mid;
        }
        return max(make_pair(det(vec, conv[r]), r),
            make_pair(det(vec, conv[0]), 0));
    }
    void upd_tang(const Pt &p, int id, int &i0, int &i1){
        if(det(a[i0] - p, a[id] - p) > 0) i0 = id;
        if(det(a[i1] - p, a[id] - p) < 0) i1 = id;
    }
    void bi_search(int l, int r, Pt p, int &i0, int &i1){
        if(l == r) return;
        upd_tang(p, l % n, i0, i1);
        int sl=sign(det(a[l % n] - p, a[(l + 1) % n] - p));
        while(l + 1 < r) {
            int mid = (l + r) / 2;
            int smid=sign(det(a[mid%n]-p, a[(mid+1)%n]-p));
            if (smid == sl) l = mid;
            else r = mid;
        }
        upd_tang(p, r % n, i0, i1);
    }
    int bi_search(Pt u, Pt v, int l, int r) {
        int sl = sign(det(v - u, a[l % n] - u));
        while(l + 1 < r) {
            int mid = (l + r) / 2;
            int smid = sign(det(v - u, a[mid % n] - u));
            if (smid == sl) l = mid;
            else r = mid;
        }
        return l % n;
    }
}
// 1. whether a given point is inside the CH
bool contain(Pt p) {
    if (p.x < lower[0].x || p.x > lower.back().x) return
        0;
    int id = lower_bound(lower.begin(), lower.end(), Pt(
        p.x, -INF)) - lower.begin();
    if (lower[id].x == p.x) {
        if (lower[id].y > p.y) return 0;
    }else if(det(lower[id-1]-p,lower[id]-p)<0)return 0;
    id = lower_bound(upper.begin(), upper.end(), Pt(p.x,
        INF), greater<Pt>()) - upper.begin();
    if (upper[id].x == p.x) {
        if (upper[id].y < p.y) return 0;
    }else if(det(upper[id-1]-p,upper[id]-p)<0)return 0;
    return 1;
}
// 2. Find 2 tang pts on CH of a given outside point
// return true with i0, i1 as index of tangent points
// return false if inside CH
bool get_tang(Pt p, int &i0, int &i1) {

```

```

    if (contain(p)) return false;
    i0 = i1 = 0;
    int id = lower_bound(lower.begin(), lower.end(), p)
        - lower.begin();
    bi_search(0, id, p, i0, i1);
    bi_search(id, (int)lower.size(), p, i0, i1);
    id = lower_bound(upper.begin(), upper.end(), p,
        greater<Pt>()) - upper.begin();
    bi_search((int)lower.size() - 1, (int)lower.size() -
        1 + id, p, i0, i1);
    bi_search((int)lower.size() - 1 + id, (int)lower.
        size() - 1 + (int)upper.size(), p, i0, i1);
    return true;
}
// 3. Find tangent points of a given vector
// ret the idx of vertex has max cross value with vec
int get_tang(Pt vec){
    pair<LL, int> ret = get_tang(upper, vec);
    ret.second = (ret.second + (int)lower.size() - 1) % n;
    ret = max(ret, get_tang(lower, vec));
    return ret.second;
}
// 4. Find intersection point of a given line
// return 1 and intersection is on edge (i, next(i))
// return 0 if no strictly intersection
bool get_intersection(Pt u, Pt v, int &i0, int &i1){
    int p0 = get_tang(u - v), p1 = get_tang(v - u);
    if(sign(det(v-u, a[p0]-u))*sign(det(v-u, a[p1]-u)) < 0){
        if(p0 > p1) swap(p0, p1);
        i0 = bi_search(u, v, p0, p1);
        i1 = bi_search(u, v, p1, p0 + n);
        return 1;
    }
    return 0;
}
};

```

4.11 Tangent line of two circles fab32c

```

vector<Line> go(const Circle& c1, const Circle& c2, int
    sign1){
    // sign1 = 1 for outer tang, -1 for inter tang
    vector<Line> ret;
    double d_sq = norm2(c1.o - c2.o);
    if(d_sq < eps) return ret;
    double d = sqrt(d_sq);
    Pt v = (c2.o - c1.o) / d;
    double c = (c1.r - sign1 * c2.r) / d;
    if(c * c > 1) return ret;
    double h = sqrt(max(0.0, 1.0 - c * c));
    for(int sign2 = 1; sign2 >= -1; sign2 -= 2){
        Pt n = { v.x * c - sign2 * h * v.y,
            v.y * c + sign2 * h * v.x };
        Pt p1 = c1.o + n * c1.r;
        Pt p2 = c2.o + n * (c2.r * sign1);
        if(fabs(p1.x - p2.x) < eps and
            fabs(p1.y - p2.y) < eps)
            p2 = p1 + perp(c2.o - c1.o);
        ret.push_back({p1, p2});
    }
    return ret;
}

```

4.12 Tangent line of point and circle 35a7bf

```

vector<Line> PCTangent(const Circle& C, const Pt& P) {
    vector<Line> ans;
    Pt u = C.o - P;
    double dist = norm(u);
    if(dist < C.r) return ans;
    else if(fabs(dist) < eps) {
        ans.push_back({P, P+rotate(u, M_PI/2)});
        return ans;
    }
    else {
        double ang = asin(C.r/dist);
        ans.push_back({P, P+rotate(u, -ang)});
        ans.push_back({P, P+rotate(u, +ang)});
        return ans;
    }
}

```

4.13 Min distance of two convex 9b7d9c

```

double TwoConvexHullMinDis(Point P[], Point Q[], int n,
    int m) {
    int YMinP=0, YMaxQ=0; double tmp, ans=1e9;
    for(int i=0; i<n; ++i) if(P[i].y < P[YMinP].y) YMinP=i;
    for(int i=0; i<m; ++i) if(Q[i].y > Q[YMaxQ].y) YMaxQ=i;
    P[n]=P[0]; Q[m]=Q[0];
    for(int i=0; i<n; ++i) {
        while(tmp < ((Q[YMaxQ+1]-P[YMinP+1])^(P[YMinP]-P[YMinP
            +1])) > ((Q[YMaxQ]-P[YMinP+1])^(P[YMinP]-P[YMinP
            +1]))) YMaxQ=(YMaxQ+1)%m;
        if(tmp < 0) ans = min(ans, PtToSegDis(P[YMinP], P[YMinP+1],
            Q[YMaxQ]));
        else ans = min(ans, TwoSegMinDis(P[YMinP], P[YMinP+1], Q[
            YMaxQ], Q[YMaxQ+1]));
        YMinP=(YMinP+1)%n;
    }
    return ans;
}

```

4.14 Poly Union 7ac791

```

struct PY{
    int n; Pt pt[5]; double area;
    Pt& operator[](const int x){ return pt[x]; }
    void init(){ //n, pt[0~n-1] must be filled
        area = pt[n-1]^pt[0];
        for(int i=0; i<n-1; ++i) area += pt[i]^pt[i+1];
        if((area/=2) < 0) reverse(pt, pt+n), area = -area;
    }
};
PY py[500];
pair<double, int> c[5000];
inline double segP(Pt &p, Pt &p1, Pt &p2){
    if(dcmp(p1.x-p2.x) == 0) return (p.y-p1.y)/(p2.y-p1.y);
    return (p.x-p1.x)/(p2.x-p1.x);
}
double polyUnion(int n){ //py[0~n-1] must be filled
    int i, j, ii, jj, ta, tb, r, d;
    double z, w, s, sum, tc, td;
    for(i=0; i<n; ++i) py[i][py[i].n] = py[i][0];
    sum = 0;
    for(i=0; i<n; ++i){
        for(ii=0; ii<py[i].n; ++ii){
            r = 0;
            c[r++] = make_pair(0.0, 0);
            c[r++] = make_pair(1.0, 0);
            for(j=0; j<n; ++j){
                if(i==j) continue;
                for(jj=0; jj<py[j].n; ++jj){
                    ta = dcmp(tri(py[i][ii], py[i][ii+1], py[j][jj]));
                    tb = dcmp(tri(py[i][ii], py[i][ii+1], py[j][jj+1]));
                };
                if(ta==0 && tb==0){
                    if((py[j][jj+1]-py[j][jj])*(py[i][ii+1]-py[i][
                        ii]) > 0 && j < i){
                        c[r++] = make_pair(segP(py[j][jj], py[i][ii],
                            py[i][ii+1]), 1);
                        c[r++] = make_pair(segP(py[j][jj+1], py[i][ii
                            ], py[i][ii+1]), -1);
                    }
                }
                else if(ta >= 0 && tb < 0){
                    tc = tri(py[j][jj], py[j][jj+1], py[i][ii]);
                    td = tri(py[j][jj], py[j][jj+1], py[i][ii+1]);
                    c[r++] = make_pair(tc/(tc-td), 1);
                }
                else if(ta < 0 && tb >= 0){
                    tc = tri(py[j][jj], py[j][jj+1], py[i][ii]);
                    td = tri(py[j][jj], py[j][jj+1], py[i][ii+1]);
                    c[r++] = make_pair(tc/(tc-td), -1);
                }
            }
        }
    }
    sort(c, c+r);
    z = min(max(c[0].first, 0.0), 1.0);
    d = c[0].second; s = 0;
    for(j=1; j<r; ++j){
        w = min(max(c[j].first, 0.0), 1.0);
        if(!d) s += w - z;
        d += c[j].second; z = w;
    }
    sum += (py[i][ii]^py[i][ii+1])*s;
}

```



```

    }
}
return sum/2;
}

```

4.15 Lower Concave Hull dd665b

```

const ll is_query = -(1LL<<62);
struct Line {
    ll m, b;
    mutable function<const Line*> succ;
    bool operator<(const Line& rhs) const {
        if (rhs.b != is_query) return m < rhs.m;
        const Line* s = succ();
        return s ? b - s->b < (s->m - m) * rhs.m : 0;
    }
}; // maintain upper hull for maximum
struct HullDynamic : public multiset<Line> {
    bool bad(iterator y) {
        auto z = next(y);
        if (y == begin()) {
            if (z == end()) return 0;
            return y->m == z->m && y->b <= z->b;
        }
        auto x = prev(y);
        if (z == end()) return y->m == x->m && y->b <= x->b;
        return (x->b - y->b) * (z->m - y->m) >=
            (y->b - z->b) * (y->m - x->m);
    }
    void insert_line(ll m, ll b) {
        auto y = insert({m, b});
        y->succ = [=]{return next(y) == end() ? 0 : *next(y);};
        if (bad(y)) {erase(y); return;}
        while (next(y) != end() && bad(next(y))) erase(next(y));
        while (y != begin() && bad(prev(y))) erase(prev(y));
    }
    ll eval(ll x) {
        auto l = *lower_bound((Line) {x, is_query});
        return l.m * x + l.b;
    }
};

```

4.16 Delaunay Triangulation cee898

/ Delaunay Triangulation:*
 Given a sets of points on 2D plane, find a triangulation such that no points will strictly inside circumcircle of any triangle.

find : return a triangle contain given point
 add_point : add a point into triangulation

A Triangle is in triangulation iff. its has_chd is 0.
 Region of triangle u: iterate each u.edge[i].tri,
 each points are u.p[(i+1)%3], u.p[(i+2)%3]

Voronoi diagram: for each triangle in triangulation,
 the bisector of all its edges will split the region.
 nearest point will belong to the triangle containing it
*/**

