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# Part I

## 杂项

### 1 快读快写

```

1 template <typename T> inline void read(T &x) {
2     int c; T tag = 1;
3     while(!isdigit((c=getchar()))) if(c == '-') tag = -1;
4     x = c-'0';
5     while(isdigit((c=getchar()))) x = (x<<1)+(x<<3) + c-'0';
6     x *= tag;
7 }
8
9 template <typename T> void write(T x) {
10    if(x < 0) x = -x, putchar('-');
11    if(x > 9) write(x/10);
12    putchar(x%10+'0');
13 }

```

```

1 ios::sync_with_stdio(false); cin.tie(NULL); cout.tie(NULL);

```

### 2 玄学优化

吸氧，吸臭氧

```

1 #pragma GCC optimize("Ofast,no-stack-protector")
2 #pragma GCC target("sse,sse2,sse3,ssse3,sse4,popcnt,abm,mmx,avx,avx2,
   tune=native")

```

### 3 正则表达式

```

1 char str[];
2 scanf("%3s", str); // 读取长度为n的字符串
3 scanf("%[abc]", str); // 读取a,b,c,读到之外的立即停止
4 scanf("%[a-z0-9]", str); // 同上,读取小写字母和数字
5 scanf("%*[a-z]%s", str); // 过滤掉小写字母读取
6 scanf("%[^a-z]", str); // 读取小写字符外字符,^表示非

```

### 4 随机数

```

1 #include <random>
2 // 范围 unsigned int
3 mt19937 rnd(time(NULL));
4 mt19937 rnd(chrono::high_resolution_clock::now().time_since_epoch().
   count());
5 cout << rnd() << endl;
6

```

```

7 std::random_device rd; //获取随机数种子
8 std::mt19937 gen(rd()); //Standard mersenne_twister_engine seeded
  with rd()
9 std::uniform_int_distribution<> dis(0, 9);
10 std::cout << dis(gen) << endl;
11
12 inline ull xorshift128(){
13     static U SX=335634763,SY=873658265,SZ=192849106,SW=746126501;
14     U t=SX^(SX<<11);
15     SX=SY;
16     SY=SZ;
17     SZ=SW;
18     return SW=SW^(SW>>19)^t^(t>>8);
19 }
20 inline ull myrand(){return (xorshift128()<<32)^xorshift128();}

```

## 5 计算 $\log_2$

```

1 #define log(x) (31-__builtin_clz(x))
2 // lg2[i] = lg2(i) + 1
3 for(int i = 1; i <= n; ++i) lg2[i] = lg2[i>>1]+1;
4 // lg2[i] = (int)log2(i)
5 for(int i = 2; i <= n; ++i) lg2[i] = lg2[i>>1]+1;

```

## 6 快速开根号 | 牛顿迭代法

```

1 double sqrt(const double &a) {
2     double x = a, y = .0;
3     while (abs(x-y) > err) {
4         y = x;
5         x = .5*(x+a/x);
6     }
7     return x;
8 }

```

## 7 $i/k == j$ 的 $k$ 的个数

```

1 for (int i = 1; i <= n; ++i) {
2     for (int j = 1, l, r; j <= n; ++j) {
3         l = max(1, i/(j+1));
4         while (l-1 >= 1 && i/(l-1) == j) --l;
5         while (i/l > j) ++l;
6         r = i/j;
7         while (r+1 <= i && i/(r+1) == j) ++r;
8         while (i/r < j) --r;
9         if (r-l+1 != i/j-i/(j+1)) {
10             cout << i << " " << j << endl;
11         }
12     }
13 }

```

## 8 三分法

示例为凹函数

```

1 while (l < r) {
2     int mid = (l+r)>>1;
3     if (f(mid) < f(mid+1)) r = mid;
4     else l = mid+1;
5 }
6
7 while (r-l > eps) {
8     double ml = l+(r-l)/3, mr = r-(r-l)/3;
9     if (f(ml) < f(mr)) r = mr;
10    else l = ml;
11 }

```

## Part II 计算几何

## 9 向量坐标直线圆 (结构体)

```

1 struct Point {
2     typedef double T;
3     T x, y;
4     int id;
5     Point(){}
6     Point(const T &_x, const T &_y, const int &_i = 0) : x(_x), y(_y),
7         id(_i) {}
8     friend Point operator + (const Point &p1, const Point &p2) {
9         return Point(p1.x+p2.x, p1.y+p2.y, p1.id);
10    }
11    friend Point operator - (const Point &p1, const Point &p2) {
12        return Point(p1.x-p2.x, p1.y-p2.y, p1.id);
13    }
14    friend Point operator - (const Point &p) {
15        return Point(-p.x, -p.y, p.id);
16    }
17    // a*b b在a的顺负逆正
18    friend T operator * (const Point &p1, const Point &p2) {
19        return p1.x*p2.y-p1.y*p2.x;
20    }
21    template <typename TT>
22    friend Point operator / (const Point &p, const TT &k) {
23        return Point(p.x/k, p.y/k, p.id);
24    }
25    template <typename TT>
26    friend Point operator * (const Point &p, const TT &k) {
27        return Point(p.x*k, p.y*k, p.id);
28    }
29    Point operator += (const Point &p) { return *this = *this+p; }
30    Point operator -= (const Point &p) { return *this = *this-p; }
31    template <typename TT>
32    Point operator *= (const TT &k) { return *this = *this*k; }

```



```

32 template <typename TT>
33 Point operator /= (const TT &k) { return *this = *this/k; }
34 friend bool operator < (const Point &p1, const Point &p2) {
35     return make_pair(p1.x, p1.y) < make_pair(p2.x, p2.y);
36 }
37 friend bool operator > (const Point &p1, const Point &p2) {
38     return make_pair(p1.x, p1.y) > make_pair(p2.x, p2.y);
39 }
40 friend bool operator == (const Point &p1, const Point &p2) {
41     return p1.x == p2.x && p1.y == p2.y;
42 }
43 friend bool operator != (const Point &p1, const Point &p2) {
44     return p1.x != p2.x || p1.y != p2.y;
45 }
46 friend istream& operator >> (istream &is, Point &p) {
47     return is >> p.x >> p.y;
48 }
49 friend ostream& operator << (ostream &os, Point &p) {
50     return os << p.x << " " << p.y << " " << p.id << endl;
51 }
52 double length() { return sqrt(1.0*x*x+1.0*y*y); }
53 friend double dis(const Point &p1, const Point &p2) { return (p2-p1
54     ).length(); }
55 double dis(const Point &p) { return (p-*this).length(); }
56 friend T dot(const Point &p1, const Point &p2) { return p1.x*p2.x+
57     p1.y*p2.y; }
58 T dot(const Point &p) { return x*p.x+y*p.y; }
59 friend Point rotate_90_c(const Point &p) { return Point(p.y, -p.x,
60     p.id); }
61 Point rotate_90_c() { return Point(y, -x, id); }
62 friend double atan(const Point &p) { return atan2(p.y, p.x); }
63 };
64 template <typename T = double>
65 struct Vec { // 三维向量
66     T x, y, z;
67     Vec(const T &_x = 0, const T &_y = 0, const T &_z = 0) : x(_x), y(
68         _y), z(_z) {}
69     double len() { return sqrt(1.0*x*x+1.0*y*y+1.0*z*z); }
70     friend Vec operator +(const Vec &v1, const Vec &v2) { return Vec(v1
71         .x+v2.x, v1.y+v2.y, v1.z+v2.z); }
72     friend Vec operator -(const Vec &v1, const Vec &v2) { return Vec(v1
73         .x-v2.x, v1.y-v2.y, v1.z-v2.z); }
74     friend Vec operator *(const T &k, const Vec &v) { return Vec(k*v.x,
75         k*v.y, k*v.z); }
76     friend Vec operator *(const Vec &v, const T &k) { return k*v; }
77     friend Vec operator *(const Vec &v1, const Vec &v2) {
78         return Vec(
79             v1.y*v2.z-v1.z*v2.y,
80             v1.z*v2.x-v1.x*v2.z,
81             v1.x*v2.y-v1.y*v2.x
82         );
83     }
84     friend T dot(const Vec &v1, const Vec &v2) { return v1.x*v2.x+v1.y*
85         v2.y+v1.z*v2.z; }
86     T dot(const Vec &v) { return dot(*this, v); }
87     Vec& operator +=(const Vec &v) { return *this = *this+v; }

```

```

81 Vec& operator --(const Vec &v) { return *this = *this-v; }
82 Vec& operator *=(const T &k) { return *this = *this*k; }
83 Vec& operator *=(const Vec &v) { return *this = *this*v; }
84 friend istream& operator >>(istream &is, Vec &v) { return is >> v.x
    >> v.y >> v.z; }
85 };
86
87 inline bool polar_angle1(const Point &p1, const Point &p2) {
88     double d1 = atan(p1), d2 = atan(p2);
89     return d1 == d2 ? p1 < p2 : d1 < d2;
90 }
91
92 inline bool polar_angle2(const Point &p1, const Point &p2) {
93     auto tmp = p1*p2;
94     return tmp == 0 ? p1 < p2 : tmp > 0;
95 }
96
97 inline long long S(const Point &p1, const Point &p2, const Point &p3)
98 {
99     return abs(p1.x*p2.y+p1.y*p3.x+p2.x*p3.y-p1.x*p3.y-p1.y*p2.x-p2.y*
100 p3.x);
101 }
102
103 struct Line {
104     Point p1, p2;
105     Line(){}
106     Line(const Point &p1, const Point &p2) : p1(p1), p2(p2) {}
107     friend bool cross(const Line &l1, const Line &l2) {
108         #define SJ1(x) max(l1.p1.x, l1.p2.x) < min(l2.p1.x, l2.p2.x) || \
109             max(l2.p1.x, l2.p2.x) < min(l1.p1.x, l1.p2.x)
110         if (SJ1(x) || SJ1(y)) return false;
111         #undef SJ1
112         #define SJ2(a, b, c, d) ((a-b)*(a-c))*((a-b)*(a-d)) <= 0
113         return SJ2(l1.p1, l1.p2, l2.p1, l2.p2) &&
114             SJ2(l2.p1, l2.p2, l1.p1, l1.p2);
115         #undef SJ2
116     }
117     friend bool on_line(const Line &l, const Point &p) {
118         return abs((l.p1-l.p2)*(l.p1-p)) < err;
119     }
120     friend Point cross_point(const Line &l1, const Line &l2) {
121         Point v1 = l1.p2-l1.p1, v2 = l2.p2-l2.p1;
122         if (abs(v1*v2) < err) return Point(0, 0); // no cross_point
123         double t = (l2.p1-l1.p1)*v2/(v1*v2);
124         return l1.p1+v1*t;
125     }
126 };
127
128 struct Circular {
129     Point o;
130     double r;
131     Circular(){}
132     Circular(const Point &o, const double &r) : o(o), r(r) {}
133     template <typename T>
134     Circular(const T &x, const T &y, const double &r) : o(Point(x,
135         y)), r(r) {}
136     friend bool in_cir(const Circular &c, const Point &p) { return dis(

```

```

    c.o, p) <= c.r; }
134 bool in_cir(const Point &p) { return dis(o, p) <= r; }
135 };
136
137 inline Circular get_cir(const Point &p1, const Point &p2, const Point
    &p3) {
138     Circular res;
139     res.o = cross_point(Line((p1+p2)/2, (p1+p2)/2+(p2-p1).rotate_90_c(
        ),
140         Line((p1+p3)/2, (p1+p3)/2+(p3-p1).rotate_90_c()));
141     res.r = dis(res.o, p1);
142     return res;
143 }

```

## 10 二维凸包

```

1 int n;
2 int stk[N], used[N], tp;
3 Point p[N];
4
5 inline void Andrew() {
6     memset(used, 0, sizeof used);
7     sort(p+1, p+n+1);
8     tp = 0;
9     stk[++tp] = 1;
10    for (int i = 2; i <= n; ++i) {
11        while (tp >= 2 && (p[stk[tp]]-p[stk[tp-1]])*(p[i]-p[stk[tp]]) <=
            0)
12            used[stk[tp--]] = 0;
13        used[i] = 1;
14        stk[++tp] = i;
15    }
16    int tmp = tp;
17    for (int i = n-1; i; --i) {
18        if (used[i]) continue;
19        while (tp >= tmp && (p[stk[tp]]-p[stk[tp-1]])*(p[i]-p[stk[tp]])
            <= 0)
20            used[stk[tp--]] = 0;
21        used[i] = 1;
22        stk[++tp] = i;
23    }
24 }

```

## 11 平面最近点对

```

1 Point a[N];
2 int n, ansa, ansb;
3 double mindist;
4
5 inline bool cmp_y(const Point &p1, const Point &p2) { return p1.y <
    p2.y; }
6

```

```

7 void upd_ans(const Point &p1, const Point &p2) {
8     double dist = dis(p1, p2);
9     if (dist < mindist) mindist = dist, ansa = p1.id, ansb = p2.id;
10 }
11
12 void rec(int l, int r) {
13     if (r-l <= 3) {
14         for (int i = l; i < r; ++i)
15             for (int j = i+1; j <= r; ++j)
16                 upd_ans(a[i], a[j]);
17         sort(a+l, a+r+1, cmp_y);
18         return;
19     }
20
21     static Point t[N];
22     int m = (l+r)>>1, midx = a[m].x;
23     rec(l, m); rec(m+1, r);
24     merge(a+l, a+m+1, a+m+1, a+r+1, t, cmp_y);
25     copy(t, t+r-l+1, a+l);
26
27     int tsz = 0;
28     for (int i = l; i <= r; ++i)
29         if (abs(a[i].x-midx) <= mindist) {
30             for (int j = tsz; j && a[i].y-t[j].y < mindist; --j)
31                 upd_ans(a[i], t[j]);
32             t[++tsz] = a[i];
33         }
34 }
35
36 inline void mindist_pair() {
37     sort(a+1, a+n+1);
38     mindist = INF;
39     rec(1, n);
40 }

```

## 12 最小圆覆盖 | 随即增量法

```

1 inline Circular RIA() {
2     Circular cir;
3     random_shuffle(a+1, a+n+1);
4     for (int i = 1; i <= n; ++i) {
5         if (cir.in_cir(a[i])) continue;
6         cir = Circular(a[i], 0);
7         for (int j = 1; j < i; ++j) {
8             if (cir.in_cir(a[j])) continue;
9             cir = Circular((a[i]+a[j])/2, dis(a[i], a[j])/2);
10            for (int k = 1; k < j; ++k) {
11                if (cir.in_cir(a[k])) continue;
12                cir = get_cir(a[i], a[j], a[k]);
13            }
14        }
15    }
16    return cir;
17 }

```

## Part III 数据结构

### 13 堆

```

1 struct Heap {
2     static const int Maxn = 1e6+7;
3     int sz, a[Maxn];
4     Heap() { sz = 0; memset(a, 0, sizeof a); }
5     inline bool cmp(int x, int y) { return x < y; } // 小根堆
6     inline int size() { return sz; }
7     inline bool empty() { return sz == 0; }
8     inline int top() { return a[1]; }
9     inline void push(int x) { a[++sz] = x; swift_up(sz); }
10    inline void pop() { swap(a[1], a[sz--]); swift_down(1); }
11    inline void swift_up(int p) {
12        while(p > 1 && cmp(a[p], a[p>>1])) // a[p] < a[p<<1]
13            swap(a[p], a[p>>1]), p >>= 1;
14    }
15    inline void swift_down(int p) {
16        int l, r, s;
17        while(true) {
18            l = p<<1; r = p<<1|1;
19            if(l > sz) break;
20            if(r > sz || cmp(a[l], a[r])) s = l; // a[l] < a[r]
21            else s = r;
22            if(cmp(a[s], a[p])) // a[s] < a[p]
23                swap(a[p], a[s]), p = s;
24            else break;
25        }
26    }
27 };

```

### 14 二叉查找树

### 15 平衡树

#### 15.1 Splay

```

1 struct Splay {
2     #define root e[0].ch[1]
3     typedef int T;
4     struct node {
5         T v = 0;
6         int ch[2] = { 0, 0 };
7         int fa = 0, sum = 0, cnt = 0;
8     } e[N];
9     int n;
10    void update(int x) { e[x].sum = e[e[x].ch[0]].sum+e[e[x].ch[1]].sum
11        +e[x].cnt; }
12    int identify(int x) { return x == e[e[x].fa].ch[1]; }

```

```

12 void connect(int x,int f,int son) { e[x].fa = f; e[f].ch[son] = x;
    }
13 void rotate(int x) {
14     int y = e[x].fa,
15         r = e[y].fa,
16         rson = identify(y),
17         yson = identify(x),
18         b = e[x].ch[yson^1];
19     connect(b, y, yson);
20     connect(y, x, yson^1);
21     connect(x, r, rson);
22     update(y); update(x);
23 }
24 void splay(int at,int to) {
25     to = e[to].fa;
26     int up;
27     while((up = e[at].fa) != to) {
28         if(e[up].fa != to)
29             rotate(identify(up) == identify(at) ? up : at);
30         rotate(at);
31     }
32 }
33 int add_point(T v, int fa) {
34     ++n; e[n].v = v; e[n].fa = fa; e[n].sum = e[n].cnt = 1;
35     return n;
36 }
37 int find(T v) {
38     int now = root, last = 0;
39     while (now && e[now].v != v)
40         last = now, now = e[now].ch[v > e[now].v];
41     splay((now ? now : last), root);
42     return now;
43 }
44 void insert(T v) {
45     if (!root) { root = add_point(v, root); return; }
46     int now = root, last = 0;
47     while (now && e[now].v != v)
48         last = now, now = e[now].ch[v > e[now].v];
49     if (now) ++e[now].cnt;
50     else now = e[last].ch[v > e[last].v] = add_point(v, last);
51     splay(now, root);
52 }
53 void erase(T v) {
54     int del = find(v);
55     if (!del) return;
56     if (e[del].cnt > 1) {
57         --e[del].cnt;
58         --e[del].sum;
59     } else if (!e[del].ch[0]) {
60         root = e[del].ch[1];
61         e[root].fa = 0;
62     } else {
63         int oldroot = root;
64         splay(nex(e[del].ch[0], 1), root);
65         connect(e[oldroot].ch[1], root, 1);
66         update(root);
67     }

