



All-in at the River

Standard Code Library

Shanghai Jiao Tong University

Desprado2 fstqwq AntiLeaf

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1 数学

1.1 多项式

1.1.1 FFT

```

1 // 使用时一定要注意double的精度是否足够(极限大概是10 ^ ↪ 14)
2
3 const double pi = acos((double)-1.);
4
5 // 手写复数类
6 // 支持加减乘三种运算
7 // += 运算符如果用的不多可以不重载
8 struct Complex {
9     double a, b; // 由于long double精度和double几乎相同,
    → 通常没有必要用long double
10
11     Complex(double a = 0., double b = 0.) : a(a), b(b)
    → {}
12
13     Complex operator + (const Complex &x) const {
14         return Complex(a + x.a, b + x.b);
15     }
16
17     Complex operator - (const Complex &x) const {
18         return Complex(a - x.a, b - x.b);
19     }
20
21     Complex operator * (const Complex &x) const {
22         return Complex(a * x.a - b * x.b, a * x.b + b * ↪ x.a);
23     }
24
25     Complex operator * (double x) const {
26         return Complex(a * x, b * x);
27     }
28
29     Complex &operator += (const Complex &x) {
30         return *this = *this + x;
31     }
32
33     Complex conj() const { // 共轭, 一般只有MTT需要用
34         return Complex(a, -b);
35     }
36 } omega[maxn], omega_inv[maxn];
37 const Complex ima = Complex(0, 1); // i = sqrt(-1)
38
39 int fft_n; // 要在主函数里初始化
40
41 // FFT初始化
42 void FFT_init(int n) {
43     fft_n = n;
44
45     for (int i = 0; i < n; i++) // 根据单位根的旋转性质
        → 可以节省计算单位根逆元的时间
        omega[i] = Complex(cos(2 * pi / n * i), sin(2 * ↪ pi / n * i));
46
47     omega_inv[0] = omega[0];
48     for (int i = 1; i < n; i++)
        omega_inv[i] = omega[n - i];
49
50     // 当然不存单位根也可以, 只不过在FFT次数较多时很可能
        → 会增大常数
51 }
52
53 // FFT主过程
54 void FFT(Complex *a, int n, int tp) {
55     for (int i = 1, j = 0, k; i < n - 1; i++) {

```

```

57         k = n;
58         do
59             j ≈ (k >= 1);
60         while (j < k);
61
62         if (i < j)
63             swap(a[i], a[j]);
64     }
65
66     for (int k = 2, m = fft_n / 2; k ≤ n; k *= 2, m /= 2)
67         for (int i = 0; i < n; i += k)
68             for (int j = 0; j < k / 2; j++) {
69                 Complex u = a[i + j], v = (tp > 0 ?
                    → omega : omega_inv)[m * j] * a[i + j
                    → + k / 2];
70
71                 a[i + j] = u + v;
72                 a[i + j + k / 2] = u - v;
73             }
74
75         if (tp < 0)
76             for (int i = 0; i < n; i++) {
77                 a[i].a /= n;
78                 a[i].b /= n; // 一般情况下是不需要的, 只
                    → 有MTT时才需要
79     }
80 }

```

1.1.2 NTT

```

1 vector<int> omega[25];
2
3 void NTT_init(int n) {
4     for (int k = 2, d = 0; k ≤ n; k *= 2, d++) {
5         omega[d].resize(k + 1);
6
7         int wn = qpow(3, (p - 1) / k), tmp = 1;
8         for (int i = 0; i ≤ k; i++) {
9             omega[d][i] = tmp;
10            tmp = (long long)tmp * wn % p;
11        }
12    }
13
14 void NTT(int *c, int n, int tp) {
15     static unsigned long long a[maxn];
16     for (int i = 0; i < n; i++) a[i] = c[i];
17
18     for (int i = 1, j = 0; i < n - 1; i++) {
19         int k = n;
20         do
21             j ≈ (k >= 1);
22         while (j < k);
23
24         if (i < j)
25             swap(a[i], a[j]);
26     }
27
28     for (int k = 1, d = 0; k < n; k *= 2, d++) {
29         if (d == 16)
30             for (int i = 0; i < n; i++)
31                 a[i] %= p;
32
33         for (int i = 0; i < n; i += k * 2)
34             for (int j = 0; j < k; j++) {
35                 int w = omega[d][tp > 0 ? j : k * 2 - ↪ j];
36                 unsigned long long u = a[i + j],

```

```

38         v = w * a[i + j + k] % p;
39         a[i + j] = u + v;
40         a[i + j + k] = u - v + p;
41     }
42 }
43
44 if (tp>0) {
45     for (int i = 0; i < n; i++)
46         c[i] = a[i] % p;
47 }
48 else {
49     int inv = qpow(n, p - 2);
50     for (int i = 0; i < n; i++)
51         c[i] = a[i] * inv % p;
52 }
53

```

1.1.3 任意模数卷积(MTT, 毛梯梯)

三模数NTT和直接拆系数FFT都太慢了, 不要用.

MTT的原理就是拆系数FFT, 只不过优化了做变换的次数.

考虑要对 $A(x)$, $B(x)$ 两个多项式做DFT, 可以构造两个复多项式

$$P(x) = A(x) + iB(x) \quad Q(x) = A(x) - iB(x)$$

只需要DFT一个, 另一个DFT实际上就是前者反转再取共轭, 再利用

$$A(x) = \frac{P(x) + Q(x)}{2} \quad B(x) = \frac{P(x) - Q(x)}{2i}$$

即可还原出 $A(x)$, $B(x)$.

IDFT的道理更简单, 如果要对 $A(x)$ 和 $B(x)$ 做IDFT, 只需要对 $A(x) + iB(x)$ 做IDFT即可, 因为IDFT的结果必定为实数, 所以结果的实部和虚部就分别是 $A(x)$ 和 $B(x)$.

实际上任何同时对两个实序列进行DFT, 或者同时对结果为实序列的DFT进行逆变换时都可以按照上面的方法优化, 可以减少一半的DFT次数.

```

32
33 for (int i = 0; i < n; i++) {
34     a[i].a = c[i].a;
35     b[i].a = c[i].b;
36 }
37
38
39 Complex a[2][maxn], b[2][maxn], c[3][maxn];
40 int ans[maxn];
41
42 int main() {
43     int n, m;
44     scanf("%d%d%d", &n, &m, &p);
45     n++;
46     m++;
47
48     base = (int)(sqrt(p) + 0.5);
49
50     for (int i = 0; i < n; i++) {
51         int x;
52         scanf("%d", &x);
53         x %= p;
54
55         a[1][i].a = x / base;
56         a[0][i].a = x % base;
57     }
58
59     for (int i = 0; i < m; i++) {
60         int x;
61         scanf("%d", &x);
62         x %= p;
63
64         b[1][i].a = x / base;
65         b[0][i].a = x % base;
66     }
67
68     int N = 1;
69     while (N < n + m - 1)
70         N <<= 1;
71
72     FFT_init(N);
73
74     DFT(a[0], a[1], N);
75     DFT(b[0], b[1], N);
76
77     for (int i = 0; i < N; i++)
78         c[0][i] = a[0][i] * b[0][i];
79
80     for (int i = 0; i < N; i++)
81         c[1][i] = a[0][i] * b[1][i] + a[1][i] * b[0]
82             [i];
83
84     for (int i = 0; i < N; i++)
85         c[2][i] = a[1][i] * b[1][i];
86
87     FFT(c[1], N, -1);
88     IDFT(c[0], c[2], N);
89
90     for (int j = 2; ~j; j--)
91         for (int i = 0; i < n + m - 1; i++)
92             ans[i] = ((long long)ans[i] * base + (long
93                 long)(c[j][i].a + 0.5)) % p;
94             // 实际上就是c[2] * base ^ 2 + c[1] * base + c[0],
95             // 这样写可以改善地址访问连续性
96
97     for (int i = 0; i < n + m - 1; i++) {
98         if (i)
99             printf(" ");

```

```

1 // 常量和复数类略
2
3 const Complex ima = Complex(0, 1);
4
5 int p, base;
6
7 // FFT略
8
9 void DFT(Complex *a, Complex *b, int n) {
10    static Complex c[maxn];
11
12    for (int i = 0; i < n; i++)
13        c[i] = Complex(a[i].a, b[i].a);
14
15    FFT(c, n, 1);
16
17    for (int i = 0; i < n; i++) {
18        int j = (n - i) & (n - 1);
19
20        a[i] = (c[i] + c[j].conj()) * 0.5;
21        b[i] = (c[i] - c[j].conj()) * -0.5 * ima;
22    }
23
24 void IDFT(Complex *a, Complex *b, int n) {
25    static Complex c[maxn];
26
27    for (int i = 0; i < n; i++)
28        c[i] = a[i] + ima * b[i];
29
30    FFT(c, n, -1);
31

```

```

98     printf("%d", ans[i]);
99 }
100
101 return 0;
102 }
```

1.1.4 多项式操作

```

1 // A为输入, C为输出, n为所需长度且必须是2^k
2 // 多项式求逆, 要求A常数项不为0
3 void get_inv(int *A, int *C, int n) {
4     static int B[maxn];
5
6     memset(C, 0, sizeof(int) * (n * 2));
7     C[0] = qpow(A[0], p - 2); // 一般常数项都是1, 直接赋
8     → 值为1就可以
9
10    for (int k = 2; k ≤ n; k *= 2) {
11        memcpy(B, A, sizeof(int) * k);
12        memset(B + k, 0, sizeof(int) * k);
13
14        NTT(B, k * 2, 1);
15        NTT(C, k * 2, 1);
16
17        for (int i = 0; i < k * 2; i++) {
18            C[i] = (2 - (long long)B[i] * C[i]) % p *
19            → C[i] % p;
20            if (C[i] < 0)
21                C[i] += p;
22
23        NTT(C, k * 2, -1);
24
25        memset(C + k, 0, sizeof(int) * k);
26    }
27
28 // 开根
29 void get_sqrt(int *A, int *C, int n) {
30     static int B[maxn], D[maxn];
31
32     memset(C, 0, sizeof(int) * (n * 2));
33     C[0] = 1; // 如果不是1就要考虑二次剩余
34
35     for (int k = 2; k ≤ n; k *= 2) {
36         memcpy(B, A, sizeof(int) * k);
37         memset(B + k, 0, sizeof(int) * k);
38
39         get_inv(C, D, k);
40
41         NTT(B, k * 2, 1);
42         NTT(D, k * 2, 1);
43
44         for (int i = 0; i < k * 2; i++)
45             B[i] = (long long)B[i] * D[i] % p;
46
47         NTT(B, k * 2, -1);
48
49         for (int i = 0; i < k; i++)
50             C[i] = (long long)(C[i] + B[i]) * inv_2 %
51             → p; // inv_2是2的逆元
52    }
53
54 // 求导
55 void get_derivative(int *A, int *C, int n) {
56     for (int i = 1; i < n; i++)
57         C[i - 1] = (long long)A[i] * i % p;
58 }
```

```

59     C[n - 1] = 0;
60 }
61
62 // 不定积分, 最好预处理逆元
63 void get_integrate(int *A, int *C, int n) {
64     for (int i = 1; i < n; i++)
65         C[i] = (long long)A[i - 1] * qpow(i, p - 2) %
66         → p;
67
68     C[0] = 0; // 不定积分没有常数项
69 }
70
71 // 多项式ln, 要求A常数项不为0
72 void get_ln(int *A, int *C, int n) { // 通常情况下A常数
73     → 项都是1
74     static int B[maxn];
75
76     get_derivative(A, B, n);
77     memset(B + n, 0, sizeof(int) * n);
78
79     get_inv(A, C, n);
80
81     NTT(B, n * 2, 1);
82     NTT(C, n * 2, 1);
83
84     for (int i = 0; i < n * 2; i++)
85         B[i] = (long long)B[i] * C[i] % p;
86
87     NTT(B, n * 2, -1);
88
89     get_integrate(B, C, n);
90 }
91
92 // 多项式exp, 要求A没有常数项
93 // 常数很大且总代码较长, 一般来说最好替换为分治FFT
94 // 分治FFT依据: 设G(x) = exp F(x), 则有
95 // → g_i = ∑_{k=1}^{i-1} f_{i-k} * k * g_k
96 void get_exp(int *A, int *C, int n) {
97     static int B[maxn];
98
99     memset(C, 0, sizeof(int) * (n * 2));
100    C[0] = 1;
101
102    for (int k = 2; k ≤ n; k *= 2) {
103        get_ln(C, B, k);
104
105        for (int i = 0; i < k; i++) {
106            B[i] = A[i] - B[i];
107            if (B[i] < 0)
108                B[i] += p;
109
110        (++B[0]) %= p;
111
112        NTT(B, k * 2, 1);
113        NTT(C, k * 2, 1);
114
115        for (int i = 0; i < k * 2; i++)
116            C[i] = (long long)C[i] * B[i] % p;
117
118        NTT(C, k * 2, -1);
119
120        memset(C + k, 0, sizeof(int) * k);
121    }
122
123 // 多项式k次幂, 在A常数项不为1时需要转化
124 // 常数较大且总代码较长, 在时间要求不高时最好替换为暴力快
125 → 速幂
126 }
```

```

125 void get_pow(int *A, int *C, int n, int k) {
126     static int B[maxn];
127
128     get_ln(A, B, n);
129
130     for (int i = 0; i < n; i++)
131         B[i] = (long long)B[i] * k % p;
132
133     get_exp(B, C, n);
134 }
135
136 // 多项式除法, A / B, 结果输出在C
137 // A的次数为n, B的次数为m
138 void get_div(int *A, int *B, int *C, int n, int m) {
139     static int f[maxn], g[maxn], gi[maxn];
140
141     if (n < m) {
142         memset(C, 0, sizeof(int) * m);
143         return;
144     }
145
146     int N = 1;
147     while (N < (n - m + 1))
148         N *= 2;
149
150     memset(f, 0, sizeof(int) * N * 2);
151     memset(g, 0, sizeof(int) * N * 2);
152     // memset(gi, 0, sizeof(int) * N);
153
154     for (int i = 0; i < n - m + 1; i++)
155         f[i] = A[n - i - 1];
156     for (int i = 0; i < m && i < n - m + 1; i++)
157         g[i] = B[m - i - 1];
158
159     get_inv(g, gi, N);
160
161     for (int i = n - m + 1; i < N; i++)
162         gi[i] = 0;
163
164     NTT(f, N * 2, 1);
165     NTT(gi, N * 2, 1);
166
167     for (int i = 0; i < N * 2; i++)
168         f[i] = (long long)f[i] * gi[i] % p;
169
170     NTT(f, N * 2, -1);
171
172     for (int i = 0; i < n - m + 1; i++)
173         C[i] = f[n - m - i];
174 }
175
176 // 多项式取模, 余数输出到C, 商输出到D
177 void get_mod(int *A, int *B, int *C, int *D, int n, int
178             → m) {
179     static int b[maxn], d[maxn];
180
181     if (n < m) {
182         memcpy(C, A, sizeof(int) * n);
183
184         if (D)
185             memset(D, 0, sizeof(int) * m);
186
187         return;
188     }
189
190     get_div(A, B, d, n, m);
191
192     if (D) { // D是商, 可以选择不要
193         for (int i = 0; i < n - m + 1; i++)
194             D[i] = d[i];
195
196         int N = 1;
197         while (N < n)
198             N *= 2;
199
200         memcpy(b, B, sizeof(int) * m);
201
202         NTT(b, N, 1);
203         NTT(d, N, 1);
204
205         for (int i = 0; i < N; i++)
206             b[i] = (long long)d[i] * b[i] % p;
207
208         NTT(b, N, -1);
209
210         for (int i = 0; i < m - 1; i++)
211             C[i] = (A[i] - b[i] + p) % p;
212
213         memset(b, 0, sizeof(int) * N);
214         memset(d, 0, sizeof(int) * N);
215     }
216
217     // 多点求值要用的数组
218     int q[maxn], ans[maxn]; // q是要代入的各个系数, ans是求
219     → 出的值
220     int tg[25][maxn * 2], tf[25][maxn]; // 辅助数组, tg是预
221     → 处理乘积
222     // tf是项数越来越少的f, tf[0]就是原来的函数
223     void pretreat(int l, int r, int k) { // 多点求值预处理
224         static int A[maxn], B[maxn];
225
226         int *g = tg[k] + l * 2;
227
228         if (r - l + 1 ≤ 200) { // 小范围暴力, 能跑得快点
229             g[0] = 1;
230
231             for (int i = l; i ≤ r; i++) {
232                 for (int j = i - l + 1; j; j--) {
233                     g[j] = (g[j - 1] - (long long)g[j] *
234                         → q[i]) % p;
235                     if (g[j] < 0)
236                         g[j] += p;
237                 }
238             }
239             g[0] = (long long)g[0] * (p - q[i]) % p;
240
241             return;
242         }
243
244         int mid = (l + r) / 2;
245
246         pretreat(l, mid, k + 1);
247         pretreat(mid + 1, r, k + 1);
248
249         if (!k)
250             return;
251
252         int N = 1;
253         while (N ≤ r - l + 1)
254             N *= 2;
255
256         int *gl = tg[k + 1] + l * 2, *gr = tg[k + 1] + (mid
257             → + 1) * 2;
258
259         memset(A, 0, sizeof(int) * N);
260         memset(B, 0, sizeof(int) * N);

```

```

259 memcpy(A, gl, sizeof(int) * (mid - l + 2));
260 memcpy(B, gr, sizeof(int) * (r - mid + 1));
261
262 NTT(A, N, 1);
263 NTT(B, N, 1);
264
265 for (int i = 0; i < N; i++)
266     A[i] = (long long)A[i] * B[i] % p;
267
268 NTT(A, N, -1);
269
270 for (int i = 0; i <= r - l + 1; i++)
271     g[i] = A[i];
272
273
274 void solve(int l, int r, int k) { // 多项式多点求值主过
→ 程
    int *f = tf[k];
276
277 if (r - l + 1 <= 200) {
278     for (int i = l; i <= r; i++) {
279         int x = q[i];
280
281         for (int j = r - l; ~j; j--) {
282             ans[i] = ((long long)ans[i] * x + f[j])
→ % p;
283         }
284
285         return;
286     }
287
288     int mid = (l + r) / 2;
289     int *ff = tf[k + 1], *gl = tg[k + 1] + l * 2, *gr =
→ tg[k + 1] + (mid + 1) * 2;
290
291     get_mod(f, gl, ff, nullptr, r - l + 1, mid - l +
→ 2);
292     solve(l, mid, k + 1);
293
294     memset(gl, 0, sizeof(int) * (mid - l + 2));
295     memset(ff, 0, sizeof(int) * (mid - l + 1));
296
297     get_mod(f, gr, ff, nullptr, r - l + 1, r - mid +
→ 1);
298     solve(mid + 1, r, k + 1);
299
300     memset(gr, 0, sizeof(int) * (r - mid + 1));
301     memset(ff, 0, sizeof(int) * (r - mid));
302 }
303
304 // f < x^n, m个询问, 询问是0-based, 当然改成1-based也很
→ 简单
305 void get_value(int *f, int *x, int *a, int n, int m) {
306     if (m <= n)
307         m = n + 1;
308     if (n < m - 1)
309         n = m - 1; // 补零方便处理
310
311     memcpy(tf[0], f, sizeof(int) * n);
312     memcpy(q, x, sizeof(int) * m);
313
314     pretreat(0, m - 1, 0);
315     solve(0, m - 1, 0);
316
317     if (a) // 如果a是nullptr, 代表不复制答案, 直接
→ 用ans数组
            memcpy(a, ans, sizeof(int) * m);
318 }
319

```

1.1.5 更优秀的多项式多点求值

这个做法不需要写取模, 求逆也只有一次, 但是神乎其技, 完全搞不懂原理.

清空和复制之类的地方容易抄错, 抄的时候要注意.

```

1 int q[maxn], ans[maxn]; // q是要代入的各个系数, ans是求
→ 出的值
2 int tg[25][maxn * 2], tf[25][maxn]; // 辅助数组, tg是预
→ 处理乘积,
3 // tf是项数越来越少的f, tf[0]就是原来的函数
4
5 void pretreat(int l, int r, int k) { // 预处理
6     static int A[maxn], B[maxn];
7
8     int *g = tg[k] + l * 2;
9
10    if (r - l + 1 <= 1) { // 小范围暴力
11        g[0] = 1;
12
13        for (int i = l; i <= r; i++) {
14            for (int j = i - l + 1; j; j--) {
15                g[j] = (g[j - 1] - (long long)g[j] *
→ q[i]) % p;
16                if (g[j] < 0)
17                    g[j] += p;
18            }
19            g[0] = (long long)g[0] * (p - q[i]) % p;
20        }
21
22        reverse(g, g + r - l + 2);
23
24        return;
25    }
26
27    int mid = (l + r) / 2;
28
29    pretreat(l, mid, k + 1);
30    pretreat(mid + 1, r, k + 1);
31
32    int N = 1;
33    while (N <= r - l + 1)
34        N *= 2;
35
36    int *gl = tg[k + 1] + l * 2, *gr = tg[k + 1] + (mid
→ + 1) * 2;
37
38    memset(A, 0, sizeof(int) * N);
39    memset(B, 0, sizeof(int) * N);
40
41    memcpy(A, gl, sizeof(int) * (mid - l + 2));
42    memcpy(B, gr, sizeof(int) * (r - mid + 1));
43
44    NTT(A, N, 1);
45    NTT(B, N, 1);
46
47    for (int i = 0; i < N; i++)
48        A[i] = (long long)A[i] * B[i] % p;
49
50    NTT(A, N, -1);
51
52    for (int i = 0; i <= r - l + 1; i++)
53        g[i] = A[i];
54
55
56 void solve(int l, int r, int k) { // 主过程
57     static int a[maxn], b[maxn];
58
59     int *f = tf[k];
60

```

```

61 if (l == r) {
62     ans[l] = f[0];
63     return;
64 }
65
66 int mid = (l + r) / 2;
67 int *ff = tf[k + 1], *gl = tg[k + 1] + l * 2, *gr =
68     → tg[k + 1] + (mid + 1) * 2;
69
70 int N = 1;
71 while (N < r - l + 2)
72     N *= 2;
73
74 memcpy(a, f, sizeof(int) * (r - l + 2));
75 memcpy(b, gr, sizeof(int) * (r - mid + 1));
76 reverse(b, b + r - mid + 1);
77
78 NTT(a, N, 1);
79 NTT(b, N, 1);
80 for (int i = 0; i < N; i++)
81     b[i] = (long long)a[i] * b[i] % p;
82
83 reverse(b + 1, b + N);
84 NTT(b, N, 1);
85 int n_inv = qpow(N, p - 2);
86 for (int i = 0; i < N; i++)
87     b[i] = (long long)b[i] * n_inv % p;
88
89 for (int i = 0; i < mid - l + 2; i++)
90     ff[i] = b[i + r - mid];
91
92 memset(a, 0, sizeof(int) * N);
93 memset(b, 0, sizeof(int) * N);
94
95 solve(l, mid, k + 1);
96
97 memset(ff, 0, sizeof(int) * (mid - l + 2));
98
99 memcpy(a, f, sizeof(int) * (r - l + 2));
100 memcpy(b, gl, sizeof(int) * (mid - l + 2));
101 reverse(b, b + mid - l + 2);
102
103 NTT(a, N, 1);
104 NTT(b, N, 1);
105 for (int i = 0; i < N; i++)
106     b[i] = (long long)a[i] * b[i] % p;
107
108 reverse(b + 1, b + N);
109 NTT(b, N, 1);
110 for (int i = 0; i < N; i++)
111     b[i] = (long long)b[i] * n_inv % p;
112
113 for (int i = 0; i < r - mid + 1; i++)
114     ff[i] = b[i + mid - l + 1];
115
116 memset(a, 0, sizeof(int) * N);
117 memset(b, 0, sizeof(int) * N);
118
119 solve(mid + 1, r, k + 1);
120
121 memset(gl, 0, sizeof(int) * (mid - l + 2));
122 memset(gr, 0, sizeof(int) * (r - mid + 1));
123 memset(ff, 0, sizeof(int) * (r - mid + 1));
124
125 // f < x^n, m个询问, 0-based
126 void get_value(int *f, int *x, int *a, int n, int m) {
127     static int c[maxn], d[maxn];
128 }
```

```

129 if (m ≤ n)
130     m = n + 1;
131 if (n < m - 1)
132     n = m - 1; // 补零
133
134 memcpy(q, x, sizeof(int) * m);
135 pretreat(0, m - 1, 0);
136
137 int N = 1;
138 while (N < m)
139     N *= 2;
140
141 get_inv(tg[0], c, N);
142
143 fill(c + m, c + N, 0);
144 reverse(c, c + m);
145
146 memcpy(d, f, sizeof(int) * m);
147
148 NTT(c, N * 2, 1);
149 NTT(d, N * 2, 1);
150 for (int i = 0; i < N * 2; i++)
151     c[i] = (long long)c[i] * d[i] % p;
152 NTT(c, N * 2, -1);
153
154 for (int i = 0; i < m; i++)
155     tf[0][i] = c[i + n];
156
157 solve(0, m - 1, 0);
158
159 if (a) // 如果a是nullptr, 代表不复制答案, 直接
160     → 用ans数组
161     memcpy(a, ans, sizeof(int) * m);
162 }
```

1.1.6 多项式快速插值

问题: 给出 n 个 x_i 与 y_i , 求一个 $n-1$ 次多项式满足 $F(x_i) = y_i$. 考虑拉格朗日插值:

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

第一步要先对每个 i 求出

$$\prod_{i \neq j} (x_i - x_j)$$

设

$$M(x) = \prod_{i=1}^n (x - x_i)$$

那么想要的是

$$\frac{M(x)}{x - x_i}$$

取 $x = x_i$ 时, 上下都为0, 使用洛必达法则, 则原式化为 $M'(x)$. 使用分治算出 $M(x)$, 使用多点求值即可算出每个

$$\prod_{i \neq j} (x_i - x_j) = M'(x_i)$$

设

$$v_i = \frac{y_i}{\prod_{i \neq j} (x_i - x_j)}$$

第二步要求出

$$\sum_{i=1}^n v_i \prod_{i \neq j} (x - x_j)$$

使用分治. 设

$$L(x) = \prod_{i=1}^{\lfloor n/2 \rfloor} (x - x_i), R(x) = \prod_{i=\lfloor n/2 \rfloor + 1}^n (x - x_i)$$

则原式化为

$$\left(\sum_{i=1}^{\lfloor n/2 \rfloor} v_i \prod_{i \neq j, j \leq \lfloor n/2 \rfloor} (x - x_j) \right) R(x) + \\ \left(\sum_{i=\lfloor n/2 \rfloor + 1}^n v_i \prod_{i \neq j, j > \lfloor n/2 \rfloor} (x - x_j) \right) L(x)$$

递归计算, 复杂度 $O(n \log^2 n)$.

注意由于整体和局部的 $M(x)$ 都要用到, 要预处理一下.

```

1 int qx[maxn], qy[maxn];
2 int th[25][maxn * 2], ansf[maxn]; // th存的是各阶段
   ↪ 的M(x)
3
4 void pretreat2(int l, int r, int k) { // 预处理
5     static int A[maxn], B[maxn];
6     int *h = th[k] + l * 2;
7
8     if (l == r) {
9         h[0] = p - qx[l];
10    h[1] = 1;
11    return;
12 }
13
14     int mid = (l + r) / 2;
15
16     pretreat2(l, mid, k + 1);
17     pretreat2(mid + 1, r, k + 1);
18
19     int N = 1;
20     while (N <= r - l + 1)
21         N *= 2;
22
23     int *hl = th[k + 1] + l * 2, *hr = th[k + 1] + (mid
   ↪ + 1) * 2;
24
25     memset(A, 0, sizeof(int) * N);
26     memset(B, 0, sizeof(int) * N);
27
28     memcpy(A, hl, sizeof(int) * (mid - l + 2));
29     memcpy(B, hr, sizeof(int) * (r - mid + 1));
30
31     NTT(A, N, 1);
32     NTT(B, N, 1);
33
34     for (int i = 0; i < N; i++)
35         A[i] = (long long)A[i] * B[i] % p;
36
37     NTT(A, N, -1);
38
39     for (int i = 0; i <= r - l + 1; i++)
40         h[i] = A[i];
41 }
42
43 void solve2(int l, int r, int k) { // 分治
44     static int A[maxn], B[maxn], t[maxn];
45
46     if (l == r)
47         return;
48
49     int mid = (l + r) / 2;
50
51     solve2(l, mid, k + 1);
52     solve2(mid + 1, r, k + 1);
53
54     int *hl = th[k + 1] + l * 2, *hr = th[k + 1] + (mid
   ↪ + 1) * 2;
55
56     int N = 1;
57
58     while (N < r - l + 1)
59         N *= 2;
60
61     memset(A, 0, sizeof(int) * N);
62     memset(B, 0, sizeof(int) * N);
63
64     memcpy(A, ansf + l, sizeof(int) * (mid - l + 1));
65     memcpy(B, hr, sizeof(int) * (r - mid + 1));
66
67     NTT(A, N, 1);
68     NTT(B, N, 1);
69
70     for (int i = 0; i < N; i++)
71         t[i] = (long long)A[i] * B[i] % p;
72
73     memset(A, 0, sizeof(int) * N);
74     memset(B, 0, sizeof(int) * N);
75
76     memcpy(A, ansf + mid + 1, sizeof(int) * (r - mid));
77     memcpy(B, hl, sizeof(int) * (mid - l + 2));
78
79     NTT(A, N, 1);
80     NTT(B, N, 1);
81
82     for (int i = 0; i < N; i++)
83         t[i] = (t[i] + (long long)A[i] * B[i]) % p;
84
85     NTT(t, N, -1);
86
87     memcpy(ansf + l, t, sizeof(int) * (r - l + 1));
88 }
89
90 // 主过程
91 // 如果x, y传nullptr表示询问已经存在了qx, qy里
92 void interpolation(int *x, int *y, int n, int *f =
   ↪ nullptr) {
93     static int d[maxn];
94
95     if (x)
96         memcpy(qx, x, sizeof(int) * n);
97     if (y)
98         memcpy(qy, y, sizeof(int) * n);
99
100    pretreat2(0, n - 1, 0);
101
102    get_derivative(th[0], d, n + 1);
103
104    multipoint_eval(d, qx, nullptr, n, n);
105
106    for (int i = 0; i < n; i++)
107        ansf[i] = (long long)qy[i] * qpow(ans[i], p -
   ↪ 2) % p;
108
109    solve2(0, n - 1, 0);
110
111    if (f)
112        memcpy(f, ansf, sizeof(int) * n);
113 }
```

1.1.7 拉格朗日反演(多项式复合逆)

如果 $f(x)$ 与 $g(x)$ 互为复合逆, 则有

$$[x^n] g(x) = \frac{1}{n} [x^{n-1}] \left(\frac{x}{f(x)}\right)^n$$

$$[x^n] h(g(x)) = \frac{1}{n} [x^{n-1}] h'(x) \left(\frac{x}{f(x)}\right)^n$$

1.1.8 分治FFT

```

1 void solve(int l, int r) {
2     if (l == r)
3         return;
4
5     int mid = (l + r) / 2;
6
7     solve(l, mid);
8
9     int N = 1;
10    while (N <= r - l + 1)
11        N *= 2;
12
13    for (int i = l; i <= mid; i++)
14        B[i - l] = (long long)A[i] * fac_inv[i] % p;
15    fill(B + mid - l + 1, B + N, 0);
16    for (int i = 0; i < N; i++)
17        C[i] = fac_inv[i];
18
19    NTT(B, N, 1);
20    NTT(C, N, 1);
21
22    for (int i = 0; i < N; i++)
23        B[i] = (long long)B[i] * C[i] % p;
24
25    NTT(B, N, -1);
26
27    for (int i = mid + 1; i <= r; i++)
28        A[i] = (A[i] + B[i - l] * 2 % p * (long
29            → long)fac[i] % p) % p;
30
31    solve(mid + 1, r);
32 }
```

1.1.9 半在线卷积

```

1 void solve(int l, int r) {
2     if (r <= m)
3         return;
4
5     if (r - l == 1) {
6         if (l == m)
7             f[l] = a[m];
8         else
9             f[l] = (long long)f[l] * inv[l - m] % p;
10
11     for (int i = l, t = (long long)l * f[l] % p; i
12         → <= n; i += l)
13         g[i] = (g[i] + t) % p;
14
15     return;
16 }
17
18     int mid = (l + r) / 2;
19
20     solve(l, mid);
21
22     if (l == 0) {
23         for (int i = 1; i < mid; i++) {
24             A[i] = f[i];
25 }
```

```

24         B[i] = (c[i] + g[i]) % p;
25     }
26     NTT(A, r, 1);
27     NTT(B, r, 1);
28     for (int i = 0; i < r; i++)
29         A[i] = (long long)A[i] * B[i] % p;
30     NTT(A, r, -1);
31
32     for (int i = mid; i < r; i++)
33         f[i] = (f[i] + A[i]) % p;
34 }
35 else {
36     for (int i = 0; i < r - l; i++)
37         A[i] = f[i];
38     for (int i = l; i < mid; i++)
39         B[i - l] = (c[i] + g[i]) % p;
40     NTT(A, r - l, 1);
41     NTT(B, r - l, 1);
42     for (int i = 0; i < r - l; i++)
43         A[i] = (long long)A[i] * B[i] % p;
44     NTT(A, r - l, -1);
45
46     for (int i = mid; i < r; i++)
47         f[i] = (f[i] + A[i - l]) % p;
48
49     memset(A, 0, sizeof(int) * (r - l));
50     memset(B, 0, sizeof(int) * (r - l));
51
52     for (int i = l; i < mid; i++)
53         A[i - l] = f[i];
54     for (int i = 0; i < r - l; i++)
55         B[i] = (c[i] + g[i]) % p;
56     NTT(A, r - l, 1);
57     NTT(B, r - l, 1);
58     for (int i = 0; i < r - l; i++)
59         A[i] = (long long)A[i] * B[i] % p;
60     NTT(A, r - l, -1);
61
62     for (int i = mid; i < r; i++)
63         f[i] = (f[i] + A[i - l]) % p;
64 }
65
66 memset(A, 0, sizeof(int) * (r - l));
67 memset(B, 0, sizeof(int) * (r - l));
68
69 solve(mid, r);
70 }
```

1.1.10 常系数齐次线性递推 $O(k \log k \log n)$

如果只有一次这个操作可以照抄, 否则就开一个全局flag.

```

1 // 多项式取模, 余数输出到C, 商输出到D
2 void get_mod(int *A, int *B, int *C, int *D, int n, int
3 → m) {
4     static int b[maxn], d[maxn];
5     static bool flag = false;
6
7     if (n < m) {
8         memcpy(C, A, sizeof(int) * n);
9
10     if (D)
11         memset(D, 0, sizeof(int) * m);
12
13     return;
14 }
15
16     get_div(A, B, d, n, m);
17 }
```

```

17 if (D) { // D是商, 可以选择不要
18     for (int i = 0; i < n - m + 1; i++)
19         D[i] = d[i];
20 }
21
22 int N = 1;
23 while (N < n)
24     N *= 2;
25
26 if (!flag) {
27     memcpy(b, B, sizeof(int) * m);
28     NTT(b, N, 1);
29
30     flag = true;
31 }
32
33 NTT(d, N, 1);
34
35 for (int i = 0; i < N; i++)
36     d[i] = (long long)d[i] * b[i] % p;
37
38 NTT(d, N, -1);
39
40 for (int i = 0; i < m - 1; i++)
41     C[i] = (A[i] - d[i] + p) % p;
42
43 // memset(b, 0, sizeof(int) * N);
44 memset(d, 0, sizeof(int) * N);
45 }
46
47 // g < x^n, f是输出答案的数组
48 void pow_mod(long long k, int *g, int n, int *f) {
49     static int a[maxn], t[maxn];
50
51     memset(f, 0, sizeof(int) * (n * 2));
52
53     f[0] = a[1] = 1;
54
55     int N = 1;
56     while (N < n * 2 - 1)
57         N *= 2;
58
59     while (k) {
60         NTT(a, N, 1);
61
62         if (k & 1) {
63             memcpy(t, f, sizeof(int) * N);
64
65             NTT(t, N, 1);
66             for (int i = 0; i < N; i++)
67                 t[i] = (long long)t[i] * a[i] % p;
68             NTT(t, N, -1);
69
70             get_mod(t, g, f, NULL, n * 2 - 1, n);
71         }
72
73         for (int i = 0; i < N; i++)
74             a[i] = (long long)a[i] * a[i] % p;
75     NTT(a, N, -1);
76
77     memcpy(t, a, sizeof(int) * (n * 2 - 1));
78     get_mod(t, g, a, NULL, n * 2 - 1, n);
79     fill(a + n - 1, a + N, 0);
80
81     k >>= 1;
82 }
83
84 memset(a, 0, sizeof(int) * (n * 2));
85 }

```

```

87 // f_n = \sum_{i=1}^m f_{n-i} a_i
88 // f是0~m-1项的初值
89 int linear_recurrence(long long n, int m, int *f, int
90    ↪ *a) {
91     static int g[maxn], c[maxn];
92
93     memset(g, 0, sizeof(int) * (m * 2 + 1));
94
95     for (int i = 0; i < m; i++)
96         g[i] = (p - a[m - i]) % p;
97     g[m] = 1;
98
99     pow_mod(n, g, m + 1, c);
100
101    int ans = 0;
102    for (int i = 0; i < m; i++)
103        ans = (ans + (long long)c[i] * f[i]) % p;
104
105    return ans;
}

```

1.1.11 应用: $O(\sqrt{n} \log^2 n)$ 快速求阶乘

问题: 求 $n! \pmod{p}$, $n < p$, p 是NTT模数.

