ACM/ICPC Template Manaual

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Contents

0 Include

```
#include <bits/stdc++.h>
using namespace std;
#define clr(a, x) memset(a, x, sizeof(a))
#define mp(x, y) make_pair(x, y)
#define pb(x) push_back(x)
#define X first
#define Y second
#define fastin                    \
    ios_base::sync_with_stdio(0); \
    cin.tie(0);
typedef long long ll;
typedef long double ld;
typedef pair<int, int> PII;
typedef vector<int> VI;
const int INF = 0x3f3f3f3f;
const int mod = 1e9 + 7;
const double eps = 1e-6;

int main()
{
#ifndef ONLINE_JUDGE
    freopen("test.in", "r", stdin);
    freopen("test.out", "w", stdout);
#endif

    return 0;
}
```

1 Math

1.1 Prime

1.1.1 Eratosthenes Sieve

$O(n \log\log n)$ 筛出 maxn 内所有素数
$notprime[i] = 0/1$ 0 为素数 1 为非素数

```
const int maxn = "Edit";
bool notprime[maxn] = {1, 1};   // 0 && 1 为非素数
void GetPrime()
{
    for (int i = 2; i < maxn; i++)
        if (!notprime[i] && i <= maxn / i)  // 筛到√n为止
            for (int j = i * i; j < maxn; j += i)
                notprime[j] = 1;
}
```

1.1.2 Eular Sieve

$O(n)$ 得到欧拉函数 $phi[]$、素数表 $prime[]$、素数个数 tot
传入的 n 为函数定义域上界

```
const int maxn = "Edit";
bool vis[maxn];
int tot, phi[maxn], prime[maxn];
void CalPhi(int n)
{
    clr(vis, 0);
    phi[1] = 1;
    tot = 0;
    for (int i = 2; i < n; i++)
    {
        if (!vis[i])
            prime[tot++] = i, phi[i] = i - 1;
        for (int j = 0; j < tot; j++)
        {
            if (i * prime[j] > n) break;
            vis[i * prime[j]] = 1;
            if (i % prime[j] == 0)
            {
                phi[i * prime[j]] = phi[i] * prime[j];
                break;
            }
            else
                phi[i * prime[j]] = phi[i] * (prime[j] - 1);
        }
    }
}
```

1.1.3 Prime Factorization

函数返回素因数个数
数组以 $fact[i][0]^{fact[i][1]}$ 的形式保存第 i 个素因数

```
ll fact[100][2];
int getFactors(ll x)
{
    int cnt = 0;
    for (int i = 0; prime[i] <= x / prime[i]; i++)
    {
        fact[cnt][1] = 0;
        if (x % prime[i] == 0)
        {
            fact[cnt][0] = prime[i];
            while (x % prime[i] == 0) fact[cnt][1]++, x /= prime[i];
            cnt++;
        }
    }
    if (x != 1) fact[cnt][0] = x, fact[cnt++][1] = 1;
    return cnt;
}
```

1.1.4 Miller Rabin

$O(s\log n)$ 内判定 2^{63} 内的数是不是素数，s 为测定次数

```
bool Miller_Rabin(ll n, int s)
{
    if (n == 2) return 1;
    if (n < 2 || !(n & 1)) return 0;
    int t = 0;
    ll  x, y, u = n - 1;
    while ((u & 1) == 0) t++, u >>= 1;
    for (int i = 0; i < s; i++)
    {
        ll a = rand() % (n - 1) + 1;
        ll x = Pow(a, u, n);
        for (int j = 0; j < t; j++)
        {
            ll y = Mul(x, x, n);
            if (y == 1 && x != 1 && x != n - 1) return 0;
            x = y;
        }
        if (x != 1) return 0;
    }
    return 1;
}
```

1.1.5 Segment Sieve

对区间 $[a,b)$ 内的整数执行筛法。
函数返回区间内素数个数
is_prime[i-a]=true 表示 i 是素数
$a < b \leq 10^{12}, b-a \leq 10^6$

```
const int maxn = "Edit";
bool is_prime_small[maxn], is_prime[maxn];
int prime[maxn];
int segment_sieve(ll a, ll b)
{
    int tot = 0;
```

```
    for (ll i = 0; i * i < b; ++i)
        is_prime_small[i] = true;
    for (ll i = 0; i < b - a; ++i)
        is_prime[i] = true;
    for (ll i = 2; i * i < b; ++i)
        if (is_prime_small[i])
        {
            for (ll j = 2 * i; j * j < b; j += i)
                is_prime_small[j] = false;
            for (ll j = max(2LL, (a + i - 1) / i) * i; j < b; j += i)
                is_prime[j - a] = false;
        }
    for (ll i = 0; i < b - a; ++i)
        if (is_prime[i]) prime[tot++] = i + a;
    return tot;
}
```

1.2 Eular phi

1.2.1 Eular

```
ll Euler(ll n)
{
    ll rt = n;
    for (int i = 2; i * i <= n; i++)
        if (n % i == 0)
        {
            rt -= rt / i;
            while (n % i == 0) n /= i;
        }
    if (n > 1) rt -= rt / n;
    return rt;
}
```

1.2.2 Sieve

```
const int N = "Edit";
int phi[N] = {0, 1};
void CalEuler()
{
    for (int i = 2; i < N; i++)
        if (!phi[i])
            for (int j = i; j < N; j += i)
            {
                if (!phi[j]) phi[j] = j;
                phi[j] = phi[j] / i * (i - 1);
            }
}
```

1.3 Basic Number Theory

1.3.1 Extended Euclidean

```
ll exgcd(ll a, ll b, ll &x, ll &y)
{
    ll d = a;
    if (b) d = exgcd(b, a % b, y, x), y -= x * (a / b);
```

```
    else x = 1, y = 0;
    return d;
}
```

1.3.2 ax+by=c

引用返回通解: $X = x + k * dx, Y = y–k * dy$
引用返回的 x 是最小非负整数解，方程无解函数返回 0

```
#define Mod(a, b) (((a) % (b) + (b)) % (b))
bool solve(ll a, ll b, ll c, ll& x, ll& y, ll& dx, ll& dy)
{
    if (a == 0 && b == 0) return 0;
    ll x0, y0;
    ll d = exgcd(a, b, x0, y0);
    if (c % d != 0) return 0;
    dx = b / d, dy = a / d;
    x = Mod(x0 * c / d, dx);
    y = (c - a * x) / b;
    //  y = Mod(y0 * c / d, dy); x = (c - b * y) / a;
    return 1;
}
```

1.3.3 Multiplicative Inverse Modulo

利用 exgcd 求 a 在模 m 下的逆元，需要保证 $gcd(a, m) == 1$.

```
ll inv(ll a, ll m)
{
    ll x, y;
    ll d = exgcd(a, m, x, y);
    return d == 1 ? (x + m) % m : -1;
}
```

$a < p$ 且 p 为素数时，有以下两种求法
费马小定理

```
ll inv(ll a, ll p) { return Pow(a, p - 2, p); }
```

贾志鹏线性筛

```
for (int i = 2; i < n; i++) inv[i] = inv[p % i] * (p - p / i) % p;
```

1.4 Modulo Linear Equation

1.4.1 Chinese Remainder Theory

$X = r_i(mod m_i)$; 要求 m_i 两两互质
引用返回通解 $X = re + k * mo$

```
void crt(ll r[], ll m[], ll n, ll &re, ll &mo)
{
    mo = 1, re = 0;
    for (int i = 0; i < n; i++) mo *= m[i];
    for (int i = 0; i < n; i++)
    {
        ll x, y,  tm = mo / m[i];
        ll d = exgcd(tm, m[i], x, y);
        re = (re + tm * x * r[i]) % mo;
```

```
    }
    re = (re + mo) % mo;
}
```

1.4.2 ExCRT

$X = r_i(mod m_i)$; m_i 可以不两两互质
引用返回通解 $X = re + k * mo$; 函数返回是否有解

```
bool excrt(ll r[], ll m[], ll n, ll &re, ll &mo)
{
    ll x, y;
    mo = m[0], re = r[0];
    for (int i = 1; i < n; i++)
    {
        ll d = exgcd(mo, m[i],  x, y);
        if ((r[i] - re) % d != 0) return 0;
        x = (r[i] - re) / d * x % (m[i] / d);
        re += x * mo;
        mo = mo / d * m[i];
        re %= mo;
    }
    re = (re + mo) % mo;
    return 1;
}
```

1.5 Combinatorics

1.5.1 Combination

$0 \leq m \leq n \leq 1000$

```
const int maxn = 1010;
ll C[maxn][maxn];
void CalComb()
{
    C[0][0] = 1;
    for (int i = 1; i < maxn; i++)
    {
        C[i][0] = 1;
        for (int j = 1; j <= i; j++) C[i][j] = (C[i - 1][j - 1] + C[i - 1][j]) % mod;
    }
}
```

$0 \leq m \leq n \leq 10^5$, 模 p 为素数

```
const int maxn = 100010;
ll f[maxn];
ll inv[maxn]; // 阶乘的逆元
void CalFact()
{
    f[0] = 1;
    for (int i = 1; i < maxn; i++) f[i] = (f[i - 1] * i) % p;
    inv[maxn - 1] = Pow(f[maxn - 1], p - 2, p);
    for (int i = maxn - 2; ~i; i--) inv[i] = inv[i + 1] * (i + 1) % p;
}
ll C(int n, int m) { return f[n] * inv[m] % p * inv[n - m] % p; }
```

1.5.2 Lucas

$1 \le n, m \le 1000000000, 1 < p < 100000$, p 是素数

```
const int maxp = 100010;
ll f[maxn];
ll inv[maxn]; // 阶乘的逆元
void CalFact()
{
    f[0] = 1;
    for (int i = 1; i < maxn; i++) f[i] = (f[i - 1] * i) % p;
    inv[maxn - 1] = Pow(f[maxn - 1], p - 2, p);
    for (int i = maxn - 2; ~i; i--) inv[i] = inv[i + 1] * (i + 1) % p;
}
ll Lucas(ll n, ll m, ll p)
{
    ll ret = 1;
    while (n && m)
    {
        ll a = n % p, b = m % p;
        if (a < b) return 0;
        ret = ret * f[a] % p * inv[b] % p * inv[a - b] % p;
        n /= p, m /= p;
    }
    return ret;
}
```

1.5.3 Big Combination

$0 \le n \le 10^9, 0 \le m \le 10^4, 1 \le k \le 10^9 + 7$

```
vector<int> v;
int dp[110];
ll Cal(int l, int r, int k, int dis)
{
    ll res = 1;
    for (int i = l; i <= r; i++)
    {
        int t = i;
        for (int j = 0; j < v.size(); j++)
        {
            int y = v[j];
            while (t % y == 0) dp[j] += dis, t /= y;
        }
        res = res * (ll)t % k;
    }
    return res;
}
ll Comb(int n, int m, int k)
{
    clr(dp, 0);
    v.clear();
    int tmp = k;
    for (int i = 2; i * i <= tmp; i++)
        if (tmp % i == 0)
        {
            int num = 0;
            while (tmp % i == 0) tmp /= i, num++;
```

```
            v.pb(i);
        }
    if (tmp != 1) v.pb(tmp);
    ll ans = Cal(n - m + 1, n, k, 1);
    for (int j = 0; j < v.size(); j++) ans = ans * Pow(v[j], dp[j], k) % k;
    ans = ans * inv(Cal(2, m, k, -1), k) % k;
    return ans;
}
```

1.5.4 Polya

推论：一共 n 个置换，第 i 个置换的循环节个数为 $gcd(i,n)$
$N*N$ 的正方形格子，$c^{n^2}+2c^{\frac{n^2+3}{4}}+c^{\frac{n^2+1}{2}}+2c^{n\frac{n+1}{2}}+2c^{\frac{n(n+1)}{2}}$
正六面体，$\frac{m^8+17m^4+6m^2}{24}$ 正四面体，$\frac{m^4+11m^2}{12}$

```
// 长度为n的项链串用c种颜色染
ll solve(int c, int n)
{
    if (n == 0) return 0;
    ll ans = 0;
    for (int i = 1; i <= n; i++) ans += Pow(c, __gcd(i, n));
    if (n & 1) ans += n * Pow(c, n + 1 >> 1);
    else ans += n / 2 * (1 + c) * Pow(c, n >> 1);
    return ans / n / 2;
}
```

1.6 Fast Power

```
ll Mul(ll a, ll b, ll mod)
{
    ll t = 0;
    for (; b; b >>= 1, a = (a << 1) % mod)
        if (b & 1) t = (t + a) % mod;
    return t;
}
ll Pow(ll a, ll n, ll mod)
{
    ll t = 1;
    for (; n; n >>= 1, a = (a * a % mod))
        if (n & 1) t = (t * a % mod);
    return t;
}
```