```

```

68 }
69 int rank(T v) { return e[e[find(v)].ch[0]].sum+1; }
70 T atrank(int x) {
71     if (x > e[root].sum) return -INF;
72     int now = root;
73     while (true) {
74         if (x <= e[e[now].ch[0]].sum) now = e[now].ch[0];
75         else if ((x -= e[e[now].ch[0]].sum) <= e[now].cnt) break;
76         else x -= e[now].cnt, now = e[now].ch[1];
77     }
78     splay(now, root);
79     return e[now].v;
80 }
81 // small 0, big 1
82 int nex(int x, int opt) { while (e[x].ch[opt]) x = e[x].ch[opt];
83     return x; }
84 T lower(T v, int opt) {
85     insert(v);
86     T res = e[nex(e[root].ch[opt], opt^1)].v;
87     erase(v);
88     return res;
89 }
90 #undef root
};

```

## 区间反转

```

1 struct Splay {
2     typedef int T;
3     struct node {
4         T v = 0;
5         int ch[2] = { 0, 0 };
6         int fa = 0, sum = 0, cnt = 0, tag = 0;
7     } e[N];
8     int sz, &root = e[0].ch[1];
9     void update(int x) { e[x].sum = e[e[x].ch[0]].sum+e[e[x].ch[1]].sum
10         +e[x].cnt; }
11     int identify(int x) { return x == e[e[x].fa].ch[1]; }
12     void connect(int x,int f,int son) { e[x].fa = f; e[f].ch[son] = x;
13     }
14     void rotate(int x) {
15         int y = e[x].fa,
16             r = e[y].fa,
17             rson = identify(y),
18             yson = identify(x),
19             b = e[x].ch[yson^1];
20         connect(b, y, yson);
21         connect(y, x, yson^1);
22         connect(x, r, rson);
23         update(y); update(x);
24     }
25     void splay(int at,int to = 0) {
26         to = e[to].fa;
27         int up;
28         while((up = e[at].fa) != to) {
29             if(e[up].fa != to)
30                 rotate(identify(up) == identify(at) ? up : at);
31             rotate(at);
32         }
33     }
34 }

```

```

30     }
31 }
32 int add_point(T v, int fa) {
33     ++sz; e[sz].v = v; e[sz].fa = fa; e[sz].sum = e[sz].cnt = 1;
34     return sz;
35 }
36 int find(int x) {
37     if (x > e[root].sum) return -INF;
38     int now = root;
39     while (true) {
40         push_down(now);
41         if (x <= e[e[now].ch[0]].sum) now = e[now].ch[0];
42         else if ((x -= e[e[now].ch[0]].sum) <= e[now].cnt) break;
43         else x -= e[now].cnt, now = e[now].ch[1];
44     }
45     return now;
46 }
47 int build(int l, int r, int fa) {
48     if (l > r) return 0;
49     int mid = (l+r)>>1,
50     now = add_point(mid, fa);
51     e[now].ch[0] = build(l, mid-1, now);
52     e[now].ch[1] = build(mid+1, r, now);
53     update(now);
54     return now;
55 }
56 void push_down(int x) {
57     if (x && e[x].tag) {
58         e[e[x].ch[0]].tag ^= 1;
59         e[e[x].ch[1]].tag ^= 1;
60         swap(e[x].ch[0], e[x].ch[1]);
61         e[x].tag = 0;
62     }
63 }
64 void reverse(int l, int r) {
65     int pl = find(l-1+1), pr = find(r+1+1);
66     splay(pl); splay(pr, pl);
67     e[e[e[root].ch[1]].ch[0]].tag ^= 1;
68 }
69 void print_LMR(int x) {
70     if (!x) return;
71     push_down(x);
72     print_LMR(e[x].ch[0]);
73     if (e[x].v != 0 && e[x].v != n+1)
74         write(a[e[x].v]), putchar(' ');
75     print_LMR(e[x].ch[1]);
76 }
77 } tree;

```

## 16 李超线段树

李超线段树是一种用于维护平面直角坐标系内线段关系的数据结构。它常被用来处理这样一种形式的问题：给定一个平面直角坐标系，支持动态插入一条线段，询问从某一个位置  $(x, +\infty)$  向下看能看到的最高的一条线段（也就是给一条竖线，问这条竖线与所有线段的最高的交点）。



## 17 吉老师线段树 | 吉司机线段树

区间最值操作 & 区间历史最值

栗子：给出一个数列，每次操作让某个区间中对给定值取  $\min$  询问某个区间的和

## 18 树套树

在第一维线段树的每个结点建立第二维线段树

## 19 K-D Tree | KDT

高效处理  $k$  维空间信息

## 20 Link Cut Tree | LCT

## 21 树状数组

### 21.1 一维

单点修改区间查询

区间修改单点查询

```

1 template <typename T>
2 struct BinaryIndexedTree {
3     int n;
4     T tr[N];
5     BinaryIndexedTree() { memset(tr, 0, sizeof tr); }
6     void init(const int &n) { n = _n; clear(); }
7     void clear() { memset(tr+1, 0, sizeof(T)*n); }
8     void add(const int &x, const T &v) { for (int i = x; i <= n; i += i
9         &-i) tr[i] += v; }
10    void add(const int &x, const int &y, const T &v) { add(x, v); add(y
11        +1, -v); }
12    T query(const int &x) { T res = 0; for (int i = x ; i; i -= i&-i)
13        res += tr[i]; return res; }
14    T query(const int &x, const int &y) { return query(y)-query(x-1); }
15 };

```

$O(n)$  初始化

```

1 template <typename TT>
2 void init(const int &n, const TT a[]) {
3     n = _n; clear();
4     for (int i = 1; i <= n; ++i) {
5         tr[i] += a[i];
6         if (i+(i&-i) <= n) tr[i+(i&-i)] += tr[i];
7     }
8 }

```

## 21.2 二维

### 21.2.1 单点修改区间查询

```

1  template <typename T>
2  struct BIT_2D {
3      int n, m;
4      T a[N][N], tr[N][N];
5      BIT_2D() { memset(tr, 0, sizeof tr); }
6      void init(const int &n, const int &m) {
7          n = _n; m = _m;
8          memset(a, 0, sizeof a);
9          memset(tr, 0, sizeof tr);
10     }
11     void add(const int &x, const int &y, const T &k) {
12         a[x][y] += k;
13         for (int i = x; i <= n; i += i&-i)
14             for (int j = y; j <= m; j += j&-j)
15                 tr[i][j] += k;
16     }
17     T query(const int &x, const int &y) {
18         return a[x][y];
19         // return query(x, y, x, y);
20     }
21     T query(int r1, int c1, int r2, int c2) {
22         if (r1 > r2) swap(r1, r2);
23         if (c1 > c2) swap(c1, c2);
24         return _query(r2, c2) - _query(r1-1, c2) - _query(r2, c1-1) + _query(r1-1, c1-1);
25     }
26     T _query(const int &x, const int &y) {
27         T res = 0;
28         for (int i = x; i; i -= i&-i)
29             for (int j = y; j; j -= j&-j)
30                 res += tr[i][j];
31         return res;
32     }
33 };

```

## 22 可持久化线段树 (可持久化数组)

```

1  template <typename T>
2  struct PersistentArray {
3      static const int NN = N*(log2(N)+3);
4      int rt[N], ls[NN], rs[NN], val[NN], tot, n;
5      void build(const int &n) {
6          this->n = n;
7          tot = 0;
8          rt[0] = build(1, n);
9      }
10     int build(const int &l, const int &r) {
11         int cur = ++tot; assert(tot < NN);
12         if (l == r) return val[cur] = a[l], cur;
13         int mid = (l+r)>>1;
14         ls[cur] = build(l, mid);

```

```

15     rs[cur] = build(mid+1, r);
16     return cur;
17 }
18 void update(const int &cur, const int &pre, const int &x, const T &
19     k) {
20     rt[cur] = update(rt[pre], x, k, 1, n);
21 }
22 int update(const int &pre, const int &x, const T &k, const int &l,
23     const int &r) {
24     int cur = ++tot; assert(tot < NN);
25     if (l == x && r == x) return val[cur] = k, cur;
26     ls[cur] = ls[pre]; rs[cur] = rs[pre];
27     int mid = (l+r)>>1;
28     if (x <= mid) ls[cur] = update(ls[pre], x, k, l, mid);
29     else rs[cur] = update(rs[pre], x, k, mid+1, r);
30     return cur;
31 }
32 T query(const int &cur, const int &x) {
33     return query(rt[cur], x, 1, n);
34 }
35 T query(const int &cur, const int &x, const int &l, const int &r) {
36     if (l == x && r == x) return val[cur];
37     int mid = (l+r)>>1;
38     if (x <= mid) return query(ls[cur], x, l, mid);
39     return query(rs[cur], x, mid+1, r);
40 }
41 };

```

## 23 可持久化并查集

```

1 struct PersistentUnionSet {
2     static const int NN = N*(log2(N)+3);
3     int rt[N], ls[NN], rs[NN], fa[NN], dep[NN], n, tot;
4     void build(const int &n) {
5         this->n = n;
6         tot = 0;
7         rt[0] = build(1, n);
8     }
9     int build(const int &l, const int &r) {
10         int cur = ++tot; assert(tot < NN);
11         if (l == r) return fa[cur] = l, dep[cur] = 0, cur;
12         int mid = (l+r)>>1;
13         ls[cur] = build(l, mid);
14         rs[cur] = build(mid+1, r);
15         return cur;
16     }
17     bool query(const int &cur, const int &x, const int &y) {
18         return fa[getf(rt[cur], x)] == fa[getf(rt[cur], y)];
19     }
20     // return the id of fa[], dep[]
21     int query(const int &cur, const int &x, const int &l, const int &r)
22     {
23         if (l == r) return cur;
24         int mid = (l+r)>>1;
25         if (x <= mid) return query(ls[cur], x, l, mid);
26     }
27 }

```

```

25     else return query(rs[cur], x, mid+1, r);
26 }
27 // return the id of fa[], dep[]
28 int getf(const int &cur, int x) {
29     int fi;
30     while (fa[(fi = query(cur, x, 1, n))] != x) x = fa[fi];
31     return fi;
32 }
33 void merge(const int &cur, const int &pre, const int &x, const int
    &y) {
34     rt[cur] = rt[pre];
35     int fx = getf(rt[cur], x), fy = getf(rt[cur], y);
36     if (fa[fx] == fa[fy]) return;
37     if (dep[fx] > dep[fy]) swap(fx, fy);
38     rt[cur] = update(rt[pre], fa[fx], fa[fy], 1, n);
39     if (dep[fx] == dep[fy]) add(rt[cur], fa[fy], 1, n);
40 }
41 // update fa, merge x to y
42 int update(const int &pre, const int &x, const int &y, const int &l
    , const int &r) {
43     int cur = ++tot; assert(tot < NN);
44     if (l == r) return fa[cur] = y, dep[cur] = dep[pre], cur;
45     ls[cur] = ls[pre]; rs[cur] = rs[pre];
46     int mid = (l+r)>>1;
47     if (x <= mid) ls[cur] = update(ls[pre], x, y, l, mid);
48     else rs[cur] = update(rs[pre], x, y, mid+1, r);
49     return cur;
50 }
51 // add dep
52 void add(const int &cur, const int &x, const int &l, const int &r)
    {
53     if (l == r) return ++dep[cur], void();
54     int mid = (l+r)>>1;
55     if (x <= mid) add(ls[cur], x, l, mid);
56     else add(rs[cur], x, mid+1, r);
57 }
58 };

```

## 24 可持久化线段树 (主席树)

自带离散

```

1  template <typename T>
2  struct PersistentSegmentTree {
3      static const int NN = N*(log2(N)+5);
4      int rt[N], sum[NN], ls[NN], rs[NN], tot, sz;
5      vector<T> des;
6      void build(const T a[], const int &n) {
7          vector<T>(a+1, a+n+1).swap(des);
8          sort(des.begin(), des.end());
9          des.erase(unique(des.begin(), des.end()), des.end());
10         sz = des.size();
11         tot = 0;
12         rt[0] = _build(1, sz);
13         for (int i = 1; i <= n; ++i) {

```

```

14     int t = lower_bound(des.begin(), des.end(), a[i])-des.begin()
15         +1;
16     rt[i] = _update(rt[i-1], 1, sz, t);
17 }
18 void update(const int &id, const T &k) {
19     int t = lower_bound(des.begin(), des.end(), k)-des.begin()+1;
20     rt[id] = _update(rt[id-1], 1, sz, t);
21 }
22 T query(const int &l, const int &r, const int &k) {
23     return des[_query(rt[l-1], rt[r], 1, sz, k)-1];
24 }
25 private:
26 int _build(const int &l, const int &r) {
27     int cur = ++tot;
28     sum[cur] = 0;
29     if (l >= r) return cur;
30     int mid = (l+r)>>1;
31     ls[cur] = _build(l, mid);
32     rs[cur] = _build(mid+1, r);
33     return cur;
34 }
35 int _update(const int &pre, const int &l, const int &r, const int &
36     k) {
37     int cur = ++tot;
38     ls[cur] = ls[pre]; rs[cur] = rs[pre]; sum[cur] = sum[pre]+1;
39     if (l >= r) return cur;
40     int mid = (l+r)>>1;
41     if (k <= mid) ls[cur] = _update(ls[pre], l, mid, k);
42     else rs[cur] = _update(rs[pre], mid+1, r, k);
43     return cur;
44 }
45 int _query(const int &u, const int &v, const int &l, const int &r,
46     const int &k) {
47     if (l >= r) return l;
48     int num = sum[ls[v]]-sum[ls[u]], mid = (l+r)>>1;
49     if (num >= k) return _query(ls[u], ls[v], l, mid, k);
50     else return _query(rs[u], rs[v], mid+1, r, k-num);
51 }
52 };

```

## 25 分块

```

1 struct FenKuai {
2     typedef int T;
3     int t; // 每组大小
4     T a[N], b[N], add[N];
5     FenKuai() {
6         memset(a, 0, sizeof a);
7         memset(b, 0, sizeof b);
8         memset(add, 0, sizeof add);
9     }
10    void build(int x) {
11        for (int i = x*t; i < min(x*t+t, n); ++i) b[i] = a[i];
12        sort(b+x*t, b+min(x*t+t, n));

```

```

13 }
14 void init() {
15     t = static_cast<int>(sqrt(n)+0.5);
16     for (int i = 0; i*t < n; ++i) build(i);
17 }
18 void update(int x, int y, T c) {
19     int i = x;
20     for ( ; i <= y && i%t; ++i) a[i] += c;
21     build(x/t);
22     for ( ; i+t-1 <= y; i += t) add[i/t] += c;
23     for ( ; i <= y; ++i) a[i] += c;
24     build(y/t);
25 }
26 T query(int x, int y, long long c) {
27     T res = 0; int i = x;
28     for ( ; i <= y && i%t; ++i) res += (a[i]+add[i/t] < c*c);
29     for ( ; i+t-1 <= y; i += t) res += lower_bound(b+i, b+i+t, c*c-
30         add[i/t])-(b+i);
31     for ( ; i <= y; ++i) res += (a[i]+add[i/t] < c*c);
32     return res;
33 } B;

```

## 26 ST 表

### 26.1 一维

```

1 template <typename T, typename U = std::greater<T>>
2 struct ST {
3     static const int NN = (int)log2(N)+3;
4     static const T INF = 1e9;
5     int lg2[N];
6     U cmp = U();
7     T rmq[N][NN];
8     ST() {
9         fill(rmq[0], rmq[0]+N*NN, cmp(-INF, +INF) ? INF : -INF);
10        for (int i = 2; i < N; ++i) lg2[i] = lg2[i>>1]+1;
11    }
12    T& operator [] (const int &i) { return rmq[i][0]; }
13    void init(const T &val = 0) { fill(rmq[0], rmq[0]+N*NN, val); }
14    T mv(const T &x, const T &y) { return cmp(x, y) ? x : y; }
15    // rmq[i][j] ==> [i, i+2^j-1]
16    void build(T a[], const int &n) {
17        for (int i = n; i; --i) {
18            rmq[i][0] = a[i];
19            for (int j = 1; j <= lg2[n-i+1]; ++j)
20                rmq[i][j] = mv(rmq[i][j-1], rmq[i+(1<<(j-1))][j-1]);
21        }
22    }
23    T query(const int &l, const int &r) {
24        if (l > r) return query(r, l);
25        int k = lg2[r-l+1];
26        return mv(rmq[l][k], rmq[r-(1<<k)+1][k]);
27    }
28 };

```

```

29  /* rmq[i][j] ==> [i-2^j+1, i]
30  void build(T a[], const int &n) {
31      for (int i = 1; i <= n; ++i) {
32          rmq[i][0] = a[i];
33          for (int j = 1; j <= lg2[i]; ++j)
34              rmq[i][j] = mv(rmq[i][j-1], rmq[i-(1<<(j-1))][j-1]);
35      }
36  }
37  T query(const int &l, const int &r) {
38      if (l > r) return query(r, l);
39      int k = lg2[r-l+1];
40      return mv(rmq[r][k], rmq[l+(1<<k)-1][k]);
41  }
42  */

```

## 26.2 二维

$O(nm \log n \log m)$

```

1  template <typename T, typename U = std::greater<T>>
2  struct ST {
3      static const int NN = (int)log2(N)+3;
4      static const T INF = 1e9;
5      U cmp = U();
6      T rmq[N][N][NN][NN]; // rmq[i][j][k][l] [i, j] [i+2^k-1, j+2^l-1]
7      ST() { init(); }
8      ST(const T &val) { init(val); }
9      T& operator [] (const int &i) { return rmq[i][0]; }
10     void init(){ fill(rmq[0][0][0], rmq[0][0][0]+N*N*NN*NN, cmp(-INF, +
11         INF) ? INF : -INF); }
12     void init(const T &val) { fill(rmq[0][0][0], rmq[0][0][0]+N*N*NN*NN
13         , val); }
14     T mv(const T &x, const T &y) { return cmp(x, y) ? x : y; }
15     void build(T a[N][N], const int &n, const int &m) {
16         for (int k = 0; k <= log_2[n]; ++k)
17             for (int l = 0; l <= log_2[m]; ++l)
18                 for (int i = 1; i+(1<<k)-1 <= n; ++i)
19                     for (int j = 1; j+(1<<l)-1 <= m; ++j) {
20                         T &cur = rmq[i][j][k][l];
21                         if (!k && !l) cur = a[i][j];
22                         else if (!l) cur = mv(rmq[i][j][k-1][l], rmq[i+(1<<(k-1))][j][k-1][l]);
23                         else cur = mv(rmq[i][j][k][l-1], rmq[i][j+(1<<(l-1))][k][l-1]);
24                     }
25     }
26     T query(const int &r1, const int &c1, const int &r2, const int &c2)
27     {
28         int k = log_2[r2-r1+1], l = log_2[c2-c1+1];
29         return mv(mv(rmq[r1][c1][k][l], rmq[r2-(1<<k)+1][c2-(1<<l)+1][k][l]),
30             mv(rmq[r2-(1<<k)+1][c1][k][l], rmq[r1][c2-(1<<l)+1][k][l]));
31     }
32 };