考虑令 $m = \lfloor \sqrt{n} \rfloor$, 那么我们可以写出连续 m 个数相乘的多项式:

$$f(x) = \prod_{i=1}^m (x + i)$$

那么显然就有

$$n! = \left(\prod_{k=0}^{m-1} f(km) \right) \prod_{i=m^2+1}^n i$$

$f(x)$ 的系数可以用倍增求(或者懒一点直接分治FFT), 然后 $f(km)$ 可以用多项式多点求值求出, 所以总复杂度就是 $O(\sqrt{n} \log^2 n)$.

当然如果 p 不变并且多次询问的话我们只需要取一个 m , 也就是预处理 $O(\sqrt{p} \log^2 p)$, 询问 $O(\sqrt{p})$.

1.2 插值

1.2.1 牛顿插值

牛顿插值的原理是二项式反演.

二项式反演:

$$f(n) = \sum_{k=0}^n \binom{n}{k} g(k) \Leftrightarrow g(n) = \sum_{k=0}^n (-1)^{n-k} \binom{n}{k} f(k)$$

可以用 e^x 和 e^{-x} 的麦克劳林展开式证明.

套用二项式反演的结论即可得到牛顿插值:

$$f(n) = \sum_{i=0}^k \binom{n}{i} r_i$$

$$r_i = \sum_{j=0}^i (-1)^{i-j} \binom{i}{j} f(j)$$

其中 k 表示 $f(n)$ 的最高次项系数.

实现时可以用 k 次差分替代右边的式子:

```

1 for (int i = 0; i ≤ k; i++)
2     r[i] = f(i);
3 for (int j = 0; j < k; j++)
4     for (int i = k; i > j; i--)
5         r[i] -= r[i - 1];

```

注意到预处理 r_i 的式子满足卷积形式,必要时可以用FFT优化至 $O(k \log k)$ 预处理.

1.2.2 拉格朗日(Lagrange)插值

$$f(x) = \sum_i f(x_i) \prod_{j \neq i} \frac{x - x_j}{x_i - x_j}$$

1.3 FWT快速沃尔什变换

```

1 // 注意FWT常数比较小, 这点与FFT/NTT不同
2 // 以下代码均以模质数情况为例, 其中n为变换长度, tp表示
   → 正/逆变换
3
4 // 按位或版本
5 void FWT_or(int *A, int n, int tp) {
6     for (int k = 2; k ≤ n; k *= 2)
7         for (int i = 0; i < n; i += k)
8             for (int j = 0; j < k / 2; j++) {
9                 if (tp > 0)
10                     A[i + j + k / 2] = (A[i + j + k / 2] + A[i + j]) % p;
11                 else
12                     A[i + j + k / 2] = (A[i + j + k / 2] - A[i + j] + p) % p;
13             }
14 }
15
16 // 按位与版本
17 void FWT_and(int *A, int n, int tp) {
18     for (int k = 2; k ≤ n; k *= 2)
19         for (int i = 0; i < n; i += k)
20             for (int j = 0; j < k / 2; j++) {
21                 if (tp > 0)
22                     A[i + j] = (A[i + j] + A[i + j + k / 2]) % p;
23                 else
24                     A[i + j] = (A[i + j] - A[i + j + k / 2] + p) % p;
25             }
26 }
27
28 // 按位异或版本
29 void FWT_xor(int *A, int n, int tp) {
30     for (int k = 2; k ≤ n; k *= 2)
31         for (int i = 0; i < n; i += k)
32             for (int j = 0; j < k / 2; j++) {
33                 int a = A[i + j], b = A[i + j + k / 2];
34                 A[i + j] = (a + b) % p;
35                 A[i + j + k / 2] = (a - b + p) % p;
36             }
37
38     if (tp < 0) {
39         int inv = qpow(n % p, p - 2); // n的逆元, 在不取
           → 模时需要用每层除以2代替
40         for (int i = 0; i < n; i++)
41             A[i] = A[i] * inv % p;
42     }
43 }
```

1.3.1 三行FWT

```

1 void fwt_or(int *a, int n, int tp) {
2     for (int j = 0; (1 << j) < n; j++)
3         for (int i = 0; i < n; i++)
4             if (i > j & 1) {
5                 if (tp > 0)
6                     a[i] += a[i ^ (1 << j)];
7                 else
8                     a[i] -= a[i ^ (1 << j)];
9             }
10 }
```

```

6                     a[i] += a[i ^ (1 << j)];
7                 else
8                     a[i] -= a[i ^ (1 << j)];
9             }
10 }
11
12 // and自然就是or反过来
13 void fwt_and(int *a, int n, int tp) {
14     for (int j = 0; (1 << j) < n; j++)
15         for (int i = 0; i < n; i++)
16             if (!(i > j & 1)) {
17                 if (tp > 0)
18                     a[i] += a[i | (1 << j)];
19                 else
20                     a[i] -= a[i | (1 << j)];
21             }
22 }
23
24 // xor同理
```

1.4 线性代数

稀疏矩阵操作参见Berlekamp-Massey算法的应用(12页).

1.4.1 矩阵乘法

```

1 for (int i = 1; i ≤ n; i++)
2     for (int k = 1; k ≤ n; k++)
3         for (int j = 1; j ≤ n; j++)
4             a[i][j] += b[i][k] * c[k][j];
5 // 通过改善内存访问连续性, 显著提升速度
```

1.4.2 高斯消元

高斯-约当消元法 Gauss-Jordan 每次选取当前行绝对值最大的数作为代表元, 在做浮点数消元时可以很好地保证精度.

```

1 void Gauss_Jordan(int A[][maxn], int n) {
2     for (int i = 1; i ≤ n; i++) {
3         int ii = i;
4         for (int j = i + 1; j ≤ n; j++)
5             if (fabs(A[j][i]) > fabs(A[ii][i]))
6                 ii = j;
7
8         if (ii != i) // 这里没有判是否无解, 如果有可能无
           → 解的话要判一下
9             for (int j = i; j ≤ n + 1; j++)
10                 swap(A[i][j], A[ii][j]);
11
12         for (int j = 1; j ≤ n; j++)
13             if (j != i) // 消成对角
14                 for (int k = n + 1; k ≥ i; k--)
15                     A[j][k] -= A[j][i] / A[i][i] * A[i]
           → [k];
16     }
17 }
```

解线性方程组 在矩阵的右边加上一列表示系数即可, 如果消成上三角的话最后要倒序回代.

求逆矩阵 维护一个矩阵 B , 初始设为 n 阶单位矩阵, 在消元的同时对 B 进行一样的操作, 当把 A 消成单位矩阵时 B 就是逆矩阵.

行列式 消成对角之后把代表元乘起来. 如果是任意模数, 要注意消元时每交换一次行列要取反一次.


```

34 }
35
36 int calc(long long k) {
37     int n = (int)first.size();
38
39     vector<int> a(n + 1);
40     a[0] = 1;
41
42     for (int i = 0; i < 64; i++)
43         if (k > i & 1)
44             a = multi(a, bin[i]);
45
46     int ans = 0;
47     for (int i = 0; i < n; i++)
48         ans = (ans + (long long)a[i + 1] *
49             → first[i]) % p;
50
51     return ans;
52 }

```

1.6 Berlekamp-Massey最小递推式

如果要求出一个次数为 k 的递推式，则输入的数列需要至少有 $2k$ 项。返回的内容满足 $\sum_{j=0}^{m-1} a_{i-j}c_j = 0$ ，并且 $c_0 = 1$ 。称为最小递推式。如果不加最后的处理的话，代码返回的结果会变成 $a_i = \sum_{j=0}^{m-1} c_{j-1}a_{i-j}$ ，有时候这样会方便接着跑递推，需要的话就删掉最后的处理。
(实际上Berlekamp-Massey是对每个前缀都求出了递推式，但一般没啥用。)

```

1 vector<int> berlekamp_massey(const vector<int> &a) {
2     vector<int> v, last; // v is the answer, 0-based
3     int k = -1, delta = 0;
4
5     for (int i = 0; i < (int)a.size(); i++) {
6
7         int tmp = 0;
8         for (int j = 0; j < (int)v.size(); j++)
9             tmp = (tmp + (long long)a[i - j - 1] *
10                → v[j]) % p;
11
12         if (a[i] == tmp)
13             continue;
14
15         if (k < 0) {
16             k = i;
17             delta = (a[i] - tmp + p) % p;
18             v = vector<int>(i + 1);
19
20             continue;
21         }
22
23         vector<int> u = v;
24         int val = (long long)(a[i] - tmp + p) *
25             → qpow(delta, p - 2) % p;
26
27         if (v.size() < last.size() + i - k)
28             v.resize(last.size() + i - k);
29
30         (v[i - k - 1] += val) %= p;
31
32         for (int j = 0; j < (int)last.size(); j++) {
33             v[i - k + j] = (v[i - k + j] - (long
34                 → long)val * last[j]) % p;
35             if (v[i - k + j] < 0)
36                 v[i - k + j] += p;
37         }
38     }
39
40     return v;
41 }

```

```

36     if ((int)u.size() - i < (int)last.size() - k) {
37         last = u;
38         k = i;
39         delta = a[i] - tmp;
40         if (delta < 0)
41             delta += p;
42     }
43
44     for (auto &x : v) // 一般是需要最小递推式的，所以处理
45         →一下
46         x = (p - x) % p;
47     v.insert(v.begin(), 1);
48
49     return v; // ∀i, ∑_{j=0}^m a_{i-j}v_j = 0
50 }

```

如果要求向量序列的递推式，就把每位乘一个随机权值(或者说是乘一个随机行向量 v^T)变成求数列递推式即可。

如果是矩阵序列的话就随机一个行向量 u^T 和列向量 v ，然后把矩阵变成 $u^T A v$ 的数列就行了。

1.6.1 优化矩阵快速幂DP

如果 f_i 是一个向量，并且转移是一个矩阵，那显然 $\{f_i\}$ 是一个线性递推序列。

假设 f_i 有 n 维，先暴力求出 f_{0-2n-1} ，然后跑Berlekamp-Massey，最后调用前面的快速齐次线性递推(8页)即可。(快速齐次线性递推的结果是一个序列，某个给定初值的结果就是点乘，所以只需要跑一次。)

如果要求 f_m ，并且矩阵有 k 个非零项的话，复杂度就是 $O(nk + n \log m \log n)$ 。(因为暴力求前 $2n - 1$ 个 f_i 需要 $O(nk)$ 时间。)

1.6.2 求矩阵最小多项式

矩阵 A 的最小多项式是次数最小的并且 $f(A) = 0$ 的多项式 f 。

实际上最小多项式就是 $\{A^i\}$ 的最小递推式，所以直接调用Berlekamp-Massey就好了，并且显然它的次数不超过 n 。

瓶颈在于求出 A^i ，实际上我们只要处理 $A^i v$ 就行了，每次对向量做递推。

假设 A 有 k 个非零项，则复杂度为 $O(kn + n^2)$ 。

1.6.3 求稀疏矩阵的行列式

如果能求出特征多项式，则常数项乘上 $(-1)^n$ 就是行列式，但是最小多项式不一定就是特征多项式。

把 A 乘上一个随机对角阵 B (实际上就是每行分别乘一个随机数)，则 AB 的最小多项式有很大概率就是特征多项式，最后再除掉 $\det B$ 就行了。

设 A 有 k 个非零项，则复杂度为 $O(kn + n^2)$ 。

1.6.4 求稀疏矩阵的秩

设 A 是一个 $n \times m$ 的矩阵，首先随机一个 $n \times n$ 的对角阵 P 和一个 $m \times m$ 的对角阵 Q ，然后计算 $QAP^{-1}Q^T$ 的最小多项式即可。

实际上不用计算这个矩阵，因为求最小多项式时要用它乘一个向量，我们依次把这几个矩阵乘到向量里就行了。答案就是最小多项式除掉所有 x 因子后剩下的次数。

设 A 有 k 个非零项，复杂度为 $O(kn + n^2)$ 。

1.6.5 解稀疏方程组

问题 $Ax = b$ ，其中 A 是一个 $n \times n$ 的满秩稀疏矩阵， b 和 x 是 $1 \times n$ 的列向量， A, b 已知，需要解出 x 。

做法 显然 $x = A^{-1}b$. 如果我们能求出 $\{A^i b\}$ ($i \geq 0$) 的最小递推式 $\{r_{0 \sim m-1}\}$ ($m \leq n$), 那么就有结论

$$A^{-1}b = -\frac{1}{r_{m-1}} \sum_{i=0}^{m-2} A^i b r_{m-2-i}$$

因为 A 是稀疏矩阵, 直接按定义递推出 $b \sim A^{2n-1}b$ 即可. 设 A 中有 k 个非零项, 则复杂度为 $O(kn + n^2)$.

```

1 vector<int> solve_sparse_equations(const
2   → vector<tuple<int, int, int>> &A, const vector<int>
3   → &b) {
4     int n = (int)b.size(); // 0-based
5
6     vector<vector<int>> f({b});
7
8     for (int i = 1; i < 2 * n; i++) {
9       vector<int> v(n);
10      auto &u = f.back();
11
12      for (auto [x, y, z] : A) // [x, y, value]
13        v[x] = (v[x] + (long long)u[y] * z) % p;
14
15      f.push_back(v);
16
17     vector<int> w(n);
18     mt19937 gen;
19     for (auto &x : w)
20       x = uniform_int_distribution<int>(1, p - 1)
21         → (gen);
22
23     vector<int> a(2 * n);
24     for (int i = 0; i < 2 * n; i++)
25       for (int j = 0; j < n; j++)
26         a[i] = (a[i] + (long long)f[i][j] * w[j]) %
27           → p;
28
29     auto c = berlekamp_massey(a);
30     int m = (int)c.size();
31
32     vector<int> ans(n);
33
34     for (int i = 0; i < m - 1; i++)
35       for (int j = 0; j < n; j++)
36         ans[j] = (ans[j] + (long long)c[m - 2 - i]
37           → * f[i][j]) % p;
38
39     int inv = qpow(p - c[m - 1], p - 2);
40
41     for (int i = 0; i < n; i++)
42       ans[i] = (long long)ans[i] * inv % p;
43
44     return ans;
45 }
```

```

12   id[i] = i;
13
14 }
15
16 for (int i = 1; i ≤ m; i++) {
17   for (int j = 1; j ≤ n; j++)
18     scanf("%lf", &A[i][j]);
19
20   scanf("%lf", &A[i][0]);
21 }
22
23 if (!initialize())
24   printf("Infeasible"); // 无解
25 else if (!simplex())
26   printf("Unbounded"); // 最优解无限大
27
28 else {
29   printf("%.15lf\n", -A[0][0]);
30   if (t) {
31     for (int i = 1; i ≤ m; i++)
32       x[id[i + n]] = A[i][0];
33     for (int i = 1; i ≤ n; i++)
34       printf("%.15lf ", x[i]);
35   }
36   return 0;
37 }
38
39 // 初始化
40 // 对于初始解可行的问题, 可以把初始化省略掉
41 bool initialize() {
42   while (true) {
43     double t = 0.0;
44     int l = 0, e = 0;
45
46     for (int i = 1; i ≤ m; i++)
47       if (A[i][0] + eps < t) {
48         t = A[i][0];
49         l = i;
50     }
51
52     if (!l)
53       return true;
54
55     for (int i = 1; i ≤ n; i++)
56       if (A[l][i] < -eps && (!e || id[i] <
57         → id[e]))
58         e = i;
59
60     if (!e)
61       return false;
62
63     pivot(l, e);
64 }
65
66 // 求解
67 bool simplex() {
68   while (true) {
69     int l = 0, e = 0;
70     for (int i = 1; i ≤ n; i++)
71       if (A[0][i] > eps && (!e || id[i] < id[e]))
72         e = i;
73
74     if (!e)
75       return true;
76
77     double t = 1e50;
78     for (int i = 1; i ≤ m; i++)
79       if (A[i][e] > eps && A[i][0] / A[i][e] < t)
80         → {
```

1.7 单纯形

```

1 const double eps = 1e-10;
2
3 double A[maxn][maxn], x[maxn];
4 int n, m, t, id[maxn * 2];
5
6 // 方便起见, 这里附上主函数
7 int main() {
8   scanf("%d%d%d", &n, &m, &t);
9
10  for (int i = 1; i ≤ n; i++) {
11    scanf("%lf", &A[0][i]);
```

```

80     l = i;
81     t = A[i][0]/A[i][e];
82 }
83
84 if (!l)
85   return false;
86
87 pivot(l, e);
88 }
89
90 //转轴操作,本质是在凸包上沿着一条棱移动
91 void pivot(int l, int e) {
92   swap(id[e], id[n + l]);
93   double t = A[l][e];
94   A[l][e] = 1.0;
95
96   for (int i = 0; i <= n; i++)
97     A[l][i] /= t;
98
99   for (int i = 0; i <= m; i++)
100    if (i != l) {
101      t = A[i][e];
102      A[i][e] = 0.0;
103      for (int j = 0; j <= n; j++)
104        A[i][j] -= t * A[l][j];
105    }
106 }
107

```

1.7.1 线性规划对偶原理

给定一个原始线性规划:

$$\begin{aligned} \text{Minimize} \quad & \sum_{j=1}^n c_j x_j \\ \text{Subject to} \quad & \sum_{j=1}^n a_{ij} x_j \geq b_i, \\ & x_j \geq 0 \end{aligned}$$

定义它的对偶线性规划为:

$$\begin{aligned} \text{Maximize} \quad & \sum_{i=1}^m b_i y_i \\ \text{Subject to} \quad & \sum_{i=1}^m a_{ij} y_i \leq c_j, \\ & y_i \geq 0 \end{aligned}$$

用矩阵可以更形象地表示为:

$$\begin{array}{ll} \text{Minimize} & \mathbf{c}^T \mathbf{x} \\ \text{Subject to} & A\mathbf{x} \geq \mathbf{b}, \quad \Leftrightarrow \quad \text{Subject to} \quad A^T \mathbf{y} \leq \mathbf{c}, \\ & \mathbf{x} \geq 0 \quad \quad \quad \mathbf{y} \geq 0 \end{array}$$

1.8 博弈论

1.8.1 SG定理

对于一个平等游戏, 可以为每个状态定义一个SG函数。一个状态的SG函数等于所有它能一步到达的状态的SG函数的mex, 也就是最小的没有出现过的自然数。那么所有先手必败态的SG函数为0, 先手必胜态的SG函数非0。如果有一个游戏, 它由若干个独立的子游戏组成, 且每次行动时只能选一个子游戏进行操作, 则这个游戏的SG函数就是所有子游戏

的SG函数的异或和. (比如最经典的Nim游戏, 每次只能选一堆取若干个石子.) 同时操作多个子游戏的结论参见1.8.3.经典博奕(14页).

1.8.2 纳什均衡

纯策略, 混合策略 纯策略是指你一定会选择某个选项, 混合策略是指你对每个选项都有一个概率分布 p_i , 你会以相应的概率选择这个选项.

考虑这样的游戏: 有几个人(当然也可以是两个)各自独立地做决定, 然后同时公布每个人的决定, 而每个人的收益和所有人的选择有关. 那么纳什均衡就是每个人都决定一个混合策略, 使得在其他人都是纯策略的情况下, 这个人最坏情况下(也就是说其他人的纯策略最针对他的时候)的收益是最大的. 也就是说, 收益函数对这个人的混合策略求一个偏导, 结果是0(因为是极大值).

纳什均衡点可能存在多个, 不过在一个双人零和游戏中, 纳什均衡点一定唯一存在.

1.8.3 经典博奕

1. 阶梯博奕

台阶的每层都有一些石子, 每次可以选一层(但不能是第0层), 把任意个石子移到低一层.

结论 奇数层的石子数量进行异或和即可.

实际上只要路径长度唯一就可以, 比如在树上博奕, 然后石子向根节点方向移动, 那么就是奇数深度的石子数量进行异或和.

2. 可以同时操作多个子游戏

如果某个游戏由若干个独立的子游戏组成, 并且每次可以任意选几个(当然至少一个)子游戏进行操作, 那么结论是: 所有子游戏都必败时先手才会必败, 否则先手必胜.

3. 每次最多操作k个子游戏(Nim-K)

如果每次最多操作 k 个子游戏, 结论是: 把所有子游戏的SG函数写成二进制表示, 如果每一位上的1个数都是 $(k+1)$ 的倍数, 则先手必败, 否则先手必胜.

(实际上上面一条可以看做 $k = \infty$ 的情况, 也就是所有SG值都是0时才会先手必败.)

如果要求整个游戏的SG函数, 就按照上面的方法每个二进制位相加后 $\text{mod}(k+1)$, 视为 $(k+1)$ 进制数后求值即可. (未验证)

4. 反Nim游戏(Anti-Nim)

和Nim游戏差不多, 唯一的不同是取走最后一个石子的输. 分两种情况:

- 所有堆石子个数都是1: 有偶数堆时先手必胜, 否则先手必败.
- 存在某个堆石子数多于1: 异或和不为0则先手必胜, 否则先手必败.

当然石子个数实际上就是SG函数, 所以判别条件全都改成SG函数也是一样的.

5. 威佐夫博奕

有两堆石子, 每次要么从一堆中取任意个, 要么从两堆中都取走相同数量. 也等价于两个人移动一个只能向左上方走的皇后, 不能动的输.

结论 设两堆石子分别有 a 个和 b 个, 且 $a < b$, 则先手必败当且仅当 $a = \left\lfloor (b-a) \frac{1+\sqrt{5}}{2} \right\rfloor$.

6. 删子树博奕

有一棵有根树, 两个人轮流操作, 每次可以选一个点(除了根节点)然后把它的子树都删掉, 不能操作的输.

结论

$$SG(u) = \text{XOR}_{v \in son_u} (SG(v) + 1)$$

7. 无向图游戏

在一个无向图上的某个点上摆一个棋子，两个人轮流把棋子移动到相邻的点，并且每个点只能走一次，不能操作的输。

结论 如果某个点一定在最大匹配中，则先手必胜，否则先手必败。

1.8.4 例题

1. 黑白棋游戏

一些棋子排成一列，棋子两面分别是黑色和白色。两个人轮流行动，每次可以选择一个白色朝上的棋子，把它和它左边的所有棋子都翻转，不能行动的输。

快速倍增法 $F_{2k} = F_k(2F_{k+1} - F_k)$, $F_{2k+1} = F_{k+1}^2 + F_k^2$

```

1 pair<int, int> fib(int n) { // 返回F(n)和F(n + 1)
2     if (n == 0)
3         return {0, 1};
4     auto p = fib(n >> 1);
5     int c = p.first * (2 * p.second - p.first);
6     int d = p.first * p.first + p.second * p.second;
7     if (n & 1)
8         return {d, c + d};
9     else
10        return {c, d};
11 }
```

结论 只需要看最左边的棋子即可，因为每次操作最左边的棋子都一定会被翻转。

二维情况同理，如果每次是把左上角的棋子全部翻转，那么就只需要看左上角的那个棋子。

1.9 自适应Simpson积分

Forked from fstqwq's template.

```

1 // Adaptive Simpson's method : double simpson::solve
2     ↳ (double (*f) (double), double l, double r, double
3         ↳ eps) : integrates f over (l, r) with error eps.
4
5 double area (double (*f) (double), double l, double r)
6     ↳ {
7         double m = l + (r - l) / 2;
8         return (f(l) + 4 * f(m) + f(r)) * (r - l) / 6;
9     }
10
11 double solve (double (*f) (double), double l, double r,
12     ↳ double eps, double a) {
13     double m = l + (r - l) / 2;
14     double left = area(f, l, m), right = area(f, m, r);
15     if (fabs(left + right - a) ≤ 15 * eps)
16         return left + right + (left + right - a) /
17             ↳ 15.0;
18     return solve(f, l, m, eps / 2, left) + solve(f, m,
19             ↳ r, eps / 2, right);
20
21 double solve (double (*f) (double), double l, double r,
22     ↳ double eps) {
23     return solve(f, l, r, eps, area (f, l, r));
24 }
```

1.10 常见数列

查表参见8.15.OEIS(94页)。

1.10.1 斐波那契数 卢卡斯数

斐波那契数 $F_0 = 0, F_1 = 1, F_n = F_{n-1} + F_{n-2}$
 $0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, \dots$

卢卡斯数 $L_0 = 2, L_1 = 1$

$2, 1, 3, 4, 7, 11, 18, 29, 47, 76, 123, 199, \dots$

通项公式 $\phi = \frac{1+\sqrt{5}}{2}, \hat{\phi} = \frac{1-\sqrt{5}}{2}$

$F_n = \frac{\phi^n - \hat{\phi}^n}{\sqrt{5}}, L_n = \phi^n + \hat{\phi}^n$

实际上有 $\frac{L_n + F_n \sqrt{5}}{2} = \left(\frac{1+\sqrt{5}}{2}\right)^n$ ，所以求通项的话写一个类然后快
速幂就可以同时得到两者。

1.10.2 伯努利数，自然数幂次和

指数生成函数: $B(x) = \sum_{i \geq 0} \frac{B_i x^i}{i!} = \frac{x}{e^x - 1}$

$$B_n = [n=0] - \sum_{i=0}^{n-1} \binom{n}{i} \frac{B_i}{n-k+1}$$

$$\sum_{i=0}^n \binom{n+1}{i} B_i = 0$$

$$S_n(m) = \sum_{i=0}^{m-1} i^n = \sum_{i=0}^n \binom{n}{i} B_{n-i} \frac{m^{i+1}}{i+1}$$

$B_0 = 1, B_1 = -\frac{1}{2}, B_4 = -\frac{1}{30}, B_6 = \frac{1}{42}, B_8 = -\frac{1}{30}, \dots$
 (除了 $B_1 = -\frac{1}{2}$ 以外，伯努利数的奇数项都是0.)

自然数幂次和关于次数的EGF:

$$\begin{aligned} F(x) &= \sum_{k=0}^{\infty} \frac{\sum_{i=0}^n i^k}{k!} x^k \\ &= \sum_{i=0}^n e^{ix} \\ &= \frac{e^{(n+1)x-1}}{e^x - 1} \end{aligned}$$

1.10.3 分拆数

```

1 int b = sqrt(n);
2 ans[0] = tmp[0] = 1;
3
4 for (int i = 1; i ≤ b; ++i) {
5     for (int rep = 0; rep < 2; ++rep)
6         for (int j = i; j ≤ n - i * i; ++j)
7             add(tmp[j], tmp[j - i]);
8
9     for (int j = i * i; j ≤ n; ++j)
10        add(ans[j], tmp[j - i * i]);
11
12 // ——————
13
14 long long a[100010];
15 long long p[50005]; // 欧拉五边形数定理
16
17 int main() {
18     p[0] = 1;
19     p[1] = 1;
20     p[2] = 2;
21     int i;
22     for (i = 1; i < 50005; i++) { // 递推式系
23         → 数1, 2, 5, 7, 12, 15, 22, 26 ... i*(3*i-1)/2, i*(3*i+1)/2
24 }
```

```

24     a[2 * i] = i * (i * 3 - 1) / 2; // 五边形数
25     ↳ 为1, 5, 12, 22 ... i*(3*i-1)/2
26     a[2 * i + 1] = i * (i * 3 + 1) / 2;
27 }
28 for (i = 3; i < 50005; i++) { //
29     ↳ p[n]=p[n-1]+p[n-2]-p[n-5]-
30     ↳ p[n-7]+p[12]+p[15]-...+p[n-i*[3i-1]/2]+p[n-
31     ↳ i*[3i+1]/2]
32     p[i] = 0;
33     int j;
34     for (j = 2; a[j] ≤ i; j++) { // 可能为负数, 式
35         ↳ 中加1000007
36         if (j & 2)
37             p[i] = (p[i] + p[i - a[j]] + 1000007) %
38             ↳ 1000007;
39         else
40             p[i] = (p[i] - p[i - a[j]] + 1000007) %
41             ↳ 1000007;
42     }
43     int n;
44     while (~scanf("%d", &n))
45         printf("%lld\n", p[n]);
46 }

```

1.10.4 斯特林数

1. 第一类斯特林数

$[n]_k$ 表示 n 个元素划分成 k 个轮换的方案数.

递推式: $[n]_k = [n-1]_{k-1} + (n-1)[n-1]_k$.

求同一行: 分治FFT $O(n \log^2 n)$, 或者倍增 $O(n \log n)$ (每次都是 $f(x) = g(x)g(x+d)$ 的形式, 可以用 $g(x)$ 反转之后做一个卷积求出后者).

$$\sum_{k=0}^n [n]_k x^k = \prod_{i=0}^{n-1} (x+i)$$

求同一列: 用一个轮换的指数生成函数做 k 次幂

$$\sum_{n=0}^{\infty} [n]_k \frac{x^n}{n!} = \frac{(\ln(1-x))^k}{k!} = \frac{x^k}{k!} \left(\frac{\ln(1-x)}{x} \right)^k$$

2. 第二类斯特林数

$\{n\}_k$ 表示 n 个元素划分成 k 个子集的方案数.

递推式: $\{n\}_k = \{n-1\}_{k-1} + k\{n-1\}_k$.

求一个: 容斥, 狗都会做

$$\{n\}_k = \frac{1}{k!} \sum_{i=0}^k (-1)^i \binom{k}{i} (k-i)^n = \sum_{i=0}^k \frac{(-1)^i}{i!} \frac{(k-i)^n}{(k-i)!}$$

求同一行: FFT, 狗都会做

求同一列: 指数生成函数

$$\sum_{n=0}^{\infty} \{n\}_k \frac{x^n}{n!} = \frac{(e^x - 1)^k}{k!} = \frac{x^k}{k!} \left(\frac{e^x - 1}{x} \right)^k$$

普通生成函数

$$\sum_{n=0}^{\infty} \{n\}_k x^n = x^k \left(\prod_{i=1}^k (1 - ix) \right)^{-1}$$

3. 斯特林反演

$$f(n) = \sum_{k=0}^n \{n\}_k g(k) \iff g(n) = \sum_{k=0}^n (-1)^{n-k} [n]_k f(k)$$

4. 幂的转换

上升幂与普通幂的转换

$$x^{\overline{n}} = \sum_k [n]_k x^k$$

$$x^n = \sum_k \{n\}_k (-1)^{n-k} x^{\bar{k}}$$

下降幂与普通幂的转换

$$x^n = \sum_k \{n\}_k x^k = \sum_k \binom{x}{k} \{n\}_k k!$$

$$x^n = \sum_k [n]_k (-1)^{n-k} x^k$$

另外, 多项式的点值表示的每项除以阶乘之后卷上 e^{-x} 乘上阶乘之后是牛顿插值表示, 或者不乘阶乘就是下降幂系数表示. 反过来的转换当然卷上 e^x 就行了. 原理是每次差分等价于乘以 $(1-x)$, 展开之后用一次卷积取代多次差分.

5. 斯特林多项式(斯特林数关于斜线的性质)

定义:

$$\sigma_n(x) = \frac{[x]}{x(x-1)\dots(x-n)}$$

$\sigma_n(x)$ 的最高次数是 x^{n-1} . (所以作为唯一的特例, $\sigma_0(x) = \frac{1}{x}$ 不是多项式.)

斯特林多项式实际上非常神奇, 它与两类斯特林数都有关系.

$$\begin{bmatrix} n \\ n-k \end{bmatrix} = n^{k+1} \sigma_k(n)$$

$$\begin{Bmatrix} n \\ n-k \end{Bmatrix} = (-1)^{k+1} n^{k+1} \sigma_k(-(n-k))$$

不过它并不好求. 可以 $O(k^2)$ 直接计算前几个点值然后插值, 或者如果要推公式的话可以用后面提到的二阶欧拉数.

1.10.5 贝尔数

$$B_0 = 1, B_1 = 1, B_2 = 2, B_3 = 5,$$

$$B_4 = 15, B_5 = 52, B_6 = 203, \dots$$

$$B_n = \sum_{k=0}^n \{n\}_k$$

递推式:

$$B_{n+1} = \sum_{k=0}^n \binom{n}{k} B_k$$

指数生成函数:

$$B(x) = e^{e^x - 1}$$

Touchard同余:

$$B_{n+p} \equiv (B_n + B_{n+1}) \pmod{p}, p \text{ is a prime}$$

1.10.6 欧拉数(Eulerian Number)

1. 欧拉数

$\langle n \rangle_k$: n 个数的排列, 有 k 个上升的方案数.

$$\langle n \rangle_k = (n-k) \langle n-1 \rangle_{k-1} + (k+1) \langle n-1 \rangle_k$$

$$\langle n \rangle_k = \sum_{i=0}^{k+1} (-1)^i \binom{n+1}{i} (k+1-i)^n$$

$$\sum_{k=0}^{n-1} \langle n \rangle_k = n!$$

$$x^n = \sum_{k=0}^{n-1} \langle n \rangle_k \binom{x+k}{n}$$

$$k! \left\{ n \right\}_k = \sum_{i=0}^{n-1} \langle n \rangle_i \binom{i}{n-k}$$

2. 二阶欧拉数

$\langle\langle n \rangle\rangle_k$: 每个数都出现两次的多重排列, 并且每个数两次出现之间的数都比它要大. 在此前提下有 k 个上升的方案数.

$$\langle\langle n \rangle\rangle_k = (2n-k-1) \langle\langle n-1 \rangle\rangle_{k-1} + (k+1) \langle\langle n-1 \rangle\rangle_k$$

$$\sum_{k=0}^{n-1} \langle\langle n \rangle\rangle_k = (2n-1)!! = \frac{(2n)n}{2^n}$$

3. 二阶欧拉数与斯特林数的关系

$$\left\{ \begin{matrix} x \\ x-n \end{matrix} \right\}_k = \sum_{k=0}^{n-1} \langle\langle n \rangle\rangle_k \binom{x+n-k-1}{2n}$$

$$\left[\begin{matrix} x \\ x-n \end{matrix} \right]_k = \sum_{k=0}^{n-1} \langle\langle n \rangle\rangle_k \binom{x+k}{2n}$$

1.10.7 卡特兰数, 施罗德数, 默慈金数

1. 卡特兰数

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

- n 个元素按顺序入栈, 出栈序列方案数
- 长为 $2n$ 的合法括号序列数
- $n+1$ 个叶子的满二叉树个数

递推式:

$$C_n = \sum_{i=0}^{n-1} C_i C_{n-i-1}$$

$$C_n = C_{n-1} \frac{4n-2}{n+1}$$

普通生成函数:

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

扩展: 如果有 n 个左括号和 m 个右括号, 方案数为

$$\binom{n+m}{n} - \binom{n+m}{m-1}$$

2. 施罗德数

$$S_n = S_{n-1} + \sum_{i=0}^{n-1} S_i S_{n-i-1}$$

$$(n+1)S_n = (6n-3)S_{n-1} - (n-2)S_{n-2}$$

其中 S_n 是(大)施罗德数, s_n 是小施罗德数(也叫超级卡特兰数).

除了 $S_0 = s_0 = 1$ 以外, 都有 $S_i = 2s_i$.

施罗德数的组合意义:

- 从 $(0, 0)$ 走到 (n, n) , 每次可以走右, 上, 或者右上一步, 并且不能超过 $y = x$ 这条线的方案数
 - 长为 n 的括号序列, 每个位置也可以为空, 并且括号对数和空位置数加起来等于 n 的方案数
 - 凸 n 边形的任意剖分方案数
- (有些人会把大(而不是小)施罗德数叫做超级卡特兰数.)

3. 默慈金数

$$M_{n+1} = M_n + \sum_{i=0}^{n-1} M_i M_{n-1-i} = \frac{(2n+3)M_n + 3nM_{n-1}}{n+3}$$

$$M_n = \sum_{i=0}^{\frac{n}{2}} \binom{n}{2i} C_i$$

在圆上的 n 个不同的点之间画任意条不相交(包括端点)的弦的方案数.

也等价于在网格图上, 每次可以走右上, 右下, 正右方一步, 且不能走到 $y < 0$ 的位置, 在此前提下从 $(0, 0)$ 走到 $(n, 0)$ 的方案数.

扩展: 默慈金数画的弦不可以共享端点. 如果可以共享端点的话是A054726, 后面的表里可以查到.

1.11 常用公式及结论

1.11.1 方差

m 个数的方差:

$$s^2 = \frac{\sum_{i=1}^m x_i^2}{m} - \bar{x}^2$$

随机变量的方差: $D^2(x) = E(x^2) - E^2(x)$

1.11.2 min-max反演

$$\max(S) = \sum_{T \subset S} (-1)^{|T|+1} \min(T)$$

$$\min(S) = \sum_{T \subset S} (-1)^{|T|+1} \max(T)$$

推广: 求第 k 大

$$k\text{-}\max(S) = \sum_{T \subset S} (-1)^{|T|-k} \binom{|T|-1}{k-1} \min(T)$$

显然只有大小至少为 k 的子集才是有用的.