1.7 Mobius Inversion

1.7.1 Mobius

$F(n)=\sum_{d|n}f(d)\Rightarrow f(n)=\sum_{d|n}\mu(d)F(\frac{n}{d})$
$F(n)=\sum_{n|d}f(d)\Rightarrow f(n)=\sum_{n|d}\mu(\frac{d}{n})F(d)$

```
ll ans;
const int maxn = "Edit";
int n, x, prime[maxn], tot, mu[maxn];
bool check[maxn];
void calmu()
```

```
{
    mu[1] = 1;
    for (int i = 2; i < maxn; i++)
    {
        if (!check[i]) prime[tot++] = i, mu[i] = -1;
        for (int j = 0; j < tot; j++)
        {
            if (i * prime[j] >= maxn) break;
            check[i * prime[j]] = true;
            if (i % prime[j] == 0)
            {
                mu[i * prime[j]] = 0;
                break;
            }
            else mu[i * prime[j]] = -mu[i];
        }
    }
}
```

1.7.2 Number of Coprime-pair

有 n 个数 ($n \leq 100000$)，问这 n 个数中互质的数的对数

```
ll solve()
{
    int b[100005];
    ll _max, ans = 0;
    clr(b, 0);
    for (int i = 0; i < n; i++)
    {
        scanf("%d", &x);
        if (x > _max) _max = x;
        b[x]++;
    }
    for (int i = 1; i <= _max; i++)
    {
        int cnt = 0;
        for (ll j = i; j <= _max; j += i) cnt += b[j];
        ans += 1LL * mu[i] * cnt * cnt;
    }
    return (ans - b[1]) / 2;
}
```

1.7.3 VisibleTrees

$gcd(x, y) = 1$ 的对数, $x \leq n, y \leq m$

```
ll solve(int n, int m)
{
    if (n < m) swap(n, m);
    ll ans = 0;
    for (int i = 1; i <= m; ++i) ans += (ll)mu[i] * (n / i) * (m / i);
    return ans;
}
```

1.8 Fast Transformation

1.8.1 FFT

```
const double PI = acos(-1.0);
//复数结构体
struct Complex
{
    double x, y; //实部和虚部 x+yi
    Complex(double _x = 0.0, double _y = 0.0) { x = _x, y = _y; }
    Complex operator-(const Complex& b) const { return Complex(x - b.x, y - b.y); }
    Complex operator+(const Complex& b) const { return Complex(x + b.x, y + b.y); }
    Complex operator*(const Complex& b) const { return Complex(x * b.x - y * b.y, x * b.y + y * b.x); }
};
/*
* 进行FFT和IFFT前的反转变换。
* 位置i和 (i二进制反转后位置) 互换
* len必须取2的幂
*/
void change(Complex y[], int len)
{
    for (int i = 1, j = len / 2; i < len - 1; i++)
    {
        if (i < j) swap(y[i], y[j]);
        //交换互为小标反转的元素，i<j保证交换一次
        //i做正常的+1，j左反转类型的+1,始终保持i和j是反转的
        int k = len / 2;
        while (j >= k) j -= k, k /= 2;
        if (j < k) j += k;
    }
}
/*
* 做FFT
* len必须为2^k形式，
* on==1时是DFT，on==-1时是IDFT
*/
void fft(Complex y[], int len, int on)
{
    change(y, len);
    for (int h = 2; h <= len; h <<= 1)
    {
        Complex wn(cos(-on * 2 * PI / h), sin(-on * 2 * PI / h));
        for (int j = 0; j < len; j += h)
        {
            Complex w(1, 0);
            for (int k = j; k < j + h / 2; k++)
            {
                Complex u = y[k];
                Complex t = w * y[k + h / 2];
                y[k] = u + t, y[k + h / 2] = u - t;
                w = w * wn;
            }
        }
    }
    if (on == -1)
        for (int i = 0; i < len; i++) y[i].x /= len;
}
```

1.8.2 NTT

模数 P 为费马素数，G 为 P 的原根。$G^{\frac{P-1}{n}}$ 具有和 $w_n = e^{\frac{2i\pi}{n}}$ 相似的性质。具体的 P 和 G 可参考 1.11

```
const int mod = 998244353;
const int G = 3;
ll wn[20];
void getwn()
{   //  千万不要忘记
    for (int i = 0; i < 20; i++) wn[i] = Pow(G, (mod - 1) / (1 << i), mod);
}
void change(ll y[], int len)
{
    for (int i = 1, j = len / 2; i < len - 1; i++)
    {
        if (i < j) swap(y[i], y[j]);
        int k = len / 2;
        while (j >= k) j -= k, k /= 2;
        if (j < k) j += k;
    }
}
void ntt(ll y[], int len, int on)
{
    change(y, len);
    for (int h = 2, id = 1; h <= len; h <<= 1, id++)
    {
        for (int j = 0; j < len; j += h)
        {
            ll w = 1;
            for (int k = j; k < j + h / 2; k++)
            {
                ll u = y[k] % mod;
                ll t = w * (y[k + h / 2] % mod) % mod;
                y[k] = (u + t) % mod, y[k + h / 2] = ((u - t) % mod + mod) % mod;
                w = w * wn[id] % mod;
            }
        }
    }
    if (on == -1)
    {
        //  原本的除法要用逆元
        ll inv = Pow(len, mod - 2, mod);
        for (int i = 1; i < len / 2; i++) swap(y[i], y[len - i]);
        for (int i = 0; i < len; i++) y[i] = y[i] * inv % mod;
    }
}
```

1.8.3 FWT

```
void fwt(int f[], int m)
{
    int n = __builtin_ctz(m);
    for (int i = 0; i < n; ++i)
        for (int j = 0; j < m; ++j)
            if (j & (1 << i))
            {
                int l = f[j ^ (1 << i)], r = f[j];
                f[j ^ (1 << i)] = l + r, f[j] = l - r;
```

```
                // or: f[j] += f[j ^ (1 << i)];
                // and: f[j ^ (1 << i)] += f[j];
            }
}
void ifwt(int f[], int m)
{
    int n = __builtin_ctz(m);
    for (int i = 0; i < n; ++i)
        for (int j = 0; j < m; ++j)
            if (j & (1 << i))
            {
                int l = f[j ^ (1 << i)], r = f[j];
                f[j ^ (1 << i)] = (l + r) / 2, f[j] = (l - r) / 2;
                // 如果有取模需要使用逆元
                // or: f[j] -= f[j ^ (1 << i)];
                // and: f[j ^ (1 << i)] -= f[j];
            }
}
```

1.9 Numerical Integration

1.9.1 Adaptive Simpson's Rule

$\int_a^b f(x)dx \approx \frac{b-a}{6}[f(a)+4f(\frac{a+b}{2})+f(b)]$
$|S(a,c)+S(c,b)-S(a,b)|/15<\epsilon$

```
double F(double x) {}
double simpson(double a, double b)
{ // 三点Simpson法
    double c = a + (b - a) / 2;
    return (F(a) + 4 * F(c) + F(b)) * (b - a) / 6;
}
double asr(double a, double b, double eps, double A)
{ //自适应Simpson公式（递归过程）。已知整个区间[a,b]上的三点Simpson值A
    double c = a + (b - a) / 2;
    double L = simpson(a, c), R = simpson(c, b);
    if (fabs(L + R - A) <= 15 * eps) return L + R + (L + R - A) / 15.0;
    return asr(a, c, eps / 2, L) + asr(c, b, eps / 2, R);
}
double asr(double a, double b, double eps) { return asr(a, b, eps, simpson(a, b)); }
```

1.10 Others

约瑟夫问题
n 个人围成一圈，从第一个开始报数，第 m 个将被杀掉

```
int josephus(int n, int m)
{
    int r = 0;
    for (int k = 1; k <= n; ++k) r = (r + m) % k;
    return r + 1;
}
```

n^n 最左边一位数

```
int leftmost(int n)
{
    double m = n * log10((double)n);
```

```
    double g = m - (ll)m;
    return (int)pow(10.0, g);
}
```

$n!$ 位数

```
int count(ll n)
{
    if (n == 1) return 1;
    return (int)ceil(0.5 * log10(2 * M_PI * n) + n * log10(n) - n * log10(M_E));
}
```

1.11 Formula

1. 约数定理：若 $n = \prod_{i=1}^{k} p_i^{a_i}$，则
   (a) 约数个数 $f(n) = \prod_{i=1}^{k}(a_i + 1)$
   (b) 约数和 $g(n) = \prod_{i=1}^{k}(\sum_{j=0}^{a_i} p_i^j)$
2. 小于 n 且互素的数之和为 $n\varphi(n)/2$
3. 若 $gcd(n, i) = 1$，则 $gcd(n, n - i) = 1(1 \le i \le n)$
4. 错排公式：$D(n) = (n-1)(D(n-2) + D(n-1)) = \sum_{i=2}^{n} \frac{(-1)^k n!}{k!} = [\frac{n!}{e} + 0.5]$
5. 威尔逊定理：$p\ is\ prime\ \Rightarrow (p-1)! \equiv -1(mod\ p)$
6. 欧拉定理：$gcd(a, n) = 1 \Rightarrow a^{\varphi(n)} \equiv 1(mod\ n)$
7. 欧拉定理推广：$gcd(n, p) = 1 \Rightarrow a^n \equiv a^{n\%\varphi(p)}(mod\ p)$
8. 素数定理：对于不大于 n 的素数个数 $\pi(n)$，$\lim_{n\to\infty} \pi(n) = \frac{n}{\ln n}$
9. 位数公式：正整数 x 的位数 $N = log10(n) + 1$
10. 斯特灵公式 $n! \approx \sqrt{2\pi n}(\frac{n}{e})^n$
11. 设 $a > 1, m, n > 0$, 则 $gcd(a^m - 1, a^n - 1) = a^{gcd(m,n)} - 1$
12. 设 $a > b, gcd(a, b) = 1$, 则 $gcd(a^m - b^m, a^n - b^n) = a^{gcd(m,n)} - b^{gcd(m,n)}$

$$G = gcd(C_n^1, C_n^2, ..., C_n^{n-1}) = \begin{cases} n, & n \text{ is prime} \\ 1, & n \text{ has multy prime factors} \\ p, & n \text{ has single prime factor } p \end{cases}$$

   $gcd(Fib(m), Fib(n)) = Fib(gcd(m, n))$
13. 若 $gcd(m, n) = 1$, 则:
   (a) 最大不能组合的数为 $m * n - m - n$
   (b) 不能组合数个数 $N = \frac{(m-1)(n-1)}{2}$
14. $(n+1)lcm(C_n^0, C_n^1, ..., C_n^{n-1}, C_n^n) = lcm(1, 2, ..., n+1)$
15. 若 p 为素数，则 $(x + y + ... + w)^p \equiv x^p + y^p + ... + w^p(mod\ p)$
16. 卡特兰数：1, 1, 2, 5, 14, 42, 132, 429, 1430, 4862, 16796, 58786, 208012
   $h(0) = h(1) = 1, h(n) = \frac{(4n-2)h(n-1)}{n+1} = \frac{C_{2n}^n}{n+1} = C_{2n}^n - C_{2n}^{n-1}$
17. FFT 常用素数

$r\ 2^k + 1$	r	k	g
3	1	1	2
5	1	2	2
17	1	4	3
97	3	5	5
193	3	6	5
257	1	8	3
7681	15	9	17
12289	3	12	11
40961	5	13	3
65537	1	16	3
786433	3	18	10
5767169	11	19	3
7340033	7	20	3
23068673	11	21	3
104857601	25	22	3
167772161	5	25	3
469762049	7	26	3
998244353	119	23	3
1004535809	479	21	3
2013265921	15	27	31
2281701377	17	27	3
3221225473	3	30	5
75161927681	35	31	3
77309411329	9	33	7
206158430209	3	36	22
2061584302081	15	37	7
2748779069441	5	39	3
6597069766657	3	41	5
39582418599937	9	42	5
79164837199873	9	43	5
263882790666241	15	44	7
1231453023109121	35	45	3
1337006139375617	19	46	3
3799912185593857	27	47	5
4222124650659841	15	48	19
7881299347898369	7	50	6
31525197391593473	7	52	3
180143985094819841	5	55	6
1945555039024054273	27	56	5
4179340454199820289	29	57	3