```

## 26.3 反向 ST

```

1  template <typename T, typename U = std::greater<T>>
2  struct rST {
3      static const int NN = (int)log2(N)+3;
4      static const T INF = 1e9;
5      int n;
6      int lg2[N];
7      U cmp = U();
8      T rmq[N][NN]; // rmq[i][j] ==> [i, i+2^j-1]
9      rST() { for (int i = 2; i < N; ++i) lg2[i] = lg2[i>>1]+1; }
10     T& operator [] (const int &i) { return rmq[i][0]; }
11     T mv(const T &x, const T &y) { return cmp(x, y) ? x : y; }
12     void init(const int &n, const T &val = 0) {
13         n = n;
14         for (int i = 1; i <= n; ++i) fill(rmq[i], rmq[i]+NN, val);
15     }
16     void update(const int &l, const int &r, const T &k) {
17         if (l > r) return void(update(r, l, k));
18         int b = lg2[r-l+1];
19         rmq[l][b] = mv(rmq[l][b], k);
20         rmq[r-(1<<b)+1][b] = mv(rmq[r-(1<<b)+1][b], k);
21     }
22     void build() {
23         for (int i = lg2[n]; i >= 0; --i) {
24             for (int l = 1, r; l <= n; ++l) {
25                 r = l+(1<<i);
26                 if (r <= n) rmq[r][i] = mv(rmq[r][i], rmq[l][i+1]);
27                 rmq[l][i] = mv(rmq[l][i], rmq[l][i+1]);
28             }
29         }
30     }
31     T query(const int &l, const int &r) {
32         if (l > r) return query(r, l);
33         int b = lg2[r-l+1];
34         return mv(rmq[l][b], rmq[r-(1<<b)+1][b]);
35     }
36 };

```

## 27 并查集

```

1  struct DSU {
2      int fa[N];
3      void init(int sz) { for (int i = 0; i <= sz; ++i) fa[i] = i; }
4      int get(int s) { return s == fa[s] ? s : fa[s] = get(fa[s]); }
5      int& operator [] (int i) { return fa[get(i)]; }
6      bool merge(int x, int y) { // merge x to y
7          int fx = get(x), fy = get(y);
8          if (fx == fy) return false;
9          fa[fx] = fy; return true;
10     }
11 } dsu;

```

加上数量



```

1 struct DSU {
2     int fa[N], num[N];
3     void init(int sz) { for (int i = 0; i <= sz; ++i) fa[i] = i, num[i]
        = 1; }
4     int get(int s) { return s == fa[s] ? s : fa[s] = get(fa[s]); }
5     int& operator [] (int i) { return fa[get(i)]; }
6     bool merge(int x, int y) {
7         int fx = get(x), fy = get(y);
8         if (fx == fy) return false;
9         if (num[fx] >= num[fy]) num[fx] += num[fy], fa[fy] = fx;
10        else num[fy] += num[fx], fa[fx] = fy;
11        return true;
12    }
13 } dsu;

```

## 28 单调队列

```

1 template <typename T>
2 struct MonotonousQueue {
3     unsigned head;
4     vector<T> q;
5     MonotonousQueue() { clear(); }
6     T& operator [] { return q[head+i]; }
7     void clear() { head = 0; q.clear(); }
8     size_t size() { return q.size()-head; }
9     bool empty() { return head == q.size(); }
10    T front() { return q[head]; }
11    T back() { return q.back(); }
12    void push_front(const T &x) { /*unsupported*/ }
13    void push_back(const T &x) { q.push_back(x); }
14    void pop_front() { ++head; }
15    void pop_back() { q.pop_back(); }
16 };

```

## Part IV 字符串

### 29 回文字符串 | manacher 算法

从 0 开始, 第  $i$  位对应  $p[i*2+2]$

```

1 inline int manacher(const char *str, char *buf, int *p) {
2     int str_len = strlen(str), buf_len = 2;
3     buf[0] = buf[1] = '#';
4     for(int i = 0; i < str_len; ++i)
5         buf[buf_len++] = str[i], buf[buf_len++] = '#';
6
7     int mx = 0, id, ans = 0;
8     for(int i = 1; i < buf_len; ++i) {
9         if(i <= mx) p[i] = min(p[id*2-i], mx-i);

```

```

10     else p[i] = 1;
11     while(buf[i-p[i]] == buf[i+p[i]]) p[i]++;
12     if(i+p[i] > mx) mx = i+p[i], id = i;
13     ans = max(ans, p[i]-1);
14 }
15 return ans;
16 }

```

## 29.1 判断 $s[l, r]$ 是否为回文

```

1 p[l+r+2]-1 >= r-l+1

```

## 30 KMP

```

1 inline void get_next(const string &s, int nex[]) { get_next(s.c_str(),
  , nex); }
2 inline void get_next(const char *s, int nex[]) {
3     nex[0] = nex[1] = 0;
4     for (int i = 1, j = 0, l = strlen(s); i < l; ++i) {
5         while (j && s[i] != s[j]) j = nex[j];
6         nex[i+1] = s[i] == s[j] ? ++j : 0;
7     }
8 }
9
10 inline void kmp(const string &s1, const string &s2, int nex[]) { kmp(
  s1.c_str(), s2.c_str(), nex); }
11 inline void kmp(const char *s1, const char *s2, int nex[]) {
12     for (int i = 0, j = 0, l1 = strlen(s1), l2 = strlen(s2); i < l1; ++
  i){
13         while (j && s1[i] != s2[j]) j = nex[j];
14         if (s1[i] == s2[j]) ++j;
15         if (j == l2) {
16             cout << i-l2+2 << endl;
17             j = nex[j];
18         }
19     }
20 }

```

```

1 inline void get_next(const string &s, int nex[]) {
2     nex[0] = nex[1] = 0;
3     for (int i = 1, j = 0; i < (int)s.size(); ++i) {
4         while (j && s[i] != s[j]) j = nex[j];
5         nex[i+1] = s[i] == s[j] ? ++j : 0;
6     }
7 }
8
9 inline void kmp(const string &s1, const string &s2, int nex[]) {
10     for (int i = 0, j = 0; i < (int)s1.size(); ++i) {
11         while (j && s1[i] != s2[j]) j = nex[j];
12         if (s1[i] == s2[j]) ++j;
13         if (j == (int)s2.size()) {
14             cout << i-s2.size()+2 << endl;

```

```

15     j = nex[j];
16   }
17 }
18 }

```

## 31 扩展 KMP|Z 函数

```

1 inline void GetNext(char *s, int *_nex) {
2     int len = strlen(s);
3     int a = 0, p = 0;
4     _nex[0] = len;
5     for (int i = 1; i < len; ++i) {
6         if (i >= p || i+_nex[i-a] >= p) {
7             if (i > p) p = i;
8             while (p < len && s[p] == s[p-i]) ++p;
9             a = i;
10            _nex[i] = p-i;
11        } else {
12            _nex[i] = _nex[i-a];
13        }
14    }
15 }
16
17 inline void GetExtend(char *s, char *ss, int *_ext, int *_nex) {
18     int lens = strlen(s), lenss = strlen(ss);
19     int a = 0, p = 0;
20     for (int i = 0; i < lens; ++i) {
21         if (i >= p || i+_nex[i-a] >= p) {
22             if (i > p) p = i;
23             while (p < lens && p-i < lenss && s[p] == ss[p-i]) ++p;
24             a = i;
25             _ext[i] = p-i;
26         } else {
27             _ext[i] = _nex[i-a];
28         }
29     }
30 }

```

## 32 后缀数组 |SA

### 32.1 $O(n\log^2 n)$

```

1 int sa[N], rk[N<<1], height[N];
2 template <typename T> // s start from 1
3 inline void SA(const T *s, const int &n) {
4     static int oldrk[N<<1];
5     memset(rk+n+1, 0, sizeof(int)*n);
6     for (int i = 1; i <= n; ++i) rk[i] = s[i];
7     for (int w = 1; w <= n; w <= 1) {
8         iota(sa+1, sa+n+1, 1);
9         sort(sa+1, sa+n+1, &{
10             return rk[x] == rk[y] ? rk[x+w] < rk[y+w] : rk[x] < rk[y];

```

```

11     });
12     memcpy(olldrk+1, rk+1, sizeof(int)*2*n);
13     for (int p = 0, i = 1; i <= n; ++i) {
14         if (olldrk[sa[i]] == oldrk[sa[i-1]] &&
15             oldrk[sa[i]+w] == oldrk[sa[i-1]+w]) {
16             rk[sa[i]] = p;
17         } else {
18             rk[sa[i]] = ++p;
19         }
20     }
21 }
22 for (int i = 1, k = 0; i <= n; ++i) {
23     if (k) --k;
24     while (s[i+k] == s[sa[rk[i]-1]+k]) ++k;
25     height[rk[i]] = k;
26 }
27 }

```

### 32.2 $O(n \log n)$

```

1 int sa[N], rk[N<<1], height[N];
2 template <typename T> // s start from 1
3 inline void SA(const T *s, const int &n) {
4     #define cmp(x, y, w) oldrk[x] == oldrk[y] && oldrk[x + w] == oldrk[y
5         + w]
6     static int oldrk[N<<1], id[N], px[N], cnt[N], m;
7     memset(cnt, 0, sizeof(int) * (m = 128));
8     for (int i = 1; i <= n; ++i) ++cnt[rk[i] = s[i]];
9     for (int i = 1; i <= m; ++i) cnt[i] += cnt[i - 1];
10    for (int i = n; i; --i) sa[cnt[rk[i]]--] = i;
11    for (int w = 1, p, i; w <= n; w <= 1, m = p) {
12        for (p = 0, i = n; i > n - w; --i) id[++p] = i;
13        for (int i = 1; i <= n; ++i)
14            if (sa[i] > w)
15                id[++p] = sa[i] - w;
16        memset(cnt + 1, 0, sizeof(int) * m);
17        for (int i = 1; i <= n; ++i) ++cnt[px[i] = rk[id[i]]];
18        for (int i = 1; i <= m; ++i) cnt[i] += cnt[i - 1];
19        for (int i = n; i; --i) sa[cnt[px[i]]--] = id[i];
20        memcpy(olldrk + 1, rk + 1, sizeof(int) * 2 * n);
21        for (p = 0, i = 1; i <= n; ++i) rk[sa[i]] = cmp(sa[i], sa[i - 1],
22            w) ? p : ++p;
23    }
24    for (int i = 1, k = 0; i <= n; ++i) {
25        if (k) --k;
26        while (s[i+k] == s[sa[rk[i]-1]+k]) ++k;
27        height[rk[i]] = k;
28    }
29    #undef cmp
30 }

```

### 32.3 $O(n)$

```

1 namespace SuffixArray {
2
3 int sa[N], rk[N], ht[N];
4 bool t[N << 1];
5
6 inline bool islms(const int i, const bool *t) { return i > 0 && t[i]
    && !t[i - 1]; }
7
8 template <class T>
9 inline void sort(T s, int *sa, const int len, const int sz, const int
    sigma, bool *t, int *b, int *cb, int *p) {
10     memset(b, 0, sizeof(int) * sigma);
11     memset(sa, -1, sizeof(int) * len);
12     for (register int i = 0; i < len; i++) b[static_cast<int>(s[i])]++;
13     cb[0] = b[0];
14     for (register int i = 1; i < sigma; i++) cb[i] = cb[i - 1] + b[i];
15     for (register int i = sz - 1; i >= 0; i--) sa[--cb[static_cast<int>
        >(s[p[i]])]] = p[i];
16     for (register int i = 1; i < sigma; i++) cb[i] = cb[i - 1] + b[i -
        1];
17     for (register int i = 0; i < len; i++)
18         if (sa[i] > 0 && !t[sa[i] - 1])
19             sa[cb[static_cast<int>(s[sa[i] - 1])]++] = sa[i] - 1;
20     cb[0] = b[0];
21     for (register int i = 1; i < sigma; i++) cb[i] = cb[i - 1] + b[i];
22     for (register int i = len - 1; i >= 0; i--)
23         if (sa[i] > 0 && t[sa[i] - 1])
24             sa[--cb[static_cast<int>(s[sa[i] - 1])]] = sa[i] - 1;
25 }
26
27 template <class T>
28 inline void sais(T s, int *sa, const int len, bool *t, int *b, int *
    b1, const int sigma) {
29     register int i, j, x, p = -1, cnt = 0, sz = 0, *cb = b + sigma;
30     for (t[len - 1] = 1, i = len - 2; i >= 0; i--) t[i] = s[i] < s[i +
        1] || (s[i] == s[i + 1] && t[i + 1]);
31     for (i = 1; i < len; i++)
32         if (t[i] && !t[i - 1])
33             b1[sz++] = i;
34     sort(s, sa, len, sz, sigma, t, b, cb, b1);
35     for (i = sz = 0; i < len; i++)
36         if (islms(sa[i], t))
37             sa[sz++] = sa[i];
38     for (i = sz; i < len; i++) sa[i] = -1;
39     for (i = 0; i < sz; i++) {
40         for (x = sa[i], j = 0; j < len; j++) {
41             if (p == -1 || s[x + j] != s[p + j] || t[x + j] != t[p + j]) {
42                 cnt++, p = x;
43                 break;
44             } else if (j > 0 && (islms(x + j, t) || islms(p + j, t))) {
45                 break;
46             }
47         }
48         sa[sz + (x >>= 1)] = cnt - 1;
49     }
50     for (i = j = len - 1; i >= sz; i--)

```

```

51     if (sa[i] >= 0)
52         sa[j--] = sa[i];
53     register int *s1 = sa + len - sz, *b2 = b1 + sz;
54     if (cnt < sz)
55         sais(s1, sa, sz, t + len, b, b1 + sz, cnt);
56     else
57         for (i = 0; i < sz; i++) sa[s1[i]] = i;
58         for (i = 0; i < sz; i++) b2[i] = b1[sa[i]];
59     sort(s, sa, len, sz, sigma, t, b, cb, b2);
60 }
61
62 template <class T>
63 inline void getHeight(T s, int n) {
64     for (register int i = 1; i <= n; i++) rk[sa[i]] = i;
65     register int j = 0, k = 0;
66     for (register int i = 0; i < n; ht[rk[i++]] = k)
67         for (k ? k-- : 0, j = sa[rk[i] - 1]; s[i + k] == s[j + k]; k++)
68             ;
69 }
70
71 template <class T> // s start from 0
72 inline void init(T s, const int len, const int sigma = 128) {
73     sais(s, sa, len + 1, t, rk, ht, sigma);
74     getHeight(s, len);
75     for (int i = 1; i <= len; ++i) ++sa[i];
76     for (int i = len; i; --i) rk[i] = rk[i-1];
77 }
78
79 } // namespace SuffixArray

```

## 33 字典树

```

1 struct TireTree {
2     static const int NN = 5e5+7;
3     static const int SZ = 26;
4     char beg;
5     int nex[NN][SZ], num[NN], cnt;
6     bool exist[NN];
7     TireTree(char _beg = 'a') : beg(_beg) { clear(); }
8     void clear() {
9         memset(nex, 0, sizeof nex);
10        memset(num, 0, sizeof num);
11        memset(exist, 0, sizeof exist);
12        cnt = 0;
13    }
14    void insert(const char *s) {
15        int len = strlen(s), p = 0;
16        for (int i = 0, c; i < len; ++i) {
17            c = s[i] - beg;
18            if (!nex[p][c]) nex[p][c] = ++cnt;
19            p = nex[p][c];
20            ++num[p];
21        }
22        exist[p] = true;
23    }

```

```

24 bool find(const char *s) {
25     int len = strlen(s), p = 0;
26     for (int i = 0, c; i < len; ++i) {
27         c = s[i]-beg;
28         if (!nex[p][c]) return false;
29         p = nex[p][c];
30     }
31     return exist[p];
32 }
33 int count(const char *s) {
34     int len = strlen(s), p = 0;
35     for (int i = 0, c; i < len; ++i) {
36         c = s[i]-beg;
37         if (!nex[p][c]) return 0;
38         p = nex[p][c];
39     }
40     return num[p];
41 }
42 void insert(const string &s) { insert(s.c_str()); }
43 bool find(const string &s) { return find(s.c_str()); }
44 int count(const string &s) { return count(s.c_str()); }
45 };

```

## 34 AC 自动机

如需构造可重建 AC 自动机，每次构造建一个 nex 数组的拷贝

```

1 struct Aho_Corasick_Automaton {
2     static const int NN = 5e6+7;
3     static const int SZ = 26;
4     char beg;
5     int nex[NN][SZ], num[NN], fail[NN], cnt;
6     Aho_Corasick_Automaton(const char &_beg = 'a') : beg(_beg) {}
7     void clear() {
8         memset(nex, 0, sizeof(nex[0])*(cnt+1));
9         memset(num, 0, sizeof(int)*(cnt+1));
10        memset(fail, 0, sizeof(int)*(cnt+1));
11        cnt = 0;
12    }
13    void insert(const char *s) {
14        int len = strlen(s), p = 0;
15        for (int i = 0, c; i < len; ++i) {
16            c = s[i]-beg;
17            if (!nex[p][c]) nex[p][c] = ++cnt;
18            p = nex[p][c];
19        }
20        ++num[p];
21    }
22    void build() {
23        static queue<int> q;
24        for (int i = 0; i < SZ; ++i) if (nex[0][i]) q.push(nex[0][i]);
25        while (q.size()) {
26            int u = q.front();
27            q.pop();
28            for (int i = 0; i < SZ; ++i) {
29                if (nex[u][i]) {