1.11.3 单位根反演(展开整除条件 $[n|k]$)

$$[n|k] = \frac{1}{n} \sum_{i=0}^{n-1} \omega_n^{ik}$$

$$\sum_{i \geq 0} [x^{ik}] f(x) = \frac{1}{k} \sum_{j=0}^{k-1} f(\omega_k^j)$$

1.11.4 康托展开(排列的排名)

求排列的排名：先对每个数都求出它后面有几个数比它小（可以用树状数组预处理），记为 c_i ，则排列的排名就是

$$\sum_{i=1}^n c_i(n-i)!$$

已知排名构造排列：从前到后先分别求出 c_i ，有了 c_i 之后再用一个平衡树(需要维护排名)倒序处理即可。

1.11.5 连通图计数

设大小为 n 的满足一个限制 P 的简单无向图数量为 g_n , 满足限制 P 且连通的简单无向图数量为 f_n , 如果已知 $g_{1 \dots n}$ 求 f_n , 可以得到递推式

$$f_n = g_n - \sum_{k=1}^{n-1} \binom{n-1}{k-1} f_k g_{n-k}$$

这个递推式的意义就是用任意图的数量减掉不连通的数量，而不连通的数量可以通过枚举1号点所在连通块大小来计算。

注意，由于 $f_0 = 0$ ，因此递推式的枚举下界取0和1都是可以的。

推一推式子会发现得到一个多项式求逆，再仔细看看，其实就是一个多项式 \ln .

1.11.6 常系数齐次线性递推求通项

- 定理3.1: 设数列 $\{u_n : n \geq 0\}$ 满足 r 阶齐次线性常系数递推

关系 $u_n = \sum_{j=1}^r c_j u_{n-j}$ ($n \geq r$). 则

$$(i). \quad U(x) = \sum_{n \geq 0} u_n x^n = \frac{h(x)}{1 - \sum_{j=1}^r c_j x^j}, \quad \deg(h(x)) < r.$$

(ii). 若特征多项式

$$c(x) = x^r - \sum_{i=1}^r c_i x^{r-i} = (x - \alpha_1)^{e_1} \cdots (x - \alpha_s)^{e_s},$$

其中 $\alpha_1, \dots, \alpha_s$ 互异, $e_1 + \dots + e_s = r$ 则 u_n 有表达式

$$u_n = p_1(n)\alpha_1^n + \cdots + p_s(n)\alpha_s^n, \quad \deg(p_i) < e_i, i = 1, \dots, s.$$

多项式 p_1, \dots, p_s 的共 $e_1 + \dots + e_s = r$ 个系数可由初始值 u_0, \dots, u_{r-1} 唯一确定。

1.12 常用生成函数变换

$$\frac{x}{(1-x)^2} = \sum_{i \geq 0} ix^i$$

$$\frac{1}{(1-x)^k} = \sum_{i \geq 0} \binom{i+k-1}{i} x^i = \sum_{i \geq 0} \binom{i+k-1}{k-1} x^i, \quad k > 0$$

$$\begin{aligned} \sum_{i=0}^{\infty} i^n x^i &= \sum_{k=0}^n \binom{n}{k} k! \frac{x^k}{(1-x)^{k+1}} = \sum_{k=0}^n \binom{n}{k} k! \frac{x^k (1-x)^{n-k}}{(1-x)^{n+1}} \\ &= \frac{1}{(1-x)^{n+1}} \sum_{i=0}^n \frac{x^i}{(n-i)!} \sum_{k=0}^i \binom{n}{k} k!(n-k)! \frac{(-1)^{i-k}}{(i-k)!} \end{aligned}$$

(用上面的方法可以把分子化成一个 n 次以内的多项式，并且可以用一次卷积求出来。)

如果把 i^n 换成任意的一个 n 次多项式，那么我们可以求出它的下降幂表示形式(或者说是牛顿插值)的系数 r_i ，发现用 r_k 替换掉上面的 $\binom{n}{k} k!$ 之后其余过程完全相同。

2 数论

2.1 $O(n)$ 预处理逆元

```
// 要求p为质数
1 inv[0] = inv[1] = 1;
2 for (int i = 2; i <= n; i++)
3     inv[i] = (long long)(p - (p / i)) * inv[p % i] % p;
4     // p为模数
5 // i ^ -1 = -(p / i) * (p % i) ^ -1
```

2.2 线性筛

```

1 // 此代码以计算约数之和函数\sigma_1(对10^9+7取模)为例
2 // 适用于任何f(p^k)便于计算的积性函数
3 constexpr int p = 1000000007;
4
5 int prime[maxn / 10], sigma_one[maxn], f[maxn],
6    → g[maxn];
7 // f: 除掉最小质因子后剩下的部分
8 // g: 最小质因子的幂次, 在f(p^k)比较复杂时很有用,
9 // → 但f(p^k)可以递推时就可以省略了
10 // 这里没有记录最小质因子, 但根据线性筛的性质, 每个合数只
11 // → 会被它最小的质因子筛掉
12 bool notp[maxn]; // 顾名思义
13
14 void get_table(int n) {
15     sigma_one[1] = 1; // 积性函数必有f(1) = 1
16     for (int i = 2; i ≤ n; i++) {
17         if (!notp[i]) { // 质数情况
18             prime[++prime[0]] = i;
19             sigma_one[i] = i + 1;
20             f[i] = g[i] = 1;
21         }
22
23         for (int j = 1; j ≤ prime[0] && i * prime[j]
24             → ≤ n; j++) {
25             notp[i * prime[j]] = true;
26
27             if (i % prime[j]) { // 加入一个新的质因子,
28                 → 这种情况很简单
29                 sigma_one[i * prime[j]] = (long
30                     → long)sigma_one[i] * (prime[j] + 1)
31                     → % p;
32                 f[i * prime[j]] = i;
33                 g[i * prime[j]] = 1;
34             }
35             else { // 再加入一次最小质因子, 需要再进行分类
36                 → 讨论
37                 f[i * prime[j]] = f[i];
38                 g[i * prime[j]] = g[i] + 1;
39                 // 对于f(p^k)可以直接递推的函数, 这里的判
40                 → 断可以改成
41                 // i / prime[j] % prime[j] != 0, 这样可
42                 → 以省下f[]的空间,
43                 // 但常数很可能会稍大一些
44
45                 if (f[i] == 1) // 质数的幂次, 这
46                     → 里\sigma_1可以递推
47                     sigma_one[i * prime[j]] =
48                         → (sigma_one[i] + i * prime[j]) %
49                         → p;
50                     // 对于更一般的情况, 可以借助g[]计
51                     → 算f(p^k)
52             else sigma_one[i * prime[j]] = // 否则直
53                 → 接利用积性, 两半乘起来
54                 (long long)sigma_one[i * prime[j] /
55                     → f[i]] * sigma_one[f[i]] % p;
56         }
57     }
58 }

```

A graph of a function $f(x)$ on a coordinate plane. The vertical axis (y-axis) has tick marks at 40, 41, 42, 43, and 44. The horizontal axis (x-axis) has tick marks at 1, 3, and 5. The function is plotted as follows:

- From $x=1$ to $x=3$, the function is a straight line segment with a negative slope, decreasing from approximately 43.5 at $x=1$ to 41.5 at $x=3$.
- At $x=3$, there is a jump discontinuity. A brace indicates a jump of 2 units upwards. The function continues as a straight line segment with a positive slope, increasing from 41.5 at $x=3$ to approximately 43.5 at $x=5$.

The overall shape is a V-shape opening upwards, with a sharp corner at $(3, 41.5)$.

2.3 杜教筛

$$S_\varphi(n) = \frac{n(n+1)}{2} - \sum_{d=2}^n S_\varphi\left(\left\lfloor \frac{n}{d} \right\rfloor\right)$$

$$S_\mu(n) = 1 - \sum_{d=2}^n S_\mu\left(\left\lfloor \frac{n}{d} \right\rfloor\right)$$

```

1 // 用于求可以用狄利克雷卷积构造出好求和的东西的函数的前缀
2 // → 和(有点绕)
3 // 有些题只要求  $n \leq 10^9$ , 这时就没必要开 long long 了, 但
4 // → 记得乘法时强转
5 // 常量/全局变量/数组定义
6 const int maxn = 5000005, table_size = 5000000, p =
7 // → 1000000007, inv_2 = (p + 1) / 2;
8 bool notp[maxn];
9 int prime[maxn / 20], phi[maxn], tbl[100005];
10 // tbl用来顶替哈希表, 其实开到  $n^{1/3}$  就够了, 不过保险
11 // → 起见开成  $\sqrt{n}$  比较好
12 long long N;
13
14 // 主函数前面加上这么一句
15 memset(tbl, -1, sizeof(tbl));
16
17 // 线性筛预处理部分略去
18
19 // 杜教筛主过程 总计  $O(n^{2/3})$ 
20 // 递归调用自身
21 // 递推式还需具体情况具体分析, 这里以求欧拉函数前缀和(mod
22 // →  $10^9 + 7$ )为例
23 int S(long long n) {
24     if (n <= table_size)
25         return phi[n];
26     else if (~tbl[N / n])
27         return tbl[N / n];
28     // 原理: n除以所有可能的数的结果一定互不相同
29
30     int ans = 0;
31     for (long long i = 2, last; i <= n; i = last + 1) {
32         last = n / (n / i);
33         ans = (ans + (last - i + 1) % p * S(n / i)) %
34             p; // 如果n是int范围的话记得强转
35     }
36
37     ans = (n % p * ((n + 1) % p) % p * inv_2 - ans + p)
38     // → % p; // 同上
39     return tbl[N / n] = ans;
40 }

```

2.4 Powerful Number篇

注意 Powerful Number 篩只能求积性函数的前缀和。

本质上就是构造一个方便求前缀和的函数，然后做类似杜教筛的操作。

定义 Powerful Number 表示每个质因子幂次都大于 1 的数，显然最多有 \sqrt{n} 个。

设我们要求和的函数是 $f(n)$, 构造一个方便求前缀和的积性函数 $g(n)$ 使得 $g(p) = f(p)$.

那么就存在一个积性函数 $h = f * g^{-1}$, 也就是 $f = g * h$. 可以证明 $h(p) = 0$, 所以只有 Powerful Number 的 h 值不为 0.

$$S_f(i) = \sum_{d=1}^n h(d) S_g\left(\left\lfloor \frac{n}{d} \right\rfloor\right)$$

只需要枚举每个 Powerful Number 作为 d , 然后用杜教筛计算 g 的前缀和.

求 $h(d)$ 时要先预处理 $h(p^k)$, 显然有

$$h(p^k) = f(p^k) - \sum_{i=1}^k g(p^i) h(p^{k-i})$$

处理完之后 DFS 就行了. (显然只需要筛 \sqrt{n} 以内的质数.)

复杂度取决于杜教筛的复杂度, 特殊题目构造的好也可以做到 $O(\sqrt{n})$.

例题:

- $f(p^k) = p^k (p^k - 1) : g(n) = \text{id}(n)\varphi(n)$.
- $f(p^k) = p \text{ xor } k : n$ 为偶数时 $g(n) = 3\varphi(n)$, 否则 $g(n) = \varphi(n)$.

2.5 洲阁筛

计算积性函数 $f(n)$ 的前 n 项之和时, 我们可以把所有项按照是否有 $> \sqrt{n}$ 的质因子分两类讨论, 最后将两部分的贡献加起来即可.

1. 有 $> \sqrt{n}$ 的质因子

显然 $> \sqrt{n}$ 的质因子幂次最多为 1, 所以这一部分的贡献就是

$$\sum_{i=1}^{\sqrt{n}} f(i) \sum_{d=\sqrt{n}+1}^{\lfloor \frac{n}{i} \rfloor} [d \in \mathbb{P}] f(d)$$

我们可以 DP 后面的和式. 由于 $f(p)$ 是一个关于 p 的低次多项式, 我们可以对每个次幂分别 DP: 设 $g_{i,j}$ 表示 $[1, j]$ 中和前 i 个质数都互质的数的 k 次方之和. 设 \sqrt{n} 以内的质数总共有 m 个, 显然贡献就转换成了

$$\sum_{i=1}^{\sqrt{n}} i^k g_{m, \lfloor \frac{n}{i} \rfloor}$$

边界显然就是自然数幂次和, 转移是

$$g_{i,j} = g_{i-1,j} - p_i^k g_{i-1, \lfloor \frac{j}{p_i} \rfloor}$$

也就是减掉和第 i 个质数不互质的贡献.

在滚动数组的基础上再优化一下: 首先如果 $j < p_i$ 那肯定就只有 1 一个数; 如果 $p_i \leq j < p_i^2$, 显然就有 $g_{i,j} = g_{i-1,j} - p_i^k$, 那么对每个 j 记下最大的 i 使得 $p_i^2 \leq j$, 比这个还大的情况就不需要递推了, 用到的时候再加上一个前缀和解决.

2. 所有质因子都 $\leq \sqrt{n}$

类似的道理, 我们继续 DP: $h_{i,j}$ 表示只含有第 i 到 m 个质数作为质因子的所有数的 $f(i)$ 之和. (这里不需要对每个次幂单独 DP 了; 另外倒着 DP 是为了方便卡上限.)

边界显然是 $h_{m+1,j} = 1$, 转移是

$$h_{i,j} = h_{i+1,j} + \sum_c f(p_i^c) h_{i+1, \lfloor \frac{j}{p_i^c} \rfloor}$$

跟上面一样的道理优化, 分成三段: $j < p_i$ 时 $h_{i,j} = 1$, $j < p_i^2$ 时 $h_{i,j} = h_{i+1,j} + f(p_i)$ (同样用前缀和解决), 再小的部分就老实递推.

预处理 \sqrt{n} 以内的部分之后跑两次 DP, 最后把两部分的贡献加起来就行了.

两部分的复杂度都是 $\Theta\left(\frac{n^{\frac{3}{4}}}{\log n}\right)$ 的.

以下代码以洛谷 P5325 ($f(p^k) = p^k(p^k - 1)$) 为例.

```

1 constexpr int maxn = 200005, p = 1000000007;
2
3 long long N, val[maxn]; // 询问的n和存储所有整除结果的表
4 int sqrtn;
5
6 inline int getid(long long x) {
7     if (x <= sqrtn)
8         return x;
9
10    return val[0] - N / x + 1;
11}
12
13 bool notp[maxn];
14 int prime[maxn], prime_cnt, rem[maxn]; // 线性筛用数组
15
16 int f[maxn], pr[maxn], g[2][maxn], dp[maxn];
17 int l[maxn], r[maxn];
18
19 // 线性筛省略
20
21 inline int get_sum(long long n, int k) {
22     n %= p;
23
24     if (k == 1)
25         return n * (n + 1) % p * ((p + 1) / 2) % p;
26
27     else
28         return n * (n + 1) % p * (2 * n + 1) % p * (((p
29             - 1) / 6) % p);
30 }
31
32 void get_dp(long long n, int k, int *dp) {
33     for (int j = 1; j <= val[0]; j++)
34         dp[j] = get_sum(val[j], k);
35
36     for (int i = 1; i <= prime_cnt; i++) {
37         long long lb = (long long)prime[i] * prime[i];
38         int pw = (k == 1 ? prime[i] : (int)(lb % p));
39
40         pr[i] = (pr[i - 1] + pw) % p;
41
42         for (int j = val[0]; j && val[j] >= lb; j--) {
43             int t = getid(val[j] / prime[i]);
44
45             int tmp = dp[t];
46             if (l[t] < i)
47                 tmp = (tmp - pr[min(i - 1, r[t])] +
48                     pr[l[t]]) % p;
49
50             dp[j] = (dp[j] - (long long)pw * tmp) % p;
51             if (dp[j] < 0)
52                 dp[j] += p;
53         }
54
55         for (int j = 1; j <= val[0]; j++) {
56             dp[j] = (dp[j] - pr[r[j]] + pr[l[j]]) % p;
57
58             dp[j] = (dp[j] + p - 1) % p; // 因为DP数组是
59             // 有1的, 但后面计算不应该有1
60         }
61
62         int calc1(long long n) {
63             get_dp(n, 1, g[0]);
64             get_dp(n, 2, g[1]);
65
66             int ans = 0;

```

```

67     for (int i = 1; i ≤ sqrtN; i++)
68         ans = (ans + (long long)f[i] * (g[1][getid(N /
69             → i)] - g[0][getid(N / i)])) % p;
70
71     if (ans < 0)
72         ans += p;
73
74     return ans;
75
76 int calc2(long long n) {
77     for (int j = 1; j ≤ val[0]; j++)
78         dp[j] = 1;
79
80     for (int i = 1; i ≤ prime_cnt; i++)
81         pr[i] = (pr[i - 1] + f[prime[i]]) % p;
82
83     for (int i = prime_cnt; i; i--) {
84         long long lb = (long long)prime[i] * prime[i];
85
86         for (int j = val[0]; j && val[j] ≥ lb; j--)
87             for (long long pc = prime[i]; pc ≤ val[j];
88                 → pc *= prime[i]) {
89                 int t = getid(val[j] / pc);
90
91                 int tmp = dp[t];
92                 if (r[t] > i)
93                     tmp = (tmp + pr[r[t]] - pr[max(i,
94                         → l[t])]) % p;
95
96                 dp[j] = (dp[j] + pc % p * ((pc - 1) %
97                     → p) % p * tmp) % p;
98             }
99
100    return (long long)(dp[val[0]] + pr[r[val[0]]] -
101        → pr[l[val[0]]] + p) % p;
102
103    int main() {
104
105        // ios::sync_with_stdio(false);
106
107        cin >> N;
108
109        sqrtN = (int)sqrt(N);
110
111        get_table(sqrtN);
112
113        for (int i = 1; i ≤ sqrtN; i++)
114            val[+val[0]] = i;
115
116        for (int i = 1; i ≤ sqrtN; i++)
117            val[+val[0]] = N / i;
118
119        sort(val + 1, val + val[0] + 1);
120
121        val[0] = unique(val + 1, val + val[0] + 1) - val -
122            → 1;
123
124        int li = 0, ri = 0;
125        for (int j = 1; j ≤ val[0]; j++) {
126            while (ri < prime_cnt && prime[ri + 1] ≤
127                → val[j])
128                ri++;
129
130            while (li ≤ prime_cnt && (long long)prime[li]
131                → * prime[li] ≤ val[j])
132                li++;
133
134            l[j] = li - 1;
135            r[j] = ri;
136        }
137
138        cout << (calc1(N) + calc2(N)) % p << endl;
139
140        return 0;
141    }
142
143
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1 // 注意, 虽然Pollard's Rho的理论复杂度是O(n ^ {1 / 4})的,
2 // 但实际跑起来比较慢, 一般用于做long long范围内的质因数
3 // 分解
4
5 // 封装好的函数体
6 // 需要调用solve
7 void factorize(long long n, vector<long long> &v) { //
8     → v用于存分解出来的质因子, 重复的会放多个
9     for (int i : {2, 3, 5, 7, 11, 13, 17, 19}) {
10        while (n % i == 0) {
11            v.push_back(i);
12            n /= i;
13        }
14
15        solve(n, v);
16        sort(v.begin(), v.end()); // 从小到大排序后返回
17    }
18
19 // 递归过程
20 // 需要调用Pollard's Rho主过程, 同时递归调用自身
21 void solve(long long n, vector<long long> &v) {
22     if (n == 1)
23         return;
24
25     long long p;
26     do
27         p = Pollards_Rho(n);
28     while (!p); // p是任意一个非平凡因子
29
30     if (p == n) {
31         v.push_back(p); // 说明n本身就是质数
32         return;
33     }
34
35     solve(p, v); // 递归分解两半
36     solve(n / p, v);
37
38 // Pollard's Rho主过程
39 // 需要使用Miller-Rabin作为子算法
40 // 同时需要调用O(1)快速乘和gcd函数
41 long long Pollards_Rho(long long n) {
42     // assert(n > 1);
43
44     if (Miller_Rabin(n))
45         return n;
46
47     long long c = rand() % (n - 2) + 1, i = 1, k = 2, x
48     ← = rand() % (n - 3) + 2, u = 2; // 注意这里rand函
49     → 数需要重定义一下
50     while (true) {
51         i++;
52         x = (mul(x, x, n) + c) % n; // mul是O(1)快速乘函
53         ← 数
54
55         long long g = gcd((u - x + n) % n, n);
56         if (g > 1 && g < n)
57             return g;
58
59         if (u == x)
60             return 0; // 失败, 需要重新调用
61
62         if (i == k) {
63             u = x;
64             k *= 2;
65         }
66     }
67 }
```

64 }

2.9 快速阶乘算法

参见1.1.11.应用: $O(\sqrt{n} \log^2 n)$ 快速求阶乘(9页).

2.10 扩展欧几里德 exgcd

```

1 void exgcd(LL a, LL b, LL &c, LL &x, LL &y) {
2     if (b == 0) {
3         c = a;
4         x = 1;
5         y = 0;
6         return;
7     }
8
9     exgcd(b, a % b, c, x, y);
10
11    LL tmp = x;
12    x = y;
13    y = tmp - (a / b) * y;
14 }
```

2.10.1 求通解的方法

假设我们已经找到了一组解 (p_0, q_0) 满足 $ap_0 + bq_0 = \gcd(a, b)$, 那么其他的解都满足

$$p = p_0 + \frac{b}{\gcd(p, q)} \times t \quad q = q_0 - \frac{a}{\gcd(p, q)} \times t$$

其中 t 为任意整数.

2.10.2 类欧几里德算法(直线下整点个数)

$a, b \geq 0, m > 0$, 计算 $\sum_{i=0}^{n-1} \lfloor \frac{a+bi}{m} \rfloor$.

```

1 int solve(int n, int a, int b, int m) {
2     if (!b)
3         return n * (a / m);
4     if (a ≥ m)
5         return n * (a / m) + solve(n, a % m, b, m);
6     if (b ≥ m)
7         return (n - 1) * n / 2 * (b / m) + solve(n, a,
8             ← b % m, m);
9
10    return solve((a + b * n) / m, (a + b * n) % m, m,
11             ← b);
12 }
```

2.11 中国剩余定理

$$x \equiv a_i \pmod{m_i}$$

$$M = \prod_i m_i, M_i = \frac{M}{m_i}$$

$$M'_i \equiv M_i^{-1} \pmod{m_i}$$

$$x \equiv \sum_i a_i M_i M'_i \pmod{M}$$

2.11.1 ex-CRT

设两个方程分别是 $x \equiv a_1 \pmod{m_1}$ 和 $x \equiv a_2 \pmod{m_2}$.

将它们转化为不定方程 $x = m_1p + a_1 = m_2q + a_2$, 其中 p, q 是整数, 则有 $m_1p - m_2q = a_2 - a_1$.

当 $a_2 - a_1$ 不能被 $\gcd(m_1, m_2)$ 整除时无解, 否则可以通过扩展欧几里得解出来一组可行解 (p, q) .

则原来的两方程组成的模方程组的解为 $x \equiv b \pmod{M}$, 其中 $b = m_1p + a_1$, $M = \text{lcm}(m_1, m_2)$.

```

56 do {
57     a = rand() % p;
58     w = ((long long)a * a - b) % p;
59     if (w < 0)
60         w += p;
61 } while (my_legendre(w) != p - 1);
62
63 return qpow(pi(a, 1), (p + 1) / 2).a;
64 }
```

2.12 二次剩余

```

1 int p, w;
2
3 struct pi {
4     int a, b; // a + b * sqrt(w)
5
6     pi(int a = 0, int b = 0) : a(a), b(b) {}
7
8     friend pi operator * (const pi &u, const pi &v) {
9         return pi((long long)u.a * v.a + (long
10            → long)u.b * v.b % p * w) % p,
11            → ((long long)u.a * v.b + (long long)u.b *
12            → v.a) % p;
13    }
14
15 pi qpow(pi a, int b) {
16     pi ans(1, 0);
17
18     while (b) {
19         if (b & 1)
20             ans = ans * a;
21
22         b >>= 1;
23         a = a * a;
24     }
25
26     return ans;
27 }
28
29 int qpow(int a, int b) {
30     int ans = 1;
31
32     while (b) {
33         if (b & 1)
34             ans = (long long)ans * a % p;
35
36         b >>= 1;
37         a = (long long)a * a % p;
38     }
39
40     return ans;
41 }
42
43 int my_legendre(int a) { // std有同名函数, 最好换个名字,
44     → 不然传了两个数都查不出来
45     return qpow(a, (p - 1) / 2);
46 }
47
48 int quadratic_residual(int b, int mod) {
49     p = mod;
50
51     if (p == 2)
52         return 1;
53
54     if (my_legendre(b) == p - 1)
55         return -1; // 无解
56     int a;
```

2.13 原根 阶

阶 最小的整数 k 使得 $a^k \equiv 1 \pmod{p}$, 记为 $\delta_p(a)$.

显然 a 在阶以下的幂次是两两不同的.

一个性质: 如果 a, b 均与 p 互质, 则 $\delta_p(ab) = \delta_p(a)\delta_p(b)$ 的充分必要条件是 $\gcd(\delta_p(a), \delta_p(b)) = 1$.

另外, 如果 a 与 p 互质, 则有 $\delta_p(a^k) = \frac{\delta_p(a)}{\gcd(\delta_p(a), k)}$. (也就是环上一次跳 k 步的周期.)

原根 阶等于 $\varphi(p)$ 的数.

只有形如 $2, 4, p^k, 2p^k$ (p 是奇素数) 的数才有原根, 并且如果一个数 n 有原根, 那么原根的个数是 $\varphi(\varphi(n))$ 个.

暴力找原根代码:

```

1 def split(n): # 分解质因数
2     i = 2
3     a = []
4     while i * i <= n:
5         if n % i == 0:
6             a.append(i)
7
8             while n % i == 0:
9                 n /= i
10
11            i += 1
12
13        if n > 1:
14            a.append(n)
15
16    return a
17
18 def getg(p): # 找原根
19     def judge(g):
20         for i in d:
21             if pow(g, (p - 1) / i, p) == 1:
22                 return False
23         return True
24
25     d = split(p - 1)
26     g = 2
27
28     while not judge(g):
29         g += 1
30
31     return g
32
33 print(getg(int(input())))
```

2.14 常用数论公式

2.14.1 莫比乌斯反演

$$f(n) = \sum_{d|n} g(d) \Leftrightarrow g(n) = \sum_{d|n} \mu\left(\frac{n}{d}\right) f(d)$$

$$f(d) = \sum_{d|k} g(k) \Leftrightarrow g(d) = \sum_{d|k} \mu\left(\frac{k}{d}\right) f(k)$$

2.14.2 降幂公式

$$a^k \equiv a^{k \bmod \varphi(p) + \varphi(p)}, \quad k \geq \varphi(p)$$

2.14.3 其他常用公式

$$\mu * I = e \quad (e(n) = [n = 1])$$

$$\varphi * I = id$$

$$\mu * id = \varphi$$

$$\sigma_0 = I * I, \sigma_1 = id * I, \sigma_k = id^{k-1} * I$$

$$\sum_{i=1}^n [(i, n) = 1] i = n \frac{\varphi(n) + e(n)}{2}$$

$$\sum_{i=1}^n \sum_{j=1}^i [(i, j) = d] = S_\varphi \left(\left\lfloor \frac{n}{d} \right\rfloor \right)$$

$$\sum_{i=1}^n \sum_{j=1}^m [(i, j) = d] = \sum_{d|k} \mu \left(\frac{k}{d} \right) \left\lfloor \frac{n}{k} \right\rfloor \left\lfloor \frac{m}{k} \right\rfloor$$

$$\sum_{i=1}^n f(i) \sum_{j=1}^{\left\lfloor \frac{n}{i} \right\rfloor} g(j) = \sum_{i=1}^n g(i) \sum_{j=1}^{\left\lfloor \frac{n}{i} \right\rfloor} f(j)$$

3 图论

3.1 最小生成树

3.1.1 Boruvka算法

思想: 每次选择连接每个连通块的最小边, 把连通块缩起来.

每次连通块个数至少减半, 所以迭代 $O(\log n)$ 次即可得到最小生成树.

一种比较简单的实现方法: 每次迭代遍历所有边, 用并查集维护连通性和每个连通块的最小边权.

应用: 最小异或生成树

3.1.2 动态最小生成树

动态最小生成树的离线算法比较容易, 而在线算法通常极为复杂.

一个跑得比较快的离线做法是对时间分治, 在每层分治时找出一定在不在MST上的边, 只带着不确定边继续递归.

简单起见, 找确定边的过程用Kruskal算法实现, 过程中的两种重要操作如下:

- Reduction: 待修改边标为 $+\infty$, 跑MST后把非树边删掉, 减少无用边
- Contraction: 待修改边标为 $-\infty$, 跑MST后缩除待修改边之外的所有MST边, 计算必须边

每轮分治需要Reduction-Contraction, 借此减少不确定边, 从而保证复杂度.

复杂度证明: 假设当前区间有 k 条待修改边, n 和 m 表示点数和边数, 那么最坏情况下R-C的效果为 $(n, m) \rightarrow (n, n + k - 1) \rightarrow (k + 1, 2k)$.

```

1 // 全局结构体与数组定义
2 struct edge { // 边的定义
3     int u, v, w, id; // id表示边在原图中的编号
4     bool vis; // 在Kruskal时用, 记录这条边是否是树边
5     bool operator < (const edge &e) const { return w <
6         → e.w; }
7 } e[20][maxn], t[maxn]; // 为了便于回滚, 在每层分治存一个
8 → 副本
9
10 // 用于存储修改的结构体, 表示第id条边的权值从u修改为v
11 struct A {
12     int id, u, v;
13 } a[maxn];
14
15 int id[20][maxn]; // 每条边在当前图中的编号
16 int p[maxn], size[maxn], stk[maxn], top; // p和size是并
17 → 查集数组, stk是用来撤销的栈
18 int n, m, q; // 点数, 边数, 修改数
19
20 // 方便起见, 附上可能需要用到的预处理代码
21 int main() {
22     for (int i = 1; i ≤ n; i++) { // 并查集初始化
23         p[i] = i;
24         size[i] = 1;
25     }
26
27     for (int i = 1; i ≤ m; i++) { // 读入与预标号
28         scanf("%d%d%d", &e[0][i].u, &e[0][i].v, &e[0]
29             → [i].w);
30         e[0][i].id = i;
31         id[0][i] = i;
32     }
33
34     for (int i = 1; i ≤ q; i++) { // 预处理出调用数组
35         scanf("%d%d", &a[i].id, &a[i].v);
36     }
37 }
```

```

35     a[i].u = e[0][a[i].id].w;
36     e[0][a[i].id].w = a[i].v;
37 }
38
39 for(int i = q; i; i--)
40     e[0][a[i].id].w = a[i].u;
41
42 CDQ(1, q, 0, m, 0); // 这是调用方法
43 }

44 // 分治主过程 O(nlog^2n)
45 // 需要调用Reduction和Contraction
46 void CDQ(int l, int r, int d, int m, long long ans) {
47     ← // CDQ分治
48     if (l == r) { // 区间长度已减小到1, 输出答案, 退出
49         e[d][id[d][a[l].id]].w = a[l].v;
50         printf("%lld\n", ans + Kruskal(m, e[d]));
51         e[d][id[d][a[l].id]].w = a[l].u;
52         return;
53     }
54
55     int tmp = top;
56
57     Reduction(l, r, d, m);
58     ans += Contraction(l, r, d, m); // R-C
59
60     int mid = (l + r) / 2;
61
62     copy(e[d] + 1, e[d] + m + 1, e[d + 1] + 1);
63     for (int i = 1; i ≤ m; i++)
64         id[d + 1][e[d][i].id] = i; // 准备好下一层要用的
65 → 数组
66
67     CDQ(l, mid, d + 1, m, ans);
68
69     for (int i = l; i ≤ mid; i++)
70         e[d][id[d][a[i].id]].w = a[i].v; // 进行左边的修
71 → 改
72
73     copy(e[d] + 1, e[d] + m + 1, e[d + 1] + 1);
74     for (int i = 1; i ≤ m; i++)
75         id[d + 1][e[d][i].id] = i; // 重新准备下一层要用
76 → 的数组
77
78     CDQ(mid + 1, r, d + 1, m, ans);
79
80     for (int i = top; i > tmp; i--)
81         cut(stk[i]); // 撤销所有操作
82     top = tmp;
83
84 // Reduction(减少无用边): 待修改边标为 $+\infty$ , 跑MST后把非树边
85 → 删掉, 减少无用边
86 // 需要调用Kruskal
87 void Reduction(int l, int r, int d, int &m) {
88     for (int i = l; i ≤ r; i++)
89         e[d][id[d][a[i].id]].w = INF; // 待修改的边标为INF
90
91     Kruskal(m, e[d]);
92
93     copy(e[d] + 1, e[d] + m + 1, t + 1);
94
95     int cnt = 0;
96     for (int i = 1; i ≤ m; i++)
97         if (t[i].w == INF || t[i].vis) { // 非树边扔掉
98             id[d][t[i].id] = ++cnt; // 给边重新编号
99             e[d][cnt] = t[i];
99     }
99 }
```

```

100
101    for (int i = r; i >= l; i--) {
102        e[d][id[d][a[i].id]].w = a[i].u; // 把待修改的边
103        ↪ 改回去
104    }
105
106
107
108 // Contraction(缩必须边):待修改边标为- $\text{INF}$ ,跑MST后缩除待修
109 → 改边之外的所有树边
110 // 返回缩掉的边的总权值
111 // 需要调用Kruskal
112 long long Contraction(int l, int r, int d, int &m) {
113     long long ans = 0;
114
115     for (int i = l; i <= r; i++) {
116         e[d][id[d][a[i].id]].w = - $\text{INF}$ ; // 待修改边标
117         ↪ 为- $\text{INF}$ 
118
119         Kruskal(m, e[d]);
120         copy(e[d] + 1, e[d] + m + 1, t + 1);
121
122         int cnt = 0;
123         for (int i = 1; i <= m; i++) {
124
125             if (t[i].w != - $\text{INF}$  && t[i].vis) { // 必须边
126                 ans += t[i].w;
127                 mergeset(t[i].u, t[i].v);
128             }
129             else { // 不确定边
130                 id[d][t[i].id] = ++cnt;
131                 e[d][cnt] = t[i];
132             }
133
134         for (int i = r; i >= l; i--) {
135             e[d][id[d][a[i].id]].w = a[i].u; // 把待修改的边
136             ↪ 改回去
137             e[d][id[d][a[i].id]].vis = false;
138
139         m = cnt;
140
141         return ans;
142
143
144 // Kruskal算法  $O(m \log n)$ 
145 // 方便起见,这里直接沿用进行过缩点的并查集,在过程结束后撤
146 → 销即可
147 long long Kruskal(int m, edge *e) {
148     int tmp = top;
149     long long ans = 0;
150
151     sort(e + 1, e + m + 1); // 比较函数在结构体中定义过
152     ↪ 了
153
154     for (int i = 1; i <= m; i++) {
155         if (findroot(e[i].u) != findroot(e[i].v)) {
156             e[i].vis = true;
157             ans += e[i].w;
158             mergeset(e[i].u, e[i].v);
159         }
160         else
161             e[i].vis = false;
162
163     for (int i = top; i > tmp; i--)
164         cut(stk[i]); // 撤销所有操作

```

```

164     top = tmp;
165
166     return ans;
167 }
168
169 // 以下是并查集相关函数
170 int findroot(int x) { // 因为需要撤销,不写路径压缩
171     while (p[x] != x)
172         x = p[x];
173
174     return x;
175 }
176
177 void mergeset(int x, int y) { // 按size合并,如果想跑得更
178 → 快就写一个按秩合并
179     x = findroot(x); // 但是按秩合并要再开一个栈记录合并
180     ↪ 之前的秩
181     y = findroot(y);
182
183     if (x == y)
184         return;
185
186     if (size[x] > size[y])
187         swap(x, y);
188
189     p[x] = y;
190     size[y] += size[x];
191     stk[++top] = x;
192
193 void cut(int x) { // 并查集撤销
194     int y = x;
195
196     do
197         size[y = p[y]] -= size[x];
198     while (p[y] != y);
199
200     p[x] = x;
201 }

```

3.1.3 最小树形图

对每个点找出最小的入边, 如果是一个DAG那么就已经结束了。否则把环都缩起来, 每个点的边权减去环上的边权之后再跑一遍, 直到没有环为止。

可以用可并堆优化到 $O(m \log n)$, 需要写一个带懒标记的左偏树。
 $O(nm)$ 版本

```

1 constexpr int maxn = 105, maxe = 10005, inf =
2   ↪ 0x3f3f3f3f;
3
4 struct edge {
5     int u, v, w;
6 } e[maxe];
7
8 int mn[maxn], pr[maxn], ufs[maxn], vis[maxn];
9 bool alive[maxn];
10
11 int edmonds(int n, int m, int rt) {
12     for (int i = 1; i <= n; i++)
13         alive[i] = true;
14
15     int ans = 0;
16
17     while (true) {
18         memset(mn, 63, sizeof(int) * (n + 1));
19         memset(pr, 0, sizeof(int) * (n + 1));
20         memset(ufs, 0, sizeof(int) * (n + 1));
21
22         for (int i = 1; i <= m; i++) {
23             if (mn[e[i].u] < mn[e[i].v]) {
24                 mn[e[i].v] = mn[e[i].u];
25                 pr[e[i].v] = e[i].u;
26             }
27         }
28
29         for (int i = 1; i <= n; i++) {
30             if (!alive[i]) continue;
31
32             int cur = i;
33             int sum = 0;
34
35             while (cur != pr[cur]) {
36                 sum += e[pr[cur]].w;
37                 cur = pr[cur];
38             }
39
40             if (sum > mn[i]) {
41                 mn[i] = sum;
42                 pr[i] = rt;
43             }
44         }
45
46         int flag = 0;
47
48         for (int i = 1; i <= n; i++) {
49             if (alive[i] && mn[i] == 63) {
50                 flag = 1;
51                 break;
52             }
53         }
54
55         if (!flag) break;
56     }
57
58     for (int i = 1; i <= n; i++) {
59         if (mn[i] == 63) ans++;
60     }
61
62     return ans;
63 }