```

const int N = 100000 + 5;
const type inf = 2e3;
type eps = 1e-6; // 0 when integer
type sqr(type x) { return x*x; }
// return p4 is in circumcircle of tri(p1,p2,p3)
bool in_cc(const Pt& p1, const Pt& p2, const Pt& p3,
    const Pt& p4){
    type u11 = p1.x - p4.x; type u12 = p1.y - p4.y;
    type u21 = p2.x - p4.x; type u22 = p2.y - p4.y;
    type u31 = p3.x - p4.x; type u32 = p3.y - p4.y;
    type u13 = sqr(p1.x)-sqr(p4.x)+sqr(p1.y)-sqr(p4.y);
    type u23 = sqr(p2.x)-sqr(p4.x)+sqr(p2.y)-sqr(p4.y);
    type u33 = sqr(p3.x)-sqr(p4.x)+sqr(p3.y)-sqr(p4.y);
    type det = -u13*u22*u31 + u12*u23*u31 + u13*u21*u32
        -u11*u23*u32 - u12*u21*u33 + u11*u22*u33;
    return det > eps;
}
type side(const Pt& a, const Pt& b, const Pt& p)
{ return (b - a) ^ (p - a); }
typedef int SdRef;
struct Tri;
typedef Tri* TriRef;

```

```

struct Edge {
    TriRef tri; SdRef side;
    Edge():tri(0), side(0){}
    Edge(TriRef _tri, SdRef _side):tri(_tri), side(_side)
    {}
};
struct Tri {
    Pt p[3];
    Edge edge[3];
    TriRef chd[3];
    Tri() {}
    Tri(const Pt& p0, const Pt& p1, const Pt& p2) {
        p[0] = p0; p[1] = p1; p[2] = p2;
        chd[0] = chd[1] = chd[2] = 0;
    }
    bool has_chd() const { return chd[0] != 0; }
    int num_chd() const {
        return chd[0] == 0 ? 0
            : chd[1] == 0 ? 1
            : chd[2] == 0 ? 2 : 3;
    }
    bool contains(Pt const& q) const {
        for (int i = 0; i < 3; i++)
            if (side(p[i], p[(i+1)%3], q) < -eps)
                return false;
        return true;
    }
} pool[ N * 10 ], *tris;
void edge( Edge a, Edge b ){
    if(a.tri) a.tri->edge[a.side] = b;
    if(b.tri) b.tri->edge[b.side] = a;
}
struct Trig { // Triangulation
    Trig(){
        the_root = // Tri should at least contain all points
            new(tris++)Tri(Pt(-inf,-inf),Pt(+inf+inf,-inf),Pt
                (-inf,+inf+inf));
    }
    TriRef find(Pt p){ return find(the_root,p); }
    void add_point(const Pt& p){ add_point(find(the_root,p),p); }
    TriRef the_root;
    static TriRef find(TriRef root, const Pt& p) {
        while( true ){
            if( !root->has_chd() )
                return root;
            for( int i = 0; i < 3 && root->chd[i] ; ++i )
                if (root->chd[i]->contains(p)) {
                    root = root->chd[i];
                    break;
                }
        }
        assert( false ); // "point not found"
    }
    void add_point(TriRef root, Pt const& p) {
        TriRef tab,tbc,tca;
        /* split it into three triangles */
        tab=new(tris++) Tri(root->p[0],root->p[1],p);
        tbc=new(tris++) Tri(root->p[1],root->p[2],p);
        tca=new(tris++) Tri(root->p[2],root->p[0],p);
        edge(Edge(tab,0), Edge(tbc,1));
        edge(Edge(tbc,0), Edge(tca,1));
        edge(Edge(tca,0), Edge(tab,1));
        edge(Edge(tab,2), root->edge[2]);
        edge(Edge(tbc,2), root->edge[0]);
        edge(Edge(tca,2), root->edge[1]);
        root->chd[0] = tab;
        root->chd[1] = tbc;
        root->chd[2] = tca;
        flip(tab,2);
        flip(tbc,2);
        flip(tca,2);
    }
    void flip(TriRef tri, SdRef pi) {
        TriRef trj = tri->edge[pi].tri;
        int pj = tri->edge[pi].side;
        if (!trj) return;
        if (!in_cc(tri->p[0],tri->p[1],tri->p[2],trj->p[pj]))
            return;
        /* flip edge between tri,trj */
        TriRef trk = new(tris++) Tri(tri->p[(pi+1)%3], trj->
            p[pj], tri->p[pi]);
    }
}

```



```

    TriRef trl = new(tris++) Tri(trj->p[(pj+1)%3], tri->
        p[pi], trj->p[pj]);
    edge(Edge(trk,0), Edge(trl,0));
    edge(Edge(trk,1), tri->edge[(pi+2)%3]);
    edge(Edge(trk,2), trj->edge[(pj+1)%3]);
    edge(Edge(trl,1), trj->edge[(pj+2)%3]);
    edge(Edge(trl,2), tri->edge[(pi+1)%3]);
    tri->chd[0]=trk; tri->chd[1]=trl; tri->chd[2]=0;
    trj->chd[0]=trk; trj->chd[1]=trl; trj->chd[2]=0;
    flip(trk,1); flip(trk,2);
    flip(trl,1); flip(trl,2);
}
};
vector<TriRef> triang; // vector of all triangle
set<TriRef> vst;
void go( TriRef now ){ // store all tri into triang
    if( vst.find( now ) != vst.end() )
        return;
    vst.insert( now );
    if( !now->has_chd() ){
        triang.push_back( now );
        return;
    }
    for( int i = 0 ; i < now->num_chd() ; i ++ )
        go( now->chd[ i ] );
}
void build( int n , Pt* ps ){ // build triangulation
    tris = pool; triang.clear(); vst.clear();
    random_shuffle(ps, ps + n);
    Trig tri; // the triangulation structure
    for(int i = 0; i < n; ++ i)
        tri.add_point(ps[i]);
    go( tri.the_root );
}

```

4.17 Min Enclosing Circle 9ca717

```

struct Mec{
    // return pair of center and r
    static const int N = 101010;
    int n;
    Pt p[ N ], cen;
    double r2;
    void init( int _n , Pt _p[] ){
        n = _n;
        memcpy( p , _p , sizeof(Pt) * n );
    }
    double sqr(double a){ return a*a; }
    Pt center(Pt p0, Pt p1, Pt p2) {
        Pt a = p1-p0;
        Pt b = p2-p0;
        double c1=norm2( a ) * 0.5;
        double c2=norm2( b ) * 0.5;
        double d = a ^ b;
        double x = p0.x + (c1 * b.y - c2 * a.y) / d;
        double y = p0.y + (a.x * c2 - b.x * c1) / d;
        return Pt(x,y);
    }
    pair<Pt,double> solve(){
        random_shuffle(p,p+n);
        r2=0;
        for (int i=0; i<n; i++){
            if (norm2(cen-p[i]) <= r2) continue;
            cen = p[i];
            r2 = 0;
            for (int j=0; j<i; j++){
                if (norm2(cen-p[j]) <= r2) continue;
                cen=Pt((p[i].x+p[j].x)/2,(p[i].y+p[j].y)/2);
                r2 = norm2(cen-p[j]);
                for (int k=0; k<j; k++){
                    if (norm2(cen-p[k]) <= r2) continue;
                    cen = center(p[i],p[j],p[k]);
                    r2 = norm2(cen-p[k]);
                }
            }
        }
        return {cen,sqrt(r2)};
    }
} mec;

```

4.18 Min Enclosing Ball 64186c

```

// Pt : { x , y , z }
#define N 202020
int n, nouter; Pt pt[ N ], outer[4], res;
double radius,tmp;
double det(double m[3][3]){
    return m[0][0]*m[1][1]*m[2][2]
        + m[0][1]*m[1][2]*m[2][0]
        + m[0][2]*m[1][0]*m[2][1]
        - m[0][2]*m[1][1]*m[2][0]
        - m[0][1]*m[1][0]*m[2][2]
        - m[0][0]*m[1][2]*m[2][1];
}
void ball() {
    Pt q[3]; double m[3][3], sol[3], L[3], d;
    int i,j; res.x = res.y = res.z = radius = 0;
    switch ( nouter ) {
        case 1: res=outer[0]; break;
        case 2: res=(outer[0]+outer[1])/2; radius=norm2(res,
            outer[0]); break;
        case 3:
            for(i=0; i<2; ++i) q[i]=outer[i+1]-outer[0];
            for(i=0; i<2; ++i) for(j=0; j<2; ++j) m[i][j]=(q[i]
                * q[j])*2;
            for(i=0; i<2; ++i) sol[i]=(q[i] * q[i]);
            if(fabs(d=m[0][0]*m[1][1]-m[0][1]*m[1][0])<eps)
                return;
            L[0]=(sol[0]*m[1][1]-sol[1]*m[0][1])/d;
            L[1]=(sol[1]*m[0][0]-sol[0]*m[1][0])/d;
            res=outer[0]+q[0]*L[0]+q[1]*L[1];
            radius=norm2(res, outer[0]);
            break;
        case 4:
            for(i=0; i<3; ++i) q[i]=outer[i+1]-outer[0], sol[i]
                =(q[i] * q[i]);
            for(i=0; i<3; ++i) for(j=0; j<3; ++j) m[i][j]=(q[i] *
                q[j])*2;
            d=det(m);
            if(fabs(d)<eps) return;
            for(j=0; j<3; ++j) {
                for(i=0; i<3; ++i) m[i][j]=sol[i];
                L[j]=det(m) / d;
                for(i=0; i<3; ++i) m[i][j]=(q[i] * q[j])*2;
            }
            res=outer[0];
            for(i=0; i<3; ++i) res = res + q[i] * L[i];
            radius=norm2(res, outer[0]);
    }
}
void minball(int n){ ball();
    if(nouter < 4) for(int i = 0; i < n; i ++){
        if(norm2(res, pt[i]) - radius > eps){
            outer[nouter ++] = pt[i]; minball(i); --nouter;
            if(i>0){ Pt Tt = pt[i];
                memmove(&pt[1], &pt[0], sizeof(Pt)*i); pt[0]=Tt;
            }
        }
    }
    double solve(){
        // n points in pt
        random_shuffle(pt, pt+n); radius=-1;
        for(int i=0; i<n; i++){ if(norm2(res,pt[i])-radius>eps)
            nouter=1, outer[0]=pt[i], minball(i);
        }
        return sqrt(radius);
    }
}

```

4.19 Minkowski sum 71066d

```

vector<Pt> minkowski(vector<Pt> p, vector<Pt> q){
    int n = p.size() , m = q.size();
    Pt c = Pt(0, 0);
    for( int i = 0; i < m; i ++ ) c = c + q[i];
    c = c / m;
    for( int i = 0; i < m; i ++ ) q[i] = q[i] - c;
    int cur = -1;
    for( int i = 0; i < m; i ++ )
        if( (q[i] ^ (p[0] - p[n-1])) > -eps)
            if( cur == -1 || (q[i] ^ (p[0] - p[n-1])) >
                (q[cur] ^ (p[0] - p[n-1])) )
                cur = i;
    vector<Pt> h;
    p.push_back(p[0]);
    for( int i = 0; i < n; i ++ )
        while( true ){
            h.push_back(p[i] + q[cur]);
            int nxt = (cur + 1 == m ? 0 : cur + 1);
            if((q[cur] ^ (p[i+1] - p[i])) < -eps) cur = nxt;
        }
    }

```