```

```

30         fail[nex[u][i]] = nex[fail[u]][i];
31         q.push(nex[u][i]);
32     } else {
33         nex[u][i] = nex[fail[u]][i];
34     }
35 }
36 }
37 }
38 int query(const char *s) {
39     int len = strlen(s), p = 0, res = 0;
40     for (int i = 0; i < len; ++i) {
41         p = nex[p][s[i]-beg];
42         for (int t = p; t && ~num[t]; t = fail[t]) {
43             res += num[t];
44             num[t] = -1;
45         }
46     }
47     return res;
48 }
49 };

```

```

1 struct Aho_Corasick_Automaton {
2     static const int NN = 2e5+7;
3     static const int SZ = 26;
4     char beg;
5     int cnt;
6     int nex[NN][SZ], fail[NN], vis[NN];
7     Aho_Corasick_Automaton(const char &_beg = 'a') : beg(_beg) {}
8     void clear() {
9         memset(nex, 0, sizeof(nex[0])*(cnt+1));
10        memset(fail, 0, sizeof(int)*(cnt+1));
11        memset(vis, 0, sizeof(int)*(cnt+1));
12        cnt = 0;
13    }
14    int insert(const char *s) {
15        int len = strlen(s), p = 0;
16        for (int i = 0, c; i < len; ++i) {
17            c = s[i]-beg;
18            if (!nex[p][c]) nex[p][c] = ++cnt;
19            p = nex[p][c];
20        }
21        return p;
22    }
23    void build() {
24        static queue<int> q;
25        for (int i = 0; i < SZ; ++i) if (nex[0][i]) q.push(nex[0][i]);
26        while (q.size()) {
27            int u = q.front();
28            q.pop();
29            for (int i = 0; i < SZ; ++i) {
30                if (nex[u][i]) {
31                    fail[nex[u][i]] = nex[fail[u]][i];
32                    q.push(nex[u][i]);
33                } else {
34                    nex[u][i] = nex[fail[u]][i];
35                }
36            }
37        }
38    }
39 }

```



```

37     }
38 }
39 void query(char *s) {
40     static int deg[NN];
41     static queue<int> q;
42
43     int len = strlen(s);
44     for (int i = 0, p = 0; i < len; ++i) {
45         p = nex[p][s[i]-beg];
46         ++vis[p];
47         // for (int t = p; t; t = fail[t]) ++vis[t];
48     }
49     for (int i = 1; i <= cnt; ++i) ++deg[fail[i]];
50     for (int i = 1; i <= cnt; ++i) if (!deg[i]) q.push(i);
51     while (q.size()) {
52         int u = q.front();
53         q.pop();
54         vis[fail[u]] += vis[u];
55         if (--deg[fail[u]] == 0) q.push(fail[u]);
56     }
57 }
58 } ac;

```

## Part V

# 图论 | 树论

## 35 DFS 树

## 36 树的重心

```

1 void treedp(int cur, int fa) {
2     s[cur] = c[cur];
3     for(int i = fir[cur]; i; i = nex[i]) {
4         if(e[i] == fa) continue;
5         treedp(e[i], cur);
6         s[cur] += s[e[i]];
7         maxs[cur] = max(maxs[cur], s[e[i]]);
8     }
9     maxs[cur] = max(maxs[cur], sum-s[cur]);
10 }

```

## 37 最大团

最大独立集数 = 补图的最大团

```

1 struct MaxClique {
2     vector<int> res, tmp, cnt;
3     bool dfs(int p) {
4         for (int i = p+1, flag; i <= n; ++i) {
5             if (cnt[i]+tmp.size() <= res.size()) return false;

```

```

6         if (!g[p][i]) continue;
7         flag = 1;
8         for (int j : tmp)
9             if (!g[i][j]) flag = 0;
10        if (!flag) continue;
11        tmp.push_back(i);
12        if (dfs(i)) return true;
13        tmp.pop_back();
14    }
15    if (tmp.size() > res.size()) {
16        res = tmp;
17        return true;
18    }
19    return false;
20 }
21 void solve() {
22     vector<int>(n+1, 0).swap(cnt);
23     vector<int>().swap(res);
24     for (int i = n; i; --i) {
25         vector<int>(1, i).swap(tmp);
26         dfs(i);
27         cnt[i] = res.size();
28     }
29 }
30 } MC;

```

## 38 稳定婚姻匹配

```

1 template <typename T = int> struct Stable_Marriage {
2     int t[N], b[N], g[N], rkb[N][N], rkg[N][N];
3     T wb[N][N], wg[N][N];
4     queue<int> q;
5     void init(const int &n) {
6         queue<int>().swap(q);
7         memset(t, 0, sizeof(int)*(n+3));
8         memset(b, 0, sizeof(int)*(n+3));
9         memset(g, 0, sizeof(int)*(n+3));
10        for (int i = 1; i <= n; ++i) {
11            q.push(i);
12            for (int j = 1; j <= n; ++j)
13                rkb[i][j] = rkg[i][j] = j;
14            sort(rkb[i]+1, rkb[i]+n+1,
15                &);
16            //sort(rkg[i]+1, rkg[i]+n+1,
17                //    &);
18        }
19    }
20    bool match(const int &x, const int &y) {
21        if (g[y]) {
22            if (wg[y][x] < wg[y][g[y]]) return false;
23            b[g[y]] = 0;
24            q.push(g[y]);
25        }
26        b[x] = y; g[y] = x;
27        return true;

```

```

28     }
29     void gale_shapely(const int &n) {
30         init(n);
31         while (q.size()) {
32             int x = q.front(); q.pop();
33             int y = rkb[x][++t[x]];
34             if (!match(x, y)) q.push(x);
35         }
36     }
37 };

```

## 39 最小生成树

Prim

```

1 inline void prim() {
2     fill(dis, dis+n+1, INF);
3     dis[1] = 0;
4     for(int t = 1; t <= n; ++t)
5     {
6         int mini = 0;
7         for(int i = 1; i <= n; ++i)
8             if(!vis[i] && dis[i] < dis[mini])
9                 mini = i;
10        vis[mini] = 1;
11        ans += dis[mini];
12        for(int i = 1; i <= n; ++i)
13            if(!vis[i]) dis[i] = min(dis[i], calc(mini, i));
14    }
15 }

```

Kruskal (略)

## 40 二分图

### 40.1 二分图匹配

匈牙利算法

```

1 bool check(int u) {
2     for (int v : e[u]) {
3         if (vis[v]) continue;
4         vis[v] = 1;
5         if (!co[v] || check(co[v])) {
6             co[v] = u;
7             return true;
8         }
9     }
10    return false;
11 }
12
13 inline int solve() {
14     int res = 0;
15     memset(co, 0, sizeof co);
16     for (int i = 1; i <= n; ++i) {

```

```

17     memset(vis, 0, sizeof(int)*(n+3));
18     res += check(i);
19 }
20 return res;
21 }

```

## 40.2 二分图最小顶点覆盖

定义：假如选了一个点就相当于覆盖了以它为端点的所有边。最小顶点覆盖就是选择最少的点来覆盖所有的边。

定理：最小顶点覆盖等于二分图的最大匹配。

## 40.3 最大独立集

定义：选出一些顶点使得这些顶点两两不相邻，则这些点构成的集合称为独立集。找出一个包含顶点数最多的独立集称为最大独立集。

定理：最大独立集 = 所有顶点数 - 最小顶点覆盖 = 所有顶点数 - 最大匹配

# 41 最近公共祖先 |LCA

## 41.1 倍增

```

1 struct LCA {
2     static const int NN = (int)log2(N)+3;
3     int f[N][NN], d[N], lg2[N];
4     LCA() { for (int i = 2; i < N; ++i) lg2[i] = lg2[i>>1]+1; }
5     template <typename TT>
6     void build(const TT e[], const int &u = 1, const int &fa = 0) {
7         d[u] = d[fa]+1;
8         f[u][0] = fa;
9         for (int i = 1; (1<<i) <= d[u]; ++i)
10             f[u][i] = f[f[u][i-1]][i-1];
11         for (auto v : e[u]) if (v != fa)
12             build(e, v, u);
13     }
14     int get(int x, int y) {
15         if (d[x] < d[y]) swap(x, y);
16         while (d[x] > d[y])
17             x = f[x][lg2[d[x]-d[y]]];
18         if (x == y) return x;
19         for (int i = lg2[d[x]]; i >= 0; --i)
20             if (f[x][i] != f[y][i])
21                 x = f[x][i], y = f[y][i];
22         return f[x][0];
23     }
24 };

```

## 41.2 树剖

```

1 struct HLD {
2     int dfn;
3     int fa[N], d[N], num[N], son[N], id[N], tp[N];

```

```

4  vector<int> *e;
5  template <typename E>
6  void build(E *_e, const int &rt = 1) {
7      e = _e;
8      fa[rt] = dfn = 0;
9      dfs1(rt);
10     dfs2(rt);
11 }
12 void dfs1(const int &u = 1) {
13     d[u] = d[fa[u]]+1;
14     num[u] = 1;
15     son[u] = 0;
16     for (const int &v : e[u]) if (v != fa[u]) {
17         fa[v] = u;
18         dfs1(v);
19         num[u] += num[v];
20         if (num[v] > num[son[u]]) son[u] = v;
21     }
22 }
23 void dfs2(const int &u = 1) {
24     tp[u] = son[fa[u]] == u ? tp[fa[u]] : u;
25     id[u] = ++dfn;
26     if (son[u]) dfs2(son[u]);
27     for (const int &v : e[u]) if (v != son[u] && v != fa[u])
28         dfs2(v);
29 }
30 int lca(int x, int y) {
31     while (tp[x] != tp[y]) {
32         if (d[tp[x]] < d[tp[y]]) swap(x, y);
33         x = fa[tp[x]];
34     }
35     return d[x] < d[y] ? x : y;
36 }
37 };

```

### 41.3 帶权 LCA

```

1  template <typename T>
2  struct LCA {
3      static const int NN = (int)log2(N)+3;
4      int f[N][NN], d[N], lg2[N];
5      T w[N][NN], init_val = 0;
6      LCA() {
7          for (int i = 2; i < N; ++i) lg2[i] = lg2[i>>1]+1;
8          init();
9      }
10     // set sum or min or max, and don't forget to set init_val
11     T update(const T &x, const T &y) { return x+y; }
12     void init(const int &n = N-1) {
13         fill(w[0], w[0]+(n+1)*NN, init_val);
14     }
15     template <typename TT>
16     void build(const TT e[], const int &u = 1, const int &fa = 0) {
17         d[u] = d[fa]+1;
18         f[u][0] = fa;

```

```

19     for (int i = 1; (1<<i) <= d[u]; ++i) {
20         f[u][i] = f[f[u][i-1]][i-1];
21         w[u][i] = update(w[u][i-1], w[f[u][i-1]][i-1]);
22     }
23     for (auto v : e[u]) if (v.first != fa) {
24         w[v.first][0] = v.second;
25         build(e, v.first, u);
26     }
27 }
28 T get(int x, int y) {
29     T res = init_val;
30     if (d[x] < d[y]) swap(x, y);
31     while (d[x] > d[y]) {
32         res = update(res, w[x][lg2[d[x]-d[y]]]);
33         x = f[x][lg2[d[x]-d[y]]];
34     }
35     if (x == y) return res;
36     for (int i = lg2[d[x]]; i >= 0; --i)
37         if (f[x][i] != f[y][i]) {
38             res = update(res, w[x][i]);
39             res = update(res, w[y][i]);
40             x = f[x][i], y = f[y][i];
41         }
42     return update(res, update(w[x][0], w[y][0]));
43 }
44 };

```

## 42 树上差分

```

1 template <typename T>
2 struct Tree {
3     T val[N];
4     void update_point(const int &x, const int &y, const T &k) {
5         int _lca = lca(x, y);
6         val[x] += k; val[y] += k;
7         val[_lca] -= k; val[f[_lca][0]] -= k;
8     }
9     void update_edge(const int &x, const int &y, const T &k) {
10        int _lca = lca(x, y);
11        val[x] += k; val[y] += k; val[_lca] -= 2*k;
12    }
13    void dfs(const int &u = 1, const int &fa = 0) {
14        for (int v : e[u]) if (v != fa) {
15            dfs(v, u);
16            val[u] += val[v];
17        }
18    }
19 };

```

## 43 树链剖分

```

1 template <typename T>

```

```

2 struct HLD {
3     int dfn;
4     int fa[N], d[N], num[N], son[N], id[N], tp[N];
5     T init_val[N];
6     SegmentTree<T> ST;
7     template <typename Edge, typename TT>
8     void build(const Edge e[], const TT a[], const int &n, const int &
9         rt = 1) {
10         fa[rt] = dfn = 0;
11         dfs1(e, rt);
12         dfs2(e, rt);
13         for (int i = 1; i <= n; ++i)
14             init_val[id[i]] = a[i];
15         ST.build(init_val, n);
16     }
17     template <typename Edge>
18     void dfs1(const Edge e[], const int &u = 1) {
19         d[u] = d[fa[u]]+1;
20         num[u] = 1;
21         son[u] = 0;
22         for (const int &v : e[u]) if (v != fa[u]) {
23             fa[v] = u;
24             dfs1(e, v);
25             num[u] += num[v];
26             if (num[v] > num[son[u]]) son[u] = v;
27         }
28     }
29     template <typename Edge>
30     void dfs2(const Edge e[], const int &u = 1) {
31         tp[u] = son[fa[u]] == u ? tp[fa[u]] : u;
32         id[u] = ++dfn;
33         if (son[u]) dfs2(e, son[u]);
34         for (const int &v : e[u]) if (v != son[u] && v != fa[u])
35             dfs2(e, v);
36     }
37     void add_sons(const int &x, const T &k) { ST.add(id[x], id[x]+num[x]-1, k); }
38     void add(int x, int y, const T &k, const int &is_edge = 0) {
39         while (tp[x] != tp[y]) {
40             if (d[tp[x]] < d[tp[y]]) swap(x, y);
41             ST.add(id[tp[x]], id[x], k);
42             x = fa[tp[x]];
43         }
44         if (d[x] > d[y]) swap(x, y);
45         ST.add(id[x], id[y], k);
46         if (is_edge) ST.add(id[x], -k);
47     }
48     T query_sons(const int &x) { return ST.query(id[x], id[x]+num[x]-1); }
49     T query(const int &x) { return ST.query(id[x]); }
50     T query(int x, int y) {
51         T res = 0;
52         while (tp[x] != tp[y]) {
53             if (d[tp[x]] < d[tp[y]]) swap(x, y);
54             res += ST.query(id[tp[x]], id[x]);
55             x = fa[tp[x]];
56         }
57     }
58 }

```

```

56     if (d[x] > d[y]) swap(x, y);
57     return res+ST.query(id[x], id[y]);
58 }
59 };

```

## 44 网络流

### 44.1 最大流

#### 44.1.1 EK

$O(nm^2)$

```

1  template <typename T>
2  struct EK {
3      struct Edge {
4          int v, nex;
5          T w;
6      } e[M<<1];
7      int tot = 0, n;
8      int fir[N], vis[N], pre[N];
9      T incf[N];
10     T work(const int &s, const int &t) {
11         T res = 0;
12         while (bfs(s, t)) {
13             int u = t, id;
14             while (u != s) {
15                 id = pre[u];
16                 e[id].w -= incf[t];
17                 e[id^1].w += incf[t];
18                 u = e[id^1].v;
19             }
20             res += incf[t];
21         }
22         return res;
23     }
24     void init(const int &sz) {
25         n = sz;
26         tot = 0;
27         memset(fir, -1, sizeof(int)*(n+3));
28     }
29     void add_edge(const int &u, const int &v, const T &w) {
30         e[tot] = {v, fir[u], w}; fir[u] = tot++;
31         e[tot] = {u, fir[v], 0}; fir[v] = tot++;
32     }
33     bool bfs(const int &s, const int &t) {
34         queue<int> q;
35         memset(vis, 0, sizeof(int)*(n+3));
36         q.push(s);
37         vis[s] = 1;
38         incf[s] = INF;
39         while (q.size()) {
40             int u = q.front();
41             q.pop();
42             for (int i = fir[u], v; i != -1; i = e[i].nex) {
43                 v = e[i].v;

```



```

44         if (vis[v] || !e[i].w) continue;
45         incf[v] = min(incf[u], e[i].w);
46         pre[v] = i;
47         if (v == t) return true;
48         q.push(v);
49         vis[v] = 1;
50     }
51 }
52 return false;
53 }
54 };

```

#### 44.1.2 Dinic

普通情况下  $O(n^2m)$  二分图中  $O(\sqrt{nm})$

```

1  template <typename T>
2  struct Dinic {
3      struct EDGE {
4          int v, nex;
5          T w;
6          EDGE(const int &_v, const int &_nex, const T &_w) : v(_v), nex(
              _nex), w(_w) {}
7      };
8      vector<EDGE> e;
9      int n, s, t;
10     int fir[N], dep[N], cur[N];
11     Dinic() { e.reserve(N<<2); }
12     T work(const int &_s, const int &_t) {
13         s = _s; t = _t;
14         T maxflow = 0, flow;
15         while (bfs())
16             while ((flow = dfs(s, INF)))
17                 maxflow += flow;
18         return maxflow;
19     }
20     void init(const int &n) {
21         n = n;
22         e.clear();
23         memset(fir, -1, sizeof(int)*(n+3));
24     }
25     void add_edge(const int &u, const int &v, const T &w) {
26         e.emplace_back(v, fir[u], w); fir[u] = e.size()-1;
27         e.emplace_back(u, fir[v], 0); fir[v] = e.size()-1;
28     }
29     bool bfs() {
30         queue<int> q;
31         memset(dep, 0, sizeof(int)*(n+3));
32         q.push(s);
33         dep[s] = 1;
34         for (int i = 0; i <= n; ++i) cur[i] = fir[i];
35         while (q.size()) {
36             int u = q.front();
37             q.pop();
38             for (int i = fir[u], v; i != -1; i = e[i].nex) {
39                 v = e[i].v;
40                 if (dep[v] || !e[i].w) continue;