2 String Processing

2.1 KMP

```
// 返回y中x的个数
const int N = "Edit";
int next[N];
void initkmp(char x[], int m)
{
    int i = 0, j = next[0] = -1;
    while (i < m)
    {
        while (j != -1 && x[i] != x[j]) j = next[j];
        next[++i] = ++j;
    }
}
int kmp(char x[], int m, char y[], int n)
{
    int i, j, ans;
    i = j = ans = 0;
    initkmp(x, m);
    while (i < n)
    {
        while (j != -1 && y[i] != x[j]) j = next[j];
        i++, j++;
        if (j >= m) ans++, j = next[j];
    }
    return ans;
}
```

2.2 ExtendKMP

```
//next[i]:x[i...m-1]与x[0...m-1]的最长公共前缀
//extend[i]:y[i...n-1]与x[0...m-1]的最长公共前缀
const int N = "Edit";
int next[N], extend[N];
void pre_ekmp(char x[], int m)
{
    next[0] = m;
    int j = 0;
    while (j + 1 < m && x[j] == x[j + 1]) j++;
    next[1] = j;
    int k = 1;
    for (int i = 2; i < m; i++)
    {
        int p = next[k] + k - 1;
        int L = next[i - k];
        if (i + L < p + 1)
            next[i] = L;
        else
        {
            j = max(0, p - i + 1);
            while (i + j < m && x[i + j] == x[j]) j++;
            next[i] = j;
            k = i;
        }
    }
}
```

```
void ekmp(char x[], int m, char y[], int n)
{
    pre_ekmp(x, m, next);
    int j = 0;
    while (j < n && j < m && x[j] == y[j]) j++;
    extend[0] = j;
    int k = 0;
    for (int i = 1; i < n; i++)
    {
        int p = extend[k] + k - 1;
        int L = next[i - k];
        if (i + L < p + 1)
            extend[i] = L;
        else
        {
            j = max(0, p - i + 1);
            while (i + j < n && j < m && y[i + j] == x[j]) j++;
            extend[i] = j, k = i;
        }
    }
}
```

2.3 Manacher

O(n) 求解最长回文子串

```
const int N = "Edit";
char s[N], str[N << 1];
int p[N << 1];
void Manacher(char s[], int& n)
{
    str[0] = '$', str[1] = '#';
    for (int i = 0; i < n; i++) str[(i << 1) + 2] = s[i], str[(i << 1) + 3] = '#';
    n = 2 * n + 2;
    str[n] = 0;
    int mx = 0, id;
    for (int i = 1; i < n; i++)
    {
        p[i] = mx > i ? min(p[2 * id - i], mx - i) : 1;
        while (str[i - p[i]] == str[i + p[i]]) p[i]++;
        if (p[i] + i > mx) mx = p[i] + i, id = i;
    }
}
int solve(char s[])
{
    int n = strlen(s);
    Manacher(s, n);
    return *max_elememt(p, p + n) - 1;
}
```

2.4 Aho-Corasick Automaton

```
const int maxn = "Edit";
struct Trie
{
    int ch[maxn][26], f[maxn], val[maxn];
    int sz, rt;
```

```
    int newnode() { clr(ch[sz], -1), val[sz] = 0; return sz++; }
    void init() { sz = 0, rt = newnode(); }
    inline int idx(char c) { return c - 'A'; };
    void insert(const char* s)
    {
        int u = 0, n = strlen(s);
        for (int i = 0; i < n; i++)
        {
            int c = idx(s[i]);
            if (ch[u][c] == -1) ch[u][c] = newnode();
            u = ch[u][c];
        }
        val[u]++;
    }
    void build()
    {
        queue<int> q;
        f[rt] = rt;
        for (int c = 0; c < 26; c++)
        {
            if (~ch[rt][c])
                f[ch[rt][c]] = rt, q.push(ch[rt][c]);
            else
                ch[rt][c] = rt;
        }
        while (!q.empty())
        {
            int u = q.front();
            q.pop();
            // val[u] |= val[f[u]];
            for (int c = 0; c < 26; c++)
            {
                if (~ch[u][c])
                    f[ch[u][c]] = ch[f[u]][c], q.push(ch[u][c]);
                else
                    ch[u][c] = ch[f[u]][c];
            }
        }
    }
    //返回主串中有多少模式串
    int query(const char* s)
    {
        int u = rt, n = strlen(s);
        int res = 0;
        for (int i = 0; i < n; i++)
        {
            int c = idx(s[i]);
            u = ch[u][c];
            int tmp = u;
            while (tmp != rt)
            {
                res += val[tmp];
                val[tmp] = 0;
                tmp = f[tmp];
            }
        }
        return res;
    }
};
```

2.5 Suffix Array

```
//倍增算法构造后缀数组,复杂度O(nlogn)
const int maxn = "Edit";
char s[maxn];
int sa[maxn], t[maxn], t2[maxn], c[maxn], rank[maxn], height[maxn];
//n为字符串的长度,字符集的值为0~m-1
void build_sa(int m, int n)
{
    n++;
    int *x = t, *y = t2;
    //基数排序
    for (int i = 0; i < m; i++) c[i] = 0;
    for (int i = 0; i < n; i++) c[x[i] = s[i]]++;
    for (int i = 1; i < m; i++) c[i] += c[i - 1];
    for (int i = n - 1; ~i; i--) sa[--c[x[i]]] = i;
    for (int k = 1; k <= n; k <<= 1)
    {
        //直接利用sa数组排序第二关键字
        int p = 0;
        for (int i = n - k; i < n; i++) y[p++] = i;
        for (int i = 0; i < n; i++)
            if (sa[i] >= k) y[p++] = sa[i] - k;
        //基数排序第一关键字
        for (int i = 0; i < m; i++) c[i] = 0;
        for (int i = 0; i < n; i++) c[x[y[i]]]++;
        for (int i = 0; i < m; i++) c[i] += c[i - 1];
        for (int i = n - 1; ~i; i--) sa[--c[x[y[i]]]] = y[i];
        //根据sa和y数组计算新的x数组
        swap(x, y);
        p = 1;
        x[sa[0]] = 0;
        for (int i = 1; i < n; i++)
            x[sa[i]] = y[sa[i - 1]] == y[sa[i]] && y[sa[i - 1] + k] == y[sa[i] + k] ? p - 1 : p++;
        if (p >= n) break; //以后即使继续倍增，sa也不会改变，推出
        m = p;             //下次基数排序的最大值
    }
    n--;
    int k = 0;
    for (int i = 0; i <= n; i++) rank[sa[i]] = i;
    for (int i = 0; i < n; i++)
    {
        if (k) k--;
        int j = sa[rank[i] - 1];
        while (s[i + k] == s[j + k]) k++;
        height[rank[i]] = k;
    }
}

int dp[maxn][30];
void initrmq(int n)
{
    for (int i = 1; i <= n; i++)
        dp[i][0] = height[i];
    for (int j = 1; (1 << j) <= n; j++)
        for (int i = 1; i + (1 << j) - 1 <= n; i++)
            dp[i][j] = min(dp[i][j - 1], dp[i + (1 << (j - 1))][j - 1]);
}
```

```
int rmq(int l, int r)
{
    int k = 31 - __builtin_clz(r - l + 1);
    return min(dp[l][k], dp[r - (1 << k) + 1][k]);
}
int lcp(int a, int b)
{ // 求两个后缀的最长公共前缀
    a = rank[a], b = rank[b];
    if (a > b) swap(a, b);
    return rmq(a + 1, b);
}
```

2.6 Suffix Automation

```
const int maxn = "Edit";
struct SAM
{
    int len[maxn << 1], link[maxn << 1], ch[maxn << 1][26];
    int sz, rt, last;
    int newnode(int x = 0)
    {
        len[sz] = x;
        link[sz] = -1;
        clr(ch[sz], -1);
        return sz++;
    }
    void init() { sz = last = 0, rt = newnode(); }
    void extend(int c)
    {
        int np = newnode(len[last] + 1);
        int p;
        for (p = last; ~p && ch[p][c] == -1; p = link[p]) ch[p][c] = np;
        if (p == -1)
            link[np] = rt;
        else
        {
            int q = ch[p][c];
            if (len[p] + 1 == len[q])
                link[np] = q;
            else
            {
                int nq = newnode(len[p] + 1);
                memcpy(ch[nq], ch[q], sizeof(ch[q]));
                link[nq] = link[q], link[q] = link[np] = nq;
                for (; ~p && ch[p][c] == q; p = link[p]) ch[p][c] = nq;
            }
        }
        last = np;
    }
    int topcnt[maxn], topsam[maxn << 1];
    void sort()
    { // 加入串后拓扑排序
        clr(topcnt, 0);
        for (int i = 0; i < sz; i++) topcnt[len[i]]++;
        for (int i = 0; i < maxn - 1; i++) topcnt[i + 1] += topcnt[i];
        for (int i = 0; i < sz; i++) topsam[--topcnt[len[i]]] = i;
    }
};
```

3 Data Structure

3.1 Binary Indexed Tree

$O(\log n)$ 查询和修改数组的前缀和

```
// 注意下标应从1开始 n是全局变量
const int maxn = "Edit";
int bit[N], n;
int sum(int x)
{
    int s = 0;
    for (int i = x; i; i -= i & -i) s += bit[i];
    return s;
}
void add(int x, int v)
{
    for (int i = x; i <= n; i += i & -i) bit[i] += v;
}
```

3.2 Segment Tree

```
#define lson rt << 1         // 左儿子
#define rson rt << 1 | 1     // 右儿子
#define Lson l, m, lson      // 左子树
#define Rson m + 1, r, rson // 右子树
void PushUp(int rt);         // 用lson和rson更新rt
void PushDown(int rt[, int m]);                     // rt的标记下移，m为区间长度（若与标记有关）
void build(int l, int r, int rt);                   // 以rt为根节点，对区间[l, r]建立线段树
void update([...,] int l, int r, int rt)            // rt[l, r]内寻找目标并更新
int query(int L, int R, int l, int r, int rt)    // rt[l, r]内查询[L, R]
```

3.2.1 Single-point Update

```
const int maxn = "Edit";
int sum[maxn << 2]; // sum[rt]用于维护区间和
void PushUp(int rt) { sum[rt] = sum[lson] + sum[rson]; }
void build(int l, int r, int rt)
{
    if (l == r)
    {
        scanf("%d", &sum[rt]); // 建立的时候直接输入叶节点
        return;
    }
    int m = (l + r) >> 1;
    build(Lson);
    build(Rson);
    PushUp(rt);
}
void update(int p, int add, int l, int r, int rt)
{
    if (l == r)
    {
        sum[rt] += add;
        return;
    }
    int m = (l + r) >> 1;
```

```
    if (p <= m)
        update(p, add, Lson);
    else
        update(p, add, Rson);
    PushUp(rt);
}
int query(int L, int R, int l, int r, int rt)
{
    if (L <= l && r <= R) return sum[rt];
    int m = (l + r) >> 1, s = 0;
    if (L <= m) s += query(L, R, Lson);
    if (m < R) s += query(L, R, Rson);
    return s;
}
```

3.2.2 Interval Update

```
const int maxn = "Edit";
int seg[maxn << 2], sum[maxn << 2]; // seg[rt]用于存放懒惰标记，注意PushDown时标记的传递
void PushUp(int rt) { sum[rt] = sum[lson] + sum[rson]; }
void PushDown(int rt, int m)
{
    if (seg[rt] == 0) return;
    seg[lson] += seg[rt];
    seg[rson] += seg[rt];
    sum[lson] += seg[rt] * (m - (m >> 1));
    sum[rson] += seg[rt] * (m >> 1);
    seg[rt] = 0;
}
void build(int l, int r, int rt)
{
    seg[rt] = 0;
    if (l == r)
    {
        scanf("%lld", &sum[rt]);
        return;
    }
    int m = (l + r) >> 1;
    build(Lson);
    build(Rson);
    PushUp(rt);
}
void update(int L, int R, int add, int l, int r, int rt)
{
    if (L <= l && r <= R)
    {
        seg[rt] += add;
        sum[rt] += add * (r - l + 1);
        return;
    }
    PushDown(rt, r - l + 1);
    int m = (l + r) >> 1;
    if (L <= m) update(L, R, add, Lson);
    if (m < R) update(L, R, add, Rson);
    PushUp(rt);
}
int query(int L, int R, int l, int r, int rt)
{
```

```
    if (L <= l && r <= R) return sum[rt];
    PushDown(rt, r - l + 1);
    int m = (l + r) >> 1, ret = 0;
    if (L <= m) ret += query(L, R, Lson);
    if (m < R) ret += query(L, R, Rson);
    return ret;
}
```