```

    else if( (q[nxt] ^ (p[i+1] - p[i])) >
             (q[cur] ^ (p[i+1] - p[i])) ) cur = nxt;
    else break;
}
for(auto &&i : h) i = i + c;
return convex_hull(h);
}

```

4.20 Min dist on Cuboid 30cd50

```

typedef LL T;
T r;
void turn(T i, T j, T x, T y, T z,
          T x0, T y0, T L, T W, T H) {
    if (z==0) { T R = x*x+y*y; if (R<r) r=R; return; }
    if(i>=0 && i< 2) turn(i+1, j, x0+L+z, y, x0+L-x,
                        x0+L, y0, H, W, L);
    if(j>=0 && j< 2) turn(i, j+1, x, y0+W+z, y0+W-y,
                        x0, y0+W, L, H, W);
    if(i<=0 && i>-2) turn(i-1, j, x0-z, y, x-x0,
                        x0-H, y0, H, W, L);
    if(j<=0 && j>-2) turn(i, j-1, x, y0-z, y-y0,
                        x0, y0-H, L, H, W);
}
T solve(T L, T W, T H,
        T x1, T y1, T z1, T x2, T y2, T z2){
    if( z1!=0 && z1!=H ){
        if( y1==0 || y1==W )
            swap(y1,z1), swap(y2,z2), swap(W,H);
        else swap(x1,z1), swap(x2,z2), swap(L,H);
    }
    if (z1==H) z1=0, z2=H-z2;
    r=INF; turn(0,0,x2-x1,y2-y1,z2,-x1,-y1,L,W,H);
    return r;
}

```

4.21 Heart of Triangle 4da867

```

Pt inCenter( Pt &A, Pt &B, Pt &C) { // 內心
    double a = norm(B-C), b = norm(C-A), c = norm(A-B);
    return (A * a + B * b + C * c) / (a + b + c);
}
Pt circumCenter( Pt &a, Pt &b, Pt &c) { // 外心
    Pt bb = b - a, cc = c - a;
    double db=norm2(bb), dc=norm2(cc), d=2*(bb ^ cc);
    return a-Pt(bb.Y*dc-cc.Y*db, cc.X*db-bb.X*dc) / d;
}
Pt othroCenter( Pt &a, Pt &b, Pt &c) { // 垂心
    Pt ba = b - a, ca = c - a, bc = b - c;
    double Y = ba.Y * ca.Y * bc.Y,
           A = ca.X * ba.Y - ba.X * ca.Y,
           x0= (Y+ca.X*ba.Y*b.X-ba.X*ca.Y*c.X) / A,
           y0= -ba.X * (x0 - c.X) / ba.Y + ca.Y;
    return Pt(x0, y0);
}

```

5 Graph

5.1 DominatorTree aea6b3

```

const int MAXN = 100010;
struct DominatorTree{
#define REP(i,s,e) for(int i=(s);i<=(e);i++)
#define REPD(i,s,e) for(int i=(s);i>=(e);i--)
    int n, m, s;
    vector< int > g[ MAXN ], pred[ MAXN ];
    vector< int > cov[ MAXN ];
    int dfn[ MAXN ], nfd[ MAXN ], ts;
    int par[ MAXN ];
    int sdom[ MAXN ], idom[ MAXN ];
    int mom[ MAXN ], mn[ MAXN ];
    inline bool cmp( int u, int v )
    { return dfn[ u ] < dfn[ v ]; }
    int eval( int u ){
        if( mom[ u ] == u ) return u;
        int res = eval( mom[ u ] );
        if(cmp( sdom[ mn[ mom[ u ] ] ], sdom[ mn[ u ] ] ))
            mn[ u ] = mn[ mom[ u ] ];
        return mom[ u ] = res;
    }
    void init( int _n, int _m, int _s ){
        ts = 0; n = _n; m = _m; s = _s;

```

```

        REP( i, 1, n ) g[ i ].clear(), pred[ i ].clear();
    }
    void addEdge( int u, int v ){
        g[ u ].push_back( v );
        pred[ v ].push_back( u );
    }
    void dfs( int u ){
        ts++;
        dfn[ u ] = ts;
        nfd[ ts ] = u;
        for( int v : g[ u ] ) if( dfn[ v ] == 0 ){
            par[ v ] = u;
            dfs( v );
        }
    }
    void build(){
        REP( i, 1, n ){
            dfn[ i ] = nfd[ i ] = 0;
            cov[ i ].clear();
            mom[ i ] = mn[ i ] = sdom[ i ] = i;
        }
        dfs( s );
        REPD( i, n, 2 ){
            int u = nfd[ i ];
            if( u == 0 ) continue;
            for( int v : pred[ u ] ) if( dfn[ v ] ){
                eval( v );
                if( cmp( sdom[ mn[ v ] ], sdom[ u ] ) )
                    sdom[ u ] = sdom[ mn[ v ] ];
            }
            cov[ sdom[ u ] ].push_back( u );
            mom[ u ] = par[ u ];
            for( int w : cov[ par[ u ] ] ){
                eval( w );
                if( cmp( sdom[ mn[ w ] ], par[ u ] ) )
                    idom[ w ] = mn[ w ];
                else idom[ w ] = par[ u ];
            }
            cov[ par[ u ] ].clear();
        }
        REP( i, 2, n ){
            int u = nfd[ i ];
            if( u == 0 ) continue;
            if( idom[ u ] != sdom[ u ] )
                idom[ u ] = idom[ idom[ u ] ];
        }
    }
} domT;

```

5.2 Directed MST(ElogE) 4b46a2

```

struct RollbackUF {
    vi e; vector<pii> st;
    RollbackUF(int n) : e(n, -1) {}
    int size(int x) {return -e[find(x)];}
    int find(int x) {return e[x] < 0 ? x : find(e[x]);}
    int time() {return st.size();}
    void rollback(int t) {
        for(int i = time(); i-->t;)
            e[st[i].first] = st[i].second;
        st.resize(t);
    }
    bool join(int a, int b) {
        a = find(a), b = find(b);
        if(a == b) return false;
        if(e[a] > e[b]) swap(a, b);
        st.push_back({a, e[a]}); st.push_back({b, e[b]});
        e[a] += e[b]; e[b] = a;
        return true;
    }
};
struct Edge {int a, b; ll w;};
struct Node { // lazy skew heap node
    Edge key; Node *l, *r; ll d;
    void prop() {
        key.w+=d; if(l) l->d+=d; if(r) r->d+=d; d=0;
    }
    Edge top() {prop(); return key;}
};
Node *merge(Node *a, Node *b) {
    if(!a || !b) return a ? b : a->prop(), b->prop();

```

```

    if(a->key.w > b->key.w) swap(a, b);
    swap(a->l, (a->r = merge(b, a->r)));
    return a;
}
void pop(Node*& a) {a->prop(); a=merge(a->l, a->r);}
pair<ll, vi> dmst(int n, int r, vector<Edge>& g) {
    RollbackUF uf(n); vector<Node*> pq(n);
    for(Edge e:g) pq[e.b]=merge(pq[e.b], new Node{e});
    ll res = 0; vi seen(n, -1), path(n), par(n);
    seen[r] = r;
    vector<Edge> Q(n), in(n, {-1,-1});
    deque<tuple<int, int, vector<Edge>>> cys;
    rep(s,0,n) {
        int u = s, qi = 0, w;
        while(seen[u] < 0) {
            if(!pq[u]) return {-1,{};};
            Edge e = pq[u]->top();
            pq[u]->d -= e.w, pop(pq[u]);
            Q[qi] = e, path[qi++] = u, seen[u] = s;
            res += e.w, u = uf.find(e.a);
            if(seen[u] == s) { // found cycle, contract
                Node* cyc = 0; int end = qi, t = uf.time();
                do cyc = merge(cyc, pq[w = path[--qi]]);
                while(uf.join(u, w));
                u = uf.find(u), pq[u] = cyc, seen[u] = -1;
                cys.push_front({u, t, {&Q[qi], &Q[end]}});
            }
        }
        rep(i,0,qi) in[uf.find(Q[i].b)] = Q[i];
    }
    for(auto& [u,t,comp] : cys) { // restore sol
        uf.rollback(t); Edge inEdge = in[u];
        for(auto& e : comp) in[uf.find(e.b)] = e;
        in[uf.find(inEdge.b)] = inEdge;
    }
    rep(i,0,n) par[i] = in[i].a;
    return {res, par};
}

```

5.3 MaximalClique a8cba8

```

#define N 80
struct MaxClique { // 0-base
    typedef bitset<N> Int;
    Int lnk[N], v[N];
    int n;
    void init(int _n) {
        n = _n;
        for(int i = 0; i < n; i++) {
            lnk[i].reset(); v[i].reset();
        }
    }
    void addEdge(int a, int b) {
        v[a][b] = v[b][a] = 1;
    }
    int ans, stk[N], id[N], di[N], deg[N];
    Int cans;
    void dfs(int elem_num, Int candi, Int ex) {
        if(candi.none() && ex.none()) {
            cans.reset();
            for(int i = 0; i < elem_num; i++)
                cans[id[stk[i]]] = 1;
            ans = elem_num; // cans is a maximal clique
            return;
        }
        int pivot = (candi & ex)._Find_first();
        Int smaller_candi = candi & (~lnk[pivot]);
        while(smaller_candi.count()) {
            int nxt = smaller_candi._Find_first();
            candi[nxt] = smaller_candi[nxt] = 0;
            ex[nxt] = 1;
            stk[elem_num] = nxt;
            dfs(elem_num+1, candi & lnk[nxt], ex & lnk[nxt]);
        }
    }
    int solve() {
        for(int i = 0; i < n; i++) {
            id[i] = i; deg[i] = v[i].count();
        }
        sort(id, id + n, [&](int id1, int id2) {
            return deg[id1] > deg[id2];
        });
        for(int i = 0; i < n; i++) di[id[i]] = i;
        for(int i = 0; i < n; i++)

```

```

        for(int j = 0; j < n; j++)
            if(v[i][j]) lnk[di[i]][di[j]] = 1;
        ans = 1; cans.reset(); cans[0] = 1;
        dfs(0, Int(string(n, '1')), 0);
        return ans;
    }
} solver;

```

5.4 MaxCliqueDyn e0119d