```

```

41     dep[v] = dep[u]+1;
42     if (v == t) return true;
43     q.push(v);
44 }
45 }
46 return false;
47 }
48 T dfs(const int &u, const T &flow) {
49     if (!flow || u == t) return flow;
50     T rest = flow, now;
51     for (int &i = cur[u], v; i != -1; i = e[i].nex) {
52         v = e[i].v;
53         if (dep[v] != dep[u]+1 || !e[i].w) continue;
54         now = dfs(v, min(rest, e[i].w));
55         if (!now) {
56             dep[v] = 0;
57         } else {
58             e[i].w -= now;
59             e[i^1].w += now;
60             rest -= now;
61             if (rest == flow) break;
62         }
63     }
64     return flow-rest;
65 }
66 };

```

### 44.1.3 ISAP

渐进时间复杂度和 dinic 相同，但是非二分图的情况下 isap 更具优势在某些情况（题目）中远慢于 dinic

## 44.2 最小割

最小割等价最大流

## 44.3 费用流

### 44.3.1 MCMF

```

1  template <typename T>
2  struct MCMF {
3      struct Edge {
4          int v, nex;
5          T w, c; // edge wight and cost
6          Edge(const int &_v, const int &_nex, const T &_w, const T &_c) \
7              : v(_v), nex(_nex), w(_w), c(_c) {}
8      };
9      vector<Edge> e;
10     int n, s, t;
11     int fir[N], vis[N], pre[N];
12     T incf[N], dis[N];
13     void init(const int &n) {
14         n = n;
15         e.clear();

```

```

16     e.reserve(N<<4);
17     memset(fir, -1, sizeof(int)*(n+3));
18 }
19 void add_edge(const int &u, const int &v, const T &w, const T &c) {
20     e.emplace_back(v, fir[u], w, c); fir[u] = e.size()-1;
21     e.emplace_back(u, fir[v], 0, -c); fir[v] = e.size()-1;
22 }
23 pair<T, T> work(const int &s, const int &t) {
24     s = _s; t = _t;
25     T maxflow = 0, mincost = 0;
26     while (spfa()) {
27         for (int u = t, id; u != s; u = e[id^1].v) {
28             id = pre[u];
29             e[id].w -= incf[t];
30             e[id^1].w += incf[t];
31             mincost += incf[t]*e[id].c;
32         }
33         maxflow += incf[t];
34     }
35     return {maxflow, mincost};
36 }
37 bool spfa() {
38     queue<int> q;
39     memset(dis, 0x3f, sizeof(T)*(n+3));
40     memset(vis, 0, sizeof(int)*(n+3));
41     q.push(s);
42     dis[s] = 0;
43     incf[s] = INF;
44     incf[t] = 0;
45     while (q.size()) {
46         int u = q.front();
47         q.pop();
48         vis[u] = 0;
49         for (int i = fir[u], v; i != -1; i = e[i].nex) {
50             v = e[i].v;
51             if (!e[i].w || dis[v] <= dis[u]+e[i].c) continue;
52             dis[v] = dis[u]+e[i].c;
53             incf[v] = min(incf[u], e[i].w);
54             pre[v] = i;
55             if (vis[v]) continue;
56             q.push(v);
57             vis[v] = 1;
58         }
59     }
60     return incf[t];
61 }
62 };

```

### 44.3.2 ZKW\_SPFA

```

1 template <typename T>
2 struct ZKW_SPFA {
3     struct Edge {
4         int v, nex;
5         T w, c; // edge wight and cost
6         Edge(const int &_v, const int &_nex, const T &_w, const T &_c) \

```

```

7      : v(_v), nex(_nex), w(_w), c(_c) {}
8  };
9  vector<Edge> e;
10 int n, s, t;
11 int fir[N], vis[N];
12 T maxflow, mincost;
13 T dis[N];
14 ZKW_SPFA() { e.reserve(N<<4); }
15 void init(const int &n) {
16     n = _n;
17     maxflow = mincost = 0;
18     e.clear();
19     memset(fir, -1, sizeof(int)*(n+3));
20 }
21 void add_edge(const int &u, const int &v, const T &w = 1, const T &
    c = 0) {
22     e.emplace_back(v, fir[u], w, c); fir[u] = e.size()-1;
23     e.emplace_back(u, fir[v], 0, -c); fir[v] = e.size()-1;
24 }
25 pair<T, T> work(const int &s, const int &t) {
26     s = _s; t = _t;
27     while (spfa()) {
28         vis[t] = 1;
29         while (vis[t]) {
30             memset(vis, 0, sizeof(int)*(n+3));
31             maxflow += dfs(s, INF);
32         }
33     }
34     return {maxflow, mincost};
35 }
36 private:
37 bool spfa() {
38     memset(dis, 0x3f, sizeof(T)*(n+3));
39     memset(vis, 0, sizeof(int)*(n+3));
40     deque<int> q;
41     q.push_back(t);
42     dis[t] = 0;
43     vis[t] = 1;
44     while (q.size()) {
45         int u = q.front(); q.pop_front();
46         for (int i = fir[u], v; ~i; i = e[i].nex) {
47             v = e[i].v;
48             if (!e[i^1].w || dis[v] <= dis[u]+e[i^1].c) continue;
49             dis[v] = dis[u]+e[i^1].c;
50             if (vis[v]) continue;
51             vis[v] = 1;
52             if (q.size() && dis[v] < dis[q.front()]) q.push_front(v);
53             else q.push_back(v);
54         }
55         vis[u] = 0;
56     }
57     return dis[s] < INF;
58 }
59 T dfs(const int &u, const T &flow) {
60     vis[u] = 1;
61     if (u == t || flow <= 0) return flow;
62     T res, used = 0;

```

```

63     for (int i = fir[u], v; ~i; i = e[i].nex) {
64         v = e[i].v;
65         if (vis[v] || !e[i].w || dis[u] != dis[v]+e[i].c) continue;
66         res = dfs(v, min(e[i].w, flow-used));
67         if (!res) continue;
68         mincost += res*e[i].c;
69         e[i].w -= res;
70         e[i^1].w += res;
71         used += res;
72         if (used == flow) break;
73     }
74     return used;
75 }
76 };

```

## 45 最短路

### 45.1 Floyd

### 45.2 Dijkstra

邻接表 + 堆优化

```

1  inline void Dijkstra() {
2      priority_queue<pair<int,int>,vector<pair<int,int> >,greater<pair<
3          int,int> > >q;
4      memset(dis, 0x7f, sizeof dis);
5      dis[S] = 0;
6      q.push(make_pair(0, S));
7      pair<int, int> cur;
8      while(q.size()) {
9          cur = q.top(); q.pop();
10         if(dis[cur.second] < cur.first) continue;
11         for(int i = fir[cur.second], to, now; i; i = nex[i]) {
12             to = ver[i];
13             now = cur.first+w[i];
14             if(now >= dis[to]) continue;
15             dis[to] = now;
16             q.push(make_pair(now, to));
17         }
18     }
19 }

```

### 45.3 SPFA

```

1  inline void SPFA() {
2      fill(dis+1, dis+n+1, INT_MAX);
3      dis[S] = 0;
4      head = tail = 0;
5      q[++tail] = S;
6      while(head < tail) {
7          int cur = q[++head];
8          for(int i = fir[cur], to, tmp; i; i = nex[i]) {
9              to = ver[i];

```

```

10     tmp = dis[cur]+w[i];
11     if(tmp >= dis[to]) continue;
12     dis[to] = tmp;
13     q[++tail] = to;
14 }
15 }
16 }

```

## 46 负环

```

1 // 返回true有负环,返回false没负环
2 inline bool SPFA() {
3     q[++tail] = 1;
4     vis[1] = 1;
5     cnt[1] = 1;
6     dis[1] = 0;
7     while(head < tail) {
8         int cur = q[(++head)%Maxn];
9         vis[cur] = 0;
10        for(int i = fir[cur], to; i; i = nex[i]) {
11            to = ver[i];
12            if(dis[cur]+w[i] < dis[to]) {
13                dis[to] = dis[cur]+w[i];
14                if(!vis[to]) {
15                    q[(++tail)%Maxn] = to;
16                    vis[to] = 1;
17                    if(++cnt[to] > n) return true;
18                }
19            }
20        }
21    }
22    return false;
23 }

```

## 47 割点

```

1 void tarjan(int cur, int fa) {
2     dfn[cur] = low[cur] = ++_dfn;
3     int child = 0;
4     for(auto i : e[cur]) {
5         if(!dfn[i]) {
6             child++;
7             tarjan(i, fa);
8             low[cur] = min(low[cur], low[i]);
9             if(cur != fa && low[i] >= dfn[cur]) flag[cur] = 1;
10        }
11        low[cur] = min(low[cur], dfn[i]);
12    }
13    if(cur == fa && child >= 2) flag[cur] = 1;
14 }

```

## 48 SCC 强连通分量 | Tarjan

```

1 int dfn, _col, top;
2 int dfn[N], low[N], vis[N], col[N], sta[N];
3
4 void tarjan(const int &u) {
5     dfn[u] = low[u] = ++_dfn;
6     vis[u] = 1;
7     sta[++_top] = u;
8     for (int v : e[u]) {
9         if (!dfn[v]) {
10             tarjan(v);
11             low[u] = min(low[u], low[v]);
12         } else if (vis[v]) {
13             low[u] = min(low[u], low[v]);
14         }
15     }
16     if (dfn[u] == low[u]) {
17         ++_col;
18         do {
19             col[sta[_top]] = _col;
20             vis[sta[_top]] = 0;
21         } while (sta[_top--] != u);
22     }
23 }

```

## 49 缩点

```

1 void tarjan(int u) {
2     dfn[u] = low[u] = ++_dfn;
3     vis[u] = 1;
4     sta[++top] = u;
5     for (int v : e[u]) {
6         if (!dfn[v]) {
7             tarjan(v);
8             low[u] = min(low[u], low[v]);
9         } else if (vis[v]) {
10             low[u] = min(low[u], low[v]);
11         }
12     }
13     if (dfn[u] == low[u]) {
14         w_col[++_col] = 0;
15         do {
16             col[sta[top]] = _col;
17             vis[sta[top]] = 0;
18             w_col[_col] += w[sta[top]];
19         } while (sta[top--] != u);
20     }
21 }
22
23 inline void suodian() {
24     for (int i = 1; i <= n; ++i) {
25         if (!dfn[i]) tarjan(i);
26     }
27 }

```

```

27 for (int i = 1; i <= n; ++i) {
28     for (int j : e[i]) {
29         if (col[i] == col[j]) continue;
30         e_col[col[i]].push_back(col[j]);
31     }
32 }
33 }

```

## 50 2-SAT

### 50.1 SCC Tarjan

$O(n + m)$

```

1 struct TWO_SAT { // node stkr from 0
2     int top, _dfn, _scc;
3     int dfn[N<<1], low[N<<1], stk[N<<1], scc[N<<1], res[N];
4     vector<int> e[N<<1];
5     void init(const int &n) {
6         top = 0;
7         memset(dfn, 0, sizeof(int)*n*2);
8         memset(low, 0, sizeof(int)*n*2);
9         memset(scc, 0, sizeof(int)*n*2);
10        for (int i = 0; i < n<<1; ++i) vector<int>().swap(e[i]);
11    }
12    // if u then v
13    void add_edge(const int &u, const int &v) {
14        e[u].emplace_back(v);
15    }
16    void add_edge(const int &u, const int &uv, const int &v, const int
17        &vv) {
18        e[u<<1^uv].emplace_back(v<<1^vv);
19    }
20    // pt i ==> i<<1 && i<<1/1 ==> 0 && 1
21    inline bool work(const int &n) {
22        for (int i = 0; i <= n<<1; ++i)
23            if (!dfn[i]) tarjan(i);
24        for (int i = 0; i < n; ++i) {
25            if (scc[i<<1] == scc[i<<1|1]) return false;
26            res[i] = scc[i<<1] > scc[i<<1|1];
27        }
28        return true;
29    }
30    void tarjan(const int &u) {
31        dfn[u] = low[u] = ++_dfn;
32        stk[++top] = u;
33        for (int &v : e[u]) {
34            if (!dfn[v]) {
35                tarjan(v);
36                low[u] = min(low[u], low[v]);
37            } else if (!scc[v]) {
38                low[u] = min(low[u], dfn[v]);
39            }
40        }
41        if (dfn[u] == low[u]) {

```



```

41     ++_scc;
42     do {
43         scc[stk[top]] = _scc;
44     } while (stk[top--] != u);
45 }
46 }
47 };

```

## 50.2 DFS

$O(nm)$  所求结果字典序最小

```

1  struct TWO_SAT {
2      int n, cnt;
3      int res[N], mem[N<<1], mark[N<<1];
4      vector<int> e[N<<1];
5      void init(const int &n) {
6          n = n;
7          memset(mark, 0, sizeof(int)*n*2);
8          for (int i = 0; i < n<<1; ++i) vector<int>().swap(e[i]);
9      }
10     // if u then v
11     void add_edge(const int &u, const int &v) {
12         e[u].emplace_back(v);
13     }
14     // pt i ==> i<<1 && i<<1/1 ==> 0 && 1
15     void add_edge(const int &u, const int &uv, const int &v, const int
16         &vv) {
17         e[u<<1|uv].emplace_back(v<<1|vv);
18     }
19     // tag 0 any 1 smallest
20     bool work() {
21         for (int i = 0; i < n; ++i) {
22             if (mark[i<<1] || mark[i<<1|1]) continue;
23             cnt = 0;
24             if (!dfs(i<<1)) {
25                 while (cnt) mark[mem[cnt--]] = 0;
26                 if (!dfs(i<<1|1)) return false;
27             }
28             for (int i = 0; i < n<<1; ++i) if (mark[i]) res[i>>1] = i&1;
29             return true;
30         }
31         bool dfs(const int &u) {
32             if (mark[u^1]) return false;
33             if (mark[u]) return true;
34             mark[mem[++cnt] = u] = 1;
35             for (int v : e[u]) if (!dfs(v)) return false;
36             return true;
37         }
38     };

```

## 51 虚树

```

1 vector<int> ve[N];
2 void virtual_tree_clear(const int &u = 1) {
3     for (const int &v : ve[u]) virtual_tree_clear(v);
4     ve[u].clear();
5 }
6
7 // return the root of virtual tree
8 int virtual_tree_build(int vset[], const int &k) {
9     static int stk[N], top;
10    // id ==> dfn rank, d ==> depth
11    int *id = hld.id, *d = hld.d;
12    sort(vset+1, vset+k+1, & {
13        return id[x] < id[y];
14    });
15    top = 0;
16    int x, z;
17    for (int i = 1; i <= k; ++i) {
18        if (top && (z = hld.lca(vset[i], stk[top])) != stk[top]) {
19            x = stk[top--];
20            while (top && d[stk[top]] > d[z]) {
21                ve[stk[top]].emplace_back(x);
22                x = stk[top--];
23            }
24            ve[z].emplace_back(x);
25            if (!top || stk[top] != z) stk[++top] = z;
26        }
27        stk[++top] = vset[i];
28    }
29    x = stk[top--];
30    while (top) {
31        ve[stk[top]].emplace_back(x);
32        x = stk[top--];
33    }
34    // if (x != 1) ve[1].emplace_back(x); // force root at 1
35    return x;
36 }

```

## 52 线段树优化建图

```

1 template <typename T>
2 struct SegmentTreeGarph {
3     struct TreeNode {
4         int l, r;
5         int ls, rs;
6     } tr[N*3];
7     vector<pair<int, T>> *e;
8     int tot, root[2];
9     // op [down, 0] [up, 1]
10    template <typename E>
11    void build(const int &n, E *_e) {
12        tot = n;
13        e = _e;
14        for (int i = 1; i <= n; ++i) tr[i].l = tr[i].r = i;
15        build(1, n, root[0], 0);

```

```

16     build(1, n, root[1], 1);
17 }
18 void build(const int &l, const int &r, int &i, const int &op) {
19     if (l == r) return i = l, void();
20     i = ++tot;
21     tr[i].l = l; tr[i].r = r;
22     int mid = (l+r)>>1;
23     build(l, mid, tr[i].ls, op);
24     build(mid+1, r, tr[i].rs, op);
25     e[op ? tr[i].ls : i].emplace_back(op ? i : tr[i].ls, 0);
26     e[op ? tr[i].rs : i].emplace_back(op ? i : tr[i].rs, 0);
27 }
28 void insert(const int &o, const int &l, const int &r, const T &w,
29     const int &op) {
30     if (l == r) e[op ? l : o].emplace_back(op ? o : l, w);
31     else insert(o, l, r, w, op, root[op]);
32 }
33 void insert(const int &o, const int &l, const int &r, const T &w,
34     const int &op, const int &i) {
35     if (tr[i].l >= l && tr[i].r <= r) {
36         e[op ? i : o].emplace_back(op ? o : i, w);
37         return;
38     }
39     int mid = (tr[i].l+tr[i].r)>>1;
40     if (l <= mid) insert(o, l, r, w, op, tr[i].ls);
41     if (r > mid) insert(o, l, r, w, op, tr[i].rs);
42 }
43 };

```

## 53 矩阵树定理 |Kirchhoff

解决一张图的生成树个数计数问题 (详情见 oi-wiki)

## Part VI 数论

### 54 快排

```

1 void quick_sort(int l, int r) {
2     if(l >= r) return;
3     swap(a[l], a[l+rand()%(r-l)]);
4     int i = l, j = r, mid = a[l];
5     while(i < j) {
6         while(i < j && a[j] >= mid) --j;
7         swap(a[i], a[j]);
8         while(i < j && a[i] < mid) ++i;
9         swap(a[i], a[j]);
10    }
11    quick_sort(l, i-1);
12    quick_sort(i+1, r);
13 }

```

## 55 求第 K 大数

```

1 int kth_element(int l, int r, int k) {
2     if(l == r) return a[l];
3     swap(a[l], a[l+rand()%(r-l)]);
4     int mid = a[l], i = l, j = r;
5     while(i < j) {
6         while(i < j && a[j] >= mid) --j;
7         swap(a[i], a[j]);
8         while(i < j && a[i] < mid) ++i;
9         swap(a[i], a[j]);
10    }
11    a[i] = mid;
12    if(i == k) return mid;
13    else if(i > k) return kth_element(l, i-1, k);
14    else return kth_element(i+1, r, k);
15 }

```

STL (排序, 无返回值)

```

1 nth_element(a+1, a+k+1, a+n+1);