```

```

20     memset(vis, 0, sizeof(int) * (n + 1));
21
22     mn[rt] = 0;
23
24     for (int i = 1; i ≤ m; i++) {
25         if (e[i].u != e[i].v && e[i].w <
26             → mn[e[i].v]) {
27             mn[e[i].v] = e[i].w;
28             pr[e[i].v] = e[i].u;
29         }
30
31         for (int i = 1; i ≤ n; i++) {
32             if (!alive[i]) {
33                 if (mn[i] ≥ inf)
34                     return -1; // 不存在最小树形图
35
36             ans += mn[i];
37         }
38
39         bool flag = false;
40
41         for (int i = 1; i ≤ n; i++) {
42             if (!alive[i])
43                 continue;
44
45             int x = i;
46             while (x && !vis[x]) {
47                 vis[x] = i;
48                 x = pr[x];
49             }
50
51             if (x && vis[x] == i) {
52                 flag = true;
53                 for (int u = x; !ufs[u]; u = pr[u])
54                     ufs[u] = x;
55             }
56
57             for (int i = 1; i ≤ m; i++) {
58                 e[i].w -= mn[e[i].v];
59
60                 if (ufs[e[i].u])
61                     e[i].u = ufs[e[i].u];
62                 if (ufs[e[i].v])
63                     e[i].v = ufs[e[i].v];
64             }
65
66             if (!flag)
67                 return ans;
68
69             for (int i = 1; i ≤ n; i++)
70                 if (ufs[i] && i != ufs[i])
71                     alive[i] = false;
72     }
73 }
```

$O(m \log n)$ 版本

(堆优化版本可以参考fstqwq的模板，在最后没有目录的部分。)

3.1.4 Steiner Tree 斯坦纳树

问题：一张图上有 k 个关键点，求让关键点两两连通的最小生成树

做法：状压 DP， $f_{i,S}$ 表示以 i 号点为树根， i 与 S 中的点连通的最小边权和

转移有两种：

1. 枚举子集：

$$f_{i,S} = \min_{T \subset S} \{f_{i,T} + f_{i,S \setminus T}\}$$

2. 新加一条边：

$$f_{i,S} = \min_{(i,j) \in E} \{f_{j,S} + w_{i,j}\}$$

第一种直接枚举子集 DP 就行了，第二种可以用 SPFA 或者 Dijkstra 松弛（显然负边一开始全选就行了，所以只需要处理非负边）。

复杂度 $O(n3^k + 2^k \text{SSSP}(n, m))$ ，其中 $\text{SSSP}(n, m)$ 可以是 nm 或者 $n^2 + m$ 或者 $m \log n$ 。

```

1 constexpr int maxn = 105, inf = 0x3f3f3f3f;
2
3 int dp[maxn][(1 << 10) + 1];
4 int g[maxn][maxn], a[15];
5 bool inq[maxn];
6
7 int main() {
8
9     int n, m, k;
10    scanf("%d%d%d", &n, &m, &k);
11
12    memset(g, 63, sizeof(g));
13
14    while (m--) {
15        int u, v, c;
16        scanf("%d%d%d", &u, &v, &c);
17
18        g[u][v] = g[v][u] = min(g[u][v], c); // 不要忘了
19        → 是双向边
20    }
21
22    memset(dp, 63, sizeof(dp));
23
24    for (int i = 0; i < k; i++) {
25        scanf("%d", &a[i]);
26
27        dp[a[i]][1 << i] = 0;
28    }
29
30    for (int s = 1; s < (1 << k); s++) {
31        for (int i = 1; i ≤ n; i++)
32            for (int t = (s - 1) & s; t; (~t) &= s)
33                dp[i][s] = min(dp[i][s], dp[i][t] +
34                    → dp[i][s ^ t]);
35
36    // SPFA
37    queue<int> q;
38    for (int i = 1; i ≤ n; i++)
39        if (dp[i][s] < inf) {
40            q.push(i);
41            inq[i] = true;
42        }
43
44    while (!q.empty()) {
45        int i = q.front();
46        q.pop();
47        inq[i] = false; // 最终结束时 inq 一定全 0，所
48        → 以不用清空
49
50        for (int j = 1; j ≤ n; j++)
51            if (dp[i][s] + g[i][j] < dp[j][s]) {
52                dp[j][s] = dp[i][s] + g[i][j];
53                if (!inq[j]) {
54                    q.push(j);
55                    inq[j] = true;
56                }
57            }
58    }
59 }
```

```

57
58     int ans = inf;
59     for (int i = 1; i <= n; i++)
60         ans = min(ans, dp[i][(1 << k) - 1]);
61
62     printf("%d\n", ans);
63
64     return 0;
65 }

3.1.5 最小直径生成树
首先要找到图的绝对中心(可能在点上, 也可能在某条边上), 然后以绝对中心为起点建最短路树就是最小直径生成树.

1 #include <bits/stdc++.h>
2
3 using namespace std;
4
5 constexpr int maxn = 505;
6 constexpr long long inf = 0x3f3f3f3f3f3f3f3fll;
7
8 int g[maxn][maxn], id[maxn][maxn], pr[maxn]; // g是邻接
9     → 矩阵
10    long long f[maxn][maxn], d[maxn];
11    bool vis[maxn];
12
13 vector<pair<int, int>>
14     → minimum_diameter_spanning_tree(int n) { // 1-based
15         for (int i = 1; i <= n; i++)
16             for (int j = 1; j <= n; j++)
17                 g[i][j] *= 2; // 输入的边权都要乘2
18
19         memset(f, 63, sizeof(f));
20
21         for (int i = 1; i <= n; i++)
22             f[i][i] = 0;
23
24         for (int i = 1; i <= n; i++)
25             for (int j = 1; j <= n; j++)
26                 if (g[i][j])
27                     f[i][j] = g[i][j];
28
29         for (int k = 1; k <= n; k++)
30             for (int i = 1; i <= n; i++)
31                 for (int j = 1; j <= n; j++)
32                     f[i][j] = min(f[i][j], f[i][k] + f[k]
33                                     → [j]);
34
35         for (int i = 1; i <= n; i++) {
36             for (int j = 1; j <= n; j++)
37                 id[i][j] = j; // 距离i第j近的点
38
39             sort(id[i] + 1, id[i] + n + 1, [&i] (int x, int
40                                         → y) {
41                 return f[i][x] < f[i][y];
42             });
43
44         int o = 0;
45         long long ansv = inf; // vertex
46
47         for (int i = 1; i <= n; i++)
48             if (f[i][id[i][n]] * 2 < ansv) {
49                 ansv = f[i][id[i][n]] * 2;
50                 o = i;
51             }
52
53         for (int x = 1; x <= n; x++)
54             for (int y = 1; y <= n; y++)
55                 if (g[x][y]) { // 如果g[x][y] = 0说明没有边
56                     int w = g[x][y];
57
58                     for (int i = n - 1, j = n; i; i--)
59                         if (f[y][id[x][i]] > f[y][id[x]
60                                         → [j]]) {
61                             long long tmp = f[x][id[x][i]]
62                                         → + f[y][id[x][j]] + w;
63                             if (tmp < anse) {
64                                 anse = tmp;
65                                 u = x;
66                                 v = y;
67
68                                 disu = tmp / 2 - f[x][id[x]
69                                         → [i]];
69                                 disv = w - disu;
70
71                             j = i;
72                         }
73
74                     printf("%lld\n", min(ansv, anse) / 2); // 直径
75                     memset(d, 63, sizeof(d));
76
77                     if (ansv <= anse)
78                         d[o] = 0;
79                     else {
80                         d[u] = disu;
81                         d[v] = disv;
82                     }
83
84                     for (int k = 1; k <= n; k++) { // Dijkstra
85                         int x = 0;
86                         for (int i = 1; i <= n; i++)
87                             if (!vis[i] && d[i] < d[x])
88                                 x = i;
89
90                         vis[x] = true;
91                         for (int y = 1; y <= n; y++)
92                             if (g[x][y] && !vis[y]) {
93                                 if (d[y] > d[x] + g[x][y]) {
94                                     d[y] = d[x] + g[x][y];
95                                     pr[y] = x;
96                                 }
97                                 else if (d[y] == d[x] + g[x][y] &&
98                                         → d[pr[y]] < d[x])
99                                     pr[y] = x;
100
101                     vector<pair<int, int>> vec;
102                     for (int i = 1; i <= n; i++)
103                         if (pr[i])
104                             vec.emplace_back(i, pr[i]);
105
106                     if (ansv > anse)
107                         vec.emplace_back(u, v);
108
109                     return vec;
110
111     }
112
113     int main() {
114
115         int n, m;

```

```

116 scanf("%d%d", &n, &m);
117
118 while (m--) {
119     int x, y, z;
120     scanf("%d%d%d", &x, &y, &z);
121
122     g[x][y] = g[y][x] = z; // 无向图
123 }
124
125 auto vec = minimum_diameter_spanning_tree(n);
126 for (auto [x, y] : vec)
127     printf("%d %d\n", x, y);
128
129 return 0;
130

```

3.2 最短路

3.2.1 Dijkstra

参见3.2.3.k短路(28页), 注意那边是求到 t 的最短路.

3.2.2 Johnson算法(负权图多源最短路)

首先前提是图没有负环.

先任选一个起点 s , 跑一遍SPFA, 计算每个点的势 $h_u = d_{s,u}$, 然后将每条边 $u \rightarrow v$ 的权值 w 修改为 $w + h[u] - h[v]$ 即可, 由最短路的性质显然修改后边权非负.

然后对每个起点跑Dijkstra, 再修正距离 $d_{u,v} = d'_{u,v} - h_u + h_v$ 即可, 复杂度 $O(nm \log n)$, 在稀疏图上是要优于Floyd的.

3.2.3 k短路

```

1 // 注意这是个多项式算法, 在k比较大时很有优势, 但k比较小时
2 // →最好还是用A*
3 // DAG和有环的情况都可以, 有重边或自环也无所谓, 但不能有
4 // →零环
5 // 以下代码以Dijkstra + 可持久化左偏树为例
6
7 constexpr int maxn = 1005, maxe = 10005, maxm = maxe *
8 //→ 30; //点数,边数,左偏树结点数
9
10 struct A { // 用来求最短路
11     int x, d;
12
13     A(int x, int d) : x(x), d(d) {}
14
15     bool operator < (const A &a) const {
16         return d > a.d;
17     }
18
19 struct node { // 左偏树结点
20     int w, i, d; // i: 最后一条边的编号 d: 左偏树附加信息
21     node *lc, *rc;
22
23     node() {}
24
25     node(int w, int i) : w(w), i(i), d(0) {}
26
27     void refresh(){
28         d = rc → d + 1;
29    }
30 } null[maxm], *ptr = null, *root[maxn];
31
32 struct B { // 维护答案用
33     int x, w; // x是结点编号, w表示之前已经产生的权值

```

```

33     node *rt; // 这个答案对应的堆顶,注意可能不等于任何一个结点的堆
34
35     B(int x, node *rt, int w) : x(x), w(w), rt(rt) {}
36
37     bool operator < (const B &a) const {
38         return w + rt → w > a.w + a.rt → w;
39     }
40 }
41
42 // 全局变量和数组定义
43 vector<int> G[maxn], W[maxn], id[maxn]; // 最开始要存反
44 //→ 向图, 然后把G清空作为儿子列表
45 bool vis[maxn], used[maxe]; // used表示边是否在最短路树
46 //→ 上
47 int u[maxe], v[maxe], w[maxe]; // 存下每条边,注意是有向
48 //→ 边
49 int d[maxn], p[maxn]; // p表示最短路树上每个点的父边
50 int n, m, k, s, t; // s, t分别表示起点和终点
51
52 // 以下是主函数中较关键的部分
53 for (int i = 0; i ≤ n; i++)
54     root[i] = null; // 一定要加上!!!
55
56 // (读入&建反向图)
57 Dijkstra();
58
59 // (清空G, W, id)
60
61 for (int i = 1; i ≤ n; i++)
62     if (p[i]) {
63         used[p[i]] = true; // 在最短路树上
64         G[v[p[i]]].push_back(i);
65     }
66
67 for (int i = 1; i ≤ m; i++) {
68     w[i] = d[u[i]] - d[v[i]]; // 现在的w[i]表示这条边能
69 //→ 使路径长度增加多少
70     if (!used[i])
71         root[u[i]] = merge(root[u[i]], newnode(w[i],
72 //→ i));
73
74 dfs(t);
75
76 priority_queue<B> heap;
77 heap.push(B(s, root[s], 0)); // 初始状态是找贡献最小的边
78 //→ 加进去
79
80 printf("%d\n", d[s]); // 第1短路需要特判
81 while (--k) { // 其余k - 1短路径用二叉堆维护
82     if (heap.empty())
83         printf("-1\n");
84     else {
85         int x = heap.top().x, w = heap.top().w;
86         node *rt = heap.top().rt;
87         heap.pop();
88
89         printf("%d\n", d[s] + w + rt → w);
90
91         if (rt → lc != null || rt → rc != null)
92             heap.push(B(x, merge(rt → lc, rt → rc),
93 //→ w)); // pop掉当前边,换成另一条贡献大一
94 //→ 点的边
95         if (root[v[rt → i]] != null)
96             heap.push(B(v[rt → i], root[v[rt → i]], w
97 //→ + rt → w)); // 保留当前边,往后面再接上
98 //→ 另一条边
99     }
100 }
```

```

93 }
94 // 主函数到此结束
95
96
97 // Dijkstra预处理最短路  $O(m \log n)$ 
98 void Dijkstra() {
99     memset(d, 63, sizeof(d));
100    d[t] = 0;
101    priority_queue<A> heap;
102    heap.push(A(t, 0));
103
104    while (!heap.empty()) {
105        int x = heap.top().x;
106        heap.pop();
107
108        if (vis[x])
109            continue;
110
111        vis[x] = true;
112        for (int i = 0; i < (int)G[x].size(); i++)
113            if (!vis[G[x][i]] && d[G[x][i]] > d[x] +
114                → W[x][i]) {
115                d[G[x][i]] = d[x] + W[x][i];
116                p[G[x][i]] = id[x][i];
117
118                heap.push(A(G[x][i], d[G[x][i]]));
119            }
120    }
121
122 // dfs求出每个点的堆 总计 $O(m \log n)$ 
123 // 需要调用merge，同时递归调用自身
124 void dfs(int x) {
125     root[x] = merge(root[x], root[v[p[x]]]);
126
127     for (int i = 0; i < (int)G[x].size(); i++)
128         dfs(G[x][i]);
129 }
130
131 // 包装过的new node() O(1)
132 node *newnode(int w, int i) {
133     *ptr = node(w, i);
134     ptr → lc = ptr → rc = null;
135     return ptr;
136 }
137
138 // 带可持久化的左偏树合并 总计 $O(\log n)$ 
139 // 递归调用自身
140 node *merge(node *x, node *y) {
141     if (x == null)
142         return y;
143     if (y == null)
144         return x;
145
146     if (x → w > y → w)
147         swap(x, y);
148
149     node *z = newnode(x → w, x → i);
150     z → lc = x → lc;
151     z → rc = merge(x → rc, y);
152
153     if (z → lc → d < z → rc → d)
154         swap(z → lc, z → rc);
155     z → refresh();
156
157     return z;
158 }

```

3.3 Tarjan算法

3.3.1 强连通分量

```

1 int dfn[maxn], low[maxn], tim = 0;
2 vector<int> G[maxn], scc[maxn];
3 int sccid[maxn], scc_cnt = 0, stk[maxn];
4 bool instk[maxn];
5
6 void dfs(int x) {
7     dfn[x] = low[x] = ++tim;
8
9     stk[stk[0]] = x;
10    instk[x] = true;
11
12    for (int y : G[x]) {
13        if (!dfn[y]) {
14            dfs(y);
15            low[x] = min(low[x], low[y]);
16        } else if (instk[y])
17            low[x] = min(low[x], dfn[y]);
18    }
19
20    if (dfn[x] == low[x]) {
21        scc_cnt++;
22
23        int u;
24        do {
25            u = stk[stk[0]--];
26            instk[u] = false;
27            sccid[u] = scc_cnt;
28            scc[scc_cnt].push_back(u);
29        } while (u != x);
30    }
31 }
32
33 void tarjan(int n) {
34     for (int i = 1; i ≤ n; i++)
35         if (!dfn[i])
36             dfs(i);
37 }
38

```

3.3.2 割点 点双

```

1 vector<int> G[maxn], bcc[maxn];
2 int dfn[maxn], low[maxn], tim = 0, bccid[maxn], bcc_cnt
3 → = 0;
4 bool iscut[maxn];
5
6 pair<int, int> stk[maxn];
7 int stk_cnt = 0;
8
9 void dfs(int x, int pr) {
10    int child = 0;
11    dfn[x] = low[x] = ++tim;
12
13    for (int y : G[x]) {
14        if (!dfn[y]) {
15            stk[stk[0]] = make_pair(x, y);
16            child++;
17            dfs(y, x);
18            low[x] = min(low[x], low[y]);
19
20            if (low[y] ≥ dfn[x]) {
21                iscut[x] = true;
22                bcc_cnt++;
23            }
24        }
25    }
26 }
27
28
29
30
31
32
33
34
35
36
37
38

```

```

24     auto pi = stk[stk_cnt--];
25
26     if (bccid[pi.first] != bcc_cnt) {
27         bcc[bcc_cnt].push_back(pi.first);
28         bccid[pi.first] = bcc_cnt;
29     }
30     if (bccid[pi.second] != bcc_cnt) {
31         bcc[bcc_cnt].push_back(pi.second);
32         bccid[pi.second] = bcc_cnt;
33     }
34
35     if (pi.first == x && pi.second ==
36         ~y)
37         break;
38 }
39
40 else if (dfn[y] < dfn[x] && y != pr) {
41     stk[++stk_cnt] = make_pair(x, y);
42     low[x] = min(low[x], dfn[y]);
43 }
44
45 if (!pr && child == 1)
46     iscut[x] = false;
47 }
48
49 void Tarjan(int n) {
50     for (int i = 1; i ≤ n; i++)
51         if (!dfn[i])
52             dfs(i, 0);
53 }

```

3.3.3 桥 边双

```

1 int u[maxe], v[maxe];
2 vector<int> G[maxn]; // 存的是边的编号
3
4 int stk[maxn], top, dfn[maxn], low[maxn], tim, bcc_cnt;
5 vector<int> bcc[maxn];
6
7 bool isbridge[maxe];
8
9 void dfs(int x, int pr) { // 这里pr是入边的编号
10    dfn[x] = low[x] = ++tim;
11    stk[++top] = x;
12
13    for (int i : G[x]) {
14        int y = (u[i] == x ? v[i] : u[i]);
15
16        if (!dfn[y]) {
17            dfs(y, i);
18            low[x] = min(low[x], low[y]);
19
20            if (low[y] > dfn[x])
21                bridge[i] = true;
22        }
23        else if (i != pr)
24            low[x] = min(low[x], dfn[y]);
25    }
26
27    if (dfn[x] == low[x]) {
28        bcc_cnt++;
29        int y;
30        do {
31            y = stk[top--];
32            bcc[bcc_cnt].push_back(y);
33        } while (y != x);
34    }

```

35 }

3.4 欧拉回路

$C[x]$ 是记录每条边对应的编号的.
另外为了保证复杂度需要加当前弧优化.

```

1 vector<int> G[maxn], C[maxn], v[maxn]; // C是边的编号
2 int cur[maxn];
3 bool vis[maxn * 2];
4
5 vector<pair<int, int> > vec;
6
7 int d[maxn];
8
9 void dfs(int x) {
10    bool bad = false;
11
12    while (!bad) {
13        bad = true;
14
15        for (int &i = cur[x]; i < (int)G[x].size(); i++)
16            if (!vis[C[x][i]]) {
17                vis[C[x][i]] = true;
18                vec.emplace_back(x, i);
19                x = G[x][i];
20                bad = false;
21            }
22        }
23    }
24 }

```

3.5 仙人掌

一般来说仙人掌问题都可以通过圆方树转成有两种点的树上问题来做.

3.5.1 仙人掌DP

```

1 struct edge {
2     int to, w, prev;
3 } e[maxn * 2];
4
5 vector<pair<int, int> > v[maxn];
6 vector<long long> d[maxn];
7 stack<int> stk;
8
9 int p[maxn];
10 bool vis[maxn], vise[maxn * 2];
11 int last[maxn], cnte;
12
13 long long f[maxn], g[maxn], sum[maxn];
14 int n, m, cnt;
15
16 void addedge(int x, int y, int w) {
17     v[x].push_back(make_pair(y, w));
18 }
19
20 void dfs(int x) {
21
22     vis[x] = true;
23
24     for (int i = last[x]; ~i; i = e[i].prev) {
25         if (vise[i ^ 1])
26             continue;

```

```

28     int y = e[i].to, w = e[i].w;
29
30     vise[i] = true;
31
32     if (!vis[y]) {
33         stk.push(i);
34         p[y] = x;
35         dfs(y);
36
37         if (!stk.empty() && stk.top() == i) {
38             stk.pop();
39             addedge(x, y, w);
40         }
41     }
42
43     else {
44         cnt++;
45
46         long long tmp = w;
47         while (!stk.empty()) {
48             int i = stk.top();
49             stk.pop();
50
51             int yy = e[i].to, ww = e[i].w;
52
53             addedge(cnt, yy, 0);
54
55             d[cnt].push_back(tmp);
56
57             tmp += ww;
58
59             if (e[i ^ 1].to == y)
60                 break;
61         }
62
63         addedge(y, cnt, 0);
64
65         sum[cnt] = tmp;
66     }
67 }
68
69 void dp(int x) {
70
71     for (auto o : v[x]) {
72         int y = o.first, w = o.second;
73         dp(y);
74     }
75
76
77     if (x <= n) {
78         for (auto o : v[x]) {
79             int y = o.first, w = o.second;
80
81             f[x] += 2 * w + f[y];
82         }
83
84         g[x] = f[x];
85
86         for (auto o : v[x]) {
87             int y = o.first, w = o.second;
88
89             g[x] = min(g[x], f[x] - f[y] - 2 * w + g[y]
90                         → + w);
91         }
92     }
93     else {
94         f[x] = sum[x];
95         for (auto o : v[x]) {
96             int y = o.first;

```

```

97             f[x] += f[y];
98         }
99
100        g[x] = f[x];
101
102        for (int i = 0; i < (int)v[x].size(); i++) {
103            int y = v[x][i].first;
104
105            g[x] = min(g[x], f[x] - f[y] + g[y] +
106                         → min(d[x][i], sum[x] - d[x][i]));
107        }
108    }

```

3.6 二分图

3.6.1 匈牙利

```

1 vector<int> G[maxn];
2
3 int girl[maxn], boy[maxn]; // 男孩在左边, 女孩在右边
4 bool vis[maxn];
5
6 bool dfs(int x) {
7     for (int y : G[x])
8         if (!vis[y]) {
9             vis[y] = true;
10
11             if (!boy[y] || dfs(boy[y])) {
12                 girl[x] = y;
13                 boy[y] = x;
14
15                 return true;
16             }
17         }
18
19     return false;
20 }
21
22 int hungary() {
23     int ans = 0;
24
25     for (int i = 1; i ≤ n; i++)
26         if (!girl[i]) {
27             memset(vis, 0, sizeof(vis));
28             ans += dfs(i);
29         }
30
31     return ans;
32 }

```

3.6.2 Hopcroft-Karp二分图匹配

其实长得和Dinic差不多，或者说像匈牙利和Dinic的缝合怪。

```

1 vector<int> G[maxn];
2
3 int girl[maxn], boy[maxn]; // girl: 左边匹配右边 boy:
4                         → 右边匹配左边
5
6 bool vis[maxn]; // 右半的点是否已被访问
7 int dx[maxn], dy[maxn];
8 int q[maxn];
9
10 bool bfs(int n) {
11     memset(dx, -1, sizeof(int) * (n + 1));
12     memset(dy, -1, sizeof(int) * (n + 1));

```

```

13 int head = 0, tail = 0;
14 for (int i = 1; i <= n; i++) {
15     if (!girl[i]) {
16         q[tail++] = i;
17         dx[i] = 0;
18     }
19
20     bool flag = false;
21
22     while (head != tail) {
23         int x = q[head++];
24
25         for (auto y : G[x])
26             if (dy[y] == -1) {
27                 dy[y] = dx[x] + 1;
28
29                 if (boy[y]) {
30                     if (dx[boy[y]] == -1) {
31                         dx[boy[y]] = dy[y] + 1;
32                         q[tail++] = boy[y];
33                     }
34                 } else
35                     flag = true;
36             }
37     }
38
39     return flag;
40 }
41
42 bool dfs(int x) {
43     for (int y : G[x])
44         if (!vis[y] && dy[y] == dx[x] + 1) {
45             vis[y] = true;
46
47             if (boy[y] && !dfs(boy[y]))
48                 continue;
49
50             girl[x] = y;
51             boy[y] = x;
52             return true;
53         }
54
55     return false;
56 }
57
58 int hopcroft_karp(int n) {
59     int ans = 0;
60
61     for (int x = 1; x <= n; x++) // 先贪心求出一组初始匹
62         // 配, 当然不写贪心也行
63         for (int y : G[x])
64             if (!boy[y]) {
65                 girl[x] = y;
66                 boy[y] = x;
67                 ans++;
68                 break;
69             }
70
71     while (bfs(n)) {
72         memset(vis, 0, sizeof(bool) * (n + 1));
73
74         for (int x = 1; x <= n; x++)
75             if (!girl[x])
76                 ans += dfs(x);
77     }
78
79     return ans;
80 }

```

3.6.3 KM二分图最大权匹配

```

1 const long long INF = 0x3f3f3f3f3f3f3f3f;
2
3 long long w[maxn][maxn], lx[maxn], ly[maxn],
4     → slack[maxn];
// 边权 顶标 slack
// 如果要求最大权完美匹配就把不存在的边设为-INF, 否则所有
// 边对0取max
5
6 bool visx[maxn], visy[maxn];
7
8 int boy[maxn], girl[maxn], p[maxn], q[maxn], head,
9     → tail; // p : pre
10
11 int n, m, N, e;
12
13 // 增广
14 bool check(int y) {
15     visy[y] = true;
16
17     if (boy[y]) {
18         visx[boy[y]] = true;
19         q[tail++] = boy[y];
20         return false;
21     }
22
23     while (y) {
24         boy[y] = p[y];
25         swap(y, girl[p[y]]);
26     }
27
28     return true;
29 }
30
31 // bfs每个点
32 void bfs(int x) {
33     memset(q, 0, sizeof(q));
34     head = tail = 0;
35
36     q[tail++] = x;
37     visx[x] = true;
38
39     while (true) {
40         while (head != tail) {
41             int x = q[head++];
42
43             for (int y = 1; y <= N; y++)
44                 if (!visy[y]) {
45                     long long d = lx[x] + ly[y] - w[x]
46                     → [y];
47
48                     if (d < slack[y]) {
49                         p[y] = x;
50                         slack[y] = d;
51
52                         if (!slack[y] && check(y))
53                             return;
54                     }
55                 }
56
57         long long d = INF;
58         for (int i = 1; i <= N; i++)
59             if (!visy[i])
60                 d = min(d, slack[i]);
61
62         for (int i = 1; i <= N; i++) {

```

```

63     if (visx[i])
64         lx[i] -= d;
65
66     if (visy[i])
67         ly[i] += d;
68     else
69         slack[i] -= d;
70 }
71
72 for (int i = 1; i ≤ N; i++)
73     if (!visy[i] && !slack[i] && check(i))
74         return;
75 }
76
77 // 主过程
78 long long KM() {
79     for (int i = 1; i ≤ N; i++) {
80         // lx[i] = 0;
81         ly[i] = -INF;
82         // boy[i] = girl[i] = -1;
83
84         for (int j = 1; j ≤ N; j++)
85             ly[i] = max(ly[i], w[j][i]);
86     }
87
88     for (int i = 1; i ≤ N; i++) {
89         memset(slack, 0x3f, sizeof(slack));
90         memset(visx, 0, sizeof(visx));
91         memset(visy, 0, sizeof(visy));
92         bfs(i);
93     }
94
95     long long ans = 0;
96     for (int i = 1; i ≤ N; i++)
97         ans += w[i][girl[i]];
98     return ans;
99 }
100
101 // 为了方便贴上主函数
102 int main() {
103
104     scanf("%d%d%d", &n, &m, &e);
105     N = max(n, m);
106
107     while (e--) {
108         int x, y, c;
109         scanf("%d%d%d", &x, &y, &c);
110         w[x][y] = max(c, 0);
111     }
112 }
113
114 printf("%lld\n", KM());
115
116 for (int i = 1; i ≤ n; i++) {
117     if (i > 1)
118         printf(" ");
119     printf("%d", w[i][girl[i]] > 0 ? girl[i] : 0);
120 }
121 printf("\n");
122
123 return 0;
124 }
```

3.6.4 二分图原理

- **最大匹配的可行边与必须边, 关键点**

以下的“残量网络”指网络流图的残量网络.

– 可行边: 一条边的两个端点在残量网络中处于同一个SCC, 不论是正向边还是反向边.

- 必须边: 一条属于当前最大匹配的边, 且残量网络中两个端点不在同一个SCC中.
- 关键点(必须点): 这里不考虑网络流图而只考虑原始的图, 将匹配边改成从右到左之后从左边的每个未匹配点进行floodfill, 左边没有被标记的点即为关键点. 右边同理.

• 独立集

二分图独立集可以看成最小割问题, 割掉最少的点使得S和T不连通, 则剩下的点自然都在独立集中.

所以独立集输出方案就是求出不在最小割中的点, 独立集的必须点/可行点就是最小割的不可行点/非必须点.

割点等价于割掉它与源点或汇点相连的边, 可以通过设置中间的边权为无穷以保证不能割掉中间的边, 然后按照上面的方法判断即可. (由于一个点最多流出一个流量, 所以中间的边权其实是可以任取的.)

• 二分图最大权匹配

二分图最大权匹配的对偶问题是最小顶标和问题, 即: 为图中的每个顶点赋予一个非负顶标, 使得对于任意一条边, 两端点的顶标和都要不小于边权, 最小化顶标之和.

显然KM算法的原理实际上就是求最小顶标和.

3.7 一般图匹配

3.7.1 高斯消元

```

1 // 这个算法基于Tutte定理和高斯消元, 思维难度相对小一些,
2 // → 也更方便进行可行边的判定
3 // 注意这个算法复杂度是满的, 并且常数有点大, 而带花树通常
4 // → 是跑不满的
5 // 以及, 根据Tutte定理, 如果求最大匹配的大小的话直接输
6 // → 出Tutte矩阵的秩/2即可
7 // 需要输出方案时才需要再写后面那些乱七八糟的东西
8
9
10 // 复杂度和常数所限, 1s之内500已经是这个算法的极限了
11 const int maxn = 505, p = 1000000007; // p可以是任
12 // → 意10^9以内的质数
13
14 // 全局数组和变量定义
15 int A[maxn][maxn], B[maxn][maxn], t[maxn][maxn],
16 // → id[maxn], a[maxn];
17 bool row[maxn] = {false}, col[maxn] = {false};
18 int n, m, girl[maxn]; // girl是匹配点, 用来输出方案
19
20 // 为了方便使用, 贴上主函数
21 // 需要调用高斯消元和eliminate
22 int main() {
23     srand(19260817);
24
25     scanf("%d%d", &n, &m); // 点数和边数
26     while (m--) {
27         int x, y;
28         scanf("%d%d", &x, &y);
29         A[x][y] = rand() % p;
30         A[y][x] = -A[x][y]; // Tutte矩阵是反对称矩阵
31     }
32
33     for (int i = 1; i ≤ n; i++)
34         id[i] = i; // 输出方案用的, 因为高斯消元的时候会
35         // → 交换列
36         memcpy(t, A, sizeof(t));
37         Gauss(A, NULL, n);
38
39         m = n;
40         n = 0; // 这里变量复用纯属个人习惯
41
42         for (int i = 1; i ≤ m; i++)
43             if (A[id[i]][id[i]])
```

```

38     a[++n] = i; // 找出一个极大满秩子矩阵
39
40     for (int i = 1; i <= n; i++)
41         for (int j = 1; j <= n; j++)
42             A[i][j] = t[a[i]][a[j]];
43
44     Gauss(A, B, n);
45
46     for (int i = 1; i <= n; i++)
47         if (!girl[a[i]])
48             for (int j = i + 1; j <= n; j++)
49                 if (!girl[a[j]] && t[a[i]][a[j]] &&
50                     → B[j][i]) {
51                     // 注意上面那句if的写法, 现在t是邻接
52                     // 矩阵的备份,
53                     // 逆矩阵j行i列不为0当且仅当这条边可
54                     // 行
55                     girl[a[i]] = a[j];
56                     girl[a[j]] = a[i];
57
58                     eliminate(i, j);
59                     eliminate(j, i);
60                     break;
61
62     printf("%d\n", n / 2);
63     for (int i = 1; i <= m; i++)
64         printf("%d ", girl[i]);
65
66     return 0;
67 }
68 // 高斯消元 O(n^3)
69 // 在传入B时表示计算逆矩阵, 传入NULL则只需计算矩阵的秩
70 void Gauss(int A[][maxn], int B[][maxn], int n) {
71     if(B) {
72         memset(B, 0, sizeof(t));
73         for (int i = 1; i <= n; i++)
74             B[i][i] = 1;
75
76         for (int i = 1; i <= n; i++) {
77             if (!A[i][i]) {
78                 for (int j = i + 1; j <= n; j++)
79                     if (A[j][i]) {
80                         swap(id[i], id[j]);
81                         for (int k = i; k <= n; k++)
82                             swap(A[i][k], A[j][k]);
83
84                         if (B)
85                             for (int k = 1; k <= n; k++)
86                                 swap(B[i][k], B[j][k]);
87                         break;
88
89             if (!A[i][i])
90                 continue;
91         }
92
93         int inv = qpow(A[i][i], p - 2);
94
95         for (int j = 1; j <= n; j++)
96             if (i != j && A[j][i]) {
97                 int t = (long long)A[j][i] * inv % p;
98
99                 for (int k = i; k <= n; k++)
100                     if (A[i][k])
101                         A[j][k] = (A[j][k] - (long
102                                         → long)t * A[i][k]) % p;
103
104     if (B)
105         for (int k = 1; k <= n; k++)
106             if (B[i][k])
107                 B[j][k] = (B[j][k] - (long long)t * B[i][k]) % p;
108
109     if (B)
110         for (int i = 1; i <= n; i++) {
111             int inv = qpow(A[i][i], p - 2);
112
113             for (int j = 1; j <= n; j++)
114                 if (B[i][j])
115                     B[i][j] = (long long)B[i][j] * inv
116                                         % p;
117
118     }
119
120 // 消去一行一列 O(n^2)
121 void eliminate(int r, int c) {
122     row[r] = col[c] = true; // 已经被消掉
123
124     int inv = qpow(B[r][c], p - 2);
125
126     for (int i = 1; i <= n; i++)
127         if (!row[i] && B[i][c]) {
128             int t = (long long)B[i][c] * inv % p;
129
130             for (int j = 1; j <= n; j++)
131                 if (!col[j] && B[r][j])
132                     B[i][j] = (B[i][j] - (long long)t *
133                                         → B[r][j]) % p;
134
135 }
136
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```

30 head = tail = 0;
31 q[tail++] = s;
32 t[s] = 1;
33
34 while (head != tail) {
35     int x = q[head++];
36     for (int y : G[x]) {
37         if (findroot(y) == findroot(x) || t[y] ==
38             → 2)
39             continue;
40
41         if (!t[y]) {
42             t[y] = 2;
43             p[y] = x;
44
45             if (!girl[y]) {
46                 for (int u = y, t; u; u = t) {
47                     t = girl[p[u]];
48                     girl[p[u]] = u;
49                     girl[u] = p[u];
50                 }
51                 return true;
52             }
53
54             t[girl[y]] = 1;
55             q[tail++] = girl[y];
56         } else if (t[y] == 1) {
57             int z = LCA(x, y);
58
59             shrink(x, y, z);
60             shrink(y, x, z);
61         }
62     }
63 }
64
65 return false;
66 }
67
68 //缩奇环 O(n)
69 void shrink(int x, int y, int z) {
70     while (findroot(x) != z) {
71         p[x] = y;
72         y = girl[x];
73
74         if (t[y] == 2) {
75             t[y] = 1;
76             q[tail++] = y;
77         }
78
79         if (findroot(x) == x)
80             f[x] = z;
81         if (findroot(y) == y)
82             f[y] = z;
83
84         x = p[y];
85     }
86 }
87
88 //暴力找LCA O(n)
89 int LCA(int x, int y) {
90     tim++;
91     while (true) {
92         if (x) {
93             x = findroot(x);
94
95             if (vis[x] == tim)
96                 return x;
97             else {

```

```

98         vis[x] = tim;
99         x = p[girl[x]];
100    }
101   }
102   swap(x, y);
103 }
104
105 //并查集的查找 O(1)
106 int findroot(int x) {
107     return x == f[x] ? x : (f[x] = findroot(f[x]));
108 }
109

```

3.7.3 带权带花树

Forked from the template of Imperisble Night.