```

#define N 150
struct MaxClique { // Maximum Clique
    bitset<N> a[N], cs[N];
    int ans, sol[N], q, cur[N], d[N], n;
    void init(int _n) {
        n = _n; for(int i = 0; i < n; i++) a[i].reset();
    }
    void addEdge(int u, int v) { a[u][v] = a[v][u] = 1; }
    void csort(vector<int> &r, vector<int> &c) {
        int mx = 1, km = max(ans - q + 1, 1), t = 0, m = r.size();
        cs[1].reset(); cs[2].reset();
        for(int i = 0; i < m; i++) {
            int p = r[i], k = 1;
            while((cs[k] & a[p]).count()) k++;
            if(k > mx) { mx++; cs[mx+1].reset(); }
            cs[k][p] = 1;
            if(k < km) r[t++] = p;
        }
        c.resize(m);
        if(t) c[t-1] = 0;
        for(int k = km; k <= mx; k++) {
            for(int p = cs[k]._Find_first(); p < N; p = cs[k]._Find_next(p)) {
                r[t] = p; c[t] = k; t++;
            }
        }
    }
    void dfs(vector<int> &r, vector<int> &c, int l, bitset<N> mask) {
        while(!r.empty()) {
            int p = r.back(); r.pop_back(); mask[p] = 0;
            if(q + c.back() <= ans) return;
            cur[q++] = p;
            vector<int> nr, nc; bitset<N> nmask = mask & a[p];
            for(int i : r) if(a[p][i]) nr.push_back(i);
            if(!nr.empty()) {
                if(l < 4) {
                    for(int i : nr) d[i] = (a[i] & nmask).count();
                    sort(nr.begin(), nr.end(), [&](int x, int y) {
                        return d[x] > d[y];
                    });
                    csort(nr, nc); dfs(nr, nc, l+1, nmask);
                }
            }
            else if(q > ans) {
                ans = q; copy(cur, cur + q, sol);
            }
            c.pop_back(); q--;
        }
    }
    int solve(bitset<N> mask = bitset<N>(string(N, '1')) { //
        vertex mask
        vector<int> r, c; ans = q = 0;
        for(int i = 0; i < n; i++) if(mask[i]) r.push_back(i);
        for(int i = 0; i < n; i++) d[i] = (a[i] & mask).count();
        sort(r.begin(), r.end(), [&](int i, int j) { return d[i] > d[j]; });
        csort(r, c); dfs(r, c, 1, mask);
        return ans; // sol[0 ~ ans-1]
    }
} graph;

```

5.5 Strongly Connected Component 10c233

```

void dfs(int i) {
    V[i] = low[i] = ++ts, stk[top++] = i, instk[i] = 1;
    for(auto x : E[i]) {
        if(!V[x]) dfs(x), low[i] = min(low[i], low[x]);
        else if(instk[x]) low[i] = min(low[i], V[x]);
    }
    if(V[i] == low[i]) {
        int j;
        do { j = stk[--top], instk[j] = 0, scc[j] = i;

```

```

    }while(j != i);
}
}

```

5.6 Dynamic MST 12c615

```

/* Dynamic MST O( Q lg^2 Q )
n nodes, m edges, Q query
(u[i], v[i], w[i])->edge
(qid[i], qw[i])->chg weight of edge No.qid[i] to qw[i]
delete an edge: (i, \infty)
add an edge: change from \infty to specific value */
const int SZ=M+3*MXQ;
int a[N],*tz;
int find(int x){
    return x==a[x]?x:a[x]=find(a[x]);
}
bool cmp(int aa,int bb){ return tz[aa]<tz[bb]; }
int kx[N],ky[N],kt, vd[N],id[M], app[M], cur;
long long answer[MXQ]; // answer after ith query
bool extra[M];
void solve(int *qx,int *qy,int Q,int n,int *x,int *y,int
    *z,int m1,long long ans){
    if(Q==1){
        for(int i=1;i<=n;i++) a[i]=0;
        z[ qx[0] ]=qy[0]; tz = z;
        for(int i=0;i<m1;i++) id[i]=i;
        sort(id,id+m1,cmp); int ri,rj;
        for(int i=0;i<m1;i++){
            ri=find(x[id[i]]); rj=find(y[id[i]]);
            if(ri!=rj){ ans+=z[id[i]]; a[ri]=rj; }
        }
        answer[cur++]=ans;
        return;
    }
    int ri,rj;
    //contract
    kt=0;
    for(int i=1;i<=n;i++) a[i]=0;
    for(int i=0;i<Q;i++){
        ri=find(x[qx[i]]); rj=find(y[qx[i]]); if(ri!=rj) a[ri]=rj;
    }
    int tm=0;
    for(int i=0;i<m1;i++) extra[i]=true;
    for(int i=0;i<Q;i++) extra[ qx[i] ]=false;
    for(int i=0;i<m1;i++) if(extra[i]) id[tm++]=i;
    tz=z; sort(id,id+tm,cmp);
    for(int i=0;i<tm;i++){
        ri=find(x[id[i]]); rj=find(y[id[i]]);
        if(ri!=rj){
            a[ri]=rj; ans += z[id[i]];
            kx[kt]=x[id[i]]; ky[kt]=y[id[i]]; kt++;
        }
    }
    for(int i=1;i<=n;i++) a[i]=0;
    for(int i=0;i<kt;i++) a[ find(kx[i]) ]=find(ky[i]);
    int n2=0;
    for(int i=1;i<=n;i++) if(a[i]==0)
        vd[i]++;n2;
    for(int i=1;i<=n;i++) if(a[i])
        vd[i]=vd[find(i)];
    int m2=0, *Nx=x+m1, *Ny=y+m1, *Nz=z+m1;
    for(int i=0;i<m1;i++) app[i]=-1;
    for(int i=0;i<Q;i++) if(app[qx[i]]==-1){
        Nx[m2]=vd[ x[ qx[i] ] ]; Ny[m2]=vd[ y[ qx[i] ] ]; Nz
            [m2]=z[ qx[i] ];
        app[qx[i]]=m2; m2++;
    }
    for(int i=0;i<Q;i++){ z[ qx[i] ]=qy[i]; qx[i]=app[qx[i]]; }
    for(int i=1;i<=n2;i++) a[i]=0;
    for(int i=0;i<tm;i++){
        ri=find(vd[ x[id[i]] ]); rj=find(vd[ y[id[i]] ]);
        if(ri!=rj){
            a[ri]=rj; Nx[m2]=vd[ x[id[i]] ];
            Ny[m2]=vd[ y[id[i]] ]; Nz[m2]=z[id[i]]; m2++;
        }
    }
    int mid=Q/2;
    solve(qx,qy,mid,n2,Nx,Ny,Nz,m2,ans);
    solve(qx+mid,qy+mid,Q-mid,n2,Nx,Ny,Nz,m2,ans);
}

```

```

}
int u[SZ],v[SZ],w[SZ],qid[MXQ],qw[MXQ],n,m,Q;
void work(){if(Q) cur=0,solve(qid,qw,Q,n,u,v,w,m,0);}
}

```

5.7 Maximum General graph Matching a70889

```

// should shuffle vertices and edges
const int N = 100005, E = (2e5) * 2 + 40;
struct Graph{
    int to[E],bro[E],head[N],e;
    int lnk[N],vis[N],stp,n;
    void init( int _n ){
        stp = 0; e = 1; n = _n;
        for( int i = 1 ; i <= n ; i ++ )
            head[i] = lnk[i] = vis[i] = 0;
    }
    void add_edge(int u,int v){
        to[e]=v,bro[e]=head[u],head[u]=e++;
        to[e]=u,bro[e]=head[v],head[v]=e++;
    }
    bool dfs(int x){
        vis[x]=stp;
        for(int i=head[x];i;i=bro[i]){
            int v=to[i];
            if(!lnk[v]){
                lnk[x]=v,lnk[v]=x;
                return true;
            }
        }
        for(int i=head[x];i;i=bro[i]){
            int v=to[i];
            if(vis[lnk[v]]<stp){
                int w=lnk[v];
                lnk[x]=v,lnk[v]=x,lnk[w]=0;
                if(dfs(w)) return true;
                lnk[w]=v,lnk[v]=w,lnk[x]=0;
            }
        }
        return false;
    }
    int solve(){
        int ans = 0;
        for(int i=1;i<=n;i++) if(!lnk[i])
            stp++, ans += dfs(i);
        return ans;
    }
} graph;

```

5.8 Minimum General Weighted Matching 069df0

```

struct Graph {
    // Minimum General Weighted Matching (Perfect Match)
    static const int MXN = 105;
    int n, edge[MXN][MXN];
    int match[MXN],dis[MXN],onstk[MXN];
    vector<int> stk;
    void init(int _n) {
        n = _n;
        for( int i = 0 ; i < n ; i ++ )
            for( int j = 0 ; j < n ; j ++ )
                edge[ i ][ j ] = 0;
    }
    void add_edge(int u, int v, int w)
    { edge[u][v] = edge[v][u] = w; }
    bool SPFA(int u){
        if (onstk[u]) return true;
        stk.PB(u);
        onstk[u] = 1;
        for (int v=0; v<n; v++){
            if (u != v && match[u] != v && !onstk[v]){
                int m = match[v];
                if (dis[m] > dis[u] - edge[v][m] + edge[u][v]){
                    dis[m] = dis[u] - edge[v][m] + edge[u][v];
                    onstk[v] = 1;
                    stk.PB(v);
                    if (SPFA(m)) return true;
                    stk.pop_back();
                    onstk[v] = 0;
                }
            }
        }
        onstk[u] = 0;
    }
}

```

```

    stk.pop_back();
    return false;
}
int solve() {
    // find a match
    for (int i=0; i<n; i+=2){
        match[i] = i+1;
        match[i+1] = i;
    }
    while (true){
        int found = 0;
        for( int i = 0 ; i < n ; i ++ )
            onstk[ i ] = dis[ i ] = 0;
        for (int i=0; i<n; i++){
            stk.clear();
            if (!onstk[i] && SPFA(i)){
                found = 1;
                while (SZ(stk)>=2){
                    int u = stk.back(); stk.pop_back();
                    int v = stk.back(); stk.pop_back();
                    match[u] = v;
                    match[v] = u;
                }
            }
        }
        if (!found) break;
    }
    int ret = 0;
    for (int i=0; i<n; i++)
        ret += edge[i][match[i]];
    ret /= 2;
    return ret;
}
}graph;

```

5.9 Maximum General Weighted Matching b48b72

```

struct WeightGraph {
    static const int INF = INT_MAX;
    static const int N = 514;
    struct edge{
        int u,v,w; edge(){}
        edge(int ui,int vi,int wi)
            :u(ui),v(vi),w(wi){}
    };
    int n,n_x;
    edge g[N*2][N*2];
    int lab[N*2];
    int match[N*2],slack[N*2],st[N*2],pa[N*2];
    int flo_from[N*2][N+1],S[N*2],vis[N*2];
    vector<int> flo[N*2];
    queue<int> q;
    int e_delta(const edge &e){
        return lab[e.u]+lab[e.v]-g[e.u][e.v].w*2;
    }
    void update_slack(int u,int x){
        if(!slack[x]||e_delta(g[u][x])<e_delta(g[slack[x]][x]))
            slack[x]=u;
    }
    void set_slack(int x){
        slack[x]=0;
        for(int u=1;u<=n;u++)
            if(g[u][x].w>0&&st[u]!=x&&S[st[u]]==0)
                update_slack(u,x);
    }
    void q_push(int x){
        if(x<=n)q.push(x);
        else for(size_t i=0;i<flo[x].size();i++)
            q_push(flo[x][i]);
    }
    void set_st(int x,int b){
        st[x]=b;
        if(x>n)for(size_t i=0;i<flo[x].size();i++)
            set_st(flo[x][i],b);
    }
    int get_pr(int b,int xr){
        int pr=find(flo[b].begin(),flo[b].end(),xr)-flo[b].begin();
        if(pr%2==1){
            reverse(flo[b].begin()+1,flo[b].end());
            return (int)flo[b].size()-pr;
        }
    }

```