3.3 Splay Tree

```
#define key_value ch[ch[root][1]][0]
const int maxn = "Edit";
struct Splay
{
    int a[maxn];
    int sz[maxn], ch[maxn][2], fa[maxn];
    int key[maxn], rev[maxn];
    int root, tot;
    int stk[maxn], top;
    void init(int n)
    {
        tot = 0, top = 0;
        root = newnode(0, -1);
        ch[root][1] = newnode(root, -1);
        for (int i = 0; i < n; i++) a[i] = i + 1;
        key_value = build(0, n - 1, ch[root][1]);
        pushup(ch[root][1]);
        pushup(root);
    }
    int newnode(int p = 0, int k = 0)
    {
        int x = top ? stk[top--] : ++tot;
        fa[x] = p;
        sz[x] = 1;
        ch[x][0] = ch[x][1] = 0;
        key[x] = k;
        rev[x] = 0;
        return x;
    }
    void pushdown(int x)
    {
        if (rev[x])
        {
            swap(ch[x][0], ch[x][1]);
            if (ch[x][0]) rev[ch[x][0]] ^= 1;
            if (ch[x][1]) rev[ch[x][1]] ^= 1;
            rev[x] = 0;
        }
    }
    void pushup(int x) { sz[x] = sz[ch[x][0]] + sz[ch[x][1]] + 1; }
    void rotate(int x, int d)
    {
        int y = fa[x];
        pushdown(y), pushdown(x);
        ch[y][d ^ 1] = ch[x][d];
        fa[ch[x][d]] = y;
        if (fa[y]) ch[fa[y]][ch[fa[y]][1] == y] = x;
        fa[x] = fa[y];
```

```
        ch[x][d] = y;
        fa[y] = x;
        pushup(y);
    }
    void splay(int x, int goal = 0)
    {
        pushdown(x);
        while (fa[x] != goal)
        {
            if (fa[fa[x]] == goal)
                rotate(x, ch[fa[x]][0] == x);
            else
            {
                int y = fa[x];
                int d = ch[fa[y]][0] == y;
                ch[y][d] == x ? rotate(x, d ^ 1) : rotate(y, d);
                rotate(x, d);
            }
        }
        pushup(x);
        if (goal == 0) root = x;
    }
    int kth(int r, int k)
    {
        pushdown(r);
        int t = sz[ch[r][0]] + 1;
        if (t == k) return r;
        return t > k ? kth(ch[r][0], k) : kth(ch[r][1], k - t);
    }
    int build(int l, int r, int p)
    {
        if (l > r) return 0;
        int mid = l + r >> 1;
        int x = newnode(p, a[mid]);
        ch[x][0] = build(l, mid - 1, x);
        ch[x][1] = build(mid + 1, r, x);
        pushup(x);
        return x;
    }
    void select(int l, int r)
    {
        splay(kth(root, l), 0);
        splay(kth(ch[root][1], r - l + 2), root);
    }
    // 各种操作
};
```

3.4 Functional Segment Tree

静态查询区间第 k 小的值
必要时进行离散化

```
const int maxn = "Edit";
int a[maxn], rt[maxn];
int cnt;
int lson[maxn << 5], rson[maxn << 5], sum[maxn << 5];
#define Lson l, m, lson[x], lson[y]
#define Rson m + 1, r, rson[x], rson[y]
```

```
void update(int p, int l, int r, int& x, int y)
{
    lson[++cnt] = lson[y], rson[cnt] = rson[y], sum[cnt] = sum[y] + 1, x = cnt;
    if (l == r) return;
    int m = (l + r) >> 1;
    if (p <= m) update(p, Lson);
    else update(p, Rson);
}
int query(int l, int r, int x, int y, int k)
{
    if (l == r) return l;
    int m = (l + r) >> 1;
    int s = sum[lson[y]] - sum[lson[x]];
    if (s >= k) return query(Lson, k);
    else return query(Rson, k - s);
}
```

3.5 Sparse Table

```
const int maxn = "Edit";
int mmax[maxn][30], mmin[maxn][30];
int a[maxn], n, k;
void init()
{
    for (int i = 1; i <= n; i++) mmax[i][0] = mmin[i][0] = a[i];
    for (int j = 1; (1 << j) <= n; j++)
        for (int i = 1; i + (1 << j) - 1 <= n; i++)
        {
            mmax[i][j] = max(mmax[i][j - 1], mmax[i + (1 << (j - 1))][j - 1]);
            mmin[i][j] = min(mmin[i][j - 1], mmin[i + (1 << (j - 1))][j - 1]);
        }
}
// op=0/1 返回[l,r]最大/小值
int rmq(int l, int r, int op)
{
    int k = 31 - __builtin_clz(r - l + 1);
    if (op == 0)
        return max(mmax[l][k], mmax[r - (1 << k) + 1][k]);
    return min(mmin[l][k], mmin[r - (1 << k) + 1][k]);
}
```

二维 RMQ

```
void init()
{
    for (int i = 0; (1 << i) <= n; i++)
        for (int j = 0; (1 << j) <= m; j++)
        {
            if (i == 0 && j == 0) continue;
            for (int row = 1; row + (1 << i) - 1 <= n; row++)
                for (int col = 1; col + (1 << j) - 1 <= m; col++)
                    if (i)
                        dp[row][col][i][j] = max(dp[row][col][i - 1][j],
                                                 dp[row + (1 << (i - 1))][col][i - 1][j]);
                    else
                        dp[row][col][i][j] = max(dp[row][col][i][j - 1],
                                                 dp[row][col + (1 << (j - 1))][i][j - 1]);
        }
}
```

```
int rmq(int x1, int y1, int x2, int y2)
{
    int kx = 31 - __builtin_clz(x2 - x1 + 1);
    int ky = 31 - __builtin_clz(y2 - y1 + 1);
    int m1 = dp[x1][y1][kx][ky];
    int m2 = dp[x2 - (1 << kx) + 1][y1][kx][ky];
    int m3 = dp[x1][y2 - (1 << ky) + 1][kx][ky];
    int m4 = dp[x2 - (1 << kx) + 1][y2 - (1 << ky) + 1][kx][ky];
    return max(max(m1, m2), max(m3, m4));
}
```

4 Graph Theory

4.1 Union-Find Set

```
const int maxn = "Edit";
int n, fa[maxn], ra[maxn];
void init()
{
    for (int i = 0; i <= n; i++) fa[i] = i, ra[i] = 0;
}
int find(int x) { return fa[x] != x ? fa[x] = find(fa[x]) : x; }
void unite(int x, int y)
{
    x = find(x), y = find(y);
    if (x == y) return;
    if (ra[x] < ra[y])
        fa[x] = y;
    else
    {
        fa[y] = x;
        if (ra[x] == ra[y]) ra[x]++;
    }
}
bool same(int x, int y) { return find(x) == find(y); }
```

4.2 Minimal Spanning Tree

4.2.1 Kruskal

```
typedef pair<int, PII> Edge;
vector<Edge> G;
void add_edge(int u, int v, int d) { G.pb(mp(d, mp(u, v))); }
int Kruskal(int n)
{
    init(n); // 并查集初始化
    sort(G.begin(), G.end());
    int num = 0, ret = 0;
    for (auto& e : G)
    {
        int x = e.Y.X, y = e.Y.Y;
        int d = e.X;
        if (!same(x, y))
        {
            unite(x, y);
            num++;
            ret += d;
        }
        if (num == n - 1) break;
    }
    return ret;
}
```

4.2.2 Prim

```
// 耗费矩阵cost[][],标号从0开始,0~n-1
// 返回最小生成树的权值,返回-1表示原图不连通
const int maxn = "Edit";
bool vis[maxn];
```

```
int lowc[maxn];
int Prim(int cost[][maxn], int n)
{
    int ans = 0;
    clr(vis, 0);
    vis[0] = 1;
    for (int i = 1; i < n; i++)
        lowc[i] = cost[0][i];
    for (int i = 1; i < n; i++)
    {
        int minc = INF;
        int p = -1;
        for (int j = 0; j < n; j++)
            if (!vis[j] && minc > lowc[j])
            {
                minc = lowc[j];
                p = j;
            }
        if (minc == INF) return -1;
        vis[p] = 1;
        ans += minc;
        for (int j = 0; j < n; j++)
            if (!vis[j] && lowc[j] > cost[p][j])
                lowc[j] = cost[p][j];
    }
    return ans;
}
```

4.3 Shortest Path

4.3.1 Dijkstra

```
// pair<权值, 点>
// 记得初始化
const int maxn = "Edit";
typedef pair<int, int> PII;
typedef vector<PII> VII;
VII G[maxn];
int vis[maxn], dis[maxn];
void init(int n)
{
    for (int i = 0; i < n; i++) G[i].clear();
}
void add_edge(int u, int v, int w) { G[u].pb(mp(w, v)); }
void Dijkstra(int s, int n)
{
    clr(vis, 0), clr(dis, 0x3f);
    dis[s] = 0;
    priority_queue<PII, VII, greater<PII> > q;
    q.push(mp(dis[s], s));
    while (!q.empty())
    {
        PII t = q.top();
        int x = t.Y;
        q.pop();
        if (vis[x]) continue;
        vis[x] = 1;
        for (int i = 0; i < G[x].size(); i++)
        {
```

```
            int y = G[x][i].Y, w = G[x][i].X;
            if (!vis[y] && dis[y] > dis[x] + w)
            {
                dis[y] = dis[x] + w;
                q.push(mp(dis[y], y));
            }
        }
    }
}
```

4.3.2 Bellman-Ford

```
// G[u] = mp(v, w)
// BellmanFord()返回0表示存在负环
const int maxn = "Edit";
vector<PII> G[maxn];
bool vis[maxn];
int dis[maxn];
int inqueue[maxn];
void init(int n)
{
    for (int i = 0; i < n; i++) G[i].clear();
}
void add_edge(int u, int v, int w) { G[u].pb(mp(v, w)); }
bool BellmanFord(int s, int n)
{
    clr(vis, 0), clr(dis, 0x3f), clr(inqueue, 0);
    dis[s] = 0;
    queue<int> q; // 待优化的节点入队
    q.push(s);
    vis[s] = true, ++inqueue[s];
    while (!q.empty())
    {
        int x = q.front();
        q.pop();
        vis[x] = false;
        for (int i = 0; i < G[x].size(); i++)
        {
            int y = G[x][i].X, w = G[x][i].Y;
            if (dis[y] > dis[x] + w)
            {
                dis[y] = dis[x] + w;
                if (!vis[y])
                {
                    q.push(y);
                    vis[y] = true;
                    if (++inqueue[y] >= n) return 0;
                }
            }
        }
    }
    return 1;
}
```

4.3.3 Floyd

$O(n^3)$ 求出任意两点间最短路
领接矩阵存图需注意判断重边

```
const int maxn = "Edit";
int G[maxn][maxn];
void init(int n)
{
    clr(G, 0x3f);
    for (int i = 0; i < n; i++) G[i][i] = 0;
}
void add_edge(int u, int v, int w) { G[u][v] = min(G[u][v], w); }
void Floyd(int n)
{
    for (int k = 0; k < n; k++)
        for (int i = 0; i < n; i++)
            for (int j = 0; j < n; j++)
                G[i][j] = min(G[i][j], G[i][k] + G[k][j]);
}
```

4.4 Topo Sort

存图前记得初始化 Ans 排序结果，G 邻接表，deg 入度，map 用于判断重边排序成功返回 1，存在环返回 0

```
const int maxn = "Edit";
int Ans[maxn];
vector<int> G[maxn];
int deg[maxn];
map<PII, bool> S;
void init(int n)
{
    S.clear();
    for (int i = 0; i < n; i++) G[i].clear();
    clr(deg, 0), clr(Ans, 0);
}
void add_edge(int u, int v)
{
    if (S[mp(u, v)]) return;
    G[u].pb(v);
    S[mp(u, v)] = 1;
    deg[v]++;
}
bool Toposort(int n)
{
    int tot = 0;
    queue<int> q;
    for (int i = 0; i < n; ++i)
        if (deg[i] == 0) q.push(i);
    while (!q.empty())
    {
        int v = q.front();
        que.pop();
        Ans[tot++] = v;
        for (int i = 0; i < G[v].size(); ++i)
        {
            int t = G[v][i];
            if (--deg[t] == 0) q.push(t);
        }
    }
    if (tot < n - 1) return false;
    return true;
}
```