(有一说一这玩意实在太难写了，抄之前建议先想想算法是不是假的或者有SB做法)

```

1 //maximum weight blossom, change g[u][v].w to INF -
2 → g[u][v].w when minimum weight blossom is needed
3 //type of ans is long long
4 //replace all int to long long if weight of edge is
→ long long
5
6 struct WeightGraph {
7     static const int INF = INT_MAX;
8     static const int MAXN = 400;
9     struct edge{
10         int u, v, w;
11         edge() {}
12         edge(int u, int v, int w): u(u), v(v), w(w) {}
13     };
14     int n, n_x;
15     edge g[MAXN * 2 + 1][MAXN * 2 + 1];
16     int lab[MAXN * 2 + 1];
17     int match[MAXN * 2 + 1], slack[MAXN * 2 + 1],
→ st[MAXN * 2 + 1], pa[MAXN * 2 + 1];
18     int flower_from[MAXN * 2 + 1][MAXN+1], S[MAXN * 2 +
→ 1], vis[MAXN * 2 + 1];
19     vector<int> flower[MAXN * 2 + 1];
20     queue<int> q;
21     inline int e_delta(const edge &e){ // does not work
→ inside blossoms
22         return lab[e.u] + lab[e.v] - g[e.u][e.v].w * 2;
23     }
24     inline void update_slack(int u, int x){
25         if(!slack[x] || e_delta(g[u][x]) <
→ e_delta(g[slack[x]][x]))
26             slack[x] = u;
27     }
28     inline void set_slack(int x){
29         slack[x] = 0;
30         for(int u = 1; u ≤ n; ++u)
31             if(g[u][x].w > 0 && st[u] != x && S[st[u]] ==
→ 0)
32                 update_slack(u, x);
33     }
34     void q_push(int x){
35         if(x ≤ n)q.push(x);
36         else for(size_t i = 0; i < flower[x].size(); i+
→ +)
37             q.push(flower[x][i]);
38     }
39     inline void set_st(int x, int b){
40         st[x]=b;
41         if(x > n) for(size_t i = 0; i <
→ flower[x].size(); ++i)
42             set_st(flower[x][i], b);

```

```

42 }
43 inline int get_pr(int b, int xr){
44     int pr = find(flower[b].begin(),
45                   flower[b].end(), xr) - flower[b].begin();
46     if(pr % 2 == 1){
47         reverse(flower[b].begin() + 1,
48                 flower[b].end());
49         return (int)flower[b].size() - pr;
50     } else return pr;
51 }
52 inline void set_match(int u, int v){
53     match[u]=g[u][v].v;
54     if(u > n){
55         edge e=g[u][v];
56         int xr = flower_from[u][e.u], pr=get_pr(u,
57                                         xr);
58         for(int i = 0;i < pr; ++i)
59             set_match(flower[u][i], flower[u][i ^ 1]);
60         set_match(xr, v);
61         rotate(flower[u].begin(),
62                flower[u].begin() + pr, flower[u].end());
63     }
64 }
65 inline void augment(int u, int v){
66     for(; ; ){
67         int xnv=st[match[u]];
68         set_match(u, v);
69         if(!xnv) return;
70         set_match(xnv, st[pa[xnv]]);
71         u=st[pa[xnv]], v=xnv;
72     }
73 }
74 inline int get_lca(int u, int v){
75     static int t=0;
76     for(++; u || v; swap(u, v)){
77         if(u == 0) continue;
78         if(vis[u] == t) return u;
79         vis[u] = t;
80         u = st[match[u]];
81         if(u) u = st[pa[u]];
82     }
83     return 0;
84 }
85 inline void add_blossom(int u, int lca, int v){
86     int b = n + 1;
87     while(b <= n_x && st[b]) ++b;
88     if(b > n_x) ++n_x;
89     lab[b] = 0, S[b] = 0;
90     match[b] = match[lca];
91     flower[b].clear();
92     flower[b].push_back(lca);
93     for(int x = u, y; x != lca; x = st[pa[y]]) {
94         flower[b].push_back(x),
95         flower[b].push_back(y = st[match[x]]),
96         q_push(y);
97     }
98     reverse(flower[b].begin() + 1,
99             flower[b].end());
100    for(int x = v, y; x != lca; x = st[pa[y]]) {
101        flower[b].push_back(x),
102        flower[b].push_back(y = st[match[x]]),
103        q_push(y);
104    }
105    set_st(b, b);
106    for(int x = 1; x <= n_x; ++x) g[b][x].w = g[x]
107        .w = 0;
108    for(int x = 1; x <= n; ++x) flower_from[b][x] =
109        0;
110
111    for(size_t i = 0 ; i < flower[b].size(); ++i){
112        int xs = flower[b][i];
113        for(int x = 1; x <= n_x; ++x)
114            if(g[b][x].w == 0 || e_delta(g[xs][x])
115                < e_delta(g[b][x]))
116                g[b][x] = g[xs][x], g[x][b] = g[x]
117                    .w = xs;
118        for(int x = 1;x <= n; ++x)
119            if(flower_from[xs][x]) flower_from[b]
120                [x] = xs;
121    }
122    set_slack(b);
123 }
124 inline void expand_blossom(int b){ // S[b] == 1
125     for(size_t i = 0; i < flower[b].size(); ++i)
126         set_st(flower[b][i], flower[b][i]);
127     int xr = flower_from[b][g[b][pa[b]].u], pr =
128         get_pr(b, xr);
129     for(int i = 0; i < pr; i += 2){
130         int xs = flower[b][i], xns = flower[b][i +
131             1];
132         pa[xs] = g[xns][xs].u;
133         S[xs] = 1, S[xns] = 0;
134         slack[xs] = 0, set_slack(xns);
135         q_push(xns);
136     }
137     S[xr] = 1, pa[xr] = pa[b];
138     for(size_t i = pr + 1;i < flower[b].size(); +
139         i){
140         int xs = flower[b][i];
141         S[xs] = -1, set_slack(xs);
142     }
143     st[b] = 0;
144 }
145 inline bool on_found_edge(const edge &e){
146     int u = st[e.u], v = st[e.v];
147     if(S[v] == -1){
148         pa[v] = e.u, S[v] = 1;
149         int nu = st[match[v]];
150         slack[v] = slack[nu] = 0;
151         S[nu] = 0, q_push(nu);
152     }else if(S[v] == 0){
153         int lca = get_lca(u, v);
154         if(!lca) return augment(u, v), augment(v,
155                                         u), true;
156         else add_blossom(u, lca, v);
157     }
158     return false;
159 }
160 inline bool matching(){
161     memset(S + 1, -1, sizeof(int) * n_x);
162     memset(slack + 1, 0, sizeof(int) * n_x);
163     q = queue<int>();
164     for(int x = 1;x <= n_x; ++x)
165         if(st[x] == x && !match[x]) pa[x]=0,
166             S[x]=0, q.push(x);
167     if(q.empty())return false;
168     for(;;){
169         while(q.size()){
170             int u = q.front();q.pop();
171             if(S[st[u]] == 1)continue;
172             for(int v = 1;v <= n; ++v)
173                 if(g[u][v].w > 0 && st[u] != st[v])
174                     if(e_delta(g[u][v]) == 0)
175                         if(on_found_edge(g[u]
176                                         .v))return true;
177                     else update_slack(u, st[v]);
178         }
179     }
180 }

```

```

161         }
162     }
163     int d = INF;
164     for(int b = n + 1; b <= n_x; ++b)
165     |   if(st[b] == b && S[b] == 1)d = min(d,
166     |   ↪ lab[b]/2);
167     for(int x = 1; x <= n_x; ++x)
168     |   if(st[x] == x && slack[x]){
169     |   |   if(S[x] == -1)d = min(d,
170     |   |   ↪ e_delta(g[slack[x]][x]));
171     |   |   else if(S[x] == 0)d = min(d,
172     |   |   ↪ e_delta(g[slack[x]][x])/2);
173     |   }
174     for(int u = 1; u <= n; ++u){
175     |   if(S[st[u]] == 0){
176     |   |   if(lab[u] <= d) return 0;
177     |   |   lab[u] -= d;
178     |   }else if(S[st[u]] == 1)lab[u] += d;
179     }
180     for(int b = n+1; b <= n_x; ++b)
181     |   if(st[b] == b){
182     |   |   if(S[st[b]] == 0) lab[b] += d * 2;
183     |   |   else if(S[st[b]] == 1) lab[b] -= d
184     |   |   ↪ * 2;
185     |   }
186     q=queue<int>();
187     for(int x = 1; x <= n_x; ++x)
188     |   if(st[x] == x && slack[x] &&
189     |   ↪ st[slack[x]] != x &&
190     |   ↪ e_delta(g[slack[x]][x]) == 0)
191     |   |   if(on_found_edge(g[slack[x]])
192     |   |   ↪ [x]))return true;
193     for(int b = n + 1; b <= n_x; ++b)
194     |   if(st[b] == b && S[b] == 1 && lab[b] ==
195     |   ↪ 0)expand_blossom(b);
196     }
197     return false;
198 }
199 inline pair<long long, int> solve(){
200     memset(match + 1, 0, sizeof(int) * n);
201     n_x = n;
202     int n_matches = 0;
203     long long tot_weight = 0;
204     for(int u = 0; u <= n; ++u) st[u] = u,
205     ↪ flower[u].clear();
206     int w_max = 0;
207     for(int u = 1; u <= n; ++u)
208     |   for(int v = 1; v <= n; ++v){
209     |   |   flower_from[u][v] = (u == v ? u : 0);
210     |   |   w_max = max(w_max, g[u][v].w);
211     |   }
212     for(int u = 1; u <= n; ++u) lab[u] = w_max;
213     while(matching()) ++n_matches;
214     for(int u = 1; u <= n; ++u)
215     |   if(match[u] && match[u] < u)
216     |   |   tot_weight += g[u][match[u]].w;
217     return make_pair(tot_weight, n_matches);
218 }
219 inline void init(){
220     for(int u = 1; u <= n; ++u)
221     |   for(int v = 1; v <= n; ++v)
222     |   |   g[u][v]=edge(u, v, 0);
223 }
224 };

```

3.7.4 原理

设图 G 的Tutte矩阵是 \tilde{A} , 首先是最基础的引理:

- G 的最大匹配大小是 $\frac{1}{2}\text{rank}\tilde{A}$.
- $(\tilde{A}^{-1})_{i,j} \neq 0$ 当且仅当 $G - \{v_i, v_j\}$ 有完美匹配.
(考虑到逆矩阵与伴随矩阵的关系, 这是显然的.)

构造最大匹配的方法见板子. 对于更一般的问题, 可以借助构造方法转化为完美匹配问题.

设最大匹配的大小为 k , 新建 $n - 2k$ 个辅助点, 让它们和其他所有点连边, 那么如果一个点匹配了一个辅助点, 就说明它在原图的匹配中不匹配任何点.

- 最大匹配的可行边: 对原图中的任意一条边 (u, v) , 如果删掉 u, v 后新图仍然有完美匹配(也就是 $\tilde{A}_{u,v}^{-1} \neq 0$), 则它是一条可行边.
- 最大匹配的必须边: 待补充
- 最大匹配的必须点: 可以删掉这个点和一个辅助点, 然后判断剩下的图是否还有完美匹配, 如果有则说明它不是必须的, 否则是必须的. 只需要用到逆矩阵即可.
- 最大匹配的可行点: 显然对于任意一个点, 只要它不是孤立点, 就是可行点.

3.8 支配树

记得建反图!

```

1 vector<int> G[maxn], R[maxn], son[maxn]; // R是反图,
2     ↪ son存的是sdom树上的儿子
3
4 int ufs[maxn];
5
6 int idom[maxn], sdom[maxn], anc[maxn]; // anc:
7     ↪ sdom的dfn最小的祖先
8
9 int findufs(int x) {
10    if (ufs[x] == x)
11        return x;
12
13    int t = ufs[x];
14    ufs[x] = findufs(ufs[x]);
15
16    if (dfn[sdom[anc[x]]] > dfn[sdom[anc[t]]])
17        anc[x] = anc[t];
18
19    return ufs[x];
20 }
21
22 void dfs(int x) {
23    dfn[x] = ++tim;
24    id[tim] = x;
25    sdom[x] = x;
26
27    for (int y : G[x])
28        if (!dfn[y]) {
29            p[y] = x;
30            dfs(y);
31        }
32 }
33
34 void get_dominator(int n) {
35    for (int i = 1; i <= n; i++)
36        ufs[i] = anc[i] = i;
37
38 dfs(1);
39
40 for (int i = n; i > 1; i--) {
41    int x = id[i];
42
43    for (int y : R[x])

```

```

44     if (dfn[y]) {
45         findufs(y);
46         if (dfn[sdom[x]] > dfn[sdom[anc[y]]])
47             sdom[x] = sdom[anc[y]];
48     }
49
50     son[sdom[x]].push_back(x);
51     ufs[x] = p[x];
52
53     for (int u : son[p[x]]) {
54         findufs(u);
55         idom[u] = (sdom[u] == sdom[anc[u]] ? p[x] :
56                     anc[u]);
57     }
58
59     son[p[x]].clear();
60 }
61
62 for (int i = 2; i ≤ n; i++) {
63     int x = id[i];
64
65     if (idom[x] != sdom[x])
66         idom[x] = idom[idom[x]];
67
68     son[idom[x]].push_back(x);
69 }
```

```

19 // dfs
20 bool dfs(int x) {
21     if (vis[x ^ 1])
22         return false;
23
24     if (vis[x])
25         return true;
26
27     vis[x] = true;
28     stk[++top] = x;
29
30     for (int i = 0; i < (int)G[x].size(); i++)
31         if (!dfs(G[x][i]))
32             return false;
33
34     return true;
35 }
```

3.9 2-SAT

如果限制满足对称性(每个命题的逆否命题对应的边也存在), 那么可以使用Tarjan算法求SCC搞定.

具体来说就是, 如果某个变量的两个点在同一SCC中则显然无解, 否则按拓扑序倒序尝试选择每个SCC即可.

由于Tarjan算法的特性, 找到SCC的顺序就是拓扑序倒序, 所以判断完是否有解之后, 每个变量只需要取SCC编号较小的那个.

```

1 if (!ok)
2     printf("IMPOSSIBLE\n");
3 else {
4     printf("POSSIBLE\n");
5
6     for (int i = 1; i ≤ n; i++)
7         printf("%d%c", sccid[i * 2 - 1] > sccid[i * 2],
8                i < n ? ' ' : '\n');
8 }
```

如果要字典序最小就用DFS, 注意可以压位优化. 另外代码是0-base的.

```

1 bool vis[maxn];
2 int stk[maxn], top;
3
4 // 主函数
5 for (int i = 0; i < n; i += 2)
6     if (!vis[i] && !vis[i ^ 1]) {
7         top = 0;
8         if (!dfs(i)) {
9             while (top)
10                 vis[stk[top--]] = false;
11
12             if (!dfs(i + 1))
13                 bad = true;
14             break;
15         }
16     }
17
18 // 最后stk中的所有元素就是选中的值
```

3.10 最大流

3.10.1 Dinic

```

1 // 注意Dinic适用于二分图或分层图, 对于一般稀疏图ISAP更
2 → 优, 稠密图则HLPP更优
3
4 struct edge {
5     int to, cap, prev;
6 } e[maxe * 2];
7
8 int last[maxn], len, d[maxn], cur[maxn], q[maxn];
9
10 // main函数里要初始化
11 memset(last, -1, sizeof(last));
12
13 void AddEdge(int x, int y, int z) {
14     e[len].to = y;
15     e[len].cap = z;
16     e[len].prev = last[x];
17     last[x] = len++;
18 }
19
20 void addedge(int x, int y, int z) {
21     AddEdge(x, y, z);
22     AddEdge(y, x, 0);
23 }
24
25 void bfs() {
26     int head = 0, tail = 0;
27     memset(d, -1, sizeof(int) * (t + 5));
28     q[tail++] = s;
29     d[s] = 0;
30
31     while (head != tail) {
32         int x = q[head++];
33         for (int i = last[x]; ~i; i = e[i].prev)
34             if (e[i].cap > 0 && d[e[i].to] == -1) {
35                 d[e[i].to] = d[x] + 1;
36                 q[tail++] = e[i].to;
37             }
38     }
39
40     int dfs(int x, int a) {
41         if (x == t || !a)
42             return a;
43
44         int flow = 0, f;
45         for (int &i = cur[x]; ~i; i = e[i].prev)
```

```

46     if (e[i].cap > 0 && d[e[i].to] == d[x] + 1 &&
47         (f = dfs(e[i].to, min(e[i].cap, a)))) {
48         e[i].cap -= f;
49         e[i^1].cap += f;
50         flow += f;
51         a -= f;
52
53         if (!a)
54             break;
55     }
56
57     return flow;
58 }
59
60 int Dinic() {
61     int flow = 0;
62     while (bfs(), ~d[t]) {
63         memcpy(cur, last, sizeof(int) * (t + 5));
64         flow += dfs(s, inf);
65     }
66     return flow;
67 }

```

```

40         d[e[i].to] = d[x] + 1;
41         q[tail++] = e[i].to;
42     }
43 }
44
45 // augment函数 O(n) 沿增广路增广一次, 返回增广的流量
46 int augment() {
47     int a = (~0u) >> 1; // INT_MAX
48
49     for (int x = t; x != s; x = e[p[x]^1].to)
50         a = min(a, e[p[x]].cap);
51
52     for (int x = t; x != s; x = e[p[x]^1].to) {
53         e[p[x]].cap -= a;
54         e[p[x]^1].cap += a;
55     }
56
57     return a;
58 }
59
60 // 主过程 O(n^2 m), 返回最大流的流量
61 // 注意这里的n是编号最大值, 在这个值不为n的时候一定要开个
62 // 变量记录下来并修改代码
63 int ISAP() {
64     bfs();
65
66     memcpy(cur, last, sizeof(cur));
67
68     int x = s, flow = 0;
69
70     while (d[s] < n) {
71         if (x == t) { // 如果走到了t就增广一次, 并返
72             // 回s重新找增广路
73             flow += augment();
74             x = s;
75         }
76
77         bool ok = false;
78         for (int &i = cur[x]; ~i; i = e[i].prev)
79             if (e[i].cap && d[x] == d[e[i].to] + 1) {
80                 p[e[i].to] = i;
81                 x = e[i].to;
82
83                 ok = true;
84                 break;
85             }
86
87         if (!ok) { // 修改距离标号
88             int tmp = n - 1;
89             for (int i = last[x]; ~i; i = e[i].prev)
90                 if (e[i].cap)
91                     tmp = min(tmp, d[e[i].to] + 1);
92
93             if (!--c[d[x]])
94                 break; // gap优化, 一定要加上
95
96             c[d[x]] = tmp++;
97             cur[x] = last[x];
98
99             if (x != s)
100                 x = e[p[x]^1].to;
101
102     }
103 }
104
105 // 重要! main函数最前面一定要加上如下初始化
106 memset(last, -1, sizeof(last));

```

3.10.2 ISAP

可能有毒, 慎用.

```

1 // 注意ISAP适用于一般稀疏图, 对于二分图或分层图情
2 // → 况Dinic比较优, 稠密图则HLPP更优
3
4 // 边的定义
5 // 这里没有记录起点和反向边, 因为反向边即为正向边xor 1,
6 // → 起点即为反向边的终点
7 struct edge {
8     int to, cap, prev;
9 } e[maxe * 2];
10
11 // 全局变量和数组定义
12 int last[maxn], cnte = 0, d[maxn], p[maxn], c[maxn],
13 // → cur[maxn], q[maxn];
14 int n, m, s, t; // s, t一定要开成全局变量
15
16 void AddEdge(int x, int y, int z) {
17     e[cnte].to = y;
18     e[cnte].cap = z;
19     e[cnte].prev = last[x];
20     last[x] = cnte++;
21 }
22
23 void addedge(int x, int y, int z) {
24     AddEdge(x, y, z);
25     AddEdge(y, x, 0);
26 }
27
28 // 预处理到t的距离标号
29 // 在测试数据组数较少时可以省略, 把所有距离标号初始化为0
30 void bfs() {
31     memset(d, -1, sizeof(d));
32
33     int head = 0, tail = 0;
34     d[t] = 0;
35     q[tail++] = t;
36
37     while (head != tail) {
38         int x = q[head++];
39         c[d[x]]++;
40
41         for (int i = last[x]; ~i; i = e[i].prev)
42             if (e[i^1].cap && d[e[i].to] == -1) {
43
44             d[e[i].to] = d[x] + 1;
45             q[tail++] = e[i].to;
46         }
47     }
48 }
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
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136
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139

```

3.10.3 HLPP 最高标号预流推进

```

1 constexpr int maxn = 1205, maxe = 120005;
2
3 struct edge {
4     int to, cap, prev;
5 } e[maxn * 2];
6
7 int n, m, s, t;
8 int last[maxn], cnte;
9 int h[maxn], gap[maxn * 2];
10 long long ex[maxn]; // 多余流量
11 bool inq[maxn];
12
13 struct cmp {
14     bool operator<(int x, int y) const {
15         return h[x] < h[y];
16     }
17 };
18
19 priority_queue<int, vector<int>, cmp> heap;
20
21 void adde(int x, int y, int z) {
22     e[cnte].to = y;
23     e[cnte].cap = z;
24     e[cnte].prev = last[x];
25     last[x] = cnte++;
26 }
27
28 void addedge(int x, int y, int z) {
29     adde(x, y, z);
30     adde(y, x, 0);
31 }
32
33 bool bfs() {
34     static int q[maxn];
35
36     fill(h, h + n + 1, 2 * n); // 如果没有全局的n, 记得
37     // 改这里
38     int head = 0, tail = 0;
39     q[tail++] = t;
40     h[t] = 0;
41
42     while (head < tail) {
43         int x = q[head++];
44         for (int i = last[x]; ~i; i = e[i].prev)
45             if (e[i ^ 1].cap && h[e[i].to] > h[x] + 1)
46                 // {
47                 h[e[i].to] = h[x] + 1;
48                 q[tail++] = e[i].to;
49             }
50
51     return h[s] < 2 * n;
52 }
53
54 void push(int x) {
55     for (int i = last[x]; ~i; i = e[i].prev)
56         if (e[i].cap && h[x] == h[e[i].to] + 1) {
57             int d = min(ex[x], (long long)e[i].cap);
58
59             e[i].cap -= d;
60             e[i ^ 1].cap += d;
61             ex[x] -= d;
62             ex[e[i].to] += d;
63
64             if (e[i].to != s && e[i].to != t &&
65                 !inq[e[i].to]) {
66                 heap.push(e[i].to);
67                 inq[e[i].to] = true;
68             }
69         }
70     }
71 }
72
73 void relabel(int x) {
74     h[x] = 2 * n;
75
76     for (int i = last[x]; ~i; i = e[i].prev)
77         if (e[i].cap)
78             h[x] = min(h[x], h[e[i].to] + 1);
79 }
80
81 long long hlpp() {
82     if (!bfs())
83         return 0;
84
85     // memset(gap, 0, sizeof(int) * 2 * n);
86     h[s] = n;
87
88     for (int i = 1; i ≤ n; i++)
89         gap[h[i]]++;
90
91     for (int i = last[s]; ~i; i = e[i].prev)
92         if (e[i].cap) {
93             int d = e[i].cap;
94
95             e[i].cap -= d;
96             e[i ^ 1].cap += d;
97             ex[s] -= d;
98             ex[e[i].to] += d;
99
100            if (e[i].to != s && e[i].to != t &&
101                !inq[e[i].to]) {
102                heap.push(e[i].to);
103                inq[e[i].to] = true;
104            }
105        }
106
107        while (!heap.empty()) {
108            int x = heap.top();
109            heap.pop();
110            inq[x] = false;
111
112            push(x);
113            if (ex[x]) {
114                if (!--gap[h[x]]) { // gap
115                    for (int i = 1; i ≤ n; i++)
116                        if (i != s && i != t && h[i] >
117                            h[x])
118                            h[i] = n + 1;
119
120                relabel(x);
121                ++gap[h[x]];
122                heap.push(x);
123                inq[x] = true;
124            }
125
126        return ex[t];
127    }
128
129 //记得初始化
130 memset(last, -1, sizeof(last));

```

3.11 费用流

3.11.1 SPFA费用流

```

1 constexpr int maxn = 20005, maxm = 200005;
2
3 struct edge {
4     int to, prev, cap, w;
5 } e[maxm * 2];
6
7 int last[maxn], cnte, d[maxn], p[maxn]; // 记得把last初始化成-1, 不然会死循环
8 bool inq[maxn];
9
10 void spfa(int s) {
11
12     memset(d, -63, sizeof(d));
13     memset(p, -1, sizeof(p));
14
15     queue<int> q;
16
17     q.push(s);
18     d[s] = 0;
19
20     while (!q.empty()) {
21         int x = q.front();
22         q.pop();
23         inq[x] = false;
24
25         for (int i = last[x]; ~i; i = e[i].prev)
26             if (e[i].cap) {
27                 int y = e[i].to;
28
29                 if (d[x] + e[i].w > d[y]) {
30                     p[y] = i;
31                     d[y] = d[x] + e[i].w;
32                     if (!inq[y]) {
33                         q.push(y);
34                         inq[y] = true;
35                     }
36                 }
37             }
38     }
39 }
40
41 int mcmf(int s, int t) {
42     int ans = 0;
43
44     while (spfa(s), d[t] > 0) {
45         int flow = 0x3f3f3f3f;
46         for (int x = t; x != s; x = e[p[x] ^ 1].to)
47             flow = min(flow, e[p[x]].cap);
48
49         ans += flow * d[t];
50
51         for (int x = t; x != s; x = e[p[x] ^ 1].to) {
52             e[p[x]].cap -= flow;
53             e[p[x] ^ 1].cap += flow;
54         }
55     }
56
57     return ans;
58 }
59
60 void add(int x, int y, int c, int w) {
61     e[cnte].to = y;
62     e[cnte].cap = c;
63     e[cnte].w = w;
64
65     e[cnte].prev = last[x];
66     last[x] = cnte++;
67 }

```

```

69 void addedge(int x, int y, int c, int w) {
70     add(x, y, c, w);
71     add(y, x, 0, -w);
72 }

```

3.11.2 Dijkstra费用流

有的地方也叫原始-对偶费用流.

原理和求多源最短路的Johnson算法是一样的, 都是给每个点维护一个势 h_u , 使得对任何有向边 $u \rightarrow v$ 都满足 $w + h_u - h_v \geq 0$.

如果有负费用则从 s 开始跑一遍SPFA初始化, 否则可以直接初始化 $h_u = 0$.

每次增广时得到的路径长度就是 $d_{s,t} + h_t$, 增广之后让所有 $h_u = h'_u + d'_{s,u}$, 直到 $d_{s,t} = \infty$ (最小费用最大流)或 $d_{s,t} \geq 0$ (最小费用流)为止.

注意最大费用流要转成取负之后的最小费用流, 因为Dijkstra求的是最短路.

```

1 struct edge {
2     int to, cap, prev, w;
3 } e[maxe * 2];
4
5 int last[maxn], cnte;
6
7 long long d[maxn], h[maxn];
8 int p[maxn];
9
10 bool vis[maxn];
11 int s, t;
12
13 void Adde(int x, int y, int z, int w) {
14     e[cnte].to = y;
15     e[cnte].cap = z;
16     e[cnte].w = w;
17     e[cnte].prev = last[x];
18     last[x] = cnte++;
19 }
20
21 void addedge(int x, int y, int z, int w) {
22     Adde(x, y, z, w);
23     Adde(y, x, 0, -w);
24 }
25
26 void dijkstra() {
27     memset(d, 63, sizeof(d));
28     memset(vis, 0, sizeof(vis));
29
30     priority_queue<pair<long long, int>> heap;
31
32     d[s] = 0;
33     heap.push(make_pair(0ll, s));
34
35     while (!heap.empty()) {
36         int x = heap.top().second;
37         heap.pop();
38
39         if (vis[x])
40             continue;
41
42         vis[x] = true;
43         for (int i = last[x]; ~i; i = e[i].prev)
44             if (e[i].cap > 0 && d[e[i].to] > d[x] +
45                 e[i].w + h[x] - h[e[i].to]) {
46                 d[e[i].to] = d[x] + e[i].w + h[x] -
47                 h[e[i].to];
48                 p[e[i].to] = i;
49                 heap.push(make_pair(-d[e[i].to],
50                                     e[i].to));
51             }
52     }
53 }

```

```
48 } | |
49 }
50 }
51
52 pair<long long, long long> mcmf() {
53     /*
54     spfa();
55     for (int i = 1; i <= t; i++)
56         h[i] = d[i];
57     // 如果初始有负权就像这样跑一遍SPFA预处理
58 */
59
60     long long flow = 0, cost = 0;
61
62     while (dijkstra(), d[t] < 0x3f3f3f3f) {
63         for (int i = 1; i <= t; i++)
64             h[i] += d[i];
65
66         int a = 0x3f3f3f3f;
67
68         for (int x = t; x != s; x = e[p[x] ^ 1].to)
69             a = min(a, e[p[x]].cap);
70
71         flow += a;
72         cost += (long long)a * h[t];
73
74         for (int x = t; x != s; x = e[p[x] ^ 1].to)
75             e[p[x]].cap -= a;
76             e[p[x] ^ 1].cap += a;
77     }
78
79 }
80
81 return make_pair(flow, cost);
82 }
83
84 // 记得初始化
85 memset(last, -1, sizeof(last));
```

3.11.3 预流推进费用流(可处理负环) $O(nm \log C)$

不是很懂什么原理，待研究。

```

87         }
88     }
89
90     if (++co[h[u]], !--co[hi] && hi
91         ↪ < N)
92         for (int i = 0; i < N; ++i)
93             if (hi < h[i] && h[i] <
94                 ↪ N) {
95                 --co[h[i]];
96                 h[i] = N + 1;
97             }
98
99         hi = h[u];
100    }
101
102    else if (G[u][cur[u]].f && h[u] ==
103        ↪ h[G[u][cur[u]].to] + 1)
104        add_flow(G[u][cur[u]],
105            ↪ min(ex[u], G[u]
106            ↪ [cur[u]].f));
107
108    else
109        ++cur[u];
110
111    while (hi ≥ 0 && hs[hi].empty())
112        --hi;
113
114    return -ex[S];
115
116 void push(Edge &e, flow_t amt) {
117     if (e.f < amt)
118         amt = e.f;
119
120     e.f -= amt;
121     ex[e.to] += amt;
122     G[e.to][e.rev].f += amt;
123     ex[G[e.to][e.rev].to] -= amt;
124 }
125
126 void relabel(int vertex) {
127     cost_t newHeight = -INFCOST;
128
129     for (unsigned int i = 0; i < G[vertex].size();
130         → ++i) {
131         Edge const &e = G[vertex][i];
132
133         if (e.f && newHeight < h[e.to] - e.c) {
134             newHeight = h[e.to] - e.c;
135             cur[vertex] = i;
136         }
137
138     h[vertex] = newHeight - eps;
139
140     static constexpr int scale = 2;
141
142     pair<flow_t, cost_t> minCostMaxFlow() {
143         cost_t retCost = 0;
144
145         for (int i = 0; i < N; ++i)
146             for (Edge &e : G[i])
147                 retCost += e.c * (e.f);
148
149         //find max-flow
150         flow_t retFlow = max_flow();
151         h.assign(N, 0);
152         ex.assign(N, 0);
153
154         isq.assign(N, 0);
155         cur.assign(N, 0);
156         queue<int> q;
157
158         for (; eps; eps >= scale) {
159             //refine
160             fill(cur.begin(), cur.end(), 0);
161
162             for (int i = 0; i < N; ++i)
163                 for (auto &e : G[i])
164                     if (h[i] + e.c - h[e.to] < 0 &&
165                         → e.f)
166                         push(e, e.f);
167
168             for (int i = 0; i < N; ++i) {
169                 if (ex[i] > 0) {
170                     q.push(i);
171                     isq[i] = 1;
172                 }
173             }
174
175             // make flow feasible
176             while (!q.empty()) {
177                 int u = q.front();
178                 q.pop();
179                 isq[u] = 0;
180
181                 while (ex[u] > 0) {
182                     if (cur[u] == G[u].size())
183                         relabel(u);
184
185                     for (unsigned int &i = cur[u],
186                         → max_i = G[u].size(); i < max_i;
187                         → ++i) {
188                         Edge &e = G[u][i];
189
190                         if (h[u] + e.c - h[e.to] < 0) {
191                             push(e, ex[u]);
192
193                             if (ex[e.to] > 0 &&
194                                 → isq[e.to] == 0) {
195                                 q.push(e.to);
196                                 isq[e.to] = 1;
197
198                             if (ex[u] == 0)
199                                 break;
200                         }
201
202                     if (eps > 1 && eps >= scale == 0)
203                         eps = 1 << scale;
204
205                     for (int i = 0; i < N; ++i)
206                         for (Edge &e : G[i])
207                             retCost -= e.c * (e.f);
208
209                     return make_pair(retFlow, retCost / 2 / N);
210
211                 }
212             }
213
214         int main() {

```

```

215
216     int n, m;
217     scanf("%d%d", &n, &m);
218
219     mcSFlow<long long, long long> mcmf(n, 0, n - 1);
220
221     while (m--) {
222         int x, y, z, w;
223         scanf("%d%d%d%d", &x, &y, &z, &w);
224
225         mcmf.add_edge(x - 1, y - 1, z, w);
226     }
227
228     auto [flow, cost] = mcmf.minCostMaxFlow();
229
230     printf("%lld %lld\n", flow, cost);
231
232     return 0;
233 }
```

3.12 网络流原理

3.12.1 最大流

- 判断一条边是否必定满流

在残量网络中跑一遍Tarjan, 如果某条满流边的两端处于同一SCC中则说明它不一定满流. (因为可以找出包含反向边的环, 增广之后就不满流了.)

3.12.2 最小割

首先牢记最小割的定义: 选权值和尽量小的一些边, 使得删除这些边之后 s 无法到达 t .

- 最小割输出一种方案

在残量网络上从 S 开始floodfill, 源点可达的记为 S 集, 不可达的记为 T , 如果一条边的起点在 S 集而终点在 T 集, 就将其加入最小割中.

- 最小割的可行边与必须边

- 可行边: 满流, 且残量网络上不存在 u 到 v 的路径, 也就是 u 和 v 不在同一SCC中. (实际上也就是最大流必定满流的边.)
- 必须边: 满流, 且残量网络上 S 可达 u , v 可达 T .

- 字典序最小的最小割

直接按字典序从小到大的顺序依次判断每条边能否在最小割中即可.

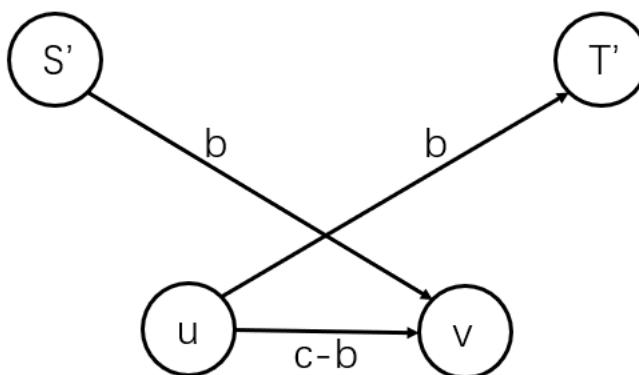
如果一条边是可行边, 我们就需要把它删掉, 同时进行退流, $u \rightarrow s$ 和 $t \rightarrow v$ 都退掉等同于这条边容量的流量.

退流用Dinic实现即可.

3.12.3 上下界网络流

无源汇上下界可行流

新建源汇 S' , T' , 然后如图所示转化每一条边.



在新图跑一遍最大流之后检查一遍辅助边, 如果有辅助边没满流则无解, 否则把每条边的流量加上 b 就是一组可行方案.

有源汇上下界最大流

如果不需判断是否有解的话可以直接按照和上面一样的方法转化. 因为附加边实际上算了两次流量, 所以最终答案应该减掉所有下界之和.

(另外这里如果要压缩附加边的话, 不能像无源汇的情况一样对每个点只开一个变量统计溢出的流量, 正确的做法是进出流量各统计一下, 每个点连两条附加边.)

如果需要判有解的话会出一点问题. 这时候就需要转化成无源汇的情况, 验证有解之后撤掉 T 到 S 的那条附加边再从 S 到 T 跑一遍最大流.

```

1 int ex[maxn], id[maxn];
2
3 int main() {
4
5     memset(last, -1, sizeof(last));
6
7     int n, m, src, sink;
8     scanf("%d%d%d", &n, &m, &src, &sink);
9     s = n + 1;
10    t = n + 2;
11
12    while (m--) {
13        int x, y, b, c;
14        scanf("%d%d%d%d", &x, &y, &b, &c);
15
16        addedge(x, y, c - b);
17
18        ex[y] += b;
19        ex[x] -= b;
20    }
21
22    for (int i = 1; i <= n; i++) {
23        id[i] = cte;
24
25        if (ex[i] >= 0)
26            addedge(s, i, ex[i]);
27        else
28            addedge(i, t, -ex[i]);
29    }
30
31    addedge(sink, src, (~0u) >> 1);
32
33    Dinic();
34
35    if (any_of(id + 1, id + n + 1, [] (int i) {return
36        ~bool e[i].cap;})) {
37        printf("please go home to sleep\n");
38    } else {
39        int flow = e[cte - 1].cap;
40        e[cte - 1].cap = e[cte - 2].cap = 0;
41        s = src;
42        t = sink;
43
44        printf("%d\n", flow + Dinic());
45    }
46
47 }
```

有源汇上下界最小流

按照上面的方法转换后先跑一遍最大流, 然后撤掉超级源汇和附加边, 反过来跑一次最大流退流, 最大流减去退掉的流量就是最小流.