```

    }else return pr;
}
void set_match(int u,int v){
    match[u]=g[u][v].v;
    if(u<=n) return;
    edge e=g[u][v];
    int xr=flo_from[u][e.u],pr=get_pr(u,xr);
    for(int i=0;i<pr;i++)set_match(flo[u][i],flo[u][i+1]);
    set_match(xr,v);
    rotate(flo[u].begin(),flo[u].begin()+pr,flo[u].end());
}
void augment(int u,int v){
    for(;;){
        int xnv=st[match[u]];
        set_match(u,v);
        if(!xnv)return;
        set_match(xnv,st[pa[xnv]]);
        u=st[pa[xnv]],v=xnv;
    }
}
int get_lca(int u,int v){
    static int t=0;
    for(++t;u||v;swap(u,v)){
        if(u==0)continue;
        if(vis[u]==t)return u;
        vis[u]=t;
        u=st[match[u]];
        if(u)u=st[pa[u]];
    }
    return 0;
}
void add_blossom(int u,int lca,int v){
    int b=n+1;
    while(b<=n_x&&st[b])++b;
    if(b>n_x)++n_x;
    lab[b]=0,S[b]=0;
    match[b]=match[lca];
    flo[b].clear();
    flo[b].push_back(lca);
    for(int x=u,y,x!=lca;x=st[pa[y]])
        flo[b].push_back(x),flo[b].push_back(y=st[match[x]]),q_push(y);
    reverse(flo[b].begin()+1,flo[b].end());
    for(int x=v,y,x!=lca;x=st[pa[y]])
        flo[b].push_back(x),flo[b].push_back(y=st[match[x]]),q_push(y);
    set_st(b,b);
    for(int x=1;x<=n_x;++x)g[b][x].w=g[x][b].w=0;
    for(int x=1;x<=n;++x)flo_from[b][x]=0;
    for(size_t i=0;i<flo[b].size();i++){
        int xs=flo[b][i];
        for(int x=1;x<=n_x;++x)
            if(g[b][x].w==0||e_delta(g[xs][x])<e_delta(g[b][x]))
                g[b][x]=g[xs][x],g[x][b]=g[x][xs];
        for(int x=1;x<=n;++x)
            if(flo_from[xs][x])flo_from[b][x]=xs;
    }
    set_slack(b);
}
void expand_blossom(int b){
    for(size_t i=0;i<flo[b].size();i++)
        set_st(flo[b][i],flo[b][i]);
    int xr=flo_from[b][g[b][pa[b]].u],pr=get_pr(b,xr);
    for(int i=0;i<pr;i+=2){
        int xs=flo[b][i],xns=flo[b][i+1];
        pa[xs]=g[xns][xs].u;
        S[xs]=1,S[xns]=0;
        slack[xs]=0,set_slack(xns);
        q_push(xns);
    }
    S[xr]=1,pa[xr]=pa[b];
    for(size_t i=pr+1;i<flo[b].size();i++){
        int xs=flo[b][i];
        S[xs]=-1,set_slack(xs);
    }
    st[b]=0;
}
bool on_found_edge(const edge &e){
    int u=st[e.u],v=st[e.v];

```



```

    if(S[v]==-1){
        pa[v]=e.u,S[v]=1;
        int nu=st[match[v]];
        slack[v]=slack[nu]=0;
        S[nu]=0,q_push(nu);
    }else if(S[v]==0){
        int lca=get_lca(u,v);
        if(!lca)return augment(u,v),augment(v,u),true;
        else add_blossom(u,lca,v);
    }
    return false;
}

bool matching(){
    memset(S+1,-1,sizeof(int)*n_x);
    memset(slack+1,0,sizeof(int)*n_x);
    q=queue<int>();
    for(int x=1;x<=n_x;++x)
        if(st[x]==x&&!match[x])pa[x]=0,S[x]=0,q_push(x);
    if(q.empty())return false;
    for(;;){
        while(q.size()){
            int u=q.front();q.pop();
            if(S[st[u]]==1)continue;
            for(int v=1;v<=n;++v)
                if(g[u][v].w>0&&st[u]!=st[v]){
                    if(e_delta(g[u][v])==0){
                        if(on_found_edge(g[u][v]))return true;
                    }else update_slack(u,st[v]);
                }
        }
        int d=INF;
        for(int b=n+1;b<=n_x;++b)
            if(st[b]==b&&S[b]==1)d=min(d,lab[b]/2);
        for(int x=1;x<=n_x;++x)
            if(st[x]==x&&slack[x]){
                if(S[x]==-1)d=min(d,e_delta(g[slack[x]][x]));
                else if(S[x]==0)d=min(d,e_delta(g[slack[x]][x])/2);
            }
        for(int u=1;u<=n;++u){
            if(S[st[u]]==0){
                if(lab[u]<=d)return 0;
                lab[u]-=d;
            }else if(S[st[u]]==1)lab[u]+=d;
        }
        for(int b=n+1;b<=n_x;++b)
            if(st[b]==b){
                if(S[st[b]]==0)lab[b]+=d*2;
                else if(S[st[b]]==1)lab[b]-=d*2;
            }
        q=queue<int>();
        for(int x=1;x<=n_x;++x)
            if(st[x]==x&&slack[x]&&st[slack[x]]!=x&&e_delta(g[slack[x]][x])==0)
                if(on_found_edge(g[slack[x]][x]))return true;
        for(int b=n+1;b<=n_x;++b)
            if(st[b]==b&&S[b]==1&&lab[b]==0)expand_blossom(b);
    }
    return false;
}

pair<long long,int> solve(){
    memset(match+1,0,sizeof(int)*n);
    n_x=n;
    int n_matches=0;
    long long tot_weight=0;
    for(int u=0;u<=n;++u)st[u]=u,flo[u].clear();
    int w_max=0;
    for(int u=1;u<=n;++u)
        for(int v=1;v<=n;++v){
            flo_from[u][v]=(u==v?u:0);
            w_max=max(w_max,g[u][v].w);
        }
    for(int u=1;u<=n;++u)lab[u]=w_max;
    while(matching())n_matches++;
    for(int u=1;u<=n;++u)
        if(match[u]&&match[u]<u)
            tot_weight+=g[u][match[u]].w;
    return make_pair(tot_weight,n_matches);
}

void add_edge( int ui , int vi , int wi ){
    g[ui][vi].w = g[vi][ui].w = wi;

```

```

    }
    void init( int _n ){
        n = _n;
        for(int u=1;u<=n;++u)
            for(int v=1;v<=n;++v)
                g[u][v]=edge(u,v,0);
    }
} graph;

```

5.10 Minimum Steiner Tree 48ef1c

```

// Minimum Steiner Tree  $O(V^3 \Delta T + V \Delta^2 2^{\Delta T})$ 
// shortest_path() should be called before solve()
// w:vertex weight, default 0
struct SteinerTree{
#define V 66
#define T 10
#define INF 1023456789
    int n , dst[V][V] , dp[1<<T][V] , tdst[V] , w[V];
    void init( int _n ){
        n = _n; fill( w , w + n , 0 );
        for( int i = 0 ; i < n ; i ++ ){
            for( int j = 0 ; j < n ; j ++ ){
                dst[ i ][ j ] = INF;
                dst[ i ][ i ] = 0;
            }
        }
    }
    void add_edge( int ui , int vi , int wi ){
        dst[ ui ][ vi ] = min( dst[ ui ][ vi ] , wi );
        dst[ vi ][ ui ] = min( dst[ vi ][ ui ] , wi );
    }
    void shortest_path(){
        for( int i = 0 ; i < n ; i ++ )
            for( int j = 0 ; j < n ; j ++ )
                if( i != j && dst[ i ][ j ] != INF )
                    dst[ i ][ j ] += w[ i ];
        for( int k = 0 ; k < n ; k ++ )
            for( int i = 0 ; i < n ; i ++ )
                for( int j = 0 ; j < n ; j ++ )
                    dst[ i ][ j ] = min( dst[ i ][ j ] ,
                        dst[ i ][ k ] + dst[ k ][ j ] );
        for( int i = 0 ; i < n ; i ++ )
            for( int j = 0 ; j < n ; j ++ )
                if( dst[ i ][ j ] != INF )
                    dst[ i ][ j ] += w[ j ];
    }
    int solve( const vector<int>& ter ){
        int t = (int)ter.size();
        for( int i = 0 ; i < ( 1 << t ) ; i ++ )
            for( int j = 0 ; j < n ; j ++ )
                dp[ i ][ j ] = INF;
        for( int i = 0 ; i < n ; i ++ )
            dp[ 0 ][ i ] = 0;
        for( int msk = 1 ; msk < ( 1 << t ) ; msk ++ ){
            if( msk == ( msk & (-msk) ) ){
                int who = __lg( msk );
                for( int i = 0 ; i < n ; i ++ )
                    dp[ msk ][ i ] = dst[ ter[ who ] ][ i ];
                continue;
            }
            for( int i = 0 ; i < n ; i ++ )
                for( int submsk = ( msk - 1 ) & msk ; submsk ;
                    submsk = ( submsk - 1 ) & msk )
                    dp[ msk ][ i ] = min( dp[ msk ][ i ] ,
                        dp[ submsk ][ i ] +
                        dp[ msk ^ submsk ][ i ] - w[ i ] );
            for( int i = 0 ; i < n ; i ++ ){
                tdst[ i ] = INF;
                for( int j = 0 ; j < n ; j ++ )
                    tdst[ i ] = min( tdst[ i ] ,
                        dp[ msk ][ j ] + dst[ j ][ i ] - w[ j ] );
            }
            for( int i = 0 ; i < n ; i ++ )
                dp[ msk ][ i ] = tdst[ i ];
        }
        int ans = INF;
        for( int i = 0 ; i < n ; i ++ )
            ans = min( ans , dp[ ( 1 << t ) - 1 ][ i ] );
        return ans;
    }
}

```

```
} solver;
```

5.11 BCC based on vertex a9edf2

```
struct BccVertex {
    int n, nScc, step, dfn[MXN], low[MXN];
    vector<int> E[MXN], sccv[MXN];
    int top, stk[MXN];
    void init(int _n) {
        n = _n; nScc = step = 0;
        for (int i=0; i<n; i++) E[i].clear();
    }
    void addEdge(int u, int v) {
        E[u].PB(v); E[v].PB(u);
    }
    void DFS(int u, int f) {
        dfn[u] = low[u] = step++;
        stk[top++] = u;
        for (auto v:E[u]) {
            if (v == f) continue;
            if (dfn[v] == -1) {
                DFS(v,u);
                low[u] = min(low[u], low[v]);
                if (low[v] >= dfn[u]) {
                    int z;
                    sccv[nScc].clear();
                    do {
                        z = stk[--top];
                        sccv[nScc].PB(z);
                    } while (z != v);
                    sccv[nScc++].PB(u);
                }
            } else {
                low[u] = min(low[u], dfn[v]);
            }
        }
    }
    vector<vector<int>> solve() {
        vector<vector<int>> res;
        for (int i=0; i<n; i++) {
            dfn[i] = low[i] = -1;
            for (int i=0; i<n; i++) {
                if (dfn[i] == -1) {
                    top = 0;
                    DFS(i,i);
                }
            }
            REP(i,nScc) res.PB(sccv[i]);
            return res;
        }
    }
} graph;
```

5.12 Min Mean Cycle b49ca6

```
/* minimum mean cycle O(VE) */
struct MMC{
#define E 101010
#define V 1021
#define inf 1e9
#define eps 1e-6
    struct Edge { int v,u; double c; };
    int n, m, prv[V][V], prve[V][V], vst[V];
    Edge e[E];
    vector<int> edgeID, cycle, rho;
    double d[V][V];
    void init( int _n )
    { n = _n; m = 0; }
    // WARNING: TYPE matters
    void addEdge( int vi , int ui , double ci )
    { e[ m ++ ] = { vi , ui , ci }; }
    void bellman_ford() {
        for(int i=0; i<n; i++) d[0][i]=0;
        for(int i=0; i<n; i++) {
            fill(d[i+1], d[i+1]+n, inf);
            for(int j=0; j<m; j++) {
                int v = e[j].v, u = e[j].u;
                if(d[i][v]<inf && d[i+1][u]>d[i][v]+e[j].c) {
                    d[i+1][u] = d[i][v]+e[j].c;
                    prv[i+1][u] = v;
                    prve[i+1][u] = j;
                }
            }
        }
    }
    double solve(){
```