```

## 56 求逆序对 (归并排序)

```

1 void merge_sort(int l, int r) {
2     if(l == r) return;
3     int mid = (l+r)>>1;
4     merge_sort(l, mid);
5     merge_sort(mid+1, r);
6     int i = l, j = mid+1, k = l;
7     while(k <= r) {
8         if(j <= r && (i > mid || a[j] < a[i])) {
9             ans += mid-i+1;
10            b[k++] = a[j++];
11        }
12        else b[k++] = a[i++];
13    }
14    memcpy(a+1, b+1, sizeof(int)*(r-l+1));
15 }

```

## 57 线性基

```

1 template <typename T>
2 struct LinearBase {
3     int sz = sizeof(T)*8, zero;
4     T tot;
5     vector<T> b, rb, p;
6     LinearBase(){ init(); }
7     void init() {
8         tot = zero = 0;;
9         vector<T>(sz, 0).swap(b);
10        vector<T>().swap(rb);

```

```

11     vector<T>().swap(p);
12 }
13 template <typename TT>
14 void build(TT a[], const int &n) {
15     init();
16     for (int i = 1; i <= n; ++i) insert(a[i]);
17 }
18 void merge(const LinearBase xj) {
19     for (int i : xj.b) if (i) insert(i);
20 }
21 void insert(T x) {
22     for (int i = sz-1; i >= 0; --i) if ((x>>i)&1) {
23         if (!b[i]) { b[i] = x; return; }
24         x ^= b[i];
25     }
26     zero = 1;
27 }
28 bool find(T x) {
29     for (int i = sz-1; i >= 0; --i) if ((x>>i)&1) {
30         if (!b[i]) { return false; }
31         x ^= b[i];
32     }
33     return true;
34 }
35 T max_xor() {
36     T res = 0;
37     for (int i = sz-1; i >= 0; --i)
38         if (~(res>>i)&1) res ^= b[i];
39     // res = max(res, res^b[i]);
40     return res;
41 }
42 T min_xor() {
43     if (zero) return 0;
44     for (int i = 0; i < sz; ++i)
45         if (b[i]) return b[i];
46 }
47 void rebuild() {
48     rb = b;
49     vector<T>().swap(p);
50     for (int i = sz-1; i >= 0; --i)
51         for (int j = i-1; j >= 0; --j)
52             if ((rb[i]>>j)&1) rb[i] ^= rb[j];
53     for (int i = 0; i < sz; ++i)
54         if (rb[i]) p.emplace_back(rb[i]);
55     tot = ((T)1<<p.size())+zero;
56 }
57 T kth_min(T k) {
58     if (k >= tot || k < 1) return -1;
59     if (zero && k == 1) return 0;
60     if (zero) --k;
61     T res = 0;
62     for (int i = (int)p.size()-1; i >= 0; --i)
63         if ((k>>i)&1) res ^= p[i];
64     return res;
65 }
66 T kth_max(const T &k) {
67     return kth_min(tot-k);

```

```

68 }
69 };

```

前缀和线性基 vector 跑贼鸡儿慢

```

1  template <class T>
2  struct PreSumLB {
3      int tot, sz = sizeof(T)*8;
4      vector<T> b[N];
5      vector<int> p[N];
6      PreSumLB() { init(); }
7      void init() {
8          tot = 0;
9          vector<T>(sz, 0).swap(b[0]);
10         vector<int>(sz, 0).swap(p[0]);
11     }
12     void append(T val) {
13         int pos = ++tot;
14         vector<T> &bb = b[tot];
15         vector<int> &pp = p[tot];
16         pp = p[tot-1];
17         bb = b[tot-1];
18         for (int i = sz-1; i >= 0; --i) if ((val>>i)&1) {
19             if (bb[i]) {
20                 if (pos > pp[i]) swap(pos, pp[i]), swap(val, bb[i]);
21                 val ^= bb[i];
22             } else {
23                 bb[i] = val;
24                 pp[i] = pos;
25                 return;
26             }
27         }
28     }
29     T query(const int &l, const int &r) {
30         T res = 0;
31         vector<T> &bb = b[r];
32         vector<int> &pp = p[r];
33         for (int i = sz-1; i >= 0; --i)
34             if (pp[i] >= l) res = max(res, res^bb[i]);
35         return res;
36     }
37 };

```

## 58 矩阵

### 58.1 矩阵快速幂

### 58.2 矩阵求逆

```

1  template <typename T>
2  struct Martix {
3      int n, m;
4      T a[N][N];
5      Martix(){}
6      Martix(const int &n) : n(_n), m(_n) { init(); }
7      Martix(const int &n, const int &m) : n(_n), m(_m) { init(); }

```

```

8   T* operator [] (const int &i) { return a[i]; }
9   void init(const int &tag = 0) {
10      for (int i = 1; i <= n; ++i) memset(a[i], 0, sizeof(T)*(n+1));
11      for (int i = 1; i <= n; ++i) a[i][i] = tag;
12  }
13  friend Martix operator * (const Martix &m1, const Martix &m2) {
14      Martix res(m1.n, m2.m);
15      for (int i = 1; i <= res.n; ++i)
16          for (int j = 1; j <= res.m; ++j)
17              for (int k = 1; k <= m1.m; ++k)
18                  res.a[i][j] = (res.a[i][j]+m1.a[i][k]*m2.a[k][j])%MOD;
19      return res;
20  }
21  Martix& operator *= (const Martix &mx) { return *this = *this*mx; }
22  template <typename TT>
23  Martix pow(const TT &p) const {
24      Martix res(n, m), a = *this;
25      res.init(1);
26      for (TT i = p; i; i >>= 1, a *= a) if (i&1) res *= a;
27      return res;
28  }
29  Martix inv() const {
30      Martix res = *this;
31      vector<int> is(n+1), js(n+1);
32      for (int k = 1; k <= n; ++k) {
33          for (int i = k; i <= n; ++i)
34              for (int j = k; j <= n; ++j) if (res.a[i][j]) {
35                  is[k] = i; js[k] = j; break;
36              }
37          for (int i = 1; i <= n; ++i) swap(res.a[k][i], res.a[is[k]][i]);
38          for (int i = 1; i <= n; ++i) swap(res.a[i][k], res.a[i][js[k]]);
39          if (!res.a[k][k]) return Martix(0);
40          res.a[k][k] = mul_inverse(res.a[k][k]); // get inv of number
41          for (int j = 1; j <= n; ++j) if (j != k)
42              res.a[k][j] = res.a[k][j]*res.a[k][k]%MOD;
43          for (int i = 1; i <= n; ++i) if (i != k)
44              for (int j = 1; j <= n; ++j) if (j != k)
45                  res.a[i][j] = (res.a[i][j]+MOD-res.a[i][k]*res.a[k][j]%MOD)
46                      %MOD;
47          for (int i = 1; i <= n; ++i) if (i != k)
48              res.a[i][k] = (MOD-res.a[i][k]*res.a[k][k]%MOD)%MOD;
49      }
50      for (int k = n; k; --k) {
51          for (int i = 1; i <= n; ++i) swap(res.a[js[k]][i], res.a[k][i]);
52          for (int i = 1; i <= n; ++i) swap(res.a[i][is[k]], res.a[i][k]);
53      }
54      return res;
55  }
56  T det() {
57      long long res = 1;
58      Martix cpy = *this;
59      for (int i = 1; i <= n; ++i) {
60          for (int j = i+1; j <= n; ++j) while (cpy.a[j][i]) {

```

```

60     long long t = cpy.a[i][i]/cpy.a[j][i];
61     for (int k = i; k <= n; ++k)
62         cpy.a[i][k] = (cpy.a[i][k]+MOD-t*cpy.a[j][k]%MOD)%MOD;
63     swap(cpy.a[i], cpy.a[j]);
64     res = -res;
65 }
66 res = res*cpy.a[i][i]%MOD;
67 }
68 return (res+MOD)%MOD;
69 }
70 friend ostream& operator << (ostream &os, Martix<T> &mx) {
71     for (int i = 1; i <= mx.n; ++i)
72         for (int j = 1; j <= mx.m; ++j)
73             os << mx[i][j] << " \n"[j==mx.m];
74     return os;
75 }
76 };

```

## 59 高斯消元

```

1 struct GaussElimination {
2     double a[N][N];
3     void init() { memset(a, 0, sizeof a); }
4     void init(const int &n) {
5         for (int i = 1; i <= n; ++i)
6             for (int j = 1; j <= n+1; ++j)
7                 a[i][j] = 0;
8     }
9     // ans is a[i][n+1]
10    bool solve(const int &n) {
11        for (int i = 1, j, k; i <= n; ++i) {
12            for (j = i+1, k = i; j <= n; ++j)
13                if (abs(a[j][i]) > abs(a[k][i])) k = j;
14            if (abs(a[k][i]) < eps) return false;
15            swap(a[k], a[i]);
16            for (j = 1; j <= n; ++j) if (i != j) {
17                double d = a[j][i]/a[i][i];
18                for (k = i+1; k <= n+1; ++k)
19                    a[j][k] -= d*a[i][k];
20            }
21        }
22        for (int i = 1; i <= n; ++i) a[i][n+1] /= a[i][i];
23        return true;
24    }
25 };

```

### 59.1 异或方程组

$a[i][j]$  第  $i$  个是否对  $j$  有影响  
 $a[i][n+1]$  第  $i$  个最后被翻转与否

```

1 // -1 : no solution, 0 : multi, 1 : one
2 template <typename T>
3 int XorGauss(T a[N], const int &n) {

```



```

4   for (int i = 1, j, k; i <= n; ++i) {
5       for (k = i; !a[k][i] && k <= n; ++k) {}
6       if (k <= n) swap(a[k], a[i]);
7       for (j = 1; j <= n; ++j) if (i != j && a[j][i])
8           for (k = i; k <= n+1; ++k) a[j][k] ^= a[i][k];
9           // a[j] ^= a[i]; // bitset<N> a[N]
10  }
11  for (int i = 1; i <= n; ++i) if (!a[i][i]) return -a[i][n+1];
12  return 1;
13 }
14 // dfs(n, 0)
15 void dfs(const int &u, const int &num) {
16     if (num >= res) return;
17     if (u <= 0) { res = num; return; }
18     if (a[u][u]) {
19         int t = a[u][n+1];
20         for (int i = u+1; i <= n; ++i) {
21             if (a[u][i]) t ^= used[i];
22         }
23         dfs(u-1, num+t);
24     } else { // 自由元
25         dfs(u-1, num);
26         used[u] = 1;
27         dfs(u-1, num+1);
28         used[u] = 0;
29     }
30 }

```

## 60 拉格朗日插值

```

1  template <typename T, typename H, typename P>
2  long long Largrange(const T &k, const int &n, const H x[], const P y
3  []) {
4      k %= MOD;
5      long long res = 0, s1 = 1, s2 = 1;
6      for (int i = 1; i <= n; ++i, s1 = s2 = 1) {
7          for (int j = 1; j <= n; ++j) if (i != j) {
8              s1 = s1*(x[i]-x[j]+MOD)%MOD;
9              s2 = s2*(k-x[j]+MOD)%MOD;
10         }
11         res = (res+y[i]*s2%MOD*mul_inverse(s1)%MOD)%MOD;
12     }
13     return res;
14 }

```

```

1  template <typename T, typename P> // x[i] = i -> y[i] = f(i)
2  long long Largrange(const T &k, const int &n, const P y[]) {
3      if (k <= n) return y[k];
4      static long long pre[N], suf[N];
5      long long res = 0;
6      k %= MOD;
7      pre[0] = suf[n+1] = 1;
8      for (int i = 1; i <= n; ++i) pre[i] = pre[i-1]*(k-i)%MOD;
9      for (int i = n; i >= 1; --i) suf[i] = suf[i+1]*(k-i)%MOD;

```

```

10   for (int i = 1; i <= n; ++i) {
11       res = (res+y[i]*(pre[i-1]*suf[i+1]%MOD)%MOD
12           *mul_inverse(((n-i)&1 ? -1 : 1)*fac[i-1]*fac[n-i]%MOD)%MOD)%MOD
13       ;
14   }
15   return (res+MOD)%MOD;
16 }

```

## 61 快速幂

```

1  template <typename T, typename H>
2  inline T qpow(const T &a, const H &p, const int &mo = MOD) {
3      long long res = 1, x = a;
4      for (H i = p; i; i >>= 1, x = x*x%mo)
5          if (i&1) res = res*x%mo;
6      return static_cast<T>(res);
7  }

```

## 62 快速乘

```

1  inline long long qmul(long long x, long long y, long long mo) {
2      long long res = 0;
3      while (y) {
4          if (y&1) res = (res+x)%mo;
5          x = (x<<1)%mo;
6          y >>= 1;
7      }
8      return res;
9  }

```

```

1  inline long long qmul(long long x, long long y, long long mo) {
2      return (long long)((__int128)x*y%mo);
3  }

```

```

1  inline long long qmul(long long x, long long y, long long mo) {
2      // x*y - floor(x*y/mo)*mo
3      typedef unsigned long long ull;
4      typedef long double ld;
5      return ((ull)x*y-(ull)((ld)x/mo*y)*mo+mo)%mo;
6  }

```

## 63 复数

```

1  struct comp {
2      typedef double T; // maybe long double ?
3      T real, imag;
4      comp (const double &_real = 0, const double &_imag = 0) : real(
        _real), imag(_imag) {}

```

```

5  friend comp operator + (const comp &c1, const comp &c2) { return
    comp(c1.real+c2.real, c1.imag+c2.imag); }
6  friend comp operator - (const comp &c1, const comp &c2) { return
    comp(c1.real-c2.real, c1.imag-c2.imag); }
7  friend comp operator * (const comp &c1, const comp &c2) { return
    comp(c1.real*c2.real-c1.imag*c2.imag, c1.real*c2.imag+c1.imag*c2
    .real); }
8  comp& operator += (const comp &c) { return *this = *this+c; }
9  comp& operator -= (const comp &c) { return *this = *this-c; }
10 comp& operator *= (const comp &c) { return *this = *this*c; }
11 friend istream& operator >> (istream &is, comp &c) { return is >> c
    .real >> c.imag; }
12 friend ostream& operator << (ostream &os, comp &c) { return os << c
    .real << setiosflags(ios::showpos) << c.imag << "i"; }
13 comp conjugate() { return comp(real, -imag); }
14 friend comp conjugate(const comp &c) { return comp(c.real, -c.imag)
    ; }
15 };

```

## 64 快速傅里叶变换 | FFT

```

1  // array [0, n)
2  namespace FFT {
3      static const int SIZE = (1<<18)+3;
4      int len, bit;
5      int rev[SIZE];
6      // #define comp complex<long double>
7      void fft(comp a[], int flag = 1) {
8          for (int i = 0; i < len; ++i)
9              if (i < rev[i]) swap(a[i], a[rev[i]]);
10         for (int base = 1; base < len; base <= 1) {
11             comp w, wn = {cos(PI/base), flag*sin(PI/base)};
12             for (int i = 0; i < len; i += base*2) {
13                 w = { 1.0, 0.0 };
14                 for (int j = 0; j < base; ++j) {
15                     comp x = a[i+j], y = w*a[i+j+base];
16                     a[i+j] = x+y;
17                     a[i+j+base] = x-y;
18                     w *= wn;
19                 }
20             }
21         }
22     }
23     void work(comp f[], const int &n, comp g[], const int &m) {
24         len = 1; bit = 0;
25         while (len < n+m) len <= 1, ++bit;
26         // multi-testcase
27         for (int i = n; i < len; ++i) f[i] = 0;
28         for (int i = m; i < len; ++i) g[i] = 0;
29         for (int i = 0; i < len; ++i)
30             rev[i] = (rev[i>>1]>>1)|((i&1)<<(bit-1));
31         fft(f, 1); fft(g, 1);
32         for (int i = 0; i < len; ++i) f[i] *= g[i];
33         fft(f, -1);

```

```

34     for (int i = 0; i < n+m; ++i) f[i].real /= len;
35 }
36 /*
37 template <class T>
38 void work(T a[], const int &n) {
39     static comp f[SIZE];
40     len = 1; bit = 0;
41     while (len < n+n) len <= 1, ++bit;
42     // multi-testcase
43     for (int i = 0; i < n; ++i) f[i] = a[i];
44     for (int i = n; i < len; ++i) f[i] = 0;
45     for (int i = 0; i < len; ++i) rev[i] = (rev[i>>1]>>1)/((i&1)<<(
        bit-1));
46     fft(f, 1);
47     for (int i = 0; i <= len; ++i) f[i] *= f[i];
48     fft(f, -1);
49     for (int i = 0; i < n+n; ++i) a[i] = static_cast<T>(f[i].real/len
        +.5);
50 }
51 */
52 }

```

## 65 快速数论变换 |NTT

```

1 // array [0, n)
2 namespace NTT {
3     static const int SIZE = (1<<18)+3;
4     const int G = 3;
5     int len, bit;
6     int rev[SIZE];
7     long long f[SIZE], g[SIZE];
8     template <class T>
9     void ntt(T a[], int flag = 1) {
10         for (int i = 0; i < len; ++i)
11             if (i < rev[i]) swap(a[i], a[rev[i]]);
12         for (int base = 1; base < len; base <= 1) {
13             long long wn = qpow(G, (MOD-1)/(base*2)), w;
14             if (flag == -1) wn = qpow(wn, MOD-2);
15             for (int i = 0; i < len; i += base*2) {
16                 w = 1;
17                 for (int j = 0; j < base; ++j) {
18                     long long x = a[i+j], y = w*a[i+j+base]%MOD;
19                     a[i+j] = (x+y)%MOD;
20                     a[i+j+base] = (x-y+MOD)%MOD;
21                     w = w*wn%MOD;
22                 }
23             }
24         }
25     }
26     template <class T>
27     void work(T a[], const int &n, T b[], const int &m) {
28         len = 1; bit = 0;
29         while (len < n+m) len <= 1, ++bit;
30         for (int i = 0; i < n; ++i) f[i] = a[i];
31         for (int i = n; i < len; ++i) f[i] = 0;

```

```

32     for (int i = 0; i < m; ++i) g[i] = b[i];
33     for (int i = m; i < len; ++i) g[i] = 0;
34     for (int i = 0; i < len; ++i)
35         rev[i] = (rev[i>>1]>>1)|((i&1)<<(bit-1));
36     ntt(f, 1); ntt(g, 1);
37     for (int i = 0; i < len; ++i) f[i] = f[i]*g[i]%MOD;
38     ntt(f, -1);
39     long long inv = qpow(len, MOD-2);
40     for (int i = 0; i < n+m-1; ++i) f[i] = f[i]*inv%MOD;
41 }
42 }