4.5 LCA

4.5.1 Tarjan

Tarjan 离线算法
时间复杂度 $O(n + q)$

```
const int maxn = "Edit";
int par[maxn];                      //并查集
int ans[maxn];                      //存储答案
vector<int> G[maxn];                //邻接表
vector<int> query[maxn], num[maxn]; //存储查询信息
bool vis[maxn];                     //是否被遍历
inline void init(int n)
{
    for (int i = 1; i <= n; i++)
    {
        G[i].clear();
        query[i].clear();
        num[i].clear();
        par[i] = i;
        vis[i] = 0;
    }
}
inline void add_edge(int u, int v) { G[u].pb(v); }
inline void add_query(int id, int u, int v)
{
    query[u].pb(v), query[v].pb(u);
    num[u].pb(id), num[v].pb(id);
}
void tarjan(int u)
{
    vis[u] = 1;
    for (auto& v : G[u])
    {
        if (vis[v]) continue;
        tarjan(v);
        unite(u, v);
    }
    for (auto& v : query[u])
    {
        if (!vis[v]) continue;
        ans[num[u][i]] = find(v);
    }
}
```

4.5.2 DFS+ST

DFS+ST 在线算法
时间复杂度 $O(nlogn + q)$

```
const int maxn = "Edit";
vector<int> G[maxn];
int dfs_clock;
int pos[maxn], f[maxn << 1], dep[maxn << 1];
int dp[maxn << 1][30];
inline void init(int n)
{
    for (int i = 0; i < n; i++) G[i].clear();
```

```
    dfs_clock = 0;
}
inline void add_edge(int u, int v) { G[u].pb(v); }
void dfs(int u, int pre, int depth)
{
    f[++dfs_clock] = u;     //记录遍历顺序
    pos[u] = dfs_clock;     //记录某个节点在f中第一次出现的位置
    dep[dfs_clock] = depth; //记录路径
    for (auto& v : G[u])
    {
        if (v == pre) continue;
        dfs(v, u, depth + 1);
        f[++dfs_clock] = u;
        dep[dfs_clock] = depth;
    }
}
void initrmq(int n) // n = dfs_clock
{
    for (int i = 1; i <= n; i++) dp[i][0] = i;
    for (int j = 1; (1 << j) <= n; j++)
        for (int i = 0; i + (1 << j) - 1 <= tot; i++)
        {
            if (dep[dp[i][j - 1]] < dep[dp[i + (1 << (j - 1))][j - 1]])
                dp[i][j] = dp[i][j - 1];
            else
                dp[i][j] = dp[i + (1 << (j - 1))][j - 1];
        }
}
int rmq(int l, int r)
{
    l = pos[l], r = pos[r];
    if (l > r) swap(l, r);
    int k = 31 - __builtin_clz(r - l + 1);
    return (dep[l][k] < dep[r - (1 << k) + 1][k]) ? dp[l][k] : dp[r - (1 << k) + 1][k];
}
```

4.6 Depth-First Traversal

4.6.1 Biconnected-Component

```
//割顶的bccno无意义
const int maxn = "Edit";
int pre[maxn], iscut[maxn], bccno[maxn], dfs_clock, bcc_cnt;
vector<int> G[maxn], bcc[maxn];
stack<PII> s;
void init(int n)
{
    for (int i = 0; i < n; i++) G[i].clear();
}
inline void add_edge(int u, int v) { G[u].pb(v), G[v].pb(u); }
int dfs(int u, int fa)
{
    int lowu = pre[u] = ++dfs_clock;
    int child = 0;
    for (auto& v : G[u])
    {
        PII e = mp(u, v);
        if (!pre[v])
        {
```

```
            //没有访问过v
            s.push(e);
            child++;
            int lowv = dfs(v, u);
            lowu = min(lowu, lowv); //用后代的low函数更新自己
            if (lowv >= pre[u])
            {
                iscut[u] = true;
                bcc_cnt++;
                bcc[bcc_cnt].clear(); //注意! bcc从1开始编号
                for (;;)
                {
                    PII x = s.top();
                    s.pop();
                    if (bccno[x.X] != bcc_cnt)
                        bcc[bcc_cnt].pb(x.X), bcc[x.X] = bcc_cnt;
                    if (bccno[x.Y] != bcc_cnt)
                        bcc[bcc_cnt].pb(x.Y), bcc[x.Y] = bcc_cnt;
                    if (x.X == u && x.Y == v) break;
                }
            }
        }
        else if (pre[v] < pre[u] && v != fa)
        {
            s.push(e);
            lowu = min(lowu, pre[v]); //用反向边更新自己
        }
    }
    if (fa < 0 && child == 1) iscut[u] = 0;
    return lowu;
}
void find_bcc(int n)
{
    //调用结束后s保证为空，所以不用清空
    clr(pre, 0), clr(iscut, 0), clr(bccno, 0);
    dfs_clock = bcc_cnt = 0;
    for (int i = 0; i < n; i++)
        if (!pre[i]) dfs(i, -1);
}
```

4.6.2 Strongly Connected Component

```
const int maxn = "Edit";
vector<int> G[maxn];
int pre[maxn], lowlink[maxn], sccno[maxn], dfs_clock, scc_cnt;
stack<int> S;
inline void init(int n)
{
    for (int i = 0; i < n; i++) G[i].clear();
}
inline void add_edge(int u, int v) { G[u].pb(v); }
void dfs(int u)
{
    pre[u] = lowlink[u] = ++dfs_clock;
    S.push(u);
    for (auto& v : G[u])
    {
        if (!pre[v])
```

```
        {
            dfs(v);
            lowlink[u] = min(lowlink[u], lowlink[v]);
        }
        else if (!sccno[v])
            lowlink[u] = min(lowlink[u], pre[v]);
    }
    if (lowlink[u] == pre[u])
    {
        scc_cnt++;
        for (;;)
        {
            int x = S.top();
            S.pop();
            sccno[x] = scc_cnt;
            if (x == u) break;
        }
    }
}
void find_scc(int n)
{
    dfs_clock = 0, scc_cnt = 0;
    clr(sccno, 0), clr(pre, 0);
    for (int i = 0; i < n; i++)
        if (!pre[i]) dfs(i);
}
```

4.6.3 2-SAT

```
struct TwoSAT
{
    int n;
    vector<int> G[maxn << 1];
    bool mark[maxn << 1];
    int S[maxn << 1], c;
    void init(int n)
    {
        this->n = n;
        for (int i = 0; i < (n << 1); i++) G[i].clear();
        clr(mark, 0);
    }
    bool dfs(int x)
    {
        if (mark[x ^ 1]) return false;
        if (mark[x]) return true;
        mark[x] = true;
        S[c++] = x;
        for (auto& y : G[x])
            if (!dfs(y)) return false;
        return true;
    }
    //x = xval or y = yval
    void add_clause(int x, int xval, int y, int yval)
    {
        x = (x << 1) + xval;
        y = (y << 1) + yval;
        G[x ^ 1].pb(y);
        G[y ^ 1].pb(x);
```

```
    }
    bool solve()
    {
        for (int i = 0; i < (n << 1); i += 2)
            if (!mark[i] && !mark[i + 1])
            {
                c = 0;
                if (!dfs(i))
                {
                    while (c > 0) mark[S[--c]] = false;
                    if (!dfs(i + 1)) return false;
                }
            }
        return true;
    }
};
```

4.7 Eular Path

- 基本概念:
  - 欧拉图: 能够没有重复地一次遍历所有边的图。(必须是连通图)
  - 欧拉路: 上述遍历的路径就是欧拉路。
  - 欧拉回路: 若欧拉路是闭合的（一个圈，从起点开始遍历最终又回到起点），则为欧拉回路。
- 无向图 G 有欧拉路径的充要条件
  - G 是连通图
  - G 中奇顶点（连接边的数量为奇数）的数量等于 0 或 2.
- 无向图 G 有欧拉回路的充要条件
  - G 是连通图
  - G 中每个顶点都是偶顶点
- 有向图 G 有欧拉路径的充要条件
  - G 是连通图
  - u 的出度比入度大 1，v 的出度比入度小 1，其他所有点出度和入度相同。(u 为起点，v 为终点)
- 有向图 G 有欧拉回路的充要条件
  - G 是连通图
  - G 中每个顶点的出度等于入度

4.7.1 Fleury

若有两个点的度数是奇数，则此时这两个点只能作为欧拉路径的起点和终点。

```
const int maxn = "Edit";
int G[maxn][maxn];
int deg[maxn][maxn];
vector<int> Ans;
inline void init() { clr(G, 0), clr(deg, 0); }
inline void AddEdge(int u, int v) { deg[u]++, deg[v]++, G[u][v]++, G[v][u]++; }
void Fleury(int s)
{
    for (int i = 0; i < n; i++)
        if (G[s][i])
        {
            G[s][i]--, G[i][s]--;
```

```
            Fleury(i);
        }
    Ans.pb(s);
}
```

4.8 Bipartite Graph Matching

1. 一个二分图中的最大匹配数等于这个图中的最小点覆盖数
2. 最小路径覆盖 =$|G|$-最大匹配数
   在一个 $N \times N$ 的有向图中, 路径覆盖就是在图中找一些路经, 使之覆盖了图中的所有顶点, 且任何一个顶点有且只有一条路径与之关联;
   (如果把这些路径中的每条路径从它的起始点走到它的终点, 那么恰好可以经过图中的每个顶点一次且仅一次); 如果不考虑图中存在回路, 那么每每条路径就是一个弱连通子集.
   由上面可以得出:
   (a) 一个单独的顶点是一条路径;
   (b) 如果存在一路径 $p_1, p_2, ...p_k$, 其中 p_1 为起点,p_k 为终点, 那么在覆盖图中, 顶点 $p_1, p2, ...p_k$ 不再与其它的顶点之间存在有向边.

   最小路径覆盖就是找出最小的路径条数, 使之成为 G 的一个路径覆盖.
   路径覆盖与二分图匹配的关系: 最小路径覆盖 =$|G|$-最大匹配数;
3. 二分图最大独立集 = 顶点数-二分图最大匹配
   独立集: 图中任意两个顶点都不相连的顶点集合。

4.8.1 Hungry(Matrix)

时间复杂度:$O(VE)$.
顶点编号从 0 开始

```
const int maxn = "Edit";
int uN, vN;         //uN是匹配左边的顶点数,vN是匹配右边的顶点数
int g[maxn][maxn]; //邻接矩阵g[i][j]表示i->j的有向边就可以了,是左边向右边的匹配
int linker[maxn];
bool used[maxn];
bool dfs(int u)
{
    for (int v = 0; v < vN; v++)
        if (g[u][v] && !used[v])
        {
            used[v] = true;
            if (linker[v] == -1 || dfs(linker[v]))
            {
                linker[v] = u;
                return true;
            }
        }
    return false;
}
int hungary()
{
    int res = 0;
    clr(linker, -1);
    for (int u = 0; u < uN; u++)
    {
        clr(used, 0);
        if (dfs(u)) res++;
    }
    return res;
}
```

4.8.2 Hungry(List)

使用前用 init() 进行初始化
加边使用函数 addedge(u,v)

```
const int maxn = "Edit";
int n;
vector<int> G[maxn];
int linker[maxn];
bool used[maxn];
inline void init(int n)
{
    for (int i = 0; i < n; i++) G[i].clear();
}
inline void addedge(int u, int v) { G[u].pb(v); }
bool dfs(int u)
{
    for (auto& v : G[u])
    {
        if (!used[v])
        {
            used[v] = true;
            if (linker[v] == -1 || dfs(linker[v]))
            {
                linker[v] = u;
                return true;
            }
        }
    }
    return false;
}
int hungary()
{
    int ans = 0;
    clr(linker, -1);
    for (int u = 0; u < n; v++)
    {
        clr(used, 0);
        if (dfs(u)) ans++;
    }
    return ans;
}
```

4.8.3 Hopcroft-Carp

复杂度 $O(\sqrt{n} * E)$
uN 为左端的顶点数, 使用前赋值 (点编号 0 开始)

```
const int maxn = "Edit";
vector<int> G[maxn];
int uN;
int Mx[maxn], My[maxn];
int dx[maxn], dy[maxn];
int dis;
bool used[maxn];
inline void init(int n)
{
    for (int i = 0; i < n; i++) G[i].clear();
```

```
}
inline void addedge(int u, int v) { G[u].pb(v); }
bool bfs()
{
    queue<int> q;
    dis = INF;
    clr(dx, -1), clr(dy, -1);
    for (int i = 0; i < uN; i++)
        if (Mx[i] == -1)
            q.push(i), dx[i] = 0;
    while (!q.empty())
    {
        int u = q.front();
        q.pop();
        if (dx[u] > dis) break;
        for (auto& v : G[u])
        {
            if (dy[v] == -1)
            {
                dy[v] = dx[u] + 1;
                if (My[v] == -1)
                    dis = dy[v];
                else
                {
                    dx[My[v]] = dy[v] + 1;
                    q.push(My[v]);
                }
            }
        }
    }
    return dis != INF;
}
bool dfs(int u)
{
    for (auto& v : G[u])
    {
        if (!used[v] && dy[v] == dx[u] + 1)
        {
            used[v] = true;
            if (My[v] != -1 && dy[v] == dis) continue;
            if (My[v] == -1 || dfs(My[v]))
            {
                My[v] = u, Mx[u] = v;
                return true;
            }
        }
    }
    return false;
}
int MaxMatch()
{
    int res = 0;
    clr(Mx, -1), clr(My, -1);
    while (bfs())
    {
        clr(used, false);
        for (int i = 0; i < uN; i++)
            if (Mx[i] == -1 && dfs(i)) res++;
    }
```

```
    return res;
}
```