```
// returns inf if no cycle, mmc otherwise
double mmc=inf;
int st = -1;
bellman_ford();
for(int i=0; i<n; i++) {
    double avg=-inf;
    for(int k=0; k<n; k++) {
        if(d[n][i]<inf-eps) avg=max(avg,(d[n][i]-d[k][i])/(n-k));
        else avg=max(avg,inf);
    }
    if (avg < mmc) tie(mmc, st) = tie(avg, i);
}
if(st==-1) return inf;
FZ(vst);edgeID.clear();cycle.clear();rho.clear();
for (int i=n; !vst[st]; st=prv[i--][st]) {
    vst[st]++;
    edgeID.PB(prve[i][st]);
    rho.PB(st);
}
while (vst[st] != 2) {
    int v = rho.back(); rho.pop_back();
    cycle.PB(v);
    vst[v]++;
}
reverse(ALL(edgeID));
edgeID.resize(SZ(cycle));
return mmc;
} mmc;
```

5.13 Directed Graph Min Cost Cycle 8de30f

```
// works in O(N M)
#define INF 10000000000000LL
#define N 5010
#define M 200010
struct edge{
    int to; LL w;
    edge(int a=0, LL b=0): to(a), w(b){}
};
struct node{
    LL d; int u, next;
    node(LL a=0, int b=0, int c=0): d(a), u(b), next(c){}
}b[M];
struct DirectedGraphMinCycle{
    vector<edge> g[N], grev[N];
    LL dp[N][N], p[N], d[N], mu;
    bool inq[N];
    int n, bn, bsz, hd[N];
    void b_insert(LL d, int u){
        int i = d/mu;
        if(i >= bn) return;
        b[++bsz] = node(d, u, hd[i]);
        hd[i] = bsz;
    }
    void init( int _n ){
        n = _n;
        for( int i = 1 ; i <= n ; i ++ )
            g[ i ].clear();
    }
    void addEdge( int ai , int bi , LL ci )
    { g[ai].push_back(edge(bi,ci)); }
    LL solve(){
        fill(dp[0], dp[0]+n+1, 0);
        for(int i=1; i<=n; i++){
            fill(dp[i+1], dp[i+1]+n+1, INF);
            for(int j=1; j<=n; j++) if(dp[i-1][j] < INF){
                for(int k=0; k<(int)g[j].size(); k++)
                    dp[i][g[j][k].to] =min(dp[i][g[j][k].to],
                                            dp[i-1][j]+g[j][k].w);
            }
        }
        mu=INF; LL bunbo=1;
        for(int i=1; i<=n; i++) if(dp[n][i] < INF){
            LL a=-INF, b=1;
            for(int j=0; j<=n-1; j++) if(dp[j][i] < INF){
                if(a*(n-j) < b*(dp[n][i]-dp[j][i])){
                    a = dp[n][i]-dp[j][i];
                    b = n-j;
                }
            }
        }
    }
}
```

```

    if(mu*b > bunbo*a)
        mu = a, bunbo = b;
}
if(mu < 0) return -1; // negative cycle
if(mu == INF) return INF; // no cycle
if(mu == 0) return 0;
for(int i=1; i<=n; i++)
    for(int j=0; j<(int)g[i].size(); j++)
        g[i][j].w *= bunbo;
memset(p, 0, sizeof(p));
queue<int> q;
for(int i=1; i<=n; i++){
    q.push(i);
    inq[i] = true;
}
while(!q.empty()){
    int i=q.front(); q.pop(); inq[i]=false;
    for(int j=0; j<(int)g[i].size(); j++){
        if(p[g[i][j].to] > p[i]+g[i][j].w-mu){
            p[g[i][j].to] = p[i]+g[i][j].w-mu;
            if(!inq[g[i][j].to]){
                q.push(g[i][j].to);
                inq[g[i][j].to] = true;
            }
        }
    }
}
for(int i=1; i<=n; i++) grev[i].clear();
for(int i=1; i<=n; i++)
    for(int j=0; j<(int)g[i].size(); j++){
        g[i][j].w += p[i]-p[g[i][j].to];
        grev[g[i][j].to].push_back(edge(i, g[i][j].w));
    }
LL mlcd = n*mu;
for(int i=1; i<=n; i++){
    bn=mlcd/mu, bsz=0;
    memset(hd, 0, sizeof(hd));
    fill(d+i+1, d+n+1, INF);
    b_insert(d[i]=0, i);
    for(int j=0; j<=bn-1; j++) for(int k=hd[j]; k; k=b[k].next){
        int u = b[k].u;
        LL du = b[k].d;
        if(du > d[u]) continue;
        for(int l=0; l<(int)g[u].size(); l++) if(g[u][l].to > i){
            if(d[g[u][l].to] > du + g[u][l].w){
                d[g[u][l].to] = du + g[u][l].w;
                b_insert(d[g[u][l].to], g[u][l].to);
            }
        }
    }
    for(int j=0; j<(int)grev[i].size(); j++) if(grev[i][j].to > i)
        mlcd=min(mlcd, d[grev[i][j].to] + grev[i][j].w);
}
return mlcd / bunbo;
}
} graph;

```

5.14 K-th Shortest Path 355040

```

// time: O(|E| \lg |E| + |V| \lg |V| + K)
// memory: O(|E| \lg |E| + |V|)
struct KSP{ // 1-base
    struct nd{
        int u, v; ll d;
        nd(int ui = 0, int vi = 0, ll di = INF)
        { u = ui; v = vi; d = di; }
    };
    struct heap{
        nd* edge; int dep; heap* chd[4];
    };
    static int cmp(heap* a, heap* b)
    { return a->edge->d > b->edge->d; }
    struct node{
        int v; ll d; heap* H; nd* E;
        node(){
            node(ll _d, int _v, nd* _E)
            { d = _d; v = _v; E = _E; }
            node(heap* _H, ll _d)
            { H = _H; d = _d; }
        }
    };

```

```

    friend bool operator<(node a, node b)
    { return a.d > b.d; }
};
int n, k, s, t, dst[ N ];
nd *nxt[ N ];
vector<nd*> g[ N ], rg[ N ];
heap *nullNd, *head[ N ];
void init( int _n , int _k , int _s , int _t ){
    n = _n; k = _k; s = _s; t = _t;
    for( int i = 1 ; i <= n ; i ++ ){
        g[ i ].clear(); rg[ i ].clear();
        nxt[ i ] = NULL; head[ i ] = NULL;
        dst[ i ] = -1;
    }
}
void addEdge( int ui , int vi , ll di ){
    nd* e = new nd(ui, vi, di);
    g[ ui ].push_back( e );
    rg[ vi ].push_back( e );
}
queue<int> dfsQ;
void dijkstra(){
    while(dfsQ.size()) dfsQ.pop();
    priority_queue<node> Q;
    Q.push(node(0, t, NULL));
    while (!Q.empty()){
        node p = Q.top(); Q.pop();
        if(dst[p.v] != -1) continue;
        dst[ p.v ] = p.d;
        nxt[ p.v ] = p.E;
        dfsQ.push( p.v );
        for(auto e: rg[ p.v ])
            Q.push(node(p.d + e->u, e->u, e));
    }
}
heap* merge(heap* curNd, heap* newNd){
    if(curNd == nullNd) return newNd;
    heap* root = new heap;
    memcpy(root, curNd, sizeof(heap));
    if(newNd->edge->d < curNd->edge->d){
        root->edge = newNd->edge;
        root->chd[2] = newNd->chd[2];
        root->chd[3] = newNd->chd[3];
        newNd->edge = curNd->edge;
        newNd->chd[2] = curNd->chd[2];
        newNd->chd[3] = curNd->chd[3];
    }
    if(root->chd[0]->dep < root->chd[1]->dep)
        root->chd[0] = merge(root->chd[0], newNd);
    else
        root->chd[1] = merge(root->chd[1], newNd);
    root->dep = max(root->chd[0]->dep, root->chd[1]->dep) + 1;
    return root;
}
vector<heap*> V;
void build(){
    nullNd = new heap;
    nullNd->dep = 0;
    nullNd->edge = new nd;
    fill(nullNd->chd, nullNd->chd+4, nullNd);
    while(not dfsQ.empty()){
        int u = dfsQ.front(); dfsQ.pop();
        if(!nxt[ u ]) head[ u ] = nullNd;
        else head[ u ] = head[nxt[ u ]->v];
        V.clear();
        for( auto&& e : g[ u ] ){
            int v = e->v;
            if( dst[ v ] == -1 ) continue;
            e->d += dst[ v ] - dst[ u ];
            if( nxt[ u ] != e ){
                heap* p = new heap;
                fill(p->chd, p->chd+4, nullNd);
                p->dep = 1;
                p->edge = e;
                V.push_back(p);
            }
        }
        if(V.empty()) continue;
        make_heap(V.begin(), V.end(), cmp);
#define L(X) ((X<<1)+1)
#define R(X) ((X<<1)+2)

```

```

    for( size_t i = 0 ; i < V.size() ; i ++ ){
        if(L(i) < V.size()) V[i]->chd[2] = V[L(i)];
        else V[i]->chd[2]=nullNd;
        if(R(i) < V.size()) V[i]->chd[3] = V[R(i)];
        else V[i]->chd[3]=nullNd;
    }
    head[u] = merge(head[u], V.front());
}
}
vector<ll> ans;
void first_KC(){
    ans.clear();
    priority_queue<node> Q;
    if( dst[ s ] == -1 ) return;
    ans.push_back( dst[ s ] );
    if( head[s] != nullNd )
        Q.push(node(head[s], dst[s]+head[s]->edge->d));
    for( int _ = 1 ; _ < k and not Q.empty() ; _ ++ ){
        node p = Q.top(), q; Q.pop();
        ans.push_back( p.d );
        if(head[ p.H->edge->v ] != nullNd){
            q.H = head[ p.H->edge->v ];
            q.d = p.d + q.H->edge->d;
            Q.push(q);
        }
        for( int i = 0 ; i < 4 ; i ++ )
            if( p.H->chd[ i ] != nullNd ){
                q.H = p.H->chd[ i ];
                q.d = p.d + p.H->edge->d + p.H->chd[ i ]->edge->d;
                Q.push( q );
            }
    }
}
void solve(){ // ans[i] stores the i-th shortest path
    dijkstra();
    build();
    first_KC(); // ans.size() might less than k
}
} solver;

```

5.15 Chordal Graph