```

## 66 任意模数 NTT|MTT

```

1 namespace MTT {
2     static const int SIZE = (1<<18)+7;
3     int Mod = MOD;
4     comp w[SIZE];
5     int bitrev[SIZE];
6     long long f[SIZE];
7     void fft(comp *a, const int &n) {
8         for (int i = 0; i < n; ++i) if (i < bitrev[i]) swap(a[i], a[
9             bitrev[i]]);
10        for (int i = 2, lyc = n >> 1; i <= n; i <= 1, lyc >>= 1)
11            for (int j = 0; j < n; j += i) {
12                comp *l = a + j, *r = a + j + (i >> 1), *p = w;
13                for (int k = 0; k < i>>1; ++k) {
14                    comp tmp = *r * *p;
15                    *r = *l - tmp, *l = *l + tmp;
16                    ++l, ++r, p += lyc;
17                }
18            }
19    }
20    template <class T>
21    inline void work(T *x, const int &n, T *y, const int &m) {
22        static int bit, L;
23        static comp a[SIZE], b[SIZE];
24        static comp dfta[SIZE], dftb[SIZE];
25
26        for (L = 1, bit = 0; L < n+m-1; ++bit, L <= 1);
27        for (int i = 0; i < L; ++i) bitrev[i] = bitrev[i >> 1] >> 1 | ((i
28            & 1) << (bit - 1));
29        for (int i = 0; i < L; ++i) w[i] = comp(cos(2 * PI * i / L), sin
30            (2 * PI * i / L));
31
32        for (int i = 0; i < n; ++i) (x[i] += Mod) %= Mod, a[i] = comp(x[i
33            ] & 32767, x[i] >> 15);
34        for (int i = n; i < L; ++i) a[i] = 0;
35        for (int i = 0; i < m; ++i) (y[i] += Mod) %= Mod, b[i] = comp(y[i
36            ] & 32767, y[i] >> 15);
37        for (int i = m; i < L; ++i) b[i] = 0;
38        fft(a, L), fft(b, L);
39        for (int i = 0; i < L; ++i) {
40            int j = (L - i) & (L - 1);
41            static comp da, db, dc, dd;

```

```

37     da = (a[i] + conjugate(a[j])) * comp(.5, 0);
38     db = (a[i] - conjugate(a[j])) * comp(0, -.5);
39     dc = (b[i] + conjugate(b[j])) * comp(.5, 0);
40     dd = (b[i] - conjugate(b[j])) * comp(0, -.5);
41     dfta[j] = da*dc + da*dd*comp(0, 1);
42     dftb[j] = db*dc + db*dd*comp(0, 1);
43 }
44 for (int i = 0; i < L; ++i) a[i] = dfta[i];
45 for (int i = 0; i < L; ++i) b[i] = dftb[i];
46 fft(a, L), fft(b, L);
47 for (int i = 0; i < L; ++i) {
48     int da = (long long)(a[i].real / L + 0.5) % Mod;
49     int db = (long long)(a[i].imag / L + 0.5) % Mod;
50     int dc = (long long)(b[i].real / L + 0.5) % Mod;
51     int dd = (long long)(b[i].imag / L + 0.5) % Mod;
52     f[i] = (da + ((long long)(db + dc) << 15) + ((long long)dd <<
53         30)) % Mod;
54 }
55 for (int i = 0; i < n+m-1; ++i) (f[i] += Mod) %= Mod;
56 }

```

## 67 分治 FFT

```

1 // give g[1, n) ask f[0, n)
2 // f[i] = sigma f[i-j]*g[j] (1 <= j <= i)
3 template <class T> // [l, r]
4 void cdq_fft(T f[], T g[], const int &l, const int &r) {
5     if (r-l <= 1) return;
6     int mid = (l+r)>>1;
7     cdq_fft(f, g, l, mid);
8     NTT::work(f+l, mid-l, g, r-l);
9     for (int i = mid; i < r; ++i)
10         (f[i] += NTT::f[i-l]) %= MOD;
11     cdq_fft(f, g, mid, r);
12 }
13 // f[0] = 1; cdq_fft(f, g, 0, n);

```

## 68 快速沃尔什变换 | FWT

复杂度  $O(n \log n) | O(n2^n)$

$$FWT(A \pm B) = FWT(A) \pm FWT(B)$$

$$FWT(cA) = cFWT(A)$$

定义  $\boxplus$  为任意集合运算

$$FWT(A \boxplus B) = FWT(A) \times FWT(B)$$

$$\text{求 } C_i = \sum_{j \boxplus k} a_j b_k$$

### 68.1 或运算

$$FWT(A)[i] = \sum_{j|i} A[j]$$

$$FWT(A) = [FWT(A_0), FWT(A_0 + A_1)]$$

$$IFWT(A) = [IFWT(A_0), IFWT(A_1) - IFWT(A_0)]$$

## 68.2 与运算

$$FWT(A)[i] = \sum_{i \& j = j} A[j]$$

$$FWT(A) = [FWT(A_0 + A_1), FWT(A_1)]$$

$$IFWT(A) = [IFWT(A_0) - IFWT(A_1), IFWT(A_1)]$$

## 68.3 异或运算

令  $d(x)$  为  $x$  在二进制下拥有的 1 的数量

$$FWT(A)[i] = \sum_j (-1)^{d(i \oplus j)} A[j]$$

$$FWT(A) = [FWT(A_0 + A_1), FWT(A_0 - A_1)]$$

$$IFWT(A) = [\frac{IFWT(A_1 - A_0)}{2}, \frac{IFWT(A_1 + A_0)}{2}]$$

## 68.4 code

```

1 namespace FWT {
2 #define forforfor for (int l = 2; l <= len; l <= 1)\
3     for (int i = 0, k = l>>1; i < len; i += l)\
4     for (int j = 0; j < k; ++j)
5
6 const int SIZE = (1<<17)+3;
7 int len;
8 int f[SIZE], g[SIZE];
9 template <class T> void init(T a[], const int &n, T b[], const int
10     &m) {
11     len = 1;
12     while (len < max(n, m)) len <= 1;
13     for (int i = 0; i < n; ++i) f[i] = a[i];
14     for (int i = n; i < len; ++i) f[i] = 0;
15     for (int i = 0; i < m; ++i) g[i] = b[i];
16     for (int i = m; i < len; ++i) g[i] = 0;
17 }
18 template <class T> void fwt_or(T a[], const int x = 1) {
19     forforfor a[i+j+k] = (a[i+j+k]+1ll*a[i+j]*x)%MOD;
20 }
21 template <class T> void fwt_and(T a[], const int x = 1) {
22     forforfor a[i+j] = (a[i+j]+1ll*a[i+j+k]*x)%MOD;
23 }
24 template <class T> void fwt_xor(T a[], const int x = 1) {
25     forforfor {
26         (a[i+j] += a[i+j+k]) %= MOD;
27         a[i+j+k] = (a[i+j]-2*a[i+j+k]%MOD+MOD)%MOD;
28         a[i+j] = 1ll*a[i+j]*x%MOD; a[i+j+k] = 1ll*a[i+j+k]*x%MOD;
29     }
30 }
31 template <class T> void work_or(const T a[], const int &n, const T
32     b[], const int &m) {
33     init(a, n, b, m); fwt_or(f); fwt_or(g);
34     for (int i = 0; i < len; ++i) f[i] = 1ll*f[i]*g[i]%MOD;
35     fwt_or(f, MOD-1); // fwt_or(x, -1)

```

```

34 }
35 template <class T> void work_and(const T a[], const int &n, const T
    b[], const int &m) {
36     init(a, n, b, m); fwt_and(f); fwt_and(g);
37     for (int i = 0; i < len; ++i) f[i] = 1ll*f[i]*g[i]%MOD;
38     fwt_and(f, MOD-1); // fwt_and(x, -1)
39 }
40 template <class T> void work_xor(const T a[], const int &n, const T
    b[], const int &m) {
41     init(a, n, b, m); fwt_xor(f); fwt_xor(g);
42     for (int i = 0; i < len; ++i) f[i] = 1ll*f[i]*g[i]%MOD;
43     fwt_xor(f, mul_inverse(2)); // fwt_xor(x, 1/2)
44 }
45 #undef forforfor
46 } // namespace FWT

```

## 69 快速莫比乌斯变换 |FMT

据说 FWT 做的事情完全包含 FMT 且常数是一半 (咕之

## 70 快速子集变换 (子集卷积)|FST

$$C_k = \sum_{i \& j = 0, i|j=k} A_i B_j$$

复杂度  $O(n \log^2 n) | O(n^2 2^n)$

```

1 namespace FST {
2     const int W = 20;
3     const int N = 1<<W;
4     int len, bit;
5     int f[W+1][N], g[W+1][N], h[W+1][N], res[N];
6     template <class T> void fwt(T a[], const int x = 1) {
7         for (int l = 2; l <= len; l <= 1)
8             for (int i = 0, k = l>>1; i < len; i += l)
9                 for (int j = 0; j < k; ++j)
10                    a[i+j+k] = (a[i+j+k]+1ll*a[i+j]*x)%MOD;
11     }
12     template <class T> void work(const T a[], const int &n, const T b
        [], const int &m) {
13         len = 1; bit = 0;
14         while (len < max(n, m)) len <= 1, ++bit;
15         for (int i = 0; i <= bit; ++i)
16             for (int j = 0; j < len; ++j)
17                 f[i][j] = g[i][j] = h[i][j] = 0;
18         for (int i = 0; i < n; ++i) f[__builtin_popcount(i)][i] = a[i];
19         for (int i = 0; i < m; ++i) g[__builtin_popcount(i)][i] = b[i];
20         for (int i = 0; i <= bit; ++i) {
21             fwt(f[i]); fwt(g[i]);
22             for (int j = 0; j <= i; ++j)
23                 for (int k = 0; k < len; ++k)
24                    h[i][k] = (h[i][k]+1ll*f[j][k]*g[i-j][k])%MOD;
25             fwt(h[i], MOD-1); // fwt(h[i], -1)
26         }

```



```

27     for (int i = 0; i < len; ++i) res[i] = h[__builtin_popcount(i)][i];
28 }
29 } // namespace FST

```

## 70.1 倍增子集卷积

设多项式  $A = \sum_{i=0}^{2^n-1} a_i x^i, B = \sum_{i=0}^{2^n-1} b_i x^i$

求  $C = A * B = \sum_{i=0}^{2^n-1} x^i \sum_{d \subseteq i} a_d b_{i-d}$

按照每个状态的最高位进行分组，然后卷  $n$  次

复杂度  $O(\sum_{i=1}^n i^2 2^i) = O(n^2 2^n)$

```

1 template <typename T> void vipfst(T a[], const int &n) { // return a
2     static int b[1<<B]; // warning: the type of b
3     int len = 1; while (len < n) len <= 1;
4     memcpy(b, a, sizeof(T)*len);
5     memset(a, 0, sizeof(T)*len); a[0] = 1;
6     for (int i = 1; i < len; i <= 1) {
7         FST::work(a, i, b+i, i);
8         for (int j = 0; j < i; ++j)
9             a[i+j] = FST::h[__builtin_popcount(j)][j];
10    }
11 }

```

## 71 第二类斯特林数

```

1 inline void stirling(const int &n) {
2     S[0][0] = 1;
3     // 注意取模
4     for (int i = 1; i <= n; ++i)
5         for (int j = 1; j <= i; ++j)
6             S[i][j] = S[i-1][j-1] + S[i-1][j]*j;
7 }

```

```

1 void stirling(const int &n) {
2     inv[0] = inv[1] = 1;
3     for (int i = 2; i <= n; ++i)
4         inv[i] = MOD-MOD/i*inv[MOD%i]%MOD;
5     for (int i = 1; i <= n; ++i)
6         inv[i] = inv[i-1]*inv[i]%MOD;
7     while (len <= (n<<1)) len <= 1, ++bit;
8     for (int i = 0; i < len; ++i)
9         rev[i] = (rev[i>>1]>>1)|((i&1)<<(bit-1));
10    for (int i = 0, one = 1; i <= n; ++i, one = MOD-one) {
11        f[i] = one*inv[i]%MOD;
12        g[i] = qpow(i, n)*inv[i]%MOD;
13    }
14    NTT(f, 1); NTT(g, 1);
15    for (int i = 0; i < len; ++i) f[i] = f[i]*g[i]%MOD;
16    NTT(f, -1);

```

```

17 long long invv = qpow(len, MOD-2);
18 for (int i = 0; i <= n; ++i)
19     printf("%lld%c", f[i]*invv%MOD, " \n"[i==n]);
20 }

```

## 72 约瑟夫环

### 72.1 $O(n)$

```

1 int solve(int n, int v) { return n == 1 ? 0 : (solve(n-1, v)+v)%n; }
2 // res = solve(num, step)+1

```

## 73 最大公因数 gcd

```

1 __gcd(a, b); // <algorithm>
2 int gcd(int a, int b) { return b ? gcd(b, a%b) : a; }
3 inline int gcd(int a, int b) { while (b) a %= b, swap(a, b); return a; }

```

## 74 最小公倍数 lcm

$$LCM\left(\frac{a}{b}, \frac{c}{d}\right) = \frac{LCM(a, c)}{GCD(b, d)}$$

$$LCM\left(\frac{a_1}{b_1}, \frac{a_2}{b_2}, \dots\right) = \frac{LCM(a_1, a_2, \dots)}{GCD(b_1, b_2, \dots)}$$

```

1 inline int lcm(int a, int b) { return a/gcd(a, b)*b; }

```

## 75 扩展欧几里得（同余方程

```

1 template <typename T>
2 T exgcd(const T a, const T b, T &x, T &y) {
3     if (!b) return x = 1, y = 0, a;
4     T d = exgcd(b, a%b, y, x);
5     y -= a/b*x;
6     return d;
7 }

```

## 76 乘法逆元

### 76.1 拓展欧几里得

```

1 template <typename T>
2 inline T mul_inverse(const T &a, const T &mo = MOD) {
3     T x, y;
4     exgcd(a, mo, x, y);
5     return (x%mo+mo)%mo;
6 }

```

## 76.2 费马小定理

```

1 template <typename T>
2 inline T mul_inverse(const T &a, const int &mo = MOD) {
3     return qpow(a, mo-2);
4 }

```

## 76.3 线性递推

```

1 template <typename T>
2 inline void mul_inverse(T *inv, int mod = MOD) {
3     inv[0] = inv[1] = 1;
4     for(int i = 2; i <= n; ++i)
5         inv[i] = 1ll*(mod-mod/i)*inv[mod%i]%mod;
6 }

```

## 77 中国剩余定理

### 77.1 中国剩余定理 CRT(m 互质)

```

1 inline long long CRT(int a[], int m[]) {
2     long long res = 0, M = 1;
3     for (int i = 1; i <= n; ++i)
4         M *= m[i];
5     for (int i = 1; i <= n; ++i)
6         res = (res + a[i]*(M/m[i])*mul_inverse(M/m[i], m[i]))%M;
7     return (res+M)%M;
8 }

```

### 77.2 扩展中国剩余定理 EXCRT(m 不互质)

```

1 inline long long EXCRT(long long a[], long long m[]) {
2     //  $M \cdot x + m[i] \cdot y = a[i] - res \pmod{m[i]}$ 
3     //  $res = res + x \cdot M$ ;
4     long long M = m[1], res = a[1], x, y, c, d;
5     for (int i = 2; i <= n; ++i) {
6         d = exgcd(M, m[i], x, y);
7         c = (a[i] - res % m[i] + m[i]) % m[i];
8         if (c % d != 0) return -1;
9         x = (c / d) * x % (m[i] / d);
10        res += x * M;
11        M *= m[i] / d;
12        res = (res % M + M) % M;
13    }
14    return res;
15 }

```

## 78 排列组合

```

1 struct Combination {
2     int fac[N], inv[N];
3     void init(const int &n) {
4         fac[0] = inv[0] = fac[1] = inv[1] = 1;
5         for (int i = 2; i <= n; ++i) {
6             fac[i] = 1ll*fac[i-1]*i%MOD;
7             inv[i] = 1ll*(MOD-MOD/i)*inv[MOD%i]%MOD;
8         }
9         for (int i = 2; i <= n; ++i) {
10            inv[i] = 1ll*inv[i]*inv[i-1]%MOD;
11        }
12    }
13    int A(const int &p, const int &q) {
14        return p >= q ? 1ll*fac[p]*inv[p-q]%MOD : 0;
15    }
16    int C(const int &p, const int &q) {
17        return p >= q ? 1ll*fac[p]*inv[q]%MOD*inv[p-q]%MOD : 0;
18    }
19 };

```

### 78.1 奇偶性

$C(n, k)$  当  $n \& k == k$  为奇数反之偶数

## 79 欧拉函数

```

1 template <typename T> inline T phi(T x) {
2     T res = x;
3     for (T i = 2; i*i <= x; ++i) {
4         if (x%i) continue;
5         res = res/i*(i-1);
6         while (x%i == 0) x /= i;
7     }
8     if (x > 1) res = res/x*(x-1);
9     return res;
10 }

```

### 79.1 筛法

```

1 struct Euler {
2     int phi[N], check[N];
3     vector<int> prime;
4     void init(int sz) {
5         for (int i = 1; i <= sz; ++i) check[i] = 1;
6         phi[1] = 1; check[1] = 0;
7         for (int i = 2; i <= sz; ++i) {
8             if (check[i]) {
9                 prime.emplace_back(i);
10                phi[i] = i-1;

```

```

11     }
12     for (int j : prime) {
13         if (i*j > sz) break;
14         check[i*j] = 0;
15         if (i%j) {
16             phi[i*j] = (j-1)*phi[i];
17         } else {
18             phi[i*j] = j*phi[i];
19             break;
20         }
21     }
22 }
23 }
24 } E;

```

## 80 莫比乌斯函数

```

1 template <typename T> inline T miu(T x) {
2     int t = 0;
3     for (T i = 2, k; i*i <= x; ++i) {
4         if (x%i) continue;
5         for (k = 0, ++t; x %i == 0; x /= i, ++k) {}
6         if (k >= 2) return 0;
7     }
8     if (x > 1) ++t;
9     return t&1 ? -1 : 1;
10 }