4.8.4 Hungry(Multiple)

```
const int maxn = "Edit";
const int maxm = "Edit";
int uN, vN;         //u,v的数目,使用前面必须赋值
int g[maxn][maxm]; //邻接矩阵
int linker[maxm][maxn];
bool used[maxm];
int num[maxm]; //右边最大的匹配数
bool dfs(int u)
{
    for (int v = 0; v < vN; v++)
        if (g[u][v] && !used[v])
        {
            used[v] = true;
            if (linker[v][0] < num[v])
            {
                linker[v][++linker[v][0]] = u;
                return true;
            }
            for (int i = 1; i <= num[0]; i++)
                if (dfs(linker[v][i]))
                {
                    linker[v][i] = u;
                    return true;
                }
        }
    return false;
}
int hungary()
{
    int res = 0;
    for (int i = 0; i < vN; i++) linker[i][0] = 0;
    for (int u = 0; u < uN; u++)
    {
        clr(used, 0);
        if (dfs(u)) res++;
    }
    return res;
}
```

4.8.5 Kuhn-Munkres

```
const int maxn = "Edit";
int nx, ny;                                 //两边的点数
int g[maxn][maxn];                          //二分图描述
int linker[maxn], lx[maxn], ly[maxn]; //y中各点匹配状态,x,y中的点标号
int slack[N];
bool visx[N], visy[N];
bool dfs(int x)
{
    visx[x] = true;
    for (int y = 0; y < ny; y++)
    {
        if (visy[y]) continue;
```

```
        int tmp = lx[x] + ly[y] - g[x][y];
        if (tmp == 0)
        {
            visy[y] = true;
            if (linker[y] == -1 || dfs(linker[y]))
            {
                linker[y] = x;
                return true;
            }
        }
        else if (slack[y] > tmp)
            slack[y] = tmp;
    }
    return false;
}
int KM()
{
    clr(linker, -1), clr(ly, 0);
    for (int i = 0; i < nx; i++)
    {
        lx[i] = -INF;
        for (int j = 0; j < ny; j++)
            if (g[i][j] > lx[i]) lx[i] = g[i][j];
    }
    for (int x = 0; x < nx; x++)
    {
        clr(slack, 0x3f);
        for (;;)
        {
            clr(visx, 0), clr(visy, 0);
            if (dfs(x)) break;
            int d = INF;
            for (int i = 0; i < ny; i++)
                if (!visy[i] && d > slack[i]) d = slack[i];
            for (int i = 0; i < nx; i++)
                if (visx[i]) lx[i] -= d;
            for (int i = 0; i < ny; i++)
                if (visy[i])
                    ly[i] += d;
                else
                    slack[i] -= d;
        }
    }
    int res = 0;
    for (int i = 0; i < ny; i++)
        if (~linker[i]) res += g[linker[i]][i];
    return res;
}
```

4.9 Network Flow

```
struct Edge
{
    int from, to, cap, flow;
    Edge(int u, int v, int c, int f)
        : from(u), to(v), cap(c), flow(f) {}
};
```

```
struct Edge
{
    int from, to, cap, flow, cost;
    Edge(int u, int v, int c, int f, int w)
        : from(u), to(v), cap(c), flow(f), cost(w) {}
};
```

建模技巧

二分图带权最大独立集。给出一个二分图，每个结点上有一个正权值。要求选出一些点，使得这些点之间没有边相连，且权值和最大。

解：在二分图的基础上添加源点 S 和汇点 T，然后从 S 向所有 X 集合中的点连一条边，所有 Y 集合中的点向 T 连一条边，容量均为该点的权值。X 结点与 Y 结点之间的边的容量均为无穷大。这样，对于图中的任意一个割，将割中的边对应的结点删掉就是一个符合要求的解，权和为所有权减去割的容量。因此，只需要求出最小割，就能求出最大权和。

公平分配问题。把 m 个任务分配给 n 个处理器。其中每个任务有两个候选处理器，可以任选一个分配。要求所有处理器中，任务数最多的那个处理器所分配的任务数尽量少。不同任务的候选处理器集 $\{p_1, p_2\}$ 保证不同。

解：本题有一个比较明显的二分图模型，即 X 结点是任务，Y 结点是处理器。二分答案 x，然后构图，首先从源点 S 出发向所有的任务结点引一条边，容量等于 1，然后从每个任务结点出发引两条边，分别到达它所能分配到的两个处理器结点，容量为 1，最后从每个处理器结点出发引一条边到汇点 T，容量为 x，表示选择该处理器的任务不能超过 x。这样网络中的每个单位流量都是从 S 流到一个任务结点，再到处理器结点，最后到汇点 T。只有当网络中的总流量等于 m 时才意味着所有任务都选择了一个处理器。这样，我们通过 $O(\log m)$ 次最大流便算出了答案。

区间 k 覆盖问题。数轴上有一些带权值的左闭右开区间。选出权和尽量大的一些区间，使得任意一个数最多被 k 个区间覆盖。

解：本题可以用最小费用流解决，构图方法是把每个数作为一个结点，然后对于权值为 w 的区间 $[u, v)$ 加边 $u \to v$，容量为 1，费用为 $-w$。再对所有相邻的点加边 $i \to i+1$，容量为 k，费用为 0。最后，求最左点到最右点的最小费用最大流即可，其中每个流量对应一组互不相交的区间。如果数值范围太大，可以先进行离散化。

最大闭合子图。给定带权图 G（权值可正可负），求一个权和最大的点集，使得起点在该点集中的任意弧，终点也在该点集中。

解：新增附加源 s 和附加汇 t，从 s 向所有正权点引一条边，容量为权值；从所有负权点向汇点引一条边，容量为权值的相反数。求出最小割以后，$S - \{s\}$ 就是最大闭合子图。

4.9.1 EdmondKarp

```
const int maxn = "Edit";
struct EdmonsKarp //时间复杂度O(v*E*E)
{
    int n, m;
    vector<Edge> edges;  //边数的两倍
    vector<int> G[maxn]; //邻接表，G[i][j]表示节点i的第j条边在e数组中的序号
    int a[maxn];         //起点到i的可改进量
    int p[maxn];         //最短路树上p的入弧编号
    void init(int n)
    {
        for (int i = 0; i < n; i++) G[i].clear();
        edges.clear();
    }
    void AddEdge(int from, int to, int cap)
    {
        edges.pb(Edge(from, to, cap, 0));
        edges.pb(Edge(to, from, 0, 0)); //反向弧
        m = edges.size();
```

```
        G[from].pb(m - 2);
        G[to].pb(m - 1);
    }
    int Maxflow(int s, int t)
    {
        int flow = 0;
        for (;;)
        {
            clr(a, 0);
            queue<int> q;
            q.push(s);
            a[s] = INF;
            while (!q.empty())
            {
                int x = q.front();
                q.pop();
                for (int i = 0; i < G[x].size(); i++)
                {
                    Edge& e = edges[G[x][i]];
                    if (!a[e.to] && e.cap > e.flow)
                    {
                        p[e.to] = G[x][i];
                        a[e.to] = min(a[x], e.cap - e.flow);
                        q.push(e.to);
                    }
                }
                if (a[t]) break;
            }
            if (!a[t]) break;
            for (int u = t; u != s; u = edges[p[u]].from)
            {
                edges[p[u]].flow += a[t];
                edges[p[u] ^ 1].flow -= a[t];
            }
            flow += a[t];
        }
        return flow;
    }
};
```

4.9.2 Dinic

```
const int maxn = "Edit";
struct Dinic
{
    int n, m, s, t;       //结点数，边数（包括反向弧），源点编号和汇点编号
    vector<Edge> edges;   //边表。edge[e]和edge[e^1]互为反向弧
    vector<int> G[maxn]; //邻接表，G[i][j]表示节点i的第j条边在e数组中的序号
    bool vis[maxn];       //BFS使用
    int d[maxn];          //从起点到i的距离
    int cur[maxn];        //当前弧下标
    void init(int n)
    {
        this->n = n;
        for (int i = 0; i < n; i++) G[i].clear();
        edges.clear();
    }
    void AddEdge(int from, int to, int cap)
```

```
    {
        edges.pb(Edge(from, to, cap, 0));
        edges.pb(Edge(to, from, 0, 0));
        m = edges.size();
        G[from].pb(m - 2);
        G[to].pb(m - 1);
    }
    bool BFS()
    {
        clr(vis, 0);
        clr(d, 0);
        queue<int> q;
        q.push(s);
        d[s] = 0;
        vis[s] = 1;
        while (!q.empty())
        {
            int x = q.front();
            q.pop();
            for (int i = 0; i < G[x].size(); i++)
            {
                Edge& e = edges[G[x][i]];
                if (!vis[e.to] && e.cap > e.flow)
                {
                    vis[e.to] = 1;
                    d[e.to] = d[x] + 1;
                    q.push(e.to);
                }
            }
        }
        return vis[t];
    }
    int DFS(int x, int a)
    {
        if (x == t || a == 0) return a;
        int flow = 0, f;
        for (int& i = cur[x]; i < G[x].size(); i++)
        {
            //从上次考虑的弧
            Edge& e = edges[G[x][i]];
            if (d[x] + 1 == d[e.to] && (f = DFS(e.to, min(a, e.cap - e.flow))) > 0)
            {
                e.flow += f;
                edges[G[x][i] ^ 1].flow -= f;
                flow += f;
                a -= f;
                if (a == 0) break;
            }
        }
        return flow;
    }
    int Maxflow(int s, int t)
    {
        this->s = s;
        this->t = t;
        int flow = 0;
        while (BFS())
        {
            clr(cur, 0);
```

```
            flow += DFS(s, INF);
        }
        return flow;
    }
};
```

4.9.3 ISAP

```
const int maxn = "Edit";
struct ISAP
{
    int n, m, s, t;      //结点数，边数（包括反向弧），源点编号和汇点编号
    vector<Edge> edges;  //边表。edges[e]和edges[e^1]互为反向弧
    vector<int> G[maxn]; //邻接表，G[i][j]表示结点i的第j条边在e数组中的序号
    bool vis[maxn];      //BFS使用
    int d[maxn];         //起点到i的距离
    int cur[maxn];       //当前弧下标
    int p[maxn];         //可增广路上的一条弧
    int num[maxn];       //距离标号计数
    void init(int n)
    {
        this->n = n;
        for (int i = 0; i < n; i++) G[i].clear();
        edges.clear();
    }
    void AddEdge(int from, int to, int cap)
    {
        edges.pb(Edge(from, to, cap, 0));
        edges.pb(Edge(to, from, 0, 0));
        int m = edges.size();
        G[from].pb(m - 2);
        G[to].pb(m - 1);
    }
    int Augumemt()
    {
        int x = t, a = INF;
        while (x != s)
        {
            Edge& e = edges[p[x]];
            a = min(a, e.cap - e.flow);
            x = edges[p[x]].from;
        }
        x = t;
        while (x != s)
        {
            edges[p[x]].flow += a;
            edges[p[x] ^ 1].flow -= a;
            x = edges[p[x]].from;
        }
        return a;
    }
    void BFS()
    {
        clr(vis, 0);
        clr(d, 0);
        queue<int> q;
        q.push(t);
        d[t] = 0;
```

```
        vis[t] = 1;
        while (!q.empty())
        {
            int x = q.front();
            q.pop();
            int len = G[x].size();
            for (int i = 0; i < len; i++)
            {
                Edge& e = edges[G[x][i]];
                if (!vis[e.from] && e.cap > e.flow)
                {
                    vis[e.from] = 1;
                    d[e.from] = d[x] + 1;
                    q.push(e.from);
                }
            }
        }
    }
    int Maxflow(int s, int t)
    {
        this->s = s;
        this->t = t;
        int flow = 0;
        BFS();
        clr(num, 0);
        for (int i = 0; i < n; i++)
            if (d[i] < INF) num[d[i]]++;
        int x = s;
        clr(cur, 0);
        while (d[s] < n)
        {
            if (x == t)
            {
                flow += Augumemt();
                x = s;
            }
            int ok = 0;
            for (int i = cur[x]; i < G[x].size(); i++)
            {
                Edge& e = edges[G[x][i]];
                if (e.cap > e.flow && d[x] == d[e.to] + 1)
                {
                    ok = 1;
                    p[e.to] = G[x][i];
                    cur[x] = i;
                    x = e.to;
                    break;
                }
            }
            if (!ok) //Retreat
            {
                int m = n - 1;
                for (int i = 0; i < G[x].size(); i++)
                {
                    Edge& e = edges[G[x][i]];
                    if (e.cap > e.flow) m = min(m, d[e.to]);
                }
                if (--num[d[x]] == 0) break; //gap优化
                num[d[x] = m + 1]++;
```

```
                    cur[x] = 0;
                    if (x != s) x = edges[p[x]].from;
                }
            }
            return flow;
        }
};
```