```

struct Chordal {
    static const int MXN = 100010;
    vector<int> E[MXN], V[MXN];
    int n, f[MXN], rk[MXN], order[MXN], stk[MXN], nsz[MXN];
    bool vis[MXN], isMaximalClique[MXN];
    void init(int _n) {
        n = _n;
        for(int i = 0; i <= n; ++i) {
            E[i].clear(), V[i].clear();
            f[i]=rk[i]=order[i]=vis[i]=0;
        }
    }
    void addEdge(int x, int y) {
        E[x].push_back(y), E[y].push_back(x);
    }
    void mcs() {
        for(int i = 1; i <= n; ++i) V[0].push_back(i);
        for(int i = n, M = 0; i >= 1; --i) {
            for(;;) {
                while(V[M].size() && vis[V[M].back()])
                    V[M].pop_back();
                if(V[M].size()) break; else M--;
            }
            auto x=V[M].back(); order[i]=x; rk[x]=i; vis[x]=1;
            for(auto y : E[x]) if(!vis[y])
                f[y]++, V[f[y]].push_back(y), M=max(M, f[y]);
        }
    }
    bool isChordal() {
        for(int i = 0; i <= n; ++i) vis[i] = stk[i] = 0;
        for(int i = n; i >= 1; --i) {
            int top = 0, cnt = 0, m = n+1;
            for(auto x : E[order[i]]) if(rk[x] > i)
                stk[top++] = x, vis[x]=1, m = min(m, rk[x]);
            if(m==n+1) continue;
            for(auto x : E[order[m]]) if(vis[x]) ++cnt;
            for(int j = 0; j < top; ++j) vis[stk[j]] = 0;
            if(cnt + 1 != top) return 0;
        }
    }
}

```

```

    return 1;
}
void getMaximalClique() {
    for(int i = n; i >= 1; --i) {
        int M = n+1, w = order[i], v = 0;
        nsz[w] = 0; isMaximalClique[w] = 1;
        for(auto x : E[w]) if(rk[x] > i) {
            nsz[w]++;
            if(rk[x] < M) M = rk[x], v = x;
        }
        if(v) isMaximalClique[v] &= nsz[v]+1 > nsz[w];
    }
}
int getMaximumClique() {
    int res = 0;
    for(int i = 1; i <= n; ++i) res = max(res, f[i]+1);
    return res;
}
int getMaximumIndependentSet() {
    for(int i = 0; i <= n; ++i) vis[i] = 0;
    int res = 0;
    for(int i = 1; i <= n; ++i) if(!vis[order[i]]) {
        res++, vis[order[i]] = 1;
        for(auto x : E[order[i]]) vis[x] = 1;
    }
    return res;
}
}

```

5.16 Graph Method

Manhattan MST

For each point, consider the points that surround it(8 octants). Then, connect it with the closest point. For example, consider 45~90. For each point p, the closest point is $\min\{x+y \mid x-y \geq p.x-p.y, x \geq p.x\}$. Finally, the answer is [this new](#) graphs($E=4N$) MST.

6 String

6.1 PalTree 7280a6

```

const int MXN = 1000010;
struct PalT{
    int nxt[MXN][26], fail[MXN], len[MXN];
    int tot, lst, n, state[MXN], cnt[MXN], num[MXN];
    int diff[MXN], sfail[MXN], fac[MXN], dp[MXN];
    char s[MXN]={'-1'};
    int newNode(int l, int f){
        len[tot]=l, fail[tot]=f, cnt[tot]=num[tot]=0;
        memset(nxt[tot], 0, sizeof(nxt[tot]));
        diff[tot]=(l>0?l-len[f]:0);
        sfail[tot]=(l>0&&diff[tot]==diff[f]?sfail[f]:f);
        return tot++;
    }
    int getfail(int x){
        while(s[n-len[x]-1]!=s[n]) x=fail[x];
        return x;
    }
    int getmin(int v){
        dp[v]=fac[n-len[sfail[v]]-diff[v]];
        if(diff[v]==diff[fail[v]])
            dp[v]=min(dp[v], dp[fail[v]]);
        return dp[v]+1;
    }
    int push(){
        int c=s[n]-'a', np=getfail(lst);
        if(!(lst=nxt[np][c])){
            lst=newNode(len[np]+2, nxt[getfail(fail[np])][c]);
            nxt[np][c]=lst; num[lst]=num[fail[lst]]+1;
        }
        fac[n]=n;
        for(int v=lst; len[v]>0; v=sfail[v])
            fac[n]=min(fac[n], getmin(v));
        return ++cnt[lst], lst;
    }
    void init(const char *_s){
        tot=lst=n=0;
        newNode(0, 1), newNode(-1, 1);
        for(;; s[n];) s[n+1]=s[n], ++n, state[n-1]=push();
        for(int i=tot-1; i>1; i--) cnt[fail[i]]+=cnt[i];
    }
}

```

```
}palt;
```

6.2 SAIS 0e93de

```
const int N = 300010;
struct SA{
#define REP(i,n) for ( int i=0; i<int(n); i++ )
#define REP1(i,a,b) for ( int i=(a); i<=int(b); i++ )
    bool _t[N*2];
    int _s[N*2], _sa[N*2], _c[N*2], x[N], _p[N], _q[N*2],
        hei[N], r[N];
    int operator [] (int i){ return _sa[i]; }
    void build(int *s, int n, int m){
        memcpy(_s, s, sizeof(int) * n);
        sais(_s, _sa, _p, _q, _t, _c, n, m);
        mkhei(n);
    }
    void mkhei(int n){
        REP(i,n) r[_sa[i]] = i;
        hei[0] = 0;
        REP(i,n) if(r[i]) {
            int ans = i>0 ? max(hei[r[i]-1] - 1, 0) : 0;
            while(_s[i+ans] == _s[_sa[r[i]-1]+ans]) ans++;
            hei[r[i]] = ans;
        }
    }
    void sais(int *s, int *sa, int *p, int *q, bool *t,
        int *c, int n, int z){
        bool uniq = t[n-1] = true, neq;
        int nn = 0, nmzx = -1, *nsa = sa + n, *ns = s + n,
            lst = -1;
#define MS0(x,n) memset((x),0,n*sizeof(*(x)))
#define MAGIC(XD) MS0(sa, n); \
        memcpy(x, c, sizeof(int) * z); \
        XD; \
        memcpy(x + 1, c, sizeof(int) * (z - 1)); \
        REP(i,n) if(sa[i] && !t[sa[i]-1]) sa[x[s[sa[i]-1]]++] =
            sa[i]-1; \
        memcpy(x, c, sizeof(int) * z); \
        for(int i = n - 1; i >= 0; i--) if(sa[i] && t[sa[i]-1])
            sa[--x[s[sa[i]-1]]] = sa[i]-1;
        MS0(c, z);
        REP(i,n) uniq &= ++c[s[i]] < 2;
        REP(i,z-1) c[i+1] += c[i];
        if (uniq) { REP(i,n) sa[--c[s[i]]] = i; return; }
        for(int i = n - 2; i >= 0; i--) t[i] = (s[i]==s[i+1])
            ? t[i+1] : s[i]<s[i+1];
        MAGIC(REP1(i,1,n-1) if(t[i] && !t[i-1]) sa[--x[s[i]
            ]]=p[q[i]=nn++]=i);
        REP(i, n) if (sa[i] && t[sa[i]] && !t[sa[i]-1]) {
            neq=lst<0||memcmp(s+sa[i],s+lst,(p[q[sa[i]]+1]-sa[i]
            )*sizeof(int));
            ns[q[lst=sa[i]]]=nmzx+=neq;
        }
        sais(ns, nsa, p + nn, q + n, t + n, c + z, nn, nmzx
            + 1);
        MAGIC(for(int i = nn - 1; i >= 0; i--) sa[--x[s[p[
            nsa[i]]]]] = p[nsa[i]]);
    }
}sa;
int H[N], SA[N], RA[N];
void suffix_array(int* ip, int len) {
    // should padding a zero in the back
    // ip is int array, len is array length
    // ip[0..n-1] != 0, and ip[len] = 0
    ip[len++] = 0;
    sa.build(ip, len, 128);
    memcpy(H,sa.hei+1,len<<2);
    memcpy(SA,sa._sa+1,len<<2);
    for(int i=0; i<len; i++) RA[i] = sa.r[i]-1;
    // resulting height, sa array \in [0,len)
}
```

6.3 SuffixAutomata 94a0a8

```
// any path start from root forms a substring of S
// occurrence of P : iff SAM can run on input word P
// number of different substring : ds[1]-1
// total length of all different substring : dsl[1]
// max/min length of state i : mx[i]/mx[mom[i]]+1
// assume a run on input word P end at state i:
// number of occurrences of P : cnt[i]
```

```
// first occurrence position of P : fp[i]-lpl+1
// all position of P : fp of "dfs from i through rmom"
const int MXM = 1000010;
struct SAM{
    int tot, root, lst, mom[MXM], mx[MXM]; //ind[MXM]
    int nxt[MXM][33]; //cnt[MXM],ds[MXM],dsl[MXM],fp[MXM]
    // bool v[MXM]
    int newNode(){
        int res = ++tot;
        fill(nxt[res], nxt[res]+33, 0);
        mom[res] = mx[res] = 0; //cnt=ds=dsl=fp=v=0
        return res;
    }
    void init(){
        tot = 0; root = newNode(); lst = root;
    }
    void push(int c){
        int p = lst;
        int np = newNode(); //cnt[np]=1
        mx[np] = mx[p]+1; //fp[np]=mx[np]-1
        for(; p && nxt[p][c] == 0; p = mom[p])
            nxt[p][c] = np;
        if(p == 0) mom[np] = root;
        else{
            int q = nxt[p][c];
            if(mx[p]+1 == mx[q]) mom[np] = q;
            else{
                int nq = newNode(); //fp[nq]=fp[q]
                mx[nq] = mx[p]+1;
                for(int i = 0; i < 33; i++)
                    nxt[nq][i] = nxt[q][i];
                mom[nq] = mom[q]; mom[q] = nq; mom[np] = nq;
                for(; p && nxt[p][c] == q; p = mom[p])
                    nxt[p][c] = nq;
            }
        }
        lst = np;
    }
    void calc(){
        calc(root); iota(ind,ind+tot,1);
        sort(ind,ind+tot,[&](int i,int j){return mx[i]<mx[j];});
        for(int i=tot-1;i>=0;i--)
            cnt[mom[ind[i]]]+=cnt[ind[i]];
    }
    void calc(int x){
        v[x]=ds[x]=1;dsl[x]=0; //rmom[mom[x]].push_back(x);
        for(int i=0;i<26;i++){
            if(nxt[x][i]){
                if(!v[nxt[x][i]]) calc(nxt[x][i]);
                ds[x]+=ds[nxt[x][i]];
                dsl[x]+=dsl[nxt[x][i]]+dsl[nxt[x][i]];
            }
        }
    }
    void push(char *str){
        for(int i = 0; str[i]; i++)
            push(str[i]-'a');
    }
} sam;
```

6.4 Z Value 391d23

```
void z_value(const char *s,int len,int *z){
    z[0]=len;
    for(int i=1,l=0,r=0;i<len;i++){
        z[i]=i<r?(i-l+z[i-l]<z[l]?z[i-l]:r-i):0;
        while(i+z[i]<len&&s[i+z[i]]==s[z[i]]) ++z[i];
        if(i+z[i]>r) l=i,r=i+z[i];
    }
}
```

6.5 BWT 12ae24

```
struct BurrowsWheeler{
#define SIGMA 26
#define BASE 'a'
    vector<int> v[ SIGMA ];
    void BWT(char* ori, char* res){
        // make ori -> ori + ori
        // then build suffix array
    }
}
```