```

## 81 线性筛素数

```

1 struct Euler {
2     int tot = 0;
3     int prime[N];
4     bool check[N];
5     bool& operator [] (const int i) { return check[i]; }
6     void init(int sz) {
7         tot = 0;
8         for (int i = 1; i <= sz; ++i) check[i] = true;
9         check[1] = false;
10        for (register int i = 2, j; i <= sz; ++i) {
11            if (check[i]) prime[++tot] = i;
12            for (j = 1; j <= tot && i*prime[j] <= sz; ++j) {
13                check[i*prime[j]] = false;
14                if (i%prime[j] == 0) break;
15            }
16        }
17    }
18 } E;

```

## 82 判断素数 (质数)

### 82.1 Miller-Rabin 素性测试

```

1 inline bool MillerRabin(int x) {
2     static const int test_time = 10;
3     if (x < 3) return x == 2;
4     int a = x-1, b = 0;
5     while (!(a&1)) a >>= 1, ++b;
6     for (int i = 1, j, v; i <= test_time; ++i) {
7         v = (qpow(rnd()%(x-2)+2, a, x));
8         if (v == 1 || v == x-1) continue;
9         for (j = 0; j < b && v != x-1; ++j)
10             v = static_cast<int>(1ll*v*v%x);
11         if (j >= b) return false;
12     }
13     return true;
14 }

```

## 83 线性筛 GCD

```

1 inline void gcd_init(const int &n) {
2     for (int i = 1; i <= n; ++i)
3         for (int j = 1; j <= n; ++j) if (!g[i][j])
4             for (int k = 1; k <= n/i; ++k)
5                 g[k*i][k*j] = k;
6 }

```

## 84 BSGS

求解关于  $t$  的方程  $a^t \equiv x \pmod{m}$ ,  $\gcd(a, m) = 1$

```

1 // map<long long, int> mmp; // a^n = x
2 inline long long BSGS(long long a, long long x, long long m) {
3     long long t = (long long)ceil(sqrt(m)); // b = a^i
4     for(int i = 0; i < t; ++i)
5         mmp[mul(x, qpow(a, i))] = i;
6     a = qpow(a, t);
7     long long now, ans; // now = (a^t)^i
8     for(int i = 0; i <= t; ++i) {
9         now = qpow(a, i);
10        if(mmp.count(now)) {
11            ans = t*i-mmp[now];
12            if(ans > 0) return ans;
13        }
14    }
15    return -1;
16 }

```

## 85 拓展 BSGS

$$\gcd(a, m) \neq 1$$

## 86 错排

$$\begin{aligned} D_1 &= 0 \\ D_2 &= 1 \\ D_n &= (n-1)(D_{n-1} + D_{n-2}) \end{aligned}$$

## 87 原根

$$\text{复杂度 } O(\sqrt{m} + g \times \log^2 m)$$

```

1 inline int getG(const int &m) {
2     static int q[100000+7];
3     int _phi = phi(m), x = _phi, tot = 0;
4     for (int i = 2; i*i <= _phi; ++i) {
5         if (x%i) continue;
6         q[++tot] = _phi/i;
7         while (x%i == 0) x /= i;
8     }
9     if (x > 1) x = q[++tot] = _phi/x;
10    for (int g = 2, flag; ; ++g) {
11        flag = 1;
12        if (qpow(g, _phi, m) != 1) continue;
13        for (int i = 1; i <= tot; ++i) {
14            if (qpow(g, q[i], m) == 1) {
15                flag = 0;
16                break;
17            }
18        }
19        if (flag) return g;
20    }
21 }

```

## Part VII

## 动态规划 DP

## 88 线性 DP

### 88.1 最长上升子序列 LIS

```

1 for(int i = 1; i <= n; ++i) {
2     f[i] = 1;
3     for(int j = 1; j < i; ++j)
4         if(a[i] > a[j]) f[i] = max(f[i], f[j]+1);
5 }

```

## 88.2 最长公共子序列 LCS

```

1 f[i][j] = max{   f[i-1][j],
2                  f[i][j-1],
3                  f[i-1][j-1]+1 (if A[i] == B[j])}

```

## 89 状压 DP

### 89.1 枚举子集

```

1 for (int i = s; i; i = (i-1)&s) {}

```

### 89.2 枚举 n 个元素大小为 k 的二进制子集

```

1 int s=(1<<k)-1;
2 while(s<(1<<n)){
3     work(s);
4     int x=s&-s,y=s+x;
5     s=((s&~y)/x>>1)|y; //这里有一个位反~
6 }

```

## 90 背包问题

### 90.1 多重背包

二进制拆分

```

1 for(int i = 1, cnt, vi, wi, m; i <= n; ++i) {
2     scanf("%d%d%d", &vi, &wi, &m);
3     cnt = 1;
4     while(m-cnt > 0) {
5         m -= cnt;
6         v.push_back(vi*cnt);
7         w.push_back(wi*cnt);
8         cnt <<= 1;
9     }
10    v.push_back(vi*m);
11    w.push_back(wi*m);
12 }
13 for(int i = 0; i < w.size(); ++i)
14     for(int j = W; j >= w[i]; --j)
15         b[j] = max(b[j], b[j-w[i]]+v[i]);

```

单调队列

```

1 for(int i = 1; i <= n; ++i) {
2     scanf("%d%d%d", &v, &w, &m);
3     for(int u = 0; u < w; ++u) {
4         int maxp = (W-u)/w;
5         head = 1; tail = 0;
6         for(int k = maxp-1; k >= max(0, maxp-m); --k) {

```



```

7   while(head <= tail && calc(u, q[tail]) <= calc(u, k)) tail--;
8   q[++tail] = k;
9   }
10  for(int p = maxp; p >= 0; --p) {
11      while(head <= tail && q[head] >= p) head++;
12      if(head <= tail) f[u+p*w] = max(f[u+p*w], p*v+calc(u, q[head]));
13      ;
14      if(p-m-1 < 0) continue;
15      while(head <= tail && calc(u, q[tail]) <= calc(u, p-m-1)) tail--;
16      q[++tail] = p-m-1;
17  }
18 }
19 int ans = 0;
20 for(int i = 1; i <= W; ++i)
21     ans = max(ans, f[i]);

```

## 91 斜率优化

若  $dp$  方程为  $dp[i] = a[i] \cdot b[j] + c[i] + d[j]$  时, 由于存在  $a[i] \cdot b[j]$  这个既有  $i$  又有  $j$  的项, 就需要使用斜率优化

### 91.1 「HNOI2008」玩具装箱 TOY

$$dp[i] = \min(dp[j] + (sum[i] + i - sum[j] - j - L - 1)^2) (j < i)$$

$$\text{令 } a[i] = sum[i] + i, b[j] = sum[j] + j + L + 1$$

$$dp[i] = dp[j] + (a[i] - b[j])^2$$

$$dp[i] = dp[j] + a[i]^2 - 2 \cdot a[i] \cdot b[j] + b[j]^2$$

$$2 \cdot a[i] \cdot b[j] + dp[i] - a[i]^2 = dp[j] + b[j]^2$$

将  $b[j]$  看作  $x$ ,  $dp[j] + b[j]^2$  看作  $y$ , 这个式子就可以看作一条斜率为  $2 \cdot a[i]$  的直线

而对于每个  $i$  来说,  $a[i]$  都是确定的, 类似线性规划

$dp[i]$  的含义转化为: 当上述直线过点  $P(b[j], dp[j] + b[j]^2)$  时, 直线在  $y$  轴的截距加上  $a[i]^2$  (一个定值) 而题目即为找这个截距的最小值

## 92 四边形不等式

### 92.1 2D1D

$$f_{l,r} = \min_{k=l}^{r-1} \{f_{l,k} + f_{k+1,r}\} + w(l,r) \quad (1 \leq l \leq r \leq n)$$

当  $w(l,r)$  满足特定性质

- 区间包含单调性: 如果对于任意  $l \leq l' \leq r' \leq r$ , 均有  $w(l', r') \leq w(l, r)$  成立, 则称函数  $w$  对于区间包含关系具有单调性。

- 四边形不等式: 如果对于任意  $l_1 \leq l_2 \leq r_1 \leq r_2$ , 均有  $w(l_1, r_1) + w(l_2, r_2) \leq w(l_1, r_2) + w(l_2, r_1)$  成立, 则称函数  $w$  满足四边形不等式 (简记为“交叉小于包含”)。若等号永远成立, 则称函数  $w$  满足四边形恒等式。

> 引理 1: 若满足关于区间包含的单调性的函数  $w(l, r)$  满足四边形不等式, 则状态  $f_{l,r}$  也满足四边形不等式。

> 定理 1: 若状态  $f$  满足四边形不等式, 记  $m_{l,r} = \min\{k : f_{l,r} = g_{k,l,r}\}$  表示最优决策点, 则有  $m_{l,r-1} \leq m_{l,r} \leq m_{l+1,r}$

## 92.2 1D1D

$$f_r = \min_{l=1}^{r-1} \{f_l + w(l, r)\} \quad (1 \leq r \leq n)$$

> 定理 2：若函数  $w(l, r)$  满足四边形不等式，记  $h_{l,r} = f_l + w(l, r)$  表示从  $l$  转移过来的状态  $r$ ， $k_r = \min\{l | f_r = h_{l,r}\}$  表示最优决策点，则有  $\forall r_1 \leq r_2 : k_{r_1} \leq k_{r_2}$

```

1 void DP(int l, int r, int k_l, int k_r) {
2     int mid = (l + r) / 2, k = k_l;
3     // 求状态  $f[mid]$  的最优决策点
4     for (int i = k_l; i <= min(k_r, mid - 1); ++i)
5         if (w(i, mid) < w(k, mid)) k = i;
6     f[mid] = w(k, mid);
7     // 根据决策单调性得出左右两部分的决策区间，递归处理
8     if (l < mid) DP(l, mid - 1, k_l, k);
9     if (r > mid) DP(mid + 1, r, k, k_r);
10 }
```

## 92.3 满足四边形不等式的函数类

- 性质 1：若函数  $w_1(l, r), w_2(l, r)$  均满足四边形不等式（或区间包含单调性），则对于任意  $c_1, c_2 \geq 0$ ，函数  $c_1 w_1 + c_2 w_2$  也满足四边形不等式（或区间包含单调性）。

- 性质 2：若存在函数  $f(x), g(x)$  使得  $w(l, r) = f(r) - g(l)$ ，则函数  $w$  满足四边形恒等式。当函数  $f, g$  单调增加时，函数  $w$  还满足区间包含单调性。

- 性质 3：设  $h(x)$  是一个单调增加的凸函数，若函数  $w(l, r)$  满足四边形不等式并且对区间包含关系具有单调性，则复合函数  $h(w(l, r))$  也满足四边形不等式和区间包含单调性。

- 性质 4：设  $h(x)$  是一个凸函数，若函数  $w(l, r)$  满足四边形恒等式并且对区间包含关系具有单调性，则复合函数  $h(w(l, r))$  也满足四边形不等式。

首先需要澄清一点，凸函数（Convex Function）的定义在国内教材中有分歧，此处的凸函数指的是（可微的）下凸函数，即一阶导数单调增加的函数。

## 93 插头 DP | 轮廓线 DP

### 93.1 一个闭合回路

```

1 const int P = 299987;
2 const int M = 1<<21;
3 const int N = 15;
4
5 int n, m;
6 int a[N][N];
7 long long dp[2][M];
8 int head[2][P], nex[2][M], tot[2], ver[2][M];
9 // Long Long dp[2][P];
10 // int head[2][P], nex[2][P], tot[2], ver[2][P];
11
12 inline void clear(const int &u) {
13     for (int i = 1; i <= tot[u]; ++i) {
14         dp[u][i] = 0; //
15         nex[u][i] = 0; //
16         head[u][ver[u][i]%P] = 0;
17     }
18     tot[u] = 0;

```

```

19 }
20
21 template <typename T, typename U>
22 inline void insert(const int &u, const T &x, const U &v) {
23     int p = x%P;
24     for (int i = head[u][p]; i; i = nex[u][i]) {
25         if (ver[u][i] == x) return dp[u][i] += v, void();
26     }
27     ++tot[u]; assert(tot[u] < M);
28     ver[u][tot[u]] = x;
29     nex[u][tot[u]] = head[u][p];
30     head[u][p] = tot[u];
31     dp[u][tot[u]] = v;
32 }
33
34 template <typename T>
35 inline int get_val(const int &u, const T &x) {
36     int p = x%P;
37     for (int i = head[u][p]; i; i = nex[u][i]) {
38         if (ver[u][i] == x) return dp[u][i];
39     }
40     return 0;
41 }
42
43 inline long long solve() {
44     int u = 0, base = (1<<m*2+2)-1;
45     long long res = 0;
46     clear(u);
47     insert(u, 0, 1);
48     for (int i = 1; i <= n; ++i) {
49         for (int j = 1; j <= m; ++j) {
50             clear(u ^= 1);
51             for (int k = 1; k <= tot[u^1]; ++k) {
52                 int state = ver[u^1][k];
53                 long long val = dp[u^1][k];
54                 if (j == 1) state = (state<<2)&base;
55                 // b1 right b2 down
56                 // 0 no 1 left 2 right
57                 int b1 = (state>>j*2-2)%4, b2 = (state>>j*2)%4;
58                 if (!a[i][j]) {
59                     if (!b1 && !b2) insert(u, state, val);
60                 } else if (!b1 && !b2) {
61                     if (a[i+1][j] && a[i][j+1]) insert(u, state+(1<<j*2-2)+(2<<
62                         j*2), val);
63                 } else if (!b1 && b2) {
64                     if (a[i][j+1]) insert(u, state, val);
65                     if (a[i+1][j]) insert(u, state+(b2<<j*2-2)-(b2<<j*2), val);
66                 } else if (b1 && !b2) {
67                     if (a[i+1][j]) insert(u, state, val);
68                     if (a[i][j+1]) insert(u, state-(b1<<j*2-2)+(b1<<j*2), val);
69                 } else if (b1 == 1 && b2 == 1) { // find 2 turn to 1
70                     for (int k = j+1, t = 1; k <= m; ++k) {
71                         if ((state>>k*2)%4 == 1) ++t;
72                         if ((state>>k*2)%4 == 2) --t;
73                         if (!t) { insert(u, state-(1<<j*2-2)-(1<<j*2)-(1<<k*2),
74                             val); break; }
75                     }
76                 }
77             }
78         }
79     }
80     return res;
81 }

```

```

74         } else if (b1 == 2 && b2 == 2) { // find 1 turn to 2
75         for (int k = j-2, t = 1; k >= 0; --k) {
76             if ((state>>k*2)%4 == 1) --t;
77             if ((state>>k*2)%4 == 2) ++t;
78             if (!t) { insert(u, state-(2<<j*2-2)-(2<<j*2)+(1<<k*2),
79                             val); break; }
80         }
81         } else if (b1 == 2 && b2 == 1) {
82             insert(u, state-(2<<j*2-2)-(1<<j*2), val);
83         } else if (i == ex && j == ey) { // b1 == 1, b2 == 2
84             res += val;
85         }
86     }
87 }
88 return res;
89 }

```

## 94 多个闭合回路

```

1         else if (b1 == 1 && b2 == 2) {
2             if (i == ex && j == ey) res += val;
3             else dp[u][bit-(1<<j*2-2)-(1<<j*2+1)] += val;
4         }

```

## 95 联通块

```

1 int n, u, res = -INF;
2 int a[N][N];
3 unordered_map<int, int> dp[2];
4
5 inline void decode(const int &state, int *const s) {
6     for (int i = 1; i <= n; ++i) s[i] = (state>>i*3-3)%8;
7 }
8
9 inline void insert(const int *const s, const int &val) {
10     static int vis[N];
11     int state = 0, cnt = 0;
12     memset(vis, 0, sizeof vis);
13     for (int i = 1; i <= n; ++i) {
14         if (s[i] && !vis[s[i]]) vis[s[i]] = ++cnt;
15         state |= (vis[s[i]]<<i*3-3);
16     }
17     if (dp[u].count(state)) dp[u][state] = max(dp[u][state], val);
18     else dp[u].insert({state, val});
19     if (cnt == 1) res = max(res, val);
20 }
21
22 inline void solve() {
23     static int s[N];
24     dp[u = 0].clear();
25     dp[u][0] = 0;

```

```

26   for (int i = 1; i <= n; ++i) {
27       for (int j = 1; j <= n; ++j) {
28           dp[u ^ 1].clear();
29           for (const auto &p : dp[u^1]) {
30               decode(p.first, s);
31               int b1 = s[j-1], b2 = s[j];
32               // not choose
33               s[j] = 0;
34               int cnt = 0;
35               for (int k = 1; k <= n; ++k) cnt += s[k] == b2;
36               if (!b2 || cnt) insert(s, p.second);
37               s[j] = b2;
38               // choose
39               if (!b1 && !b2) {
40                   s[j] = 7;
41               } else {
42                   if (b1 > b2) swap(b1, b2); // in case b2 == 0
43                   s[j] = b2;
44                   if (b1) for (int k = 1; k <= n; ++k) if (s[k] == b1) s[k] =
                        b2;
45               }
46               insert(s, p.second+a[i][j]);
47           }
48       }
49   }
50   cout << res << endl;
51 }

```

## 96 L 型

L 型地板：拐弯且仅拐弯一次。

发现没有，一个存在的插头只有两种状态：拐弯过和没拐弯过，因此我们这样定义插头：

0 表没有插头，1 表没拐过的插头，2 表已经拐过的插头。b1 代表当前点的右插头，b2 代表当前点的下插头

## Part VIII

## STL

## 97 unordered\_map 重载

```

1   struct Node {
2       int a, b;
3       // 重载 ==
4       friend bool operator == (const Node &x, const Node &y) {
5           return x.a == y.a && x.b == y.b;
6       }
7   };
8
9   // 方法一
10  namespace std {
11      template <>

```

```
12 struct hash<Node> {
13     size_t operator () (const Node &x) const {
14         return hash<int>()(x.a)^hash<int>()(x.b);
15     }
16 };
17 }
18 unordered_map<Node, int> mp;
19
20 // 方法二
21 struct KeyHasher {
22     size_t operator () (const Node &x) const {
23         return hash<int>()(x.a)^hash<int>()(x.b);
24     }
25 };
26 unordered_map<Node, int, KeyHasher> mmp;
```