3.12.4 常见建图方法

- **最大流/费用流**

流量不是很多的时候可以理解成很多条路径，并且每条边可以经过的次数有限。

- **最小割**

常用的模型是**最大权闭合子图**。当然它并不是万能的，因为限制条件可以带权值。

1. 如果某些点全部在S集或者T集则获得一个正的收益

把这个条件建成一个点，向要求的点连 ∞ 边，然后s向它连 ∞ 边。
(如果是T集就都反过来)

那么如果它在S集就一定满足它要求的点都在S集，反之如果是T集亦然。

2. 如果两个点不在同一集合中则需要付出代价

建双向边，那显然如果它们不在同一集合中就需要割掉中间的边，付出对应的代价。

3. 二分图，如果相邻的两个点在同一集合则需要付出代价

染色后给一半的点反转源汇，就转换成上面的问题了。

3.12.5 例题

- 费用流

1. 序列上选和尽量大的数，但连续 k 个数中最多选 p 个。

费用流建图，先建一条 $n + 1$ 个点的无限容量的链表示不选，然后每个点往后面 k 个位置连边，答案是流量为 p 的最大费用流。因为条件等价于选 p 次并且每次选的所有数间隔都至少是 k 。

2. 还要求连续 k 个数中最少选 q 个。

任选一个位置把图前后切开就会发现通过截面的流量总和恰为 p 。注意到如果走了最开始的链就代表不选，因此要限制至少有 q 的流量不走链，那么只需要把链的容量改成 $p - q$ 就行了。

3.13 Prufer序列

对一棵有 $n \geq 2$ 个结点的树，它的Prufer编码是一个长为 $n - 2$ ，且每个数都在 $[1, n]$ 内的序列。

构造方法：每次选取编号最小的叶子结点，记录它的父亲，然后把它删掉，直到只剩两个点为止。（并且最后剩的两个点一定有一个是 n 号点。）

相应的，由Prufer编码重构树的方法：按顺序读入序列，每次选取编号最小的且度数为1的结点，把这个点和序列当前点连上，然后两个点剩余度数同时-1。

Prufer编码的性质

- 每个至少2个结点的树都唯一对应一个Prufer编码。（当然也就去做无根树哈希。）
- 每个点在Prufer序列中出现的次数恰好是度数-1。所以如果给定某些点的度数然后求方案数，就可以用简单的组合数解决。

最后，构造和重构直接写都是 $O(n \log n)$ 的，想优化成线性需要一些技巧。

线性求Prufer序列代码：

```

1 // 0-based
2 vector<vector<int>> adj;
3 vector<int> parent;
4
5 void dfs(int v) {
6     for (int u : adj[v]) {
7         if (u != parent[v]) parent[u] = v, dfs(u);
8     }
9 }
10
11 vector<int> pruefer_code() { // pruefer是德语
12     int n = adj.size();
13     parent.resize(n), parent[n - 1] = -1;
14     dfs(n - 1);
15 }
```

```

16     int ptr = -1;
17     vector<int> degree(n);
18     for (int i = 0; i < n; i++) {
19         degree[i] = adj[i].size();
20         if (degree[i] == 1 && ptr == -1) ptr = i;
21     }
22
23     vector<int> code(n - 2);
24     int leaf = ptr;
25     for (int i = 0; i < n - 2; i++) {
26         int next = parent[leaf];
27         code[i] = next;
28         if (--degree[next] == 1 && next < ptr)
29             leaf = next;
30         else {
31             ptr++;
32             while (degree[ptr] != 1)
33                 ptr++;
34             leaf = ptr;
35         }
36     }
37     return code;
38 }
```

线性重构树代码：

```

1 // 0-based
2 vector<pair<int, int>> pruefer_decode(vector<int> const
3 &code) {
4     int n = code.size() + 2;
5     vector<int> degree(n, 1);
6     for (int i : code) degree[i]++;
7
8     int ptr = 0;
9     while (degree[ptr] != 1) ptr++;
10    int leaf = ptr;
11
12    vector<pair<int, int>> edges;
13    for (int v : code) {
14        edges.emplace_back(leaf, v);
15        if (--degree[v] == 1 && v < ptr)
16            leaf = v;
17        else {
18            ptr++;
19            while (degree[ptr] != 1)
20                ptr++;
21            leaf = ptr;
22        }
23    }
24    edges.emplace_back(leaf, n - 1);
25    return edges;
26 }
```

3.14 弦图相关

Forked from the template of NEW CODE!!.

1. 团数 \leq 色数，弦图团数 = 色数
2. 设 $next(v)$ 表示 $N(v)$ 中最前的点。令 w^* 表示所有满足 $A \in B$ 的 w 中最后的一个点，判断 $v \cup N(v)$ 是否为极大团，只需判断是否存在一个 w ，满足 $Next(w) = v$ 且 $|N(v)| + 1 \leq |N(w)|$ 即可。
3. 最小染色：完美消除序列从后往前依次给每个点染色，给每个点染上可以染的最小的颜色
4. 最大独立集：完美消除序列从前往后能选就选
5. 弦图最大独立集数 = 最小团覆盖数，最小团覆盖：设最大独立集为 $\{p_1, p_2, \dots, p_t\}$ ，则 $\{p_1 \cup N(p_1), \dots, p_t \cup N(p_t)\}$ 为最小团覆盖

3.15 其他

3.15.1 Stoer-Wagner全局最小割

```

1 const int N = 601;
2 int fa[N], siz[N], edge[N][N];
3
4 int find(int x) {
5     return fa[x] == x ? x : fa[x] = find(fa[x]);
6 }
7
8 int dist[N], vis[N], bin[N];
9 int n, m;
10
11 int contract(int& s, int& t) { // Find s, t
12     memset(dist, 0, sizeof(dist));
13     memset(vis, false, sizeof(vis));
14
15     int i, j, k, mincut, maxc;
16
17     for (i = 1; i ≤ n; i++) {
18         k = -1;
19         maxc = -1;
20
21         for (j = 1; j ≤ n; j++)
22             if (!bin[j] && !vis[j] && dist[j] > maxc) {
23                 k = j;
24                 maxc = dist[j];
25             }
26
27         if (k == -1)
28             return mincut;
29
30         s = t;
31         t = k;
32         mincut = maxc;
33         vis[k] = true;
34
35         for (j = 1; j ≤ n; j++)
36             if (!bin[j] && !vis[j]) dist[j] += edge[k]
37                 → [j];
38
39     return mincut;
40 }
41
42 const int inf = 0x3f3f3f3f;
43
44 int Stoer_Wagner() {
45     int mincut, i, j, s, t, ans;
46     for (mincut = inf, i = 1; i < n; i++) {
47         ans = contract(s, t);
48         bin[t] = true;
49
50         if (mincut > ans)
51             mincut = ans;
52         if (mincut == 0)
53             return 0;
54
55         for (j = 1; j ≤ n; j++)
56             if (!bin[j])
57                 edge[s][j] = (edge[j][s] += edge[j]
58                 → [t]);
59
60     return mincut;
61 }
62
63 int main() {
64     cin >> n >> m;

```

```

65     if (m < n - 1) {
66         cout << 0;
67         return 0;
68     }
69
70     for (int i = 1; i ≤ n; ++i)
71         fa[i] = i, siz[i] = 1;
72
73     for (int i = 1, u, v, w; i ≤ m; ++i) {
74         cin >> u >> v >> w;
75
76         int fu = find(u), fv = find(v);
77         if (fu != fv) {
78             if (siz[fu] > siz[fv]) swap(fu, fv);
79             fa[fu] = fv, siz[fv] += siz[fu];
80         }
81
82         edge[u][v] += w, edge[v][u] += w;
83     }
84
85     int fr = find(1);
86
87     if (siz[fr] != n) {
88         cout << 0;
89         return 0;
90     }
91
92     cout << Stoer_Wagner();
93
94     return 0;
95 }
96

```

4 数据结构

4.1 线段树

4.1.1 非递归线段树

- 如果 $M = 2^k$, 则只能维护 $[1, M - 2]$ 范围
- 找叶子: i 对应的叶子就是 $i + M$
- 单点修改: 找到叶子然后向上跳
- 区间查询: 左右区间各扩展一位, 转换成开区间查询

```

1 int query(int l, int r) {
2     l += M - 1;
3     r += M + 1;
4
5     int ans = 0;
6     while (l ^ r != 1) {
7         ans += sum[l ^ 1] + sum[r ^ 1];
8
9         l >>= 1;
10        r >>= 1;
11    }
12
13    return ans;
14 }
```

区间修改要标记永久化, 并且求区间和求最值的代码不太一样.

区间加, 区间求和

```

1 void update(int l, int r, int d) {
2     int len = 1, cntl = 0, cntr = 0; // cntl, cntr 是左右
3     // 两边分别实际修改的区间长度
4     for (l += n - 1, r += n + 1; l ^ r ^ 1; l >= 1, r
5     // >= 1, len <= 1) {
6         tree[l] += cntl * d, tree[r] += cntr * d;
7         if (~l & 1) tree[l ^ 1] += d * len, mark[l ^ 1]
8         // += d, cntl += len;
9         if (r & 1) tree[r ^ 1] += d * len, mark[r ^ 1]
10        // += d, cntr += len;
11    }
12
13    for (; l; l >= 1, r >= 1)
14        tree[l] += cntl * d, tree[r] += cntr * d;
15
16 int query(int l, int r) {
17     int ans = 0, len = 1, cntl = 0, cntr = 0;
18     for (l += n - 1, r += n + 1; l ^ r ^ 1; l >= 1, r
19     // >= 1, len <= 1) {
20         ans += cntl * mark[l] + cntr * mark[r];
21         if (~l & 1) ans += tree[l ^ 1], cntl += len;
22         if (r & 1) ans += tree[r ^ 1], cntr += len;
23     }
24
25     for (; l; l >= 1, r >= 1)
26         ans += cntl * mark[l] + cntr * mark[r];
27
28     return ans;
29 }
```

区间加, 区间求最大值

```

1 void update(int l, int r, int d) {
2     for (l += N - 1, r += N + 1; l ^ r ^ 1; l >= 1, r
3     // >= 1) {
4         if (l < N) {
5             tree[l] = max(tree[l < 1], tree[l < 1 |
6             // 1]) + mark[l];
7         }
8     }
9 }
```

```

5         tree[r] = max(tree[r < 1], tree[r < 1 |
6             // 1]) + mark[r];
7     }
8
9     if (~l & 1) {
10        tree[l ^ 1] += d;
11        mark[l ^ 1] += d;
12    }
13    if (r & 1) {
14        tree[r ^ 1] += d;
15        mark[r ^ 1] += d;
16    }
17
18    for (; l; l >= 1, r >= 1)
19        if (l < N) tree[l] = max(tree[l < 1], tree[l
20        // < 1 | 1]) + mark[l],
21        tree[r] = max(tree[r < 1], tree[r
22        // < 1 | 1]) + mark[r];
23
24 int query(int l, int r) {
25     int maxl = -INF, maxr = -INF;
26
27     for (l += N - 1, r += N + 1; l ^ r ^ 1; l >= 1, r
28     // >= 1) {
29         maxl += mark[l];
30         maxr += mark[r];
31
32         if (~l & 1)
33             maxl = max(maxl, tree[l ^ 1]);
34         if (r & 1)
35             maxr = max(maxr, tree[r ^ 1]);
36
37         while (l) {
38             maxl += mark[l];
39             maxr += mark[r];
40
41             l >>= 1;
42             r >>= 1;
43         }
44
45     return max(maxl, maxr);
46 }
```

4.1.2 线段树维护矩形并

为线段树的每个结点维护 $cover_i$ 表示这个区间被完全覆盖的次数. 更新时分情况讨论, 如果当前区间已被完全覆盖则长度就是区间长度, 否则长度是左右儿子相加.

```

1 constexpr int maxn = 100005, maxm = maxn * 70;
2
3 int lc[maxm], rc[maxm], cover[maxm], sum[maxm], root,
4     // seg_cnt;
5 int s, t, d;
6
7 void refresh(int l, int r, int o) {
8     if (cover[o])
9         sum[o] = r - l + 1;
10    else
11        sum[o] = sum[lc[o]] + sum[rc[o]];
12
13 void modify(int l, int r, int &o) {
14     if (!o)
15         o = ++seg_cnt;
16
17     if (s <= l && t >= r) {
```

```

18     cover[o] += d;
19     refresh(l, r, o);

20     return;
21 }

22 int mid = (l + r) / 2;

23 if (s <= mid)
24     modify(l, mid, lc[o]);
25 if (t > mid)
26     modify(mid + 1, r, rc[o]);

27 refresh(l, r, o);
28 }

29 struct modi {
30     int x, l, r, d;
31
32     bool operator < (const modi &o) {
33         return x < o.x;
34     }
35 } a[maxn * 2];
36
37 int main() {
38
39     int n;
40     scanf("%d", &n);
41
42     for (int i = 1; i <= n; i++) {
43         int lx, ly, rx, ry;
44         scanf("%d%d%d%d", &lx, &ly, &rx, &ry);
45
46         a[i * 2 - 1] = {lx, ly + 1, ry, 1};
47         a[i * 2] = {rx, ly + 1, ry, -1};
48     }
49
50     sort(a + 1, a + n * 2 + 1);
51
52     int last = -1;
53     long long ans = 0;
54
55     for (int i = 1; i <= n * 2; i++) {
56         if (last != -1)
57             ans += (long long)(a[i].x - last) * sum[1];
58         last = a[i].x;
59
60         s = a[i].l;
61         t = a[i].r;
62         d = a[i].d;
63
64         modify(1, 1e9, root);
65     }
66
67     printf("%lld\n", ans);
68
69     return 0;
70 }

```

4.1.3 历史和

EC-Final2020 G, 原题是询问某个区间有多少子区间, 满足子区间中数的种类数为奇数.

离线之后转化成枚举右端点并用线段树维护左端点, 然后就是一个支持区间反转(0/1互换)和询问历史和的线段树.

“既然标记会复合 就说明在两个标记中间没有经过任何 pushup 操作

也就是说一个这两个标记对应着 相同的 0 的数量 以及 相同的 1 的数量

那么标记对于答案的影响只能是 $a * 0 + b * 1$
我们维护 a b 即可”

```

1 #include <bits/stdc++.h>
2
3 using namespace std;
4
5 constexpr int maxn = (1 << 20) + 5;
6
7 int cnt[maxn][2], mul[maxn][2];
8 bool rev[maxn];
9 long long sum[maxn];
10
11 int now;
12
13 void build(int l, int r, int o) {
14     cnt[o][0] = r - l + 1;
15
16     if (l == r)
17         return;
18
19     int mid = (l + r) / 2;
20
21     build(l, mid, o * 2);
22     build(mid + 1, r, o * 2 + 1);
23 }
24
25 void apply(int o, bool flip, long long w0, long long
26            → w1) {
27     sum[o] += w0 * cnt[o][0] + w1 * cnt[o][1];
28
29     if (flip)
30         swap(cnt[o][0], cnt[o][1]);
31
32     if (rev[o])
33         swap(w0, w1);
34
35     mul[o][0] += w0;
36     mul[o][1] += w1;
37     rev[o] ^= flip;
38 }
39
40 void pushdown(int o) {
41     if (!mul[o][0] && !mul[o][1] && !rev[o])
42         return;
43
44     apply(o * 2, rev[o], mul[o][0], mul[o][1]);
45     apply(o * 2 + 1, rev[o], mul[o][0], mul[o][1]);
46
47     mul[o][0] = mul[o][1] = 0;
48     rev[o] = false;
49 }
50
51 void update(int o) {
52     cnt[o][0] = cnt[o * 2][0] + cnt[o * 2 + 1][0];
53     cnt[o][1] = cnt[o * 2][1] + cnt[o * 2 + 1][1];
54
55     sum[o] = sum[o * 2] + sum[o * 2 + 1];
56 }
57
58 int s, t;
59
60 void modify(int l, int r, int o) {
61     if (s <= l && t >= r) {
62         apply(o, true, 0, 0);
63         return;
64     }
65
66     int mid = (l + r) / 2;
67     pushdown(o);

```

```

67     if (s <= mid)
68         modify(l, mid, o * 2);
69     if (t > mid)
70         modify(mid + 1, r, o * 2 + 1);
71
72     update(o);
73 }
74
75 long long query(int l, int r, int o) {
76     if (s <= l && t >= r)
77         return sum[o];
78
79     int mid = (l + r) / 2;
80     pushdown(o);
81
82     long long ans = 0;
83     if (s <= mid)
84         ans += query(l, mid, o * 2);
85     if (t > mid)
86         ans += query(mid + 1, r, o * 2 + 1);
87
88     return ans;
89 }
90
91 vector<pair<int, int>> vec[maxn]; // pos, id
92 long long ans[maxn];
93 int a[maxn], last[maxn];
94
95 int main() {
96
97     int n;
98     scanf("%d", &n);
99
100    build(1, n, 1);
101
102    for (int i = 1; i <= n; i++)
103        scanf("%d", &a[i]);
104
105    int m;
106    scanf("%d", &m);
107
108    for (int i = 1; i <= m; i++) {
109        int l, r;
110        scanf("%d%d", &l, &r);
111
112        vec[r].emplace_back(l, i);
113    }
114
115    for (int i = 1; i <= n; i++) {
116        s = last[a[i]] + 1;
117        t = now = i;
118
119        modify(1, n, 1);
120        apply(1, false, 0, 1);
121
122        for (auto [l, k] : vec[i]) {
123            s = l;
124            ans[k] = query(1, n, 1);
125        }
126
127        last[a[i]] = i;
128    }
129
130    for (int i = 1; i <= m; i++)
131        printf("%lld\n", ans[i]);
132
133    return 0;
134 }
135

```

136 }

4.2 陈丹琦分治

4.2.1 动态图连通性(分治并查集)

```

1  vector<pair<int, int>> seg[(1 << 22) + 5];
2
3  int s, t;
4  pair<int, int> d;
5
6  void add(int l, int r, int o) {
7      if (s > t)
8          return;
9
10     if (s <= l && t >= r) {
11         seg[o].push_back(d);
12         return;
13     }
14
15     int mid = (l + r) / 2;
16
17     if (s <= mid)
18         add(l, mid, o * 2);
19     if (t > mid)
20         add(mid + 1, r, o * 2 + 1);
21 }
22
23 int ufs[maxn], sz[maxn], stk[maxn], top;
24
25 int findufs(int x) {
26     while (ufs[x] != x)
27         x = ufs[x];
28
29     return ufs[x];
30 }
31
32 void link(int x, int y) {
33     x = findufs(x);
34     y = findufs(y);
35
36     if (x == y)
37         return;
38
39     if (sz[x] < sz[y])
40         swap(x, y);
41
42     ufs[y] = x;
43     sz[x] += sz[y];
44     stk[++top] = y;
45 }
46
47 int ans[maxm];
48
49 void solve(int l, int r, int o) {
50     int tmp = top;
51
52     for (auto pi : seg[o])
53         link(pi.first, pi.second);
54
55     if (l == r)
56         ans[l] = top;
57     else {
58         int mid = (l + r) / 2;
59
60         solve(l, mid, o * 2);
61         solve(mid + 1, r, o * 2 + 1);
62     }
63 }

```

```

64     for (int i = top; i > tmp; i--) {
65         int x = stk[i];
66
67         sz[ufs[x]] -= sz[x];
68         ufs[x] = x;
69     }
70
71     top = tmp;
72 }
73
74 map<pair<int, int>, int> mp;

```

4.2.2 四维偏序

```

1 // 四维偏序
2
3 void CDQ1(int l, int r) {
4     if (l >= r)
5         return;
6
7     int mid = (l + r) / 2;
8
9     CDQ1(l, mid);
10    CDQ1(mid + 1, r);
11
12    int i = l, j = mid + 1, k = l;
13
14    while (i <= mid && j <= r) {
15        if (a[i].x < a[j].x) {
16            a[i].ins = true;
17            b[k++] = a[i++];
18        }
19        else {
20            a[j].ins = false;
21            b[k++] = a[j++];
22        }
23    }
24
25    while (i <= mid) {
26        a[i].ins = true;
27        b[k++] = a[i++];
28    }
29
30    while (j <= r) {
31        a[j].ins = false;
32        b[k++] = a[j++];
33    }
34
35    copy(b + l, b + r + 1, a + l); // 后面的分治会破坏排
36    ↳ 序, 所以要复制一份
37
38    CDQ2(l, r);
39
40 void CDQ2(int l, int r) {
41     if (l >= r)
42         return;
43
44     int mid = (l + r) / 2;
45
46     CDQ2(l, mid);
47     CDQ2(mid + 1, r);
48
49     int i = l, j = mid + 1, k = l;
50
51     while (i <= mid && j <= r) {
52         if (b[i].y < b[j].y) {
53             if (b[i].ins)
54                 add(b[i].z, 1); // 树状数组

```

```

55
56         t[k++] = b[i++];
57     }
58     else{
59         if (!b[j].ins)
60             ans += query(b[j].z - 1);
61
62         t[k++] = b[j++];
63     }
64
65
66     while (i <= mid) {
67         if (b[i].ins)
68             add(b[i].z, 1);
69
70         t[k++] = b[i++];
71     }
72
73     while (j <= r) {
74         if (!b[j].ins)
75             ans += query(b[j].z - 1);
76
77         t[k++] = b[j++];
78     }
79
80     for (i = l; i <= mid; i++)
81         if (b[i].ins)
82             add(b[i].z, -1);
83
84     copy(t + l, t + r + 1, b + l);
85 }

```

4.3 整体二分

修改和询问都要划分, 备份一下, 递归之前copy回去.

如果是满足可减性的问题(例如查询区间k小数)可以直接在划分的时候把查询的k修改一下. 否则需要维护一个全局的数据结构, 一般来说可以先递归右边再递归左边, 具体维护方法视情况而定.

以下代码以ZJOI K大数查询为例(区间都添加一个数, 查询区间k大数).

```

1 int op[maxn], ql[maxn], qr[maxn]; // 1: modify 2:
2   ↳ query
3 long long qk[maxn]; // 修改和询问可以一起存
4
5 int ans[maxn];
6
7 void solve(int l, int r, vector<int> v) { // 如果想卡常
8   ↳ 可以用数组, 然后只需要传一个数组的l, r; 递归的时候类
9   ↳ 似归并反过来, 开两个辅助数组, 处理完再复制回去即可
10    if (v.empty())
11        return;
12
13    if (l == r) {
14        for (int i : v)
15            if (op[i] == 2)
16                ans[i] = l;
17
18        return;
19    }
20
21    int mid = (l + r) / 2;
22
23    vector<int> vl, vr;
24
25    for (int i : v) {
26        if (op[i] == 1) {
27            if (qk[i] <= mid)
28
```

```

25     |     vl.push_back(i);
26     |     else {
27     |         update(ql[i], qr[i], 1); // update是区间
28     |         ↪ 加
29     |         vr.push_back(i);
30     |     }
31     |     else {
32     |         long long tmp = query(ql[i], qr[i]);
33
34         if (qk[i] ≤ tmp) // 因为是k大数查询
35             vr.push_back(i);
36         else {
37             qk[i] -= tmp;
38             vl.push_back(i);
39         }
40     }
41 }
42
43 for (int i : vr)
44     if (op[i] == 1)
45         update(ql[i], qr[i], -1);
46
47 v.clear();
48
49 solve(l, mid, vl);
50 solve(mid + 1, r, vr);
51 }

52
53 int main() {
54     int n, m;
55     scanf("%d%d", &n, &m);

56     M = 1;
57     while (M < n + 2)
58         M *= 2;

59
60     for (int i = 1; i ≤ m; i++)
61         scanf("%d%d%d%lld", &op[i], &ql[i], &qr[i],
62               ↪ &qk[i]);

63
64     vector<int> v;
65     for (int i = 1; i ≤ m; i++)
66         v.push_back(i);

67
68     solve(1, 1e9, v);

69
70     for (int i = 1; i ≤ m; i++)
71         if (op[i] == 2)
72             printf("%d\n", ans[i]);
73
74     return 0;
75 }

```

4.4 平衡树

pb_ds平衡树参见8.11.Public Based DataStructure(PB_DS)
(90页).

4.4.1 Treap

```

1 // 注意: 相同键值可以共存
2
3 struct node { // 结点类定义
4     int key, size, p; // 分别为键值, 子树大小, 优先度
5     node *ch[2]; // 0表示左儿子, 1表示右儿子
6
7     node(int key = 0) : key(key), size(1), p(rand()) {}
8

```

```

9     void refresh() {
10         size = ch[0] → size + ch[1] → size + 1;
11         } // 更新子树大小(和附加信息, 如果有的话)
12     } null[maxn], *root = null, *ptr = null; // 数组名叫
13     ↪ 做null是为了方便开哨兵节点
14     // 如果需要删除而空间不能直接开下所有结点, 则需要再写一个
15     ↪ 垃圾回收
16     // 注意: 数组里的元素一定不能delete, 否则会导致RE
17     // 重要! 在主函数最开始一定要加上以下预处理:
18     null → ch[0] = null → ch[1] = null;
19     null → size = 0;
20
21     // 伪构造函数 O(1)
22     // 为了方便, 在结点类外面再定义一个伪构造函数
23     node *newnode(int x) { // 键值为x
24         ***ptr = node(x);
25         ptr → ch[0] = ptr → ch[1] = null;
26         return ptr;
27     }
28
29     // 插入键值 期望O(log n)
30     // 需要调用旋转
31     void insert(int x, node *&rt) { // rt为当前结点, 建议调
32         → 用时传入root, 下同
33         if (rt == null) {
34             rt = newnode(x);
35             return;
36         }
37
38         int d = x > rt → key;
39         insert(x, rt → ch[d]);
40         rt → refresh();
41
42         if (rt → ch[d] → p < rt → p)
43             rot(rt, d ^ 1);
44
45     // 删除一个键值 期望O(log n)
46     // 要求键值必须存在至少一个, 否则会导致RE
47     // 需要调用旋转
48     void erase(int x, node *&rt) {
49         if (x == rt → key) {
50             if (rt → ch[0] != null && rt → ch[1] != null)
51                 → {
52                     int d = rt → ch[0] → p < rt → ch[1] →
53                         ↪ p;
54                     rot(rt, d);
55                     erase(x, rt → ch[d]);
56                 }
57             else
58                 rt = rt → ch[rt → ch[0] == null];
59         }
60         else
61             erase(x, rt → ch[x > rt → key]);
62     }
63
64     // 求元素的排名(严格小于键值的个数 + 1) 期望O(log n)
65     // 非递归
66     int rank(int x, node *rt) {
67         int ans = 1, d;
68         while (rt != null) {
69             if ((d = x > rt → key))
70                 ans += rt → ch[0] → size + 1;
71
72             rt = rt → ch[d];
73         }
74     }

```

```

73 }
74
75     return ans;
76 }
77
78 // 返回排名第k(从1开始)的键值对应的指针 期望O(log n)
79 // 非递归
80 node *kth(int x, node *rt) {
81     int d;
82     while (rt != null) {
83         if (x == rt → ch[0] → size + 1)
84             return rt;
85
86         if ((d = x > rt → ch[0] → size))
87             x -= rt → ch[0] → size + 1;
88
89         rt = rt → ch[d];
90     }
91
92     return rt;
93 }
94
95 // 返回前驱(最大的比给定键值小的键值)对应的指针 期
96 // →望O(log n)
97 // 非递归
98 node *pred(int x, node *rt) {
99     node *y = null;
100    int d;
101
102    while (rt != null) {
103        if ((d = x > rt → key))
104            y = rt;
105
106        rt = rt → ch[d];
107    }
108
109    return y;
110 }
111
112 // 返回后继(最小的比给定键值大的键值)对应的指针 期
113 // →望O(log n)
114 // 非递归
115 node *succ(int x, node *rt) {
116     node *y = null;
117     int d;
118
119     while (rt != null) {
120         if ((d = x < rt → key))
121             y = rt;
122
123         rt = rt → ch[d ^ 1];
124     }
125
126     return y;
127 }
128
129 // 旋转(Treap版本) O(1)
130 // 平衡树基础操作
131 // 要求对应儿子必须存在, 否则会导致后续各种莫名其妙的问题
132 void rot(node *&x, int d) { // x为被转下去的结点, 会被修
133     // 改以维护树结构
134     node *y = x → ch[d ^ 1];
135
136     x → ch[d ^ 1] = y → ch[d];
137     y → ch[d] = x;
138
139     x → refresh();
140     (x = y) → refresh();
141 }

```

4.4.2 无旋Treap/可持久化Treap

```

1 struct node {
2     int val, size;
3     node *ch[2];
4
5     node(int val) : val(val), size(1) {}
6
7     inline void refresh() {
8         size = ch[0] → size + ch[1] → size;
9     }
10
11 } null[maxn];
12
13 node *copied(node *x) { // 如果不用可持久化的话, 直接用
14     //就行了
15     return new node(*x);
16 }
17
18 node *merge(node *x, node *y) {
19     if (x == null)
20         return y;
21     if (y == null)
22         return x;
23
24     node *z;
25     if (rand() % (x → size + y → size) < x → size)
26         z = copied(y);
27         z → ch[0] = merge(x, y → ch[0]);
28     else {
29         z = copied(x);
30         z → ch[1] = merge(x → ch[1], y);
31     }
32
33     z → refresh(); // 因为每次只有一边会递归到儿子, 所
34     // →以z不可能取到null
35     return z;
36 }
37
38 pair<node*, node*> split(node *x, int k) { // 左边大小
39     // →为k
40     if (x == null)
41         return make_pair(null, null);
42
43     pair<node*, node*> pi(null, null);
44
45     if (k ≤ x → ch[0] → size) {
46         pi = split(x → ch[0], k);
47
48         node *z = copied(x);
49         z → ch[0] = pi.second;
50         z → refresh();
51         pi.second = z;
52     }
53     else {
54         pi = split(x → ch[1], k - x → ch[0] → size -
55         // → 1);
56
57         node *y = copied(x);
58         y → ch[1] = pi.first;
59         y → refresh();
60         pi.first = y;
61     }
62
63     return pi;
64 }

```

```

64 // 记得初始化null
65 int main() {
66     for (int i = 0; i <= n; i++)
67         null[i].ch[0] = null[i].ch[1] = null;
68     null → size = 0;
69
70     // do something
71
72     return 0;
73 }

```

4.4.3 Splay

如果插入的话可以直接找到底然后splay一下, 也可以直接splay前驱后继.

```

1 #define dir(x) ((x) == (x) → p → ch[1])
2
3 struct node {
4     int size;
5     bool rev;
6     node *ch[2], *p;
7
8     node() : size(1), rev(false) {}
9
10    void pushdown() {
11        if (!rev)
12            return;
13
14        ch[0] → rev ≈ true;
15        ch[1] → rev ≈ true;
16        swap(ch[0], ch[1]);
17
18        rev=false;
19    }
20
21    void refresh() {
22        size = ch[0] → size + ch[1] → size + 1;
23    }
24 } null[maxn], *root = null;
25
26 void rot(node *x, int d) {
27     node *y = x → ch[d ^ 1];
28
29     if ((x → ch[d ^ 1] = y → ch[d]) != null)
30         y → ch[d] → p = x;
31     ((y → p = x → p) != null ? x → p → ch[dir(x)] :
32         → root) = y;
33     (y → ch[d] = x) → p = y;
34
35     x → refresh();
36     y → refresh();
37 }
38
39 void splay(node *x, node *t) {
40     while (x → p != t) {
41         if (x → p → p == t) {
42             rot(x → p, dir(x) ^ 1);
43             break;
44         }
45
46         if (dir(x) == dir(x → p))
47             rot(x → p → p, dir(x → p) ^ 1);
48         else
49             rot(x → p, dir(x) ^ 1);
50     rot(x → p, dir(x) ^ 1);
51 }
52
53 node *kth(int k, node *o) {

```

```

54     int d;
55     k++; // 因为最左边有一个哨兵
56
57     while (o != null) {
58         o → pushdown();
59
60         if (k == o → ch[0] → size + 1)
61             return o;
62
63         if ((d = k > o → ch[0] → size)) {
64             k -= o → ch[0] → size + 1;
65             o = o → ch[d];
66         }
67
68         return null;
69     }
70
71 void reverse(int l, int r) {
72     splay(kth(l - 1));
73     splay(kth(r + 1), root);
74
75     root → ch[1] → ch[0] → rev ≈ true;
76 }
77
78 int n, m;
79
80 int main() {
81     null → size = 0;
82     null → ch[0] = null → ch[1] = null → p = null;
83
84     scanf("%d%d", &n, &m);
85     root = null + n + 1;
86     root → ch[0] = root → ch[1] = root → p = null;
87
88     for (int i = 1; i <= n; i++) {
89         null[i].ch[1] = null[i].p = null;
90         null[i].ch[0] = root;
91         root → p = null + i;
92         (root = null + i) → refresh();
93     }
94
95     null[n + 2].ch[1] = null[n + 2].p = null;
96     null[n + 2].ch[0] = root; // 这里直接建成一条链的,
97     // 如果想减少常数也可以递归建一个平衡的树
98     root → p = null + n + 2; // 总之记得建两个哨兵, 这
99     // 样splay起来不需要特判
100    (root = null + n + 2) → refresh();
101
102    // Do something
103 }

```

4.5 树链剖分

4.5.1 动态树形DP(最大权独立集)

```

1 #include <bits/stdc++.h>
2
3 using namespace std;
4
5 constexpr int maxn = 100005, maxm = 262155, inf =
6     → 0x3f3f3f3f;
7
8 struct binary_heap {
9     priority_queue<int> q, t;
10
11     binary_heap() {}

```

```

11     void push(int x) {
12         q.push(x);
13     }
14
15     void erase(int x) {
16         t.push(x);
17     }
18
19     int top() {
20         while (!t.empty() && q.top() == t.top()) {
21             q.pop();
22             t.pop();
23         }
24
25         return q.top();
26     }
27 } heap;
28
29 int pool[maxm][2][2], (*pt)[2][2] = pool;
30
31 void merge(int a[2][2], int b[2][2]) {
32     static int c[2][2];
33     memset(c, 0, sizeof(c));
34
35     for (int i = 0; i < 2; i++)
36         for (int j = 0; j < 2; j++)
37             for (int k = 0; k < 2; k++)
38                 if (!(j && k))
39                     for (int t = 0; t < 2; t++)
40                         c[i][t] = max(c[i][t], a[i][j]
41                                         + b[k][t]);
42
43     memcpy(a, c, sizeof(c));
44 }
45
46 vector<pair<int, int>> tw;
47
48 struct seg_tree {
49     int (*tr)[2][2], n;
50
51     int s, d[2];
52
53     seg_tree() {}
54
55     void update(int o) {
56         memcpy(tr[o], tr[o * 2], sizeof(int) * 4);
57         merge(tr[o], tr[o * 2 + 1]);
58     }
59
60     void build(int l, int r, int o) {
61         if (l == r) {
62             tr[o][0][0] = tw[l - 1].first;
63             tr[o][0][1] = tr[o][1][0] = -inf;
64             tr[o][1][1] = tw[l - 1].second;
65
66             return;
67         }
68
69         int mid = (l + r) / 2;
70
71         build(l, mid, o * 2);
72         build(mid + 1, r, o * 2 + 1);
73
74         update(o);
75     }
76
77     void modify(int l, int r, int o) {
78         if (l == r) {
79             tr[o][0][0] = d[0];
80             tr[o][0][1] = tr[o][1][0] = -inf;
81             tr[o][1][1] = d[1];
82
83             return;
84         }
85
86         int mid = (l + r) / 2;
87
88         if (s <= mid)
89             modify(l, mid, o * 2);
90         else
91             modify(mid + 1, r, o * 2 + 1);
92
93         update(o);
94     }
95
96     int getval() {
97         int ans = 0;
98         for (int i = 0; i < 2; i++)
99             for (int j = 0; j < 2; j++)
100                 ans = max(ans, tr[1][i][j]);
101
102         return ans;
103     }
104
105     pair<int, int> getpair() {
106         int ans[2] = {0};
107         for (int i = 0; i < 2; i++)
108             for (int j = 0; j < 2; j++)
109                 ans[i] = max(ans[i], tr[1][i][j]);
110
111         return make_pair(ans[0], ans[1]);
112     }
113
114     void build(int len) {
115         n = len;
116         int N = 1;
117         while (N < n * 2)
118             N *= 2;
119
120         tr = pt;
121         pt += N;
122
123         build(1, n, 1);
124     }
125
126     void modify(int x, int dat[2]) {
127         s = x;
128         for (int i = 0; i < 2; i++)
129             d[i] = dat[i];
130         modify(1, n, 1);
131     }
132 } seg[maxn];
133
134 vector<int> G[maxn];
135
136 int p[maxn], d[maxn], sz[maxn], son[maxn], top[maxn];
137 int dp[maxn][2], dptr[maxn][2], w[maxn];
138
139 void dfs1(int x) {
140     d[x] = d[p[x]] + 1;
141     sz[x] = 1;
142
143     for (int y : G[x])
144         if (y != p[x]) {
145             p[y] = x;
146             dfs1(y);
147
148             if (sz[y] > sz[son[x]])