```

void iBWT(char* ori, char* res){
    for( int i = 0 ; i < SIGMA ; i ++ )
        v[ i ].clear();
    int len = strlen( ori );
    for( int i = 0 ; i < len ; i ++ )
        v[ ori[i] - BASE ].push_back( i );
    vector<int> a;
    for( int i = 0 , ptr = 0 ; i < SIGMA ; i ++ )
        for( auto j : v[ i ] ){
            a.push_back( j );
            ori[ ptr ++ ] = BASE + i;
        }
    for( int i = 0 , ptr = 0 ; i < len ; i ++ ){
        res[ i ] = ori[ a[ ptr ] ];
        ptr = a[ ptr ];
    }
    res[ len ] = 0;
}
} bwt;

```

6.6 ZValue Palindrome 66e932

```

void z_value_pal(char *s,int len,int *z){
    len=(len<<1)+1;
    for(int i=len-1;i>=0;i--){
        s[i]=i&1?s[i>>1]:'@';
        z[0]=1;
        for(int i=1,l=0,r=0;i<len;i++){
            z[i]=i<r?min(z[l+l-i],r-i):1;
            while(i-z[i]>=0&&i+z[i]<len&&s[i-z[i]]==s[i+z[i]])++
                z[i];
            if(i+z[i]>r) l=i,r=i+z[i];
        }
    }
}

```

6.7 Smallest Rotation fb9bcf

```

//rotate(begin(s),begin(s)+minRotation(s),end(s))
int minRotation(string s) {
    int a = 0, N = s.size(); s += s;
    rep(b,0,N) rep(k,0,N) {
        if(a+k == b || s[a+k] < s[b+k])
            {b += max(0, k-1); break;}
        if(s[a+k] > s[b+k]) {a = b; break;}
    } return a;
}

```

6.8 Cyclic LCS 50b06d

```

#define L 0
#define LU 1
#define U 2
const int mov[3][2]={0,-1, -1,-1, -1,0};
int al,bl;
char a[MAXL*2],b[MAXL*2]; // 0-indexed
int dp[MAXL*2][MAXL];
char pred[MAXL*2][MAXL];
inline int lcs_length(int r) {
    int i=r+al,j=bl,l=0;
    while(i>r) {
        char dir=pred[i][j];
        if(dir==LU) l++;
        i+=mov[dir][0]; j+=mov[dir][1];
    }
    return l;
}
inline void reroot(int r) { // r = new base row
    int i=r,j=1;
    while(j<=bl&&pred[i][j]!=LU) j++;
    if(j>bl) return;
    pred[i][j]=L;
    while(i<2*al&&j<=bl) {
        if(pred[i+1][j]==U) {
            i++; pred[i][j]=L;
        } else if(j<bl&&pred[i+1][j+1]==LU) {
            i++; j++; pred[i][j]=L;
        } else j++;
    }
}
int cyclic_lcs() {
    // a, b, al, bl should be properly filled
    // note: a WILL be altered in process
}

```

```

// -- concatenated after itself
char tmp[MAXL];
if(al>bl) {
    swap(al,bl); strcpy(tmp,a);
    strcpy(a,b); strcpy(b,tmp);
}
strcpy(tmp,a); strcat(a,tmp);
// basic lcs
for(int i=0;i<=2*al;i++) {
    dp[i][0]=0; pred[i][0]=U;
}
for(int j=0;j<=bl;j++) {
    dp[0][j]=0; pred[0][j]=L;
}
for(int i=1;i<=2*al;i++) {
    for(int j=1;j<=bl;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]);
        if(dp[i][j-1]==dp[i][j]) pred[i][j]=L;
        else if(a[i-1]==b[j-1]) pred[i][j]=LU;
        else pred[i][j]=U;
    }
}
// do cyclic lcs
int clcs=0;
for(int i=0;i<al;i++) {
    clcs=max(clcs,lcs_length(i)); reroot(i+1);
}
// recover a
a[al]='\0';
return clcs;
}

```

7 Data Structure

7.1 Link-Cut Tree 775e1d

```

const int MEM = 100005;
struct Splay {
    static Splay nil, mem[MEM], *pmem;
    Splay *ch[2], *f;
    int val, rev, size;
    Splay(int _val=-1) : val(_val), rev(0), size(1) {
        f = ch[0] = ch[1] = &nil;
    }
    bool isr() {
        return f->ch[0] != this && f->ch[1] != this;
    }
    int dir() {return f->ch[0] != this;}
    void setCh(Splay *c, int d) {
        ch[d] = c; if (c != &nil) c->f = this; pull();
    }
    void push() {
        if (!rev) return;
        swap(ch[0], ch[1]);
        if (ch[0] != &nil) ch[0]->rev ^= 1;
        if (ch[1] != &nil) ch[1]->rev ^= 1;
        rev=0;
    }
    void pull() {
        size = ch[0]->size + ch[1]->size + 1;
        if (ch[0] != &nil) ch[0]->f = this;
        if (ch[1] != &nil) ch[1]->f = this;
    }
} Splay::nil, Splay::mem[MEM], *Splay::pmem=Splay::mem;
Splay *nil = &Splay::nil;
void rotate(Splay *x) {
    Splay *p = x->f; int d = x->dir();
    if (!p->isr()) p->f->setCh(x, p->dir());
    else x->f = p->f;
    p->setCh(x->ch[!d], d); x->setCh(p, !d);
}
vector<Splay*> splayVec;
void splay(Splay *x) {
    splayVec.clear();
    for (Splay *q=x;; q=q->f) {
        splayVec.push_back(q);
        if (q->isr()) break;
    }
    reverse(begin(splayVec), end(splayVec));
    for (auto it : splayVec) it->push();
    while (!x->isr()) {
        if (x->f->isr()) rotate(x);
        else if (x->dir()==x->f->dir())

```

```

        rotate(x->f), rotate(x);
    else rotate(x), rotate(x);
}
}
int id(Splay *x) { return x - Splay::mem + 1; }
Splay* access(Splay *x){
    Splay *q = nil;
    for (; x!=nil; x=x->f){
        splay(x); x->setCh(q, 1); q = x;
    }
    return q;
}
void chroot(Splay *x){
    access(x); splay(x); x->rev ^= 1;
}
void link(Splay *x, Splay *y){
    chroot(y); y->f=x;
}
void cut_p(Splay *y) {
    access(y); splay(y); y->ch[0] = y->ch[0]->f = nil;
}
void cut(Splay *x, Splay *y){
    chroot(x); cut_p(y);
}
Splay* get_root(Splay *x) {
    x=access(x);
    for(; x->ch[0] != nil; x = x->ch[0]) x->push();
    splay(x); return x;
}
bool conn(Splay *x, Splay *y) {
    return get_root(x) == get_root(y);
}
Splay* lca(Splay *x, Splay *y) {
    access(x); return access(y);
}
/* query(Splay *x, Splay *y){
    setroot(y), x=access(x); return x->size;
}*/
/* query(Splay *x, Splay *y){
    Splay *p=lca(x,y);
    return p->val+p->ch[1]->size+(x!=p?x->size:0);
}*/

```

8 Others

8.1 Find max tangent(x,y is increasing) 8fea15

```

const int MAXN = 100010;
Pt sum[MAXN], pnt[MAXN], ans, calc;
inline bool cross(Pt a, Pt b, Pt c){
    return (c.y-a.y)*(c.x-b.x) > (c.x-a.x)*(c.y-b.y);
} //pt[0]=(0,0); pt[i]=(i, pt[i-1].y+dy[i-1]), i=1~n; dx>=1
double find_max_tan(int n, int l, LL dy[]){
    int np, st, ed, now;
    sum[0].x = sum[0].y = np = st = ed = 0;
    for (int i = 1; i <= n; i++)
        sum[i].x = i, sum[i].y = sum[i-1].y + dy[i-1];
    ans.x = now = 1, ans.y = -1;
    for (int i = 0; i <= n - 1; i++){
        while(np>1&&cross(pnt[np-2], pnt[np-1], sum[i]))
            np--;
        if (np < now && np != 0) now = np;
        pnt[np++] = sum[i];
        while(now<np&&!cross(pnt[now-1], pnt[now], sum[i+1]))
            now++;
        calc = sum[i + 1] - pnt[now - 1];
        if (ans.y * calc.x < ans.x * calc.y)
            ans = calc, st = pnt[now - 1].x, ed = i + 1;
    }
    return (double)(sum[ed].y - sum[st].y) / (sum[ed].x - sum[st].x);
}

```

8.2 Exact Cover Set 01c503

```

// given n*m 0-1 matrix
// find a set of rows s.t.
// for each column, there's exactly one 1
#define N 1024 //row
#define M 1024 //column

```

```

#define NM ((N+2)*(M+2))
char A[N][M]; //n*m 0-1 matrix
bool used[N]; //answer: the row used
int id[N][M];
int L[NM], R[NM], D[NM], U[NM], C[NM], S[NM], ROW[NM];
void remove(int c){
    L[R[c]] = L[c]; R[L[c]] = R[c];
    for( int i=D[c]; i!=c; i=D[i] )
        for( int j=R[i]; j!=i; j=R[j] ){
            U[D[j]] = U[j]; D[U[j]] = D[j]; S[C[j]]--;
        }
}
void resume(int c){
    for( int i=D[c]; i!=c; i=D[i] )
        for( int j=L[i]; j!=i; j=L[j] ){
            U[D[j]] = D[U[j]] = j; S[C[j]]++;
        }
    L[R[c]] = R[L[c]] = c;
}
bool dfs(){
    if(R[0]==0) return 1;
    int md=100000000, c;
    for( int i=R[0]; i!=0; i=R[i] )
        if(S[i]<md){ md=S[i]; c=i; }
    if(md==0) return 0;
    remove(c);
    for( int i=D[c]; i!=c; i=D[i] ){
        used[ROW[i]] = 1;
        for( int j=R[i]; j!=i; j=R[j] ) remove(C[j]);
        if(dfs()) return 1;
        for( int j=L[i]; j!=i; j=L[j] ) resume(C[j]);
        used[ROW[i]] = 0;
    }
    resume(c);
    return 0;
}
bool exact_cover(int n, int m){
    for( int i=0; i<=m; i++){
        R[i] = i+1; L[i] = i-1; U[i] = D[i] = i;
        S[i] = 0; C[i] = i;
    }
    R[m] = 0; L[0] = m;
    int t=m+1;
    for( int i=0; i<n; i++){
        int k=-1;
        for( int j=0; j<m; j++){
            if(!A[i][j]) continue;
            if(k==-1) L[t]=R[t]=t;
            else{ L[t]=k; R[t]=R[k]; }
            k=t; D[t]=j+1; U[t]=U[j+1];
            L[R[t]]=R[L[t]]=U[D[t]]=D[U[t]]=t;
            C[t]=j+1; S[C[t]]++; ROW[t]=i; id[i][j]=t++;
        }
    }
    for( int i=0; i<n; i++) used[i]=0;
    return dfs();
}

```

8.3 Binary Next Permutation b7a40a

```

ull next_perm(ull v){
    ull t=v^(v-1);
    return (t+1)!(((~t&~t)-1)>>(__builtin_ctzll(v)+1));
}

```

8.4 Hilbert Curve 8fa235

```

long long hilbert(int n, int x, int y) {
    long long res = 0;
    for (int s = n / 2; s; s >>= 1) {
        int rx = (x & s) > 0;
        int ry = (y & s) > 0;
        res += s * 1ll * s * ((3 * rx) ^ ry);
        if (ry == 0) {
            if (rx == 1) x = s - 1 - x, y = s - 1 - y;
            swap(x, y);
        }
    }
    return res;
}

```