4.9.4 MinCost MaxFlow

```
const int maxn = "Edit";
struct MCMF
{
    int n, m;
    vector<Edge> edges;
    vector<int> G[maxn];
    int inq[maxn]; //是否在队列中
    int d[maxn];   //bellmanford
    int p[maxn];   //上一条弧
    int a[maxn];   //可改进量
    void init(int n)
    {
        this->n = n;
        for (int i = 0; i < n; i++) G[i].clear();
        edges.clear();
    }
    void AddEdge(int from, int to, int cap, int cost)
    {
        edges.pb(Edge(from, to, cap, 0, cost));
        edges.pb(Edge(to, from, 0, 0, -cost));
        m = edges.size();
        G[from].pb(m - 2);
        G[to].pb(m - 1);
    }
    bool BellmanFord(int s, int t, int& flow, ll& cost)
    {
        for (int i = 0; i < n; i++) d[i] = INF;
        clr(inq, 0);
        d[s] = 0;
        inq[s] = 1;
        p[s] = 0;
        a[s] = INF;
        queue<int> q;
        q.push(s);
        while (!q.empty())
        {
            int u = q.front();
            q.pop();
            inq[u] = 0;
            for (int i = 0; i < G[u].size(); i++)
            {
                Edge& e = edges[G[u][i]];
                if (e.cap > e.flow && d[e.to] > d[u] + e.cost)
                {
                    d[e.to] = d[u] + e.cost;
                    p[e.to] = G[u][i];
                    a[e.to] = min(a[u], e.cap - e.flow);
                    if (!inq[e.to])
```

```
                    {
                        q.push(e.to);
                        inq[e.to] = 1;
                    }
                }
            }
        }
        if (d[t] == INF) return false; // 当没有可增广的路时退出
        flow += a[t];
        cost += (ll)d[t] * (ll)a[t];
        for (int u = t; u != s; u = edges[p[u]].from)
        {
            edges[p[u]].flow += a[t];
            edges[p[u] ^ 1].flow -= a[t];
        }
        return true;
    }
    int MincostMaxflow(int s, int t, ll& cost)
    {
        int flow = 0;
        cost = 0;
        while (BellmanFord(s, t, flow, cost));
        return flow;
    }
};
```

5 Computational Geometry

5.1 Basic Function

```
#define zero(x) ((fabs(x) < eps ? 1 : 0))
#define sgn(x) (fabs(x) < eps ? 0 : ((x) < 0 ? -1 : 1))

struct point
{
    double x, y;
    point(double a = 0, double b = 0) { x = a, y = b; }
    point operator-(const point& b) const { return point(x - b.x, y - b.y); }
    point operator+(const point& b) const { return point(x + b.x, y + b.y); }
    // 两点是否重合
    bool operator==(point& b) { return zero(x - b.x) && zero(y - b.y); }
    // 点积(以原点为基准)
    double operator*(const point& b) const { return x * b.x + y * b.y; }
    // 叉积(以原点为基准)
    double operator^(const point& b) const { return x * b.y - y * b.x; }
    // 绕P点逆时针旋转a弧度后的点
    point rotate(point b, double a)
    {
        double dx, dy;
        (*this - b).split(dx, dy);
        double tx = dx * cos(a) - dy * sin(a);
        double ty = dx * sin(a) + dy * cos(a);
        return point(tx, ty) + b;
    }
    // 点坐标分别赋值到a和b
    void split(double& a, double& b) { a = x, b = y; }
};
struct line
{
    point s, e;
    line() {}
    line(point ss, point ee) { s = ss, e = ee; }
};
```

5.2 Position

5.2.1 Point-Point

```
double dist(point a, point b) { return sqrt((a - b) * (a - b)); }
```

5.2.2 Line-Line

```
// <0, *> 表示重合; <1, *> 表示平行; <2, P> 表示交点是P;
pair<int, point> spoint(line l1, line l2)
{
    point res = l1.s;
    if (sgn((l1.s - l1.e) ^ (l2.s - l2.e)) == 0)
        return mp(sgn((l1.s - l2.e) ^ (l2.s - l2.e)) != 0, res);
    double t = ((l1.s - l2.s) ^ (l2.s - l2.e)) / ((l1.s - l1.e) ^ (l2.s - l2.e));
    res.x += (l1.e.x - l1.s.x) * t;
    res.y += (l1.e.y - l1.s.y) * t;
    return mp(2, res);
}
```

5.2.3 Segment-Segment

```
bool segxseg(line l1, line l2)
{
    return
        max(l1.s.x, l1.e.x) >= min(l2.s.x, l2.e.x) &&
        max(l2.s.x, l2.e.x) >= min(l1.s.x, l1.e.x) &&
        max(l1.s.y, l1.e.y) >= min(l2.s.y, l2.e.y) &&
        max(l2.s.y, l2.e.y) >= min(l1.s.y, l1.e.y) &&
        sgn((l2.s - l1.e) ^ (l1.s - l1.e)) * sgn((l2.e-l1.e) ^ (l1.s - l1.e)) <= 0 &&
        sgn((l1.s - l2.e) ^ (l2.s - l2.e)) * sgn((l1.e-l2.e) ^ (l2.s - l2.e)) <= 0;
}
```

5.2.4 Line-Segment

```
//l1是直线,l2是线段
bool segxline(line l1, line l2)
{
    return sgn((l2.s - l1.e) ^ (l1.s - l1.e)) * sgn((l2.e - l1.e) ^ (l1.s - l1.e)) <=
    0;
}
```

5.2.5 Point-Line

```
double pointtoline(point p, line l)
{
    point res;
    double t = ((p - l.s) * (l.e - l.s)) / ((l.e - l.s) * (l.e - l.s));
    res.x = l.s.x + (l.e.x - l.s.x) * t, res.y = l.s.y + (l.e.y - l.s.y) * t;
    return dist(p, res);
}
```

5.2.6 Point-Segment

```
double pointtosegment(point p, line l)
{
    point res;
    double t = ((p - l.s) * (l.e - l.s)) / ((l.e - l.s) * (l.e - l.s));
    if (t >= 0 && t <= 1)
        res.x = l.s.x + (l.e.x - l.s.x) * t, res.y = l.s.y + (l.e.y - l.s.y) * t;
    else
        res = dist(p, l.s) < dist(p, l.e) ? l.s : l.e;
    return dist(p, res);
}
```

5.2.7 Point on Segment

```
bool PointOnSeg(point p, line l)
{
    return
        sgn((l.s - p) ^ (l.e-p)) == 0 &&
        sgn((p.x - l.s.x) * (p.x - l.e.x)) <= 0 &&
        sgn((p.y - l.s.y) * (p.y - l.e.y)) <= 0;
}
```

5.3 Polygon

5.3.1 Area

```
double area(point p[], int n)
{
    double res = 0;
    for (int i = 0; i < n; i++) res += (p[i] ^ p[(i + 1) % n]) / 2;
    return fabs(res);
}
```

5.3.2 Point in Convex

```
// 点形成一个凸包，而且按逆时针排序(如果是顺时针把里面的<0改为>0)
// 点的编号 : [0,n)
// -1 : 点在凸多边形外
// 0  : 点在凸多边形边界上
// 1  : 点在凸多边形内
int PointInConvex(point a, point p[], int n)
{
    for (int i = 0; i < n; i++)
        if (sgn((p[i] - a) ^ (p[(i + 1) % n] - a)) < 0)
            return -1;
        else if (PointOnSeg(a, line(p[i], p[(i + 1) % n])))
            return 0;
    return 1;
}
```

5.3.3 Point in Polygon

```
// 射线法,poly[]的顶点数要大于等于3,点的编号0~n-1
// -1 : 点在凸多边形外
// 0  : 点在凸多边形边界上
// 1  : 点在凸多边形内
int PointInPoly(point p, point poly[], int n)
{
    int cnt;
    line ray, side;
    cnt = 0;
    ray.s = p;
    ray.e.y = p.y;
    ray.e.x = -100000000000.0; // -INF,注意取值防止越界
    for (int i = 0; i < n; i++)
    {
        side.s = poly[i], side.e = poly[(i + 1) % n];
        if (PointOnSeg(p, side)) return 0;
        //如果平行轴则不考虑
        if (sgn(side.s.y - side.e.y) == 0)
            continue;
        if (PointOnSeg(sid e.s, r ay))
            cnt += (sgn(side.s.y - side.e.y) > 0);
        else if (PointOnSeg(side.e, ray))
            cnt += (sgn(side.e.y - side.s.y) > 0);
        else if (segxseg(ray, side))
            cnt++;
    }
    return cnt % 2 == 1 ? 1 : -1;
}
```

5.3.4 Judge Convex

```
//点可以是顺时针给出也可以是逆时针给出
//点的编号1~n-1
bool isconvex(point poly[], int n)
{
    bool s[3];
    clr(s, 0);
    for (int i = 0; i < n; i++)
    {
        s[sgn((poly[(i + 1) % n] - poly[i]) ^ (poly[(i + 2) % n] - poly[i])) + 1] = 1;
        if (s[0] && s[2]) return 0;
    }
    return 1;
}
```

5.4 Integer Points

5.4.1 On Segment

```
int OnSegment(line l) { return __gcd(fabs(l.s.x - l.e.x), fabs(l.s.y - l.e.y)) + 1; }
```

5.4.2 On Polygon Edge

```
int OnEdge(point p[], int n)
{
    int i, ret = 0;
    for (i = 0; i < n; i++)
        ret += __gcd(fabs(p[i].x - p[(i + 1) % n].x), fabs(p[i].y - p[(i + 1) % n].y));
    return ret;
}
```

5.4.3 Inside Polygon

```
int InSide(point p[], int n)
{
    int i, area = 0;
    for (i = 0; i < n; i++)
        area += p[(i + 1) % n].y * (p[i].x - p[(i + 2) % n].x);
    return (fabs(area) - OnEdge(n, p)) / 2 + 1;
}
```

5.5 Circle

5.5.1 Circumcenter

```
point waixin(point a, point b, point c)
{
    double a1 = b.x - a.x, b1 = b.y - a.y, c1 = (a1 * a1 + b1 * b1) / 2;
    double a2 = c.x - a.x, b2 = c.y - a.y, c2 = (a2 * a2 + b2 * b2) / 2;
    double d = a1 * b2 - a2 * b1;
    return point(a.x + (c1 * b2 - c2 * b1) / d, a.y + (a1 * c2 - a2 * c1) / d);
}
```

6 Dynamic Programming

6.1 Subsequence

6.1.1 Max Sum

```
// 传入序列a和长度n，返回最大子序列和
int MaxSeqSum(int a[], int n)
{
    int rt = 0, cur = 0;
    for (int i = 0; i < n; i++)
        cur += a[i], rt = max(cur, rt), cur = max(0, cur);
    return rt;
}
```

6.1.2 Longest Increase

```
// 序列下标从1开始，LIS()返回长度，序列存在lis[]中
const int N = "Edit";
int len, a[N], b[N], f[N];
int Find(int p, int l, int r)
{
    while (l <= r)
    {
        int mid = (l + r) >> 1;
        if (a[p] > b[mid])
            l = mid + 1;
        else
            r = mid - 1;
    }
    return f[p] = l;
}
int LIS(int lis[], int n)
{
    int len = 1;
    f[1] = 1, b[1] = a[1];
    for (int i = 2; i <= n; i++)
    {
        if (a[i] > b[len])
            b[++len] = a[i], f[i] = len;
        else
            b[Find(i, 1, len)] = a[i];
    }
    for (int i = n, t = len; i >= 1 && t >= 1; i--)
        if (f[i] == t) lis[--t] = a[i];
    return len;
}

// 简单写法(下标从0开始,只返回长度)
int dp[N];
int LIS(int a[], int n)
{
    clr(dp, 0x3f);
    for (int i = 0; i < n; i++) *lower_bound(dp, dp + n, a[i]) = a[i];
    return lower_bound(dp, dp + n, INF) - dp;
}
```