```

```

149     |     |     son[x] = y;
150
151     |     sz[x] += sz[y];
152 }
153
154 void dfs2(int x) {
155     if (x == son[p[x]]) {
156         top[x] = top[p[x]];
157     } else {
158         top[x] = x;
159
160         for (int y : G[x])
161             if (y != p[x])
162                 dfs2(y);
163
164         dp[x][1] = w[x];
165         for (int y : G[x])
166             if (y != p[x] && y != son[x]) {
167                 dp[x][1] += dptr[y][0];
168                 dp[x][0] += max(dptr[y][0], dptr[y][1]);
169             }
170
171         if (top[x] == x) {
172             tw.clear();
173
174             for (int u = x; u; u = son[u])
175                 tw.push_back(make_pair(dp[u][0], dp[u]
176                                         → [1]));
177
178             seg[x].build((int)tw.size());
179
180             tie(dptr[x][0], dptr[x][1]) = seg[x].getpair();
181
182             heap.push(seg[x].getval());
183         }
184     }
185
186 void modify(int x, int dat) {
187     dp[x][1] -= w[x];
188     dp[x][1] += (w[x] = dat);
189
190     while (x) {
191         if (p[top[x]]) {
192             dp[p[top[x]]][0] -= max(dptr[top[x]][0],
193                                     → dptr[top[x]][1]);
194             dp[p[top[x]]][1] -= dptr[top[x]][0];
195         }
196
197         heap.erase(seg[top[x]].getval());
198         seg[top[x]].modify(d[x] - d[top[x]] + 1,
199                           → dp[x]);
200         heap.push(seg[top[x]].getval());
201
202         tie(dptr[top[x]][0], dptr[top[x]][1]) =
203             → seg[top[x]].getpair();
204
205         if (p[top[x]]) {
206             dp[p[top[x]]][0] += max(dptr[top[x]][0],
207                                     → dptr[top[x]][1]);
208             dp[p[top[x]]][1] += dptr[top[x]][0];
209         }
210
211         x = p[top[x]];
212     }
213
214     int main() {
215         int n, m;

```

```

214     scanf("%d%d", &n, &m);
215
216     for (int i = 1; i ≤ n; i++)
217         scanf("%d", &w[i]);
218
219     for (int i = 1; i < n; i++) {
220         int x, y;
221         scanf("%d%d", &x, &y);
222
223         G[x].push_back(y);
224         G[y].push_back(x);
225     }
226
227     dfs1(1);
228     dfs2(1);
229
230     while (m--) {
231         int x, dat;
232         scanf("%d%d", &x, &dat);
233
234         modify(x, dat);
235
236         printf("%d\n", heap.top());
237     }
238
239     return 0;
240 }

```

4.6 树分治

4.6.1 动态树分治

```

1 // 为了减小常数, 这里采用bfs写法, 实测预处理比dfs快将近一
2 → 半
3 // 以下以维护一个点到每个黑点的距离之和为例
4
5 // 全局数组定义
6 vector<int> G[maxn], W[maxn];
7 int size[maxn], son[maxn], q[maxn];
8 int p[maxn], depth[maxn], id[maxn][20], d[maxn][20]; // → id是对应层所在子树的根
9 int a[maxn], ca[maxn], b[maxn][20], cb[maxn][20]; // 维护距离和用的
10 bool vis[maxn], col[maxn];
11
12 // 建树 总计O(n log n)
13 // 需要调用找重心和预处理距离, 同时递归调用自身
14 void build(int x, int k, int s, int pr) { // 结点, 深度,
15     → 通过块大小, 点分树上的父亲
16     x = getcenter(x, s);
17     vis[x] = true;
18     depth[x] = k;
19     p[x] = pr;
20
21     for (int i = 0; i < (int)G[x].size(); i++)
22         if (!vis[G[x][i]]) {
23             d[G[x][i]][k] = W[x][i];
24             p[G[x][i]] = x;
25
26             getdis(G[x][i], k, G[x][i]); // bfs每个子树,
27             → 预处理距离
28         }
29
30     for (int i = 0; i < (int)G[x].size(); i++)
31         if (!vis[G[x][i]])
32             build(G[x][i], k + 1, size[G[x][i]], x); // → 递归建树
33
34 }

```

```

32 // 找重心 O(n)
33 int getcenter(int x, int s) {
34     int head = 0, tail = 0;
35     q[tail++] = x;
36
37     while (head != tail) {
38         x = q[head++];
39         size[x] = 1; // 这里不需要清空，因为以后要用的话
39             ↪ 一定会重新赋值
40         son[x] = 0;
41
42         for (int i = 0; i < (int)G[x].size(); i++) {
43             if (!vis[G[x][i]] && G[x][i] != p[x]) {
44                 p[G[x][i]] = x;
45                 q[tail++] = G[x][i];
46             }
47         }
48
49         for (int i = tail - 1; i; i--) {
50             x = q[i];
51             size[p[x]] += size[x];
52
53             if (size[x] > size[son[p[x]]])
54                 son[p[x]] = x;
55         }
56
57         x = q[0];
58         while (son[x] && size[son[x]] * 2 ≥ s)
59             x = son[x];
60
61     return x;
62 }

```

```

64 // 预处理距离 O(n)
65 // 方便起见，这里直接用了笨一点的方法，O(n log n)全存下来
66 void getdis(int x, int k, int rt) {
67     int head = 0, tail = 0;
68     q[tail++] = x;
69
70     while (head != tail) {
71         x = q[head++];
72         size[x] = 1;
73         id[x][k] = rt;
74
75         for (int i = 0; i < (int)G[x].size(); i++) {
76             if (!vis[G[x][i]] && G[x][i] != p[x]) {
77                 p[G[x][i]] = x;
78                 d[G[x][i]][k] = d[x][k] + W[x][i];
79
80                 q[tail++] = G[x][i];
81             }
82         }
83
84         for (int i = tail - 1; i; i--)
85             size[p[q[i]]] += size[q[i]]; // 后面递归建树要用
85             ↪ 到子问题大小
86     }
87
88 // 修改 O(log n)
89 void modify(int x) {
90     if (col[x])
91         ca[x]--;
92     else
93         ca[x]++; // 记得先特判自己作为重心的那层
94
95     for (int u = p[x], k = depth[x] - 1; u; u = p[u],
95         ↪ k--) {
96         if (col[x])
97             a[u] -= d[x][k];
98             ca[u]--;

```

```

99
100    b[id[x][k]][k] -= d[x][k];
101    cb[id[x][k]][k]--;
102
103 } else {
104     a[u] += d[x][k];
105     ca[u]++;
106
107     b[id[x][k]][k] += d[x][k];
108     cb[id[x][k]][k]++;
109 }
110
111 col[x] = true;
112 }
113
114 // 询问 O(log n)
115 int query(int x) {
116     int ans = a[x]; // 特判自己是重心的那层
117
118     for (int u = p[x], k = depth[x] - 1; u; u = p[u],
118         ↪ k--)
119         ans += a[u] - b[id[x][k]][k] + d[x][k] * (ca[u]
119             ↪ - cb[id[x][k]][k]);
120
121     return ans;
122 }
123

```

4.6.2 紫荆花之恋

稍微重构了一下，修改了代码风格。

另外这个是BFS版本，跑得比DFS要快不少。（虽然主要复杂度并不在重构上）

```

1 #include <bits/stdc++.h>
2
3 using namespace std;
4
5 constexpr int maxn = 100005, maxk = 49;
6 constexpr double alpha = .75;
7
8 mt19937 rnd(23333333);
9
10 struct node {
11     int key, size, p;
12     node *ch[2];
13
14     node() {}
15
16     node(int key) : key(key), size(1), p(rnd()) {}
17
18     inline void update() {
19         size = ch[0] → size + ch[1] → size + 1;
20     }
21 } null[maxn * maxk], *pt = null;
22
23 vector<node*> pool;
24
25 node *newnode(int val) {
26     node *x;
27
28     if (!pool.empty()) {
29         x = pool.back();
30         pool.pop_back();
31     } else
32         x = ++pt;
33
34     *x = node(val);
35

```

```

36     x → ch[0] = x → ch[1] = null;
37
38     return x;
39 }
40
41 void rot(node *&x, int d) {
42     node *y = x → ch[d ^ 1];
43     x → ch[d ^ 1] = y → ch[d];
44     y → ch[d] = x;
45
46     x → update();
47     (x = y) → update();
48 }
49
50 void insert(node *&o, int x) {
51     if (o == null) {
52         o = newnode(x);
53         return;
54     }
55
56     int d = (x > o → key);
57
58     insert(o → ch[d], x);
59     o → update();
60
61     if (o → ch[d] → p < o → p)
62         rot(o, d ^ 1);
63 }
64
65 int get_order(node *&o, int x) {
66     int ans = 0;
67
68     while (o != null) {
69         int d = (x > o → key);
70
71         if (d)
72             ans += o → ch[0] → size + 1;
73
74         o = o → ch[d];
75     }
76
77     return ans;
78 }
79
80 void destroy(node *x) {
81     if (x == null)
82         return;
83
84     pool.push_back(x);
85     destroy(x → ch[0]);
86     destroy(x → ch[1]);
87 }
88
89 struct my_tree { // 封装了一下，如果不卡内存直接换
90     → 成PBDS就好了
91     node *rt;
92
93     my_tree() : rt(null) {}
94
95     void clear() {
96         ::destroy(rt);
97         rt = null;
98     }
99
100    void insert(int x) {
101        ::insert(rt, x);
102    }
103
104    int order_of_key(int x) { // less than x
105        return ::get_order(rt, x);
106    }
107
108    vector<pair<int, int>> G[maxn];
109
110    int p[maxn], depth[maxn], d[maxn][maxk], rid[maxn]
111        ↪ [maxk];
112    int sz[maxn], siz[maxn][maxk], q[maxn];
113    bool vis[maxn];
114
115    int w[maxn];
116
117    void destroy(int o) {
118        int head = 0, tail = 0;
119        q[tail++] = o;
120        vis[o] = false;
121
122        while (head != tail) {
123            int x = q[head++];
124            tr[x].clear();
125
126            for (int i = depth[o]; i ≤ depth[x]; i++) {
127                tre[x][i].clear();
128                d[x][i] = rid[x][i] = siz[x][i] = 0;
129            }
130
131            for (auto pi : G[x]) {
132                int y = pi.first;
133
134                if (vis[y] && depth[y] ≥ depth[o]) {
135                    vis[y] = false;
136                    q[tail++] = y;
137                }
138            }
139        }
140
141        int getcenter(int o, int s) {
142            int head = 0, tail = 0;
143            q[tail++] = o;
144
145            while (head != tail) {
146                int x = q[head++];
147                sz[x] = 1;
148
149                for (auto pi : G[x]) {
150                    int y = pi.first;
151
152                    if (!vis[y] && y != p[x]) {
153                        p[y] = x;
154                        q[tail++] = y;
155                    }
156                }
157            }
158
159            for (int i = s - 1; i; i--)
160                sz[p[q[i]]] += sz[q[i]];
161
162            int x = o;
163            while (true) {
164                bool ok = false;
165
166                for (auto pi : G[x]) {
167                    int y = pi.first;
168
169                    if (!vis[y] && y != p[x] && sz[y] * 2 > s
170                        ↪ {
171                        x = y;
172                        ok = true;
173                        break;
174                    }
175                }
176            }
177        }
178    }
179
180    void update() {
181        for (int i = 0; i < maxn; i++)
182            for (int j = 0; j < maxk; j++)
183                d[i][j] = rid[i][j] = sz[i][j] = 0;
184
185        for (auto pi : G[rt])
186            int y = pi.first;
187
188        for (int i = 0; i < maxn; i++)
189            for (int j = 0; j < maxk; j++)
190                if (p[i] == j)
191                    d[i][j] = 1;
192
193        for (auto pi : G[rt])
194            int y = pi.first;
195
196        for (int i = 0; i < maxn; i++)
197            for (int j = 0; j < maxk; j++)
198                if (p[i] == j)
199                    if (sz[i][j] * 2 > s)
200                        d[i][j] = 1;
201
202        for (auto pi : G[rt])
203            int y = pi.first;
204
205        for (int i = 0; i < maxn; i++)
206            for (int j = 0; j < maxk; j++)
207                if (p[i] == j)
208                    if (sz[i][j] * 2 > s)
209                        if (d[i][j] == 1)
210                            d[i][j] = 0;
211
212        for (auto pi : G[rt])
213            int y = pi.first;
214
215        for (int i = 0; i < maxn; i++)
216            for (int j = 0; j < maxk; j++)
217                if (p[i] == j)
218                    if (sz[i][j] * 2 > s)
219                        if (d[i][j] == 1)
220                            if (rid[i][j] == 1)
221                                rid[i][j] = 0;
222
223        for (auto pi : G[rt])
224            int y = pi.first;
225
226        for (int i = 0; i < maxn; i++)
227            for (int j = 0; j < maxk; j++)
228                if (p[i] == j)
229                    if (sz[i][j] * 2 > s)
230                        if (d[i][j] == 1)
231                            if (rid[i][j] == 1)
232                                if (sz[i][j] * 2 > s)
233                                    d[i][j] = 1;
234
235        for (auto pi : G[rt])
236            int y = pi.first;
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238        for (int i = 0; i < maxn; i++)
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240                if (p[i] == j)
241                    if (sz[i][j] * 2 > s)
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243                            if (rid[i][j] == 1)
244                                if (sz[i][j] * 2 > s)
245                                    if (d[i][j] == 1)
246                                        d[i][j] = 0;
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248        for (auto pi : G[rt])
249            int y = pi.first;
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253                if (p[i] == j)
254                    if (sz[i][j] * 2 > s)
255                        if (d[i][j] == 1)
256                            if (rid[i][j] == 1)
257                                if (sz[i][j] * 2 > s)
258                                    if (d[i][j] == 1)
259                                        if (rid[i][j] == 1)
260                                            d[i][j] = 1;
261
262        for (auto pi : G[rt])
263            int y = pi.first;
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271                                if (sz[i][j] * 2 > s)
272                                    if (d[i][j] == 1)
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277        for (auto pi : G[rt])
278            int y = pi.first;
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283                    if (sz[i][j] * 2 > s)
284                        if (d[i][j] == 1)
285                            if (rid[i][j] == 1)
286                                if (sz[i][j] * 2 > s)
287                                    if (d[i][j] == 1)
288                                        if (rid[i][j] == 1)
289                                            if (sz[i][j] * 2 > s)
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296            for (int j = 0; j < maxk; j++)
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298                    if (sz[i][j] * 2 > s)
299                        if (d[i][j] == 1)
300                            if (rid[i][j] == 1)
301                                if (sz[i][j] * 2 > s)
302                                    if (d[i][j] == 1)
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311            for (int j = 0; j < maxk; j++)
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313                    if (sz[i][j] * 2 > s)
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316                                if (sz[i][j] * 2 > s)
317                                    if (d[i][j] == 1)
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331                                if (sz[i][j] * 2 > s)
332                                    if (d[i][j] == 1)
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346                                if (sz[i][j] * 2 > s)
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374                        if (d[i][j] == 1)
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376                                if (sz[i][j] * 2 > s)
377                                    if (d[i][j] == 1)
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406                                if (sz[i][j] * 2 > s)
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451                                if (sz[i][j] * 2 > s)
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462                if (p[i] == j)
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466                                if (sz[i][j] * 2 > s)
467                                    if (d[i][j] == 1)
468                                        if (rid[i][j] == 1)
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481                                if (sz[i][j] * 2 > s)
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571                                if (sz[i][j] * 2 > s)
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750                            if (rid[i][j] == 1)
751                                if (sz[i][j] * 2 > s)
752                                    if (d[i][j] == 1)
753                                        if (rid[i][j] == 1)
754                                            if (sz[i][j] * 2 > s)
755                                                d[i][j] = 1;
756
757        for (auto pi : G[rt])
758            int y = pi.first;
759
760        for (int i = 0; i < maxn; i++)
761            for (int j = 0; j < maxk; j++)
762                if (p[i] == j)
763                    if (sz[i][j] * 2 > s)
764                        if (d[i][j] == 1)
765                            if (rid[i][j] == 1)
766                                if (sz[i][j] * 2 > s)
767                                    if (d[i][j] == 1)
768                                        if (rid[i][j] == 1)
769                                            if (sz[i][j] * 2 > s)
770                                                d[i][j] = 1;
771
772        for (auto pi : G[rt])
773            int y = pi.first;
774
775        for (int i = 0; i < maxn; i++)
776            for (int j = 0; j < maxk; j++)
777                if (p[i] == j)
778                    if (sz[i][j] * 2 > s)
779                        if (d[i][j] == 1)
780                            if (rid[i][j] == 1)
781                                if (sz[i][j] * 2 > s)
782                                    if (d[i][j] == 1)
783                                        if (rid[i][j] == 1)
784                                            if (sz[i][j] * 2 > s)
785                                                d[i][j] = 1;
786
787        for (auto pi : G[rt])
788            int y = pi.first;
789
790        for (int i = 0; i < maxn; i++)
791            for (int j = 0; j < maxk; j++)
792                if (p[i] == j)
793                    if (sz[i][j] * 2 > s)
794                        if (d[i][j] == 1)
795                            if (rid[i][j] == 1)
796                                if (sz[i][j] * 2 > s)
797                                    if (d[i][j] == 1)
798                                        if (rid[i][j] == 1)
799                                            if (sz[i][j] * 2 > s)
800                                                d[i][j] = 1;
801
802        for (auto pi : G[rt])
803            int y = pi.first;
804
805        for (int i = 0; i < maxn; i++)
806            for (int j = 0; j < maxk; j++)
807                if (p[i] == j)
808                    if (sz[i][j] * 2 > s)
809                        if (d[i][j] == 1)
810                            if (rid[i][j] == 1)
811                                if (sz[i][j] * 2 > s)
812                                    if (d[i][j] == 1)
813                                        if (rid[i][j] == 1)
814                                            if (sz[i][j] * 2 > s)
815                                                d[i][j] = 1;
816
817        for (auto pi : G[rt])
818            int y = pi.first;
819
820        for (int i = 0; i < maxn; i++)
821            for (int j = 0; j < maxk; j++)
822                if (p[i] == j)
823                    if (sz[i][j] * 2 > s)
824                        if (d[i][j] == 1)
825                            if (rid[i][j] == 1)
826                                if (sz[i][j] * 2 > s)
827                                    if (d[i][j] == 1)
828                                        if (rid[i][j] == 1)
829                                            if (sz[i][j] * 2 > s)
830                                                d[i][j] = 1;
831
832        for (auto pi : G[rt])
833            int y = pi.first;
834
835        for (int i = 0; i < maxn; i++)
836            for (int j = 0; j < maxk; j++)
837                if (p[i] == j)
838                    if (sz[i][j] * 2 > s)
839                        if (d[i][j] == 1)
840                            if (rid[i][j] == 1)
841                                if (sz[i][j] * 2 > s)
842                                    if (d[i][j] == 1)
843                                        if (rid[i][j] == 1)
844                                            if (sz[i][j] * 2 > s)
845                                                d[i][j] = 1;
846
847        for (auto pi : G[rt])
848            int y = pi.first;
849
850        for (int i = 0; i < maxn; i++)
851            for (int j = 0; j < maxk; j++)
852                if (p[i] == j)
853                    if (sz[i][j] * 2 > s)
854                        if (d[i][j] == 1)
855                            if (rid[i][j] == 1)
856                                if (sz[i][j] * 2 > s)
857                                    if (d[i][j] == 1)
858                                        if (rid[i][j] == 1)
859                                            if (sz[i][j] * 2 > s)
860                                                d[i][j] = 1;
861
862        for (auto pi : G[rt])
863            int y = pi.first;
864
865        for (int i = 0; i < maxn; i++)
866            for (int j = 0; j < maxk; j++)
867                if (p[i] == j)
868                    if (sz[i][j] * 2 >
```

```

172     }
173 
174     if (!ok)
175     | break;
176 
177 }
178 
179 return x;
180 }

181 void getdis(int st, int o, int k) {
182     int head = 0, tail = 0;
183     q[tail++] = st;
184 
185     while (head != tail) {
186         int x = q[head++];
187         sz[x] = 1;
188         rid[x][k] = st;
189 
190         tr[o].insert(d[x][k] - w[x]);
191         tre[st][k].insert(d[x][k] - w[x]);
192 
193         for (auto pi : G[x]) {
194             int y = pi.first, val = pi.second;
195 
196             if (!vis[y] && y != p[x]) {
197                 p[y] = x;
198                 d[y][k] = d[x][k] + val;
199                 q[tail++] = y;
200             }
201         }
202     }
203 
204     for (int i = tail - 1; i; i--)
205         sz[p[q[i]]] += sz[q[i]];
206 
207     siz[st][k] = sz[st];
208 }

209 }

210 void rebuild(int x, int s, int pr) {
211     x = getcenter(x, s);
212     vis[x] = true;
213     p[x] = pr;
214     depth[x] = depth[pr] + 1;
215     sz[x] = s;
216 
217     tr[x].insert(-w[x]);
218 
219     for (auto pi : G[x]) {
220         int y = pi.first, val = pi.second;
221 
222         if (!vis[y]) {
223             p[y] = x;
224             d[y][depth[x]] = val;
225             getdis(y, x, depth[x]);
226         }
227     }
228 
229     for (auto pi : G[x]) {
230         int y = pi.first;
231 
232         if (!vis[y])
233             rebuild(y, sz[y], x);
234     }
235 }

236 long long add_node(int x, int nw) { // nw是边权
237     depth[x] = depth[p[x]] + 1;
238     sz[x] = 1;
239 }

240 }

241 vis[x] = true;
242 
243 tr[x].insert(-w[x]);
244 
245 long long tmp = 0;
246 int goat = 0; // 替罪羊
247 
248 for (int u = p[x], k = depth[x] - 1; u; u = p[u],
249      ~k--) {
250     d[x][k] = d[p[x]][k] + nw;
251     rid[x][k] = (rid[p[x]][k] ? rid[p[x]][k] : x);
252 
253     tmp += tr[u].order_of_key(w[x] - d[x][k] + 1);
254     tmp -= tre[rid[x][k]][k].order_of_key(w[x] -
255      ~d[x][k] + 1);
256 
257     tr[u].insert(d[x][k] - w[x]);
258     tre[rid[x][k]][k].insert(d[x][k] - w[x]);
259 
260     sz[u]++;
261     siz[rid[x][k]][k]++;
262 
263     if (siz[rid[x][k]][k] > sz[u] * alpha + 5)
264         goat = u;
265 }
266 
267 if (goat) {
268     destroy(goat);
269     rebuild(goat, sz[goat], p[goat]);
270 }
271 
272 return tmp;
273 }

274 int main() {
275     null → ch[0] = null → ch[1] = null;
276     null → size = 0;
277 
278     int n;
279     scanf("%*d%d", &n);
280 
281     scanf("%*d%*d%d", &w[1]);
282     vis[1] = true;
283     sz[1] = 1;
284     tr[1].insert(-w[1]);
285 
286     printf("0\n");
287 
288     long long ans = 0;
289 
290     for (int i = 2; i ≤ n; i++) {
291         int nw;
292         scanf("%d%d%d", &p[i], &nw, &w[i]);
293 
294         p[i] ≈ (ans % 1000000000);
295 
296         G[i].push_back(make_pair(p[i], nw));
297         G[p[i]].push_back(make_pair(i, nw));
298 
299         ans += add_node(i, nw);
300 
301         printf("%lld\n", ans);
302     }
303 
304     return 0;
305 }

```

4.7 LCT动态树

4.7.1 不换根(弹飞绵羊)

```

1 #define isroot(x) ((x) != (x) → p → ch[0] && (x) !=
2     → (x) → p → ch[1]) // 判断是不是Splay的根
3 #define dir(x) ((x) == (x) → p → ch[1]) // 判断它是它
4     → 父亲的左 / 右儿子
5
6 struct node { // 结点类定义
7     int size; // Splay的子树大小
8     node *ch[2], *p;
9
10    node() : size(1) {}
11    void refresh() {
12        size = ch[0] → size + ch[1] → size + 1;
13    } // 附加信息维护
14 } null[maxn];
15
16 // 在主函数开头加上这句初始化
17 null → size = 0;
18
19 // 初始化结点
20 void initialize(node *x) {
21     x → ch[0] = x → ch[1] = x → p = null;
22 }
23
24 // Access 均摊O(\log n)
25 // LCT核心操作, 把结点到根的路径打通, 顺便把与重儿子的连
26     → 边变成轻边
27 // 需要调用splay
28 node *access(node *x) {
29     node *y = null;
30
31     while (x != null) {
32         splay(x);
33
34         x → ch[1] = y;
35         (y = x) → refresh();
36
37         x = x → p;
38     }
39
40     return y;
41 }
42
43 // Link 均摊O(\log n)
44 // 把x的父亲设为y
45 // 要求x必须为所在树的根节点否则会导致后续各种莫名其妙的
46     → 问题
47 // 需要调用splay
48 void link(node *x, node *y) {
49     splay(x);
50     x → p = y;
51 }
52
53 // Cut 均摊O(\log n)
54 // 把x与其父亲的连边断掉
55 // x可以是所在树的根节点, 这时此操作没有任何实质效果
56 // 需要调用access和splay
57 void cut(node *x) {
58     access(x);
59     splay(x);
60
61     x → ch[0] → p = null;
62     x → ch[0] = null;
63
64     x → refresh();
65 }
66
67 // Splay 均摊O(\log n)

```

```

64 // 需要调用旋转
65 void splay(node *x) {
66     while (!isroot(x)) {
67         if (isroot(x → p)) {
68             rot(x → p, dir(x) ^ 1);
69             break;
70         }
71
72         if (dir(x) == dir(x → p))
73             rot(x → p → p, dir(x → p) ^ 1);
74         else
75             rot(x → p, dir(x) ^ 1);
76         rot(x → p, dir(x) ^ 1);
77     }
78 }
79
80 // 旋转(LCT版本) O(1)
81 // 平衡树基本操作
82 // 要求对应儿子必须存在, 否则会导致后续各种莫名其妙的问题
83 void rot(node *x, int d) {
84     node *y = x → ch[d ^ 1];
85
86     y → p = x → p;
87     if (!isroot(x))
88         x → p → ch[dir(x)] = y;
89
90     if ((x → ch[d ^ 1] = y → ch[d]) != null)
91         y → ch[d] → p = x;
92     (y → ch[d] = x) → p = y;
93
94     x → refresh();
95     y → refresh();
96 }

```

4.7.2 换根/维护生成树

```

1 #define isroot(x) ((x) → p == null || ((x) → p →
2     → ch[0] != (x) && (x) → p → ch[1] != (x)))
3 #define dir(x) ((x) == (x) → p → ch[1])
4
5 using namespace std;
6
7 const int maxn = 200005;
8
9 struct node{
10     int key, mx, pos;
11     bool rev;
12     node *ch[2], *p;
13
14     node(int key = 0): key(key), mx(key), pos(-1),
15         → rev(false) {}
16
17     void pushdown() {
18         if (!rev)
19             return;
20
21         ch[0] → rev ^= true;
22         ch[1] → rev ^= true;
23         swap(ch[0], ch[1]);
24
25         if (pos != -1)
26             pos ^= 1;
27
28         rev = false;
29     }
30
31     void refresh() {
32         mx = key;
33         pos = -1;
34     }
35
36     void rotate(int d) {
37         if (p == null)
38             return;
39
40         if (d == 0)
41             rotateLeft();
42         else
43             rotateRight();
44     }
45
46     void rotateLeft() {
47         if (p == null)
48             return;
49
50         if (ch[1] == null)
51             return;
52
53         node *y = ch[1];
54         ch[1] = y → ch[0];
55         y → ch[0] = p;
56         p → ch[0] = y;
57
58         if (y → ch[0] == null)
59             y → ch[0] = null;
60
61         if (y → ch[1] == null)
62             y → ch[1] = null;
63
64         if (y → ch[0] != null)
65             y → ch[0] → p = y;
66
67         if (y → ch[1] != null)
68             y → ch[1] → p = y;
69
70         if (y → ch[0] == null)
71             y → ch[0] = null;
72
73         if (y → ch[1] == null)
74             y → ch[1] = null;
75
76         if (y → ch[0] != null)
77             y → ch[0] → p = y;
78
79         if (y → ch[1] != null)
80             y → ch[1] → p = y;
81
82         if (y → ch[0] == null)
83             y → ch[0] = null;
84
85         if (y → ch[1] == null)
86             y → ch[1] = null;
87
88         if (y → ch[0] != null)
89             y → ch[0] → p = y;
90
91         if (y → ch[1] != null)
92             y → ch[1] → p = y;
93
94         if (y → ch[0] == null)
95             y → ch[0] = null;
96
97         if (y → ch[1] == null)
98             y → ch[1] = null;
99
100        if (y → ch[0] != null)
101            y → ch[0] → p = y;
102
103        if (y → ch[1] != null)
104            y → ch[1] → p = y;
105
106        if (y → ch[0] == null)
107            y → ch[0] = null;
108
109        if (y → ch[1] == null)
110            y → ch[1] = null;
111
112        if (y → ch[0] != null)
113            y → ch[0] → p = y;
114
115        if (y → ch[1] != null)
116            y → ch[1] → p = y;
117
118        if (y → ch[0] == null)
119            y → ch[0] = null;
120
121        if (y → ch[1] == null)
122            y → ch[1] = null;
123
124        if (y → ch[0] != null)
125            y → ch[0] → p = y;
126
127        if (y → ch[1] != null)
128            y → ch[1] → p = y;
129
130        if (y → ch[0] == null)
131            y → ch[0] = null;
132
133        if (y → ch[1] == null)
134            y → ch[1] = null;
135
136        if (y → ch[0] != null)
137            y → ch[0] → p = y;
138
139        if (y → ch[1] != null)
140            y → ch[1] → p = y;
141
142        if (y → ch[0] == null)
143            y → ch[0] = null;
144
145        if (y → ch[1] == null)
146            y → ch[1] = null;
147
148        if (y → ch[0] != null)
149            y → ch[0] → p = y;
150
151        if (y → ch[1] != null)
152            y → ch[1] → p = y;
153
154        if (y → ch[0] == null)
155            y → ch[0] = null;
156
157        if (y → ch[1] == null)
158            y → ch[1] = null;
159
160        if (y → ch[0] != null)
161            y → ch[0] → p = y;
162
163        if (y → ch[1] != null)
164            y → ch[1] → p = y;
165
166        if (y → ch[0] == null)
167            y → ch[0] = null;
168
169        if (y → ch[1] == null)
170            y → ch[1] = null;
171
172        if (y → ch[0] != null)
173            y → ch[0] → p = y;
174
175        if (y → ch[1] != null)
176            y → ch[1] → p = y;
177
178        if (y → ch[0] == null)
179            y → ch[0] = null;
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181        if (y → ch[1] == null)
182            y → ch[1] = null;
183
184        if (y → ch[0] != null)
185            y → ch[0] → p = y;
186
187        if (y → ch[1] != null)
188            y → ch[1] → p = y;
189
190        if (y → ch[0] == null)
191            y → ch[0] = null;
192
193        if (y → ch[1] == null)
194            y → ch[1] = null;
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196        if (y → ch[0] != null)
197            y → ch[0] → p = y;
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199        if (y → ch[1] != null)
200            y → ch[1] → p = y;
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202        if (y → ch[0] == null)
203            y → ch[0] = null;
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205        if (y → ch[1] == null)
206            y → ch[1] = null;
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208        if (y → ch[0] != null)
209            y → ch[0] → p = y;
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211        if (y → ch[1] != null)
212            y → ch[1] → p = y;
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215            y → ch[0] = null;
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217        if (y → ch[1] == null)
218            y → ch[1] = null;
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220        if (y → ch[0] != null)
221            y → ch[0] → p = y;
222
223        if (y → ch[1] != null)
224            y → ch[1] → p = y;
225
226        if (y → ch[0] == null)
227            y → ch[0] = null;
228
229        if (y → ch[1] == null)
230            y → ch[1] = null;
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232        if (y → ch[0] != null)
233            y → ch[0] → p = y;
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235        if (y → ch[1] != null)
236            y → ch[1] → p = y;
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238        if (y → ch[0] == null)
239            y → ch[0] = null;
240
241        if (y → ch[1] == null)
242            y → ch[1] = null;
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244        if (y → ch[0] != null)
245            y → ch[0] → p = y;
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247        if (y → ch[1] != null)
248            y → ch[1] → p = y;
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250        if (y → ch[0] == null)
251            y → ch[0] = null;
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253        if (y → ch[1] == null)
254            y → ch[1] = null;
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256        if (y → ch[0] != null)
257            y → ch[0] → p = y;
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259        if (y → ch[1] != null)
260            y → ch[1] → p = y;
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263            y → ch[0] = null;
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266            y → ch[1] = null;
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268        if (y → ch[0] != null)
269            y → ch[0] → p = y;
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271        if (y → ch[1] != null)
272            y → ch[1] → p = y;
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274        if (y → ch[0] == null)
275            y → ch[0] = null;
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277        if (y → ch[1] == null)
278            y → ch[1] = null;
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280        if (y → ch[0] != null)
281            y → ch[0] → p = y;
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283        if (y → ch[1] != null)
284            y → ch[1] → p = y;
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286        if (y → ch[0] == null)
287            y → ch[0] = null;
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289        if (y → ch[1] == null)
290            y → ch[1] = null;
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292        if (y → ch[0] != null)
293            y → ch[0] → p = y;
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295        if (y → ch[1] != null)
296            y → ch[1] → p = y;
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299            y → ch[0] = null;
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302            y → ch[1] = null;
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304        if (y → ch[0] != null)
305            y → ch[0] → p = y;
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308            y → ch[1] → p = y;
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314            y → ch[1] = null;
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322        if (y → ch[0] == null)
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326            y → ch[1] = null;
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341            y → ch[0] → p = y;
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343        if (y → ch[1] != null)
344            y → ch[1] → p = y;
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346        if (y → ch[0] == null)
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350            y → ch[1] = null;
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352        if (y → ch[0] != null)
353            y → ch[0] → p = y;
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355        if (y → ch[1] != null)
356            y → ch[1] → p = y;
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358        if (y → ch[0] == null)
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361        if (y → ch[1] == null)
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910        if (y → ch[0] == null)
911            y → ch[0] = null;
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913        if (y → ch[1] == null)
914            y → ch[1] = null;
915
916        if (y → ch[0] != null)
917
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32     if (ch[0] → mx > mx) {
33         mx = ch[0] → mx;
34         pos = 0;
35     }
36     if (ch[1] → mx > mx) {
37         mx = ch[1] → mx;
38         pos = 1;
39     }
40 }
41 } null[maxn * 2];
42
43 void init(node *x, int k) {
44     x → ch[0] = x → ch[1] = x → p = null;
45     x → key = x → mx = k;
46 }
47
48 void rot(node *x, int d) {
49     node *y = x → ch[d ^ 1];
50     if ((x → ch[d ^ 1] = y → ch[d]) != null)
51         y → ch[d] → p = x;
52
53     y → p = x → p;
54     if (!isroot(x))
55         x → p → ch[dir(x)] = y;
56
57     (y → ch[d] = x) → p = y;
58
59     x → refresh();
60     y → refresh();
61 }
62
63 void splay(node *x) {
64     x → pushdown();
65
66     while (!isroot(x)) {
67         if (!isroot(x → p))
68             x → p → p → pushdown();
69         x → p → pushdown();
70         x → pushdown();
71
72         if (isroot(x → p)) {
73             rot(x → p, dir(x) ^ 1);
74             break;
75         }
76
77         if (dir(x) == dir(x → p))
78             rot(x → p → p, dir(x → p) ^ 1);
79         else
80             rot(x → p, dir(x) ^ 1);
81
82         rot(x → p, dir(x) ^ 1);
83     }
84 }
85
86 node *access(node *x) {
87     node *y = null;
88
89     while (x != null) {
90         splay(x);
91
92         x → ch[1] = y;
93         (y = x) → refresh();
94
95         x = x → p;
96     }
97
98     return y;
99 }
100 void makerooot(node *x) {
101
102     access(x);
103     splay(x);
104     x → rev ^= true;
105 }
106
107 void link(node *x, node *y) {
108     makerooot(x);
109     x → p = y;
110 }
111
112 void cut(node *x, node *y) {
113     makerooot(x);
114     access(y);
115     splay(y);
116
117     y → ch[0] → p = null;
118     y → ch[0] = null;
119     y → refresh();
120 }
121
122 node *getroot(node *x) {
123     x = access(x);
124     while (x → pushdown(), x → ch[0] != null)
125         x = x → ch[0];
126     splay(x);
127     return x;
128 }
129
130 node *getmax(node *x, node *y) {
131     makerooot(x);
132     x = access(y);
133
134     while (x → pushdown(), x → pos != -1)
135         x = x → ch[x → pos];
136     splay(x);
137
138     return x;
139 }
140
141 // 以下为主函数示例
142 for (int i = 1; i ≤ m; i++) {
143     init(null + n + i, w[i]);
144     if (getroot(null + u[i]) != getroot(null + v[i])) {
145         ans[q + 1] -= k;
146         ans[q + 1] += w[i];
147
148         link(null + u[i], null + n + i);
149         link(null + v[i], null + n + i);
150         vis[i] = true;
151     }
152     else {
153         int ii = getmax(null + u[i], null + v[i]) -
154             → null - n;
155         if (w[i] ≥ w[ii])
156             continue;
157
158         cut(null + u[ii], null + n + ii);
159         cut(null + v[ii], null + n + ii);
160
161         link(null + u[i], null + n + i);
162         link(null + v[i], null + n + i);
163
164         ans[q + 1] -= w[ii];
165         ans[q + 1] += w[i];
166     }
167 }