6.1.3 Longest Common Increase

```
// 序列下标从1开始
int LCIS(int a[], int b[], int n, int m)
{
    clr(dp, 0);
    for (int i = 1; i <= n; i++)
    {
        int ma = 0;
        for (int j = 1; j <= m; j++)
        {
            dp[i][j] = dp[i - 1][j];
            if (a[i] > b[j]) ma = max(ma, dp[i - 1][j]);
            if (a[i] == b[j]) dp[i][j] = ma + 1;
        }
    }
    return *max_element(dp[n] + 1, dp[n] + 1 + m);
}
```

6.2 Digit Statistics

```
int a[20];
ll dp[20][state];
ll dfs(int pos, /*state变量*/, bool lead /*前导零*/, bool limit /*数位上界变量*/)
{
    //递归边界，既然是按位枚举，最低位是0，那么pos==-1说明这个数枚举完了
    if (pos == -1) return 1;
    /*这里一般返回1，表示枚举的这个数是合法的，那么这里就需要在枚举时必须每一位都要满足题目条件，
    也就是说当前枚举到pos位，一定要保证前面已经枚举的数位是合法的。*/
    if (!limit && !lead && dp[pos][state] != -1) return dp[pos][state];
    /*常规写法都是在没有限制的条件记忆化，这里与下面记录状态是对应*/
    int up = limit ? a[pos] : 9; //根据limit判断枚举的上界up
    ll ans = 0;
    for (int i = 0; i <= up; i++) //枚举，然后把不同情况的个数加到ans就可以了
    {
        if () ...
        else if () ...
        ans += dfs(pos - 1, /*状态转移*/, lead && i == 0, limit && i == a[pos])
        //最后两个变量传参都是这样写的
        /*当前数位枚举的数是i，然后根据题目的约束条件分类讨论
        去计算不同情况下的个数，还有要根据state变量来保证i的合法性*/
    }
    //计算完，记录状态
    if (!limit && !lead) dp[pos][state] = ans;
    /*这里对应上面的记忆化，在一定条件下时记录，保证一致性，
    当然如果约束条件不需要考虑lead，这里就是lead就完全不用考虑了*/
    return ans;
}
ll solve(ll x)
{
    int pos = 0;
    do //把数位都分解出来
        a[pos++] = x % 10;
    while (x /= 10);
    return dfs(pos - 1 /*从最高位开始枚举*/, /*一系列状态 */, true, true);
    //刚开始最高位都是有限制并且有前导零的，显然比最高位还要高的一位视为0
}
```

7 Others

7.1 Matrix

7.1.1 Matrix FastPow

```
typedef vector<ll> vec;
typedef vector<vec> mat;
mat mul(mat& A, mat& B)
{
    mat C(A.size(), vec(B[0].size()));
    for (int i = 0; i < A.size(); i++)
        for (int k = 0; k < B.size(); k++)
            if (A[i][k]) // 对稀疏矩阵的优化
                for (int j = 0; j < B[0].size(); j++)
                    C[i][j] = (C[i][j] + A[i][k] * B[k][j]) % mod;
    return C;
}
mat Pow(mat A, ll n)
{
    mat B(A.size(), vec(A.size()));
    for (int i = 0; i < A.size(); i++) B[i][i] = 1;
    for (; n; n >>= 1, A = mul(A, A))
        if (n & 1) B = mul(B, A);
    return B;
}
```

7.1.2 Gauss Elimination

```
void gauss()
{
    int now = 1, to;
    double t;
    for (int i = 1; i <= n; i++, now++)
    {
        /*for (to = now; !a[to][i] && to <= n; to++);
        //做除法时减小误差，可不写
        if (to != now)
            for (int j = 1; j <= n + 1; j++)
                swap(a[to][j], a[now][j]);*/
        t = a[now][i];
        for (int j = 1; j <= n + 1; j++) a[now][j] /= t;
        for (int j = 1; j <= n; j++)
            if (j != now)
            {
                t = a[j][i];
                for (int k = 1; k <= n + 1; k++) a[j][k] -= t * a[now][k];
            }
    }
}
```

7.2 Tricks

7.2.1 Stack-Overflow

```
// 解决爆栈问题
#pragma comment(linker, "/STACK:1024000000,1024000000")
```

7.2.2 Fast-Scanner

```
// 适用于正负整数
template <class T>
inline bool scan_d(T &ret)
{
    char c;
    int sgn;
    if (c = getchar(), c == EOF) return 0; //EOF
    while (c != '-' && (c < '0' || c > '9')) c = getchar();
    sgn = (c == '-') ? -1 : 1;
    ret = (c == '-') ? 0 : (c - '0');
    while (c = getchar(), c >= '0' && c <= '9') ret = ret * 10 + (c - '0');
    ret *= sgn;
    return 1;
}
inline void out(int x)
{
    if (x > 9) out(x / 10);
    putchar(x % 10 + '0');
}
```

7.2.3 Strok-Sscanf

```
// 空格作为分隔输入,读取一行的整数
gets(buf);
int v;
char *p = strtok(buf, " ");
while (p)
{
    sscanf(p, "%d", &v);
    p = strtok(NULL," ");
}
```

7.3 Mo Algorithm

莫队算法, 可以解决一类静态, 离线区间查询问题。分成 $\sqrt{x}$ 块, 分块排序。

```
struct query { int L, R, id; };
void solve(query node[], int m)
{
    tmp = 0;
    clr(num, 0);
    clr(ans, 0);
    sort(node, node + m, [](query a, query b) { return a.l / unit < b.l / unit || a.l /
     unit == b.l / unit && a.r < b.r; });
    int L = 1, R = 0;
    for (int i = 0; i < m; i++)
    {
        while (node[i].L < L) add(a[--L]);
        while (node[i].L > L) del(a[L++]);
        while (node[i].R < R) del(a[R--]);
        while (node[i].R > R) add(a[++R]);
        ans[node[i].id] = tmp;
    }
}
```

7.4 BigNum

7.4.1 High-precision

```
// 加法 乘法 小于号 输出
struct bint
{
    int l;
    short int w[100];
    bint(int x = 0)
    {
        l = x == 0, clr(w, 0);
        while (x) w[l++] = x % 10, x /= 10;
    }
    bool operator<(const bint& x) const
    {
        if (l != x.l) return l < x.l;
        int i = l - 1;
        while (i >= 0 && w[i] == x.w[i]) i--;
        return (i >= 0 && w[i] < x.w[i]);
    }
    bint operator+(const bint& x) const
    {
        bint ans;
        ans.l = l > x.l ? l : x.l;
        for (int i = 0; i < ans.l; i++)
        {
            ans.w[i] += w[i] + x.w[i];
            ans.w[i + 1] += ans.w[i] / 10;
            ans.w[i] = ans.w[i] % 10;
        }
        if (ans.w[ans.l] != 0) ans.l++;
        return ans;
    }
    bint operator*(const bint& x) const
    {
        bint res;
        int up, tmp;
        for (int i = 0; i < l; i++)
        {
            up = 0;
            for (int j = 0; j < x.l; j++)
            {
                tmp = w[i] * x.w[j] + res.w[i + j] + up;
                res.w[i + j] = tmp % 10;
                up = tmp / 10;
            }
            if (up != 0) res.w[i + x.l] = up;
        }
        res.l = l + x.l;
        while (res.w[res.l - 1] == 0 && res.l > 1) res.l--;
        return res;
    }
    void print()
    {
        for (int i = l - 1; ~i; i--) printf("%d", w[i]);
        puts("");
    }
};
```

7.4.2 Complete High-precision

```
#define N 10000
class bint
{
private:
    int a[N]; // 用 N 控制最大位数
    int len;  // 数字长度
public:
    // 构造函数
    bint() { len = 1, clr(a, 0); }
    // int -> bint
    bint(int n)
    {
        len = 0;
        clr(a, 0);
        int d = n;
        while (n)
            d = n / 10 * 10, a[len++] = n - d, n = d / 10;
    }
    // char[] -> int
    bint(const char s[])
    {
        clr(a, 0);
        len = 0;
        int l = strlen(s);
        for (int i = l - 1; ~i; i--) a[len++] = s[i];
    }
    // 拷贝构造函数
    bint(const bint& b)
    {
        clr(a, 0);
        len = b.len;
        for (int i = 0; i < len; i++) a[i] = b.a[i];
    }
    // 重载运算符 bint = bint
    bint& operator=(const bint& n)
    {
        len = n.len;
        for (int i = 0; i < len; i++) a[i] = n.a[i];
        return *this;
    }
    // 重载运算符 bint + bint
    bint operator+(const bint& b) const
    {
        bint t(*this);
        int res = b.len > len ? b.len : len;
        for (int i = 0; i < res; i++)
        {
            t.a[i] += b.a[i];
            if (t.a[i] >= 10) t.a[i + 1]++, t.a[i] -= 10;
        }
        t.len = res + a[res] == 0;
        return t;
    }
    // 重载运算符 bint - bint
    bint operator-(const bint& b) const
    {
        bool f = *this > b;
```

```
        bint t1 = f ? *this : b;
        bint t2 = f ? b : *this;
        int res = t1.len, j;
        for (int i = 0; i < res; i++)
            if (t1.a[i] < t2.a[i])
            {
                j = i + 1;
                while (t1.a[j] == 0) j++;
                t1.a[j--]--;
                while (j > i) t1.a[j--] += 9;
                t1.a[i] += 10 - t1.a[i];
            }
            else
                t1.a[i] -= t2.a[i];
        t1.len = res;
        while (t1.a[len - 1] == 0 && t1.len > 1) t1.len--, res--;
        if (f) t1.a[res - 1] = 0 - t1.a[res - 1];
        return t1;
    }
    // 重载运算符 bint * bint
    bint operator*(const bint& b) const
    {
        bint t;
        int i, j, up, tmp, tmp1;
        for (i = 0; i < len; i++)
        {
            up = 0;
            for (j = 0; j < b.len; j++)
            {
                tmp = a[i] * b.a[j] + t.a[i + j] + up;
                if (tmp > 9)
                    tmp1 = tmp - tmp / 10 * 10, up = tmp / 10, t.a[i + j] = tmp1;
                else
                    up = 0, t.a[i + j] = tmp;
            }
            if (up) t.a[i + j] = up;
        }
        t.len = i + j;
        while (t.a[t.len - 1] == 0 && t.len > 1) t.len--;
        return t;
    }
    // 重载运算符 bint / int
    bint operator/(const int& b) const
    {
        bint t;
        int down = 0;
        for (int i = len - 1; ~i; i--)
            t.a[i] = (a[i] + down * 10) / b, down = a[i] + down * 10 - t.a[i] * b;
        t.len = len;
        while (t.a[t.len - 1] == 0 && t.len > 1) t.len--;
        return t;
    }
    // 重载运算符 bint ^ n (n次方快速幂, 需保证n非负)
    bint operator^(const int n) const
    {
        bint t(*this), rt(1);
        if (n == 0) return 1;
        if (n == 1) return *this;
        int m = n;
```

```
        for (; m; m >>= 1, t = t * t)
            if (m & 1) rt = rt * t;
        return rt;
    }
    // 重载运算符 bint > bint 比较大小
    bool operator>(const bint& b) const
    {
        int p;
        if (len > b.len) return 1;
        if (len == b.len)
        {
            p = len - 1;
            while (a[p] == b.a[p] && p >= 0) p--;
            return p >= 0 && a[p] > b.a[p];
        }
        return 0;
    }
    // 重载运算符 bint > int 比较大小
    bool operator>(const int& n) const { return *this > bint(n); }
    // 输出
    void out()
    {
        for (int i = len - 1; ~i; i--) printf("%d", a[i]);
        puts("");
    }
};
```

7.5 VIM

```
syntax on
set cindent
set nu
set tabstop=4
set shiftwidth=4
set background=dark
set mouse=a

map<C-A> ggvG"+y
map<F5> :call Run()<CR>

func! Run()
    exec "w"
    exec "!g++ -std=c++11 -O2 % -o %<"
    exec "!time ./%<"
endfunc

autocmd BufNewFile *.cpp 0r ~/include.cpp
autocmd BufNewFile *.cpp normal G

inoremap ( ()<Esc>i
inoremap [ []<Esc>i
inoremap { {<CR>}<Esc>O
inoremap ' ''<Esc>i
inoremap " ""<Esc>i

inoremap ) <c-r>=ClosePair(')')<CR>
inoremap ] <c-r>=ClosePair(']')<CR>

```

```
func ClosePair(char)
    if getline('.')[col('.')-1]==a:char
        return "\<Right>"
    else
        return a:char
    endif
endfunc
```