```

4.7.3 维护子树信息

```

1 // 这个东西虽然只需要抄板子但还是极其难写，常数极其巨大，  

2 // →没必要的时候就不要用  

3 // 如果维护子树最小值就需要套一个可删除的堆来维护，复杂度  

4 // →会变成O(n log^2 n)  

5 // 注意由于这道题与边权有关，需要边权拆点变点权  

6  

7 // 宏定义  

8 #define isroot(x) ((x) → p == null || ((x) != (x) → p  

9 // → ch[0] && (x) != (x) → p → ch[1]))  

10 #define dir(x) ((x) == (x) → p → ch[1])  

11  

12 // 节点类定义  

13 struct node { // 以维护子树中黑点到根距离和为例  

14     int w, chain_cnt, tree_cnt;  

15     long long sum, suml, sumr, tree_sum; // 由于换根需要  

16     // →子树反转，需要维护两个方向的信息  

17     bool rev, col;  

18     node *ch[2], *p;  

19  

20     node() : w(0), chain_cnt(0),  

21         tree_cnt(0), sum(0), suml(0), sumr(0),  

22         tree_sum(0), rev(false), col(false) {}  

23  

24     inline void pushdown() {  

25         if(!rev)  

26             return;  

27  

28         ch[0]→rev ≈ true;  

29         ch[1]→rev ≈ true;  

30         swap(ch[0], ch[1]);  

31         swap(suml, sumr);  

32  

33         rev = false;  

34     }  

35  

36     inline void refresh() { // 如果不想这样特判  

37         // →就pushdown一下  

38         // pushdown();  

39  

40         sum = ch[0] → sum + ch[1] → sum + w;  

41         suml = (ch[0] → rev ? ch[0] → sumr : ch[0] →  

42             suml) + (ch[1] → rev ? ch[1] → sumr :  

43                 suml) + (tree_cnt + ch[1] →  

44                 chain_cnt) * (ch[0] → sum + w) + tree_sum;  

45         sumr = (ch[0] → rev ? ch[0] → suml : ch[0] →  

46             sumr) + (ch[1] → rev ? ch[1] → suml :  

47                 sumr) + (tree_cnt + ch[0] →  

48                 chain_cnt) * (ch[1] → sum + w) + tree_sum;  

49         chain_cnt = ch[0] → chain_cnt + ch[1] →  

50             chain_cnt + tree_cnt;  

51     } null[maxn * 2]; // 如果没有边权变点权就不用乘2了  

52  

53     // 封装构造函数  

54     node *newnode(int w) {  

55         node *x = nodes.front(); // 因为有删边加边，可以用一  

56         // →个队列维护可用结点  

57         nodes.pop();  

58         initialize(x);  

59         x → w = w;  

60         x → refresh();  

61         return x;  

62     }  

63  

64     // 封装初始化函数  

65     // 记得在进行操作之前对所有结点调用一遍  

66     inline void initialize(node *x) {  

67         *x = node();  

68         x → ch[0] = x → ch[1] = x → p = null;  

69  

70         // 注意一下在Access的同时更新子树信息的方法  

71         node *access(node *x) {  

72             node *y = null;  

73  

74             while (x != null) {  

75                 splay(x);  

76  

77                 x → tree_cnt += x → ch[1] → chain_cnt - y →  

78                 chain_cnt;  

79                 x → tree_sum += (x → ch[1] → rev ? x →  

80                     ch[1] → sumr : x → ch[1] → suml) - y →  

81                     suml;  

82                 x → ch[1] = y;  

83  

84                 (y = x) → refresh();  

85                 x = x → p;  

86             }  

87  

88             return y;  

89         }  

90  

91         // 找到一个点所在连通块的根  

92         // 对比原版没有变化  

93         node *getroot(node *x) {  

94             x = access(x);  

95  

96             while (x → pushdown(), x → ch[0] != null)  

97                 x = x → ch[0];  

98             splay(x);  

99  

100            return x;  

101        }  

102  

103        // 换根，同样没有变化  

104        void makeroot(node *x) {  

105            access(x);  

106            splay(x);  

107            x → rev ≈ true;  

108            x → pushdown();  

109        }  

110  

111        // 连接两个点  

112        // !!! 注意这里必须把两者都变成根，因为只能修改根结点  

113        void link(node *x, node *y) {  

114            makeroot(x);  

115            makeroot(y);  

116  

117            x → p = y;  

118            y → tree_cnt += x → chain_cnt;  

119            y → tree_sum += x → suml;  

120            y → refresh();  

121        }  

122  

123        // 删除一条边  

124        // 对比原版没有变化  

125        void cut(node *x, node *y) {  

126            makeroot(x);  

127            access(y);  

128            splay(y);  

129  

130            y → ch[0] → p = null;  

131            y → ch[0] = null;  

132            y → refresh();  

133        }  

134  

135        // 修改/询问一个点，这里以询问为例  

136        // 如果是修改就在换根之后搞一些操作

```

```

122 long long query(node *x) {
123     makeroott(x);
124     return x -> suml;
125 }
126
127 // Splay函数
128 // 对比原版没有变化
129 void splay(node *x) {
130     x -> pushdown();
131
132     while (!isroot(x)) {
133         if (!isroot(x -> p))
134             x -> p -> p -> pushdown();
135         x -> p -> pushdown();
136         x -> pushdown();
137
138         if (isroot(x -> p)) {
139             rot(x -> p, dir(x) ^ 1);
140             break;
141         }
142
143         if (dir(x) == dir(x -> p))
144             rot(x -> p -> p, dir(x -> p) ^ 1);
145         else
146             rot(x -> p, dir(x) ^ 1);
147
148         rot(x -> p, dir(x) ^ 1);
149     }
150 }
151
152 // 旋转函数
153 // 对比原版没有变化
154 void rot(node *x, int d) {
155     node *y = x -> ch[d ^ 1];
156
157     if ((x -> ch[d ^ 1] = y -> ch[d]) != null)
158         y -> ch[d] -> p = x;
159
160     y -> p = x -> p;
161     if (!isroot(x))
162         x -> p -> ch[dir(x)] = y;
163
164     (y -> ch[d] = x) -> p = y;
165
166     x -> refresh();
167     y -> refresh();
168 }

```

```

19     void push(long long x) {
20         if (x > (-INF) >> 2)
21             q1.push(x);
22     }
23
24     void erase(long long x) {
25         if (x > (-INF) >> 2)
26             q2.push(x);
27     }
28
29     long long top() {
30         if (empty())
31             return -INF;
32
33         while (!q2.empty() && q1.top() == q2.top())
34             q1.pop();
35         q2.pop();
36
37         return q1.top();
38     }
39
40     long long top2() {
41         if (size() < 2)
42             return -INF;
43
44         long long a = top();
45         erase(a);
46         long long b = top();
47         push(a);
48         return a + b;
49     }
50
51     int size() {
52         return q1.size() - q2.size();
53     }
54
55     bool empty() {
56         return q1.size() == q2.size();
57     }
58 } heap; // 全局堆维护每条链的最大子段和
59
60 struct node {
61     long long sum, maxsum, prefix, suffix;
62     int key;
63     binary_heap heap; // 每个点的堆存的是它的子树中到它的
64     // 最远距离, 如果它是黑点的话还会包括自己
65     node *ch[2], *p;
66     bool rev;
67     node(int k = 0): sum(k), maxsum(-INF),
68         prefix(-INF), suffix(-INF), key(k), rev(false) {}
69     inline void pushdown() {
70         if (!rev)
71             return;
72
73         ch[0] -> rev = true;
74         ch[1] -> rev = true;
75         swap(ch[0], ch[1]);
76         swap(prefix, suffix);
77         rev = false;
78     }
79     inline void refresh() {
80         pushdown();
81         ch[0] -> pushdown();
82         ch[1] -> pushdown();
83         sum = ch[0] -> sum + ch[1] -> sum + key;
84         prefix = max(ch[0] -> prefix,
85             ch[0] -> sum + key + ch[1] ->
86             prefix);
87         suffix = max(ch[1] -> suffix,
88             ch[1] -> sum + key + ch[0] ->
89             suffix);
90     }
91 }
92
93 constexpr int maxn = 100005;
94 constexpr long long INF = 1000000000000000000ll;
95
96 struct binary_heap {
97     __gnu_pbds::priority_queue<long long, less<long
98     long>, binary_heap_tag> q1, q2;
99     binary_heap() {}
100 }
```

4.7.4 模板题: 动态QTREE4(询问树上相距最远点)

```

1 #include <bits/stdc++.h>
2 #include <ext/pb_ds/assoc_container.hpp>
3 #include <ext/pb_ds/tree_policy.hpp>
4 #include <ext/pb_ds/priority_queue.hpp>
5
6 #define isroot(x) ((x) -> p == null || ((x) != (x) -> p
6     -> ch[0] && (x) != (x) -> p -> ch[1]))
7 #define dir(x) ((x) == (x) -> p -> ch[1])
8
9 using namespace std;
10 using namespace __gnu_pbds;
11
12 constexpr int maxn = 100005;
13 constexpr long long INF = 1000000000000000000ll;
14
15 struct binary_heap {
16     __gnu_pbds::priority_queue<long long, less<long
17     long>, binary_heap_tag> q1, q2;
18     binary_heap() {}
19 }
```

```

87         ch[1] → sum + key + ch[0] →
88             ↪ suffix);
89     maxsum = max(max(ch[0] → maxsum, ch[1] →
90                     ↪ maxsum),
91                 ch[0] → suffix + key + ch[1] →
92                     ↪ prefix);
93
94     if (!heap.empty()) {
95         prefix = max(prefix,
96                         ch[0] → sum + key +
97                             ↪ heap.top());
98         suffix = max(suffix,
99                         ch[1] → sum + key +
100                            ↪ heap.top());
101        maxsum = max(maxsum, max(ch[0] → suffix,
102                                ch[1] → prefix) +
103                                    ↪ key +
104                                      ↪ heap.top());
105
106        if (heap.size() > 1) {
107            maxsum = max(maxsum, heap.top2() +
108                          ↪ key);
109        }
110    }
111 }
112 null[maxn << 1], *ptr = null;
113
114 void addedge(int, int, int);
115 void deledge(int, int);
116 void modify(int, int, int);
117 void modify_color(int);
118 node *newnode(int);
119 node *access(node *);
120 void makeroot(node *);
121 void link(node *, node *);
122 void cut(node *, node *);
123 void splay(node *);
124 void rot(node *, int);
125
126 queue<node *> freenodes;
127 tree<pair<int, int>, node *> mp;
128
129 bool col[maxn] = {false};
130 char c;
131 int n, m, k, x, y, z;
132
133 int main() {
134     null → ch[0] = null → ch[1] = null → p = null;
135     scanf("%d%d%d", &n, &m, &k);
136
137     for (int i = 1; i ≤ n; i++)
138         newnode(0);
139
140     heap.push(0);
141
142     while (k--) {
143         scanf("%d", &x);
144
145         col[x] = true;
146         null[x].heap.push(0);
147     }
148
149     for (int i = 1; i < n; i++) {
150         scanf("%d%d%d", &x, &y, &z);
151
152         if (x > y)
153             swap(x, y);
154         addedge(x, y, z);
155     }
156
157     while (m--) {
158         scanf("%c%d", &c, &x);
159
160         if (c == 'A') {
161             scanf("%d", &y);
162
163             if (x > y)
164                 swap(x, y);
165             deledge(x, y);
166         }
167         else if (c == 'B') {
168             scanf("%d%d", &y, &z);
169
170             if (x > y)
171                 swap(x, y);
172             addedge(x, y, z);
173         }
174         else if (c == 'C') {
175             scanf("%d%d", &y, &z);
176
177             if (x > y)
178                 swap(x, y);
179             modify(x, y, z);
180         }
181         else
182             modify_color(x);
183
184         printf("%lld\n", (heap.top() > 0 ? heap.top() :
185                           ↪ -1));
186     }
187
188     return 0;
189 }
190
191 void addedge(int x, int y, int z) {
192     node *tmp;
193
194     if (freenodes.empty())
195         tmp = newnode(z);
196     else {
197         tmp = freenodes.front();
198         freenodes.pop();
199         *tmp = node(z);
200     }
201
202     tmp → ch[0] = tmp → ch[1] = tmp → p = null;
203
204     heap.push(tmp → maxsum);
205     link(tmp, null + x);
206     link(tmp, null + y);
207     mp[make_pair(x, y)] = tmp;
208
209 }
210
211 void deledge(int x, int y) {
212     node *tmp = mp[make_pair(x, y)];
213
214     cut(tmp, null + x);
215     cut(tmp, null + y);
216
217     freenodes.push(tmp);
218     heap.erase(tmp → maxsum);
219     mp.erase(make_pair(x, y));
220
221 }
222
223 void modify(int x, int y, int z) {
224     node *tmp = mp[make_pair(x, y)];
225
226     makeroot(tmp);
227     tmp → pushdown();
228
229     heap.erase(tmp → maxsum);
230     tmp → key = z;
231     tmp → refresh();
232     heap.push(tmp → maxsum);
233
234 }
235
236 void rot(node *x, int y);
237
238 void refresh(node *x);
239
240 void pushdown(node *x);
241
242 void pushup(node *x);
243
244 void makeroot(node *x);
245
246 void link(node *x, node *y);
247
248 void cut(node *x, node *y);
249
250 void swap(int &x, int &y);
251
252 void deledge(node *x, node *y);
253
254 void modify_color(int x);
255
256 void modify(int x, int y, int z);
257
258 void addedge(int x, int y, int z);
259
260 void splay(node *x);
261
262 void pushup(node *x);
263
264 void pushdown(node *x);
265
266 void refresh(node *x);
267
268 void makeroot(node *x);
269
270 void link(node *x, node *y);
271
272 void cut(node *x, node *y);
273
274 void swap(int &x, int &y);
275
276 void deledge(node *x, node *y);
277
278 void modify_color(int x);
279
280 void modify(int x, int y, int z);
281
282 void addedge(int x, int y, int z);
283
284 void splay(node *x);
285
286 void rot(node *x, int y);
287
288 void refresh(node *x);
289
290 void pushup(node *x);
291
292 void pushdown(node *x);
293
294 void makeroot(node *x);
295
296 void link(node *x, node *y);
297
298 void cut(node *x, node *y);
299
300 void swap(int &x, int &y);
301
302 void deledge(node *x, node *y);
303
304 void modify_color(int x);
305
306 void modify(int x, int y, int z);
307
308 void addedge(int x, int y, int z);
309
310 void splay(node *x);
311
312 void rot(node *x, int y);
313
314 void refresh(node *x);
315
316 void pushup(node *x);
317
318 void pushdown(node *x);
319
320 void makeroot(node *x);
321
322 void link(node *x, node *y);
323
324 void cut(node *x, node *y);
325
326 void swap(int &x, int &y);
327
328 void deledge(node *x, node *y);
329
330 void modify_color(int x);
331
332 void modify(int x, int y, int z);
333
334 void addedge(int x, int y, int z);
335
336 void splay(node *x);
337
338 void rot(node *x, int y);
339
340 void refresh(node *x);
341
342 void pushup(node *x);
343
344 void pushdown(node *x);
345
346 void makeroot(node *x);
347
348 void link(node *x, node *y);
349
350 void cut(node *x, node *y);
351
352 void swap(int &x, int &y);
353
354 void deledge(node *x, node *y);
355
356 void modify_color(int x);
357
358 void modify(int x, int y, int z);
359
360 void addedge(int x, int y, int z);
361
362 void splay(node *x);
363
364 void rot(node *x, int y);
365
366 void refresh(node *x);
367
368 void pushup(node *x);
369
370 void pushdown(node *x);
371
372 void makeroot(node *x);
373
374 void link(node *x, node *y);
375
376 void cut(node *x, node *y);
377
378 void swap(int &x, int &y);
379
380 void deledge(node *x, node *y);
381
382 void modify_color(int x);
383
384 void modify(int x, int y, int z);
385
386 void addedge(int x, int y, int z);
387
388 void splay(node *x);
389
390 void rot(node *x, int y);
391
392 void refresh(node *x);
393
394 void pushup(node *x);
395
396 void pushdown(node *x);
397
398 void makeroot(node *x);
399
400 void link(node *x, node *y);
401
402 void cut(node *x, node *y);
403
404 void swap(int &x, int &y);
405
406 void deledge(node *x, node *y);
407
408 void modify_color(int x);
409
410 void modify(int x, int y, int z);
411
412 void addedge(int x, int y, int z);
413
414 void splay(node *x);
415
416 void rot(node *x, int y);
417
418 void refresh(node *x);
419
420 void pushup(node *x);
421
422 void pushdown(node *x);
423
424 void makeroot(node *x);
425
426 void link(node *x, node *y);
427
428 void cut(node *x, node *y);
429
430 void swap(int &x, int &y);
431
432 void deledge(node *x, node *y);
433
434 void modify_color(int x);
435
436 void modify(int x, int y, int z);
437
438 void addedge(int x, int y, int z);
439
440 void splay(node *x);
441
442 void rot(node *x, int y);
443
444 void refresh(node *x);
445
446 void pushup(node *x);
447
448 void pushdown(node *x);
449
450 void makeroot(node *x);
451
452 void link(node *x, node *y);
453
454 void cut(node *x, node *y);
455
456 void swap(int &x, int &y);
457
458 void deledge(node *x, node *y);
459
460 void modify_color(int x);
461
462 void modify(int x, int y, int z);
463
464 void addedge(int x, int y, int z);
465
466 void splay(node *x);
467
468 void rot(node *x, int y);
469
470 void refresh(node *x);
471
472 void pushup(node *x);
473
474 void pushdown(node *x);
475
476 void makeroot(node *x);
477
478 void link(node *x, node *y);
479
480 void cut(node *x, node *y);
481
482 void swap(int &x, int &y);
483
484 void deledge(node *x, node *y);
485
486 void modify_color(int x);
487
488 void modify(int x, int y, int z);
489
490 void addedge(int x, int y, int z);
491
492 void splay(node *x);
493
494 void rot(node *x, int y);
495
496 void refresh(node *x);
497
498 void pushup(node *x);
499
500 void pushdown(node *x);
501
502 void makeroot(node *x);
503
504 void link(node *x, node *y);
505
506 void cut(node *x, node *y);
507
508 void swap(int &x, int &y);
509
510 void deledge(node *x, node *y);
511
512 void modify_color(int x);
513
514 void modify(int x, int y, int z);
515
516 void addedge(int x, int y, int z);
517
518 void splay(node *x);
519
520 void rot(node *x, int y);
521
522 void refresh(node *x);
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524 void pushup(node *x);
525
526 void pushdown(node *x);
527
528 void makeroot(node *x);
529
530 void link(node *x, node *y);
531
532 void cut(node *x, node *y);
533
534 void swap(int &x, int &y);
535
536 void deledge(node *x, node *y);
537
538 void modify_color(int x);
539
540 void modify(int x, int y, int z);
541
542 void addedge(int x, int y, int z);
543
544 void splay(node *x);
545
546 void rot(node *x, int y);
547
548 void refresh(node *x);
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550 void pushup(node *x);
551
552 void pushdown(node *x);
553
554 void makeroot(node *x);
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556 void link(node *x, node *y);
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558 void cut(node *x, node *y);
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560 void swap(int &x, int &y);
561
562 void deledge(node *x, node *y);
563
564 void modify_color(int x);
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566 void modify(int x, int y, int z);
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568 void addedge(int x, int y, int z);
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570 void splay(node *x);
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572 void rot(node *x, int y);
573
574 void refresh(node *x);
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576 void pushup(node *x);
577
578 void pushdown(node *x);
579
580 void makeroot(node *x);
581
582 void link(node *x, node *y);
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584 void cut(node *x, node *y);
585
586 void swap(int &x, int &y);
587
588 void deledge(node *x, node *y);
589
590 void modify_color(int x);
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592 void modify(int x, int y, int z);
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594 void addedge(int x, int y, int z);
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596 void splay(node *x);
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598 void rot(node *x, int y);
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600 void refresh(node *x);
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602 void pushup(node *x);
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604 void pushdown(node *x);
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608 void link(node *x, node *y);
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612 void swap(int &x, int &y);
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614 void deledge(node *x, node *y);
615
616 void modify_color(int x);
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618 void modify(int x, int y, int z);
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620 void addedge(int x, int y, int z);
621
622 void splay(node *x);
623
624 void rot(node *x, int y);
625
626 void refresh(node *x);
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628 void pushup(node *x);
629
630 void pushdown(node *x);
631
632 void makeroot(node *x);
633
634 void link(node *x, node *y);
635
636 void cut(node *x, node *y);
637
638 void swap(int &x, int &y);
639
640 void deledge(node *x, node *y);
641
642 void modify_color(int x);
643
644 void modify(int x, int y, int z);
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646 void addedge(int x, int y, int z);
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648 void splay(node *x);
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650 void rot(node *x, int y);
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652 void refresh(node *x);
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670 void modify(int x, int y, int z);
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672 void addedge(int x, int y, int z);
673
674 void splay(node *x);
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676 void rot(node *x, int y);
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702 void rot(node *x, int y);
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704 void refresh(node *x);
705
706 void pushup(node *x);
707
708 void pushdown(node *x);
709
710 void makeroot(node *x);
711
712 void link(node *x, node *y);
713
714 void cut(node *x, node *y);
715
716 void swap(int &x, int &y);
717
718 void deledge(node *x, node *y);
719
720 void modify_color(int x);
721
722 void modify(int x, int y, int z);
723
724 void addedge(int x, int y, int z);
725
726 void splay(node *x);
727
728 void rot(node *x, int y);
729
730 void refresh(node *x);
731
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1391
1392 void swap(int &x, int &y);
1393
1394 void deledge(node *x, node *y);
1395
1396 void modify_color(int x);
139
```

```

222 void modify_color(int x) {
223     makeroot(null + x);
224     col[x] ^= true;
225
226     if (col[x])
227         null[x].heap.push(0);
228     else
229         null[x].heap.erase(0);
230
231     heap.erase(null[x].maxsum);
232     null[x].refresh();
233     heap.push(null[x].maxsum);
234 }
235
236 node *newnode(int k) {
237     *(++ptr) = node(k);
238     ptr → ch[0] = ptr → ch[1] = ptr → p = null;
239     return ptr;
240 }
241
242 node *access(node *x) {
243     splay(x);
244     heap.erase(x → maxsum);
245     x → refresh();
246
247     if (x → ch[1] != null) {
248         x → ch[1] → pushdown();
249         x → heap.push(x → ch[1] → prefix);
250         x → refresh();
251         heap.push(x → ch[1] → maxsum);
252     }
253
254     x → ch[1] = null;
255     x → refresh();
256     node *y = x;
257     x = x → p;
258
259     while (x != null) {
260         splay(x);
261         heap.erase(x → maxsum);
262
263         if (x → ch[1] != null) {
264             x → ch[1] → pushdown();
265             x → heap.push(x → ch[1] → prefix);
266             heap.push(x → ch[1] → maxsum);
267         }
268
269         x → heap.erase(y → prefix);
270         x → ch[1] = y;
271         (y = x) → refresh();
272         x = x → p;
273     }
274
275     heap.push(y → maxsum);
276     return y;
277 }
278
279 void makeroot(node *x) {
280     access(x);
281     splay(x);
282     x → rev ^= true;
283 }
284
285 void link(node *x, node *y) { // 新添一条虚边, 维护y对应的堆
286     makeroot(x);
287     makeroot(y);
288
289     x → pushdown();
290     x → p = y;
291     heap.erase(y → maxsum);
292     y → heap.push(x → prefix);

```

```

293     y → refresh();
294     heap.push(y → maxsum);
295 }
296
297 void cut(node *x, node *y) { // 断开一条实边, 一条链变成
298     // 两条链, 需要维护全局堆
299     makeroot(x);
300     access(y);
301     splay(y);
302
303     heap.erase(y → maxsum);
304     heap.push(y → ch[0] → maxsum);
305     y → ch[0] → p = null;
306     y → ch[0] = null;
307     y → refresh();
308     heap.push(y → maxsum);
309
310 void splay(node *x) {
311     x → pushdown();
312
313     while (!isroot(x)) {
314         if (!isroot(x → p))
315             x → p → p → pushdown();
316
317         x → p → pushdown();
318         x → pushdown();
319
320         if (isroot(x → p)) {
321             rot(x → p, dir(x) ^ 1);
322             break;
323         }
324
325         if (dir(x) == dir(x → p))
326             rot(x → p → p, dir(x → p) ^ 1);
327         else
328             rot(x → p, dir(x) ^ 1);
329
330         rot(x → p, dir(x) ^ 1);
331     }
332 }
333
334 void rot(node *x, int d) {
335     node *y = x → ch[d ^ 1];
336
337     if ((x → ch[d ^ 1] = y → ch[d]) != null)
338         y → ch[d] → p = x;
339
340     y → p = x → p;
341
342     if (!isroot(x))
343         x → p → ch[dir(x)] = y;
344
345     (y → ch[d] = x) → p = y;
346
347     x → refresh();
348     y → refresh();
349 }

```

4.8 K-D树

4.8.1 动态K-D树(定期重构)

```

1 int l[2], r[2], x[B + 10][2], w[B + 10];
2 int n, op, ans = 0, cnt = 0, tmp = 0;
3 int d;
4
5 struct node {
6     int x[2], l[2], r[2], w, sum;
7     node *ch[2];
8

```

```

9  bool operator < (const node &a) const {
10    return x[d] < a.x[d];
11  }
12
13  void refresh() {
14    sum = ch[0] → sum + ch[1] → sum + w;
15    l[0] = min(x[0], min(ch[0] → l[0], ch[1] →
16                → l[0]));
17    l[1] = min(x[1], min(ch[0] → l[1], ch[1] →
18                → l[1]));
19    r[0] = max(x[0], max(ch[0] → r[0], ch[1] →
20                → r[0]));
21    r[1] = max(x[1], max(ch[0] → r[1], ch[1] →
22                → r[1]));
23  }
24  null[maxn], *root = null;
25
26  void build(int l, int r, int k, node *&rt) {
27    if (l > r) {
28      rt = null;
29      return;
30    }
31
32    int mid = (l + r) / 2;
33
34    d = k;
35    nth_element(null + l, null + mid, null + r + 1);
36
37    rt = null + mid;
38    build(l, mid - 1, k ^ 1, rt → ch[0]);
39    build(mid + 1, r, k ^ 1, rt → ch[1]);
40
41    rt → refresh();
42
43  void query(node *rt) {
44    if (l[0] ≤ rt → l[0] && l[1] ≤ rt → l[1] && rt
45    → → r[0] ≤ r[0] && rt → r[1] ≤ r[1]) {
46      ans += rt → sum;
47      return;
48    }
49    else if (l[0] > rt → r[0] || l[1] > rt → r[1] ||
50            → r[0] < rt → l[0] || r[1] < rt → l[1])
51      return;
52
53    if (l[0] ≤ rt → x[0] && l[1] ≤ rt → x[1] && rt
54    → → x[0] ≤ r[0] && rt → x[1] ≤ r[1])
55      ans += rt → w;
56
57    query(rt → ch[0]);
58    query(rt → ch[1]);
59
60  int main() {
61
62    null → l[0] = null → l[1] = 100000000;
63    null → r[0] = null → r[1] = -100000000;
64    null → sum = 0;
65    null → ch[0] = null → ch[1] = null;
66    scanf("%*d");
67
68    while (scanf("%d", &op) == 1 && op != 3) {
69      if (op == 1) {
70        tmp++;
71        scanf("%d%d%d", &x[tmp][0], &x[tmp][1],
72              → &w[tmp]);
73        x[tmp][0] ≈ ans;
74        x[tmp][1] ≈ ans;
75        w[tmp] ≈ ans;
76      }
77    }
78  }
79
80  void update(int l, int r, int val) {
81    if (l[0] > r[0] && l[1] > r[1])
82      return;
83    else if (l[0] < r[0] && l[1] < r[1])
84      update(l[0], r[0], val);
85    else if (l[0] < r[0] && l[1] ≥ r[1])
86      update(l[0], l[1], val);
87    else if (l[0] ≥ r[0] && l[1] < r[1])
88      update(r[0], l[1], val);
89    else if (l[0] ≥ r[0] && l[1] ≥ r[1])
90      update(r[0], r[1], val);
91  }
92
93  void build() {
94    for (int i = 1; i ≤ n; i++) {
95      l[i] = i;
96      r[i] = i;
97      sum[i] = 0;
98      w[i] = 0;
99    }
100   build(1, n, 0, null);
101 }
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103  void print() {
104    for (int i = 1; i ≤ n; i++)
105      printf("%d ", sum[i]);
106  }
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108  void print() {
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967
968  void print() {
969    for (int i = 1; i ≤ n; i++)
970      printf("%d ", sum[i]);
971  }
972
973  void print() {
974    for (int i = 1; i ≤ n; i++)
975      printf("%d ", sum[i]);
976  }
977
978  void print() {
979    for (int i = 1; i ≤ n; i++)
980      printf("%d ", sum[i]);
981  }
982
983  void print() {
984    for (int i = 1; i ≤ n; i++)
985      printf("%d ", sum[i]);
986  }
987
988  void print() {
989    for (int i = 1; i ≤ n; i++)
990      printf("%d ", sum[i]);
991  }
992
993  void print() {
994    for (int i = 1; i ≤ n; i++)
995      printf("%d ", sum[i]);
996  }
997
998  void print() {
999    for (int i = 1; i ≤ n; i++)
1000      printf("%d ", sum[i]);
1001  }
1002 }
```

4.9 LCA最近公共祖先

```

71  if (tmp == B) {
72    for (int i = 1; i ≤ tmp; i++) {
73      null[cnt + i].x[0] = x[i][0];
74      null[cnt + i].x[1] = x[i][1];
75      null[cnt + i].w = w[i];
76    }
77    build(1, cnt + tmp, 0, root);
78    tmp = 0;
79  }
80  else {
81    scanf("%d%d%d%d", &l[0], &l[1], &r[0], &r[1]);
82    l[0] ≈ ans;
83    l[1] ≈ ans;
84    r[0] ≈ ans;
85    r[1] ≈ ans;
86    ans = 0;
87
88    for (int i = 1; i ≤ tmp; i++) {
89      if (l[0] ≤ x[i][0] && l[1] ≤ x[i][1] && r[0] ≤ x[i][0] && r[1] ≤ x[i][1])
90        ans += w[i];
91    }
92
93    query(root);
94    printf("%d\n", ans);
95  }
96
97  return 0;
98 }
```

```

1  vector<pair<int, int>> q[maxn];
2  int lca[maxn];
3
4  void dfs(int x) {
5    dfn[x] = ++tim; // 其实求LCA是用不到DFS序的，但是一般其他步骤要用
6    ufs[x] = x;
7
8    for (auto pi : q[x]) {
9      int y = pi.first, i = pi.second;
10     if (dfn[y])
11       lca[i] = findufs(y);
12   }
13
14   for (int y : G[x]) {
15     if (y != p[x]) {
16       p[y] = x;
17       dfs(y);
18     }
19   }
20
21   ufs[x] = p[x];
22 }
```

```

1  struct Tree {
2    vector<int> G[maxn], W[maxn];
3    int p[maxn], d[maxn], size[maxn], mn[maxn],
4        mx[maxn];
```

4.10 虚树

```

4   bool col[maxn];
5   long long ans_sum;
6   int ans_min, ans_max;
7
8   void add(int x, int y, int z) {
9     G[x].push_back(y);
10    W[x].push_back(z);
11  }
12
13  void dfs(int x) {
14    size[x] = col[x];
15    mx[x] = (col[x] ? d[x] : -inf);
16    mn[x] = (col[x] ? d[x] : inf);
17
18    for (int i = 0; i < (int)G[x].size(); i++) {
19      d[G[x][i]] = d[x] + W[x][i];
20      dfs(G[x][i]);
21      ans_sum += (long long)size[x] * size[G[x]
22        [i]] * d[x];
23      ans_max = max(ans_max, mx[x] + mx[G[x][i]]
24        - (d[x] << 1));
25      ans_min = min(ans_min, mn[x] + mn[G[x][i]]
26        - (d[x] << 1));
27      size[x] += size[G[x][i]];
28      mx[x] = max(mx[x], mx[G[x][i]]);
29      mn[x] = min(mn[x], mn[G[x][i]]);
30    }
31  }
32
33  void clear(int x) {
34    G[x].clear();
35    W[x].clear();
36    col[x] = false;
37  }
38
39  void solve(int rt) {
40    ans_sum = 0;
41    ans_max = -inf;
42    ans_min = inf;
43    dfs(rt);
44    ans_sum <= 1;
45  }
46
47  virtree;
48
49  void dfs(int);
50  int LCA(int, int);
51
52  vector<int> G[maxn];
53  int f[maxn][20], d[maxn], dfn[maxn], tim = 0;
54
55  bool cmp(int x, int y) {
56    return dfn[x] < dfn[y];
57  }
58
59  int n, m, lgn = 0, a[maxn], s[maxn], v[maxn];
60
61  int main() {
62    scanf("%d", &n);
63
64    for (int i = 1, x, y; i < n; i++) {
65      scanf("%d%d", &x, &y);
66      G[x].push_back(y);
67      G[y].push_back(x);
68    }
69
70    G[n + 1].push_back(1);
71    dfs(n + 1);
72
73    for (int i = 1; i <= n + 1; i++)
74      G[i].clear();
75
76    lgn--;
77
78    for (int j = 1; j <= lgn; j++) {
79      for (int i = 1; i <= n; i++)
80        f[i][j] = f[f[i][j - 1]][j - 1];
81
82      scanf("%d", &m);
83
84      while (m--) {
85        int k;
86        scanf("%d", &k);
87
88        for (int i = 1; i <= k; i++)
89          scanf("%d", &a[i]);
90
91        sort(a + 1, a + k + 1, cmp);
92        int top = 0, cnt = 0;
93        s[++top] = v[++cnt] = n + 1;
94        long long ans = 0;
95
96        for (int i = 1; i <= k; i++) {
97          virtree.col[a[i]] = true;
98          ans += d[a[i]] - 1;
99          int u = LCA(a[i], s[top]);
100
101         if (s[top] != u) {
102           while (top > 1 && d[s[top - 1]] >
103             d[u]) {
104             virtree.add(s[top - 1], s[top],
105               d[s[top]] - d[s[top - 1]]);
106             top--;
107           }
108
109           if (s[top] != u) {
110             virtree.add(u, s[top], d[s[top]] -
111               d[u]);
112             s[top] = v[++cnt] = u;
113           }
114
115           s[++top] = a[i];
116
117         for (int i = top - 1; i; i--)
118           virtree.add(s[i], s[i + 1], d[s[i + 1]] -
119             d[s[i]]);
120
121         virtree.solve(n + 1);
122         ans *= k - 1;
123         printf("%lld %d %d\n", ans - virtree.ans_sum,
124             virtree.ans_min, virtree.ans_max);
125
126         for (int i = 1; i <= k; i++)
127           virtree.clear(a[i]);
128         for (int i = 1; i <= cnt; i++)
129           virtree.clear(v[i]);
130
131       }
132
133       return 0;
134     }
135
136     void dfs(int x) {
137       dfn[x] = ++tim;
138       d[x] = d[f[x][0]] + 1;
139
140       while ((1 << lgn) < d[x])
141         lgn++;
142
143       for (int i = 0; i < (int)G[x].size(); i++)
144         if (G[x][i] != f[x][0]) {
145           f[G[x][i]][0] = x;
146           dfs(G[x][i]);
147         }
148     }
149   }
150 }
```

```

140     }
141 }
142 int LCA(int x, int y) {
143     if (d[x] != d[y]) {
144         if (d[x] < d[y])
145             swap(x, y);
146
147         for (int i = lgn; i ≥ 0; i--)
148             if (((d[x] - d[y]) >> i) & 1)
149                 x = f[x][i];
150     }
151
152     if (x == y)
153         return x;
154
155     for (int i = lgn; i ≥ 0; i--)
156         if (f[x][i] != f[y][i])
157             x = f[x][i];
158         y = f[y][i];
159     }
160
161     return f[x][0];
162 }

```

4.11 长链剖分

```

1 // 顾名思义，长链剖分是取最深的儿子作为重儿子
2
3 // O(n)维护以深度为下标的子树信息
4 vector<int> G[maxn], v[maxn];
5 int n, p[maxn], h[maxn], son[maxn], ans[maxn];
6
7 // 原题题意：求每个点的子树中与它距离是几的点最多，相同的
8 // → 取最大深度
9 // 由于vector只能在后面加入元素，为了写代码方便，这里反过来存
10 // 或者开一个结构体维护倒过来的vector
11 void dfs(int x) {
12     h[x] = 1;
13
14     for (int y : G[x])
15         if (y != p[x]){
16             p[y] = x;
17             dfs(y);
18
19             if (h[y] > h[son[x]])
20                 son[x] = y;
21
22         if (!son[x]) {
23             v[x].push_back(1);
24             ans[x] = 0;
25             return;
26         }
27
28         h[x] = h[son[x]] + 1;
29         swap(v[x], v[son[x]]);
30
31         if (v[x][ans[son[x]]] == 1)
32             ans[x] = h[x] - 1;
33         else
34             ans[x] = ans[son[x]];
35
36         v[x].push_back(1);
37
38         int mx = v[x][ans[x]];
39         for (int y : G[x])
40             if (y != p[x] && y != son[x]) {
41                 for (int j = 1; j ≤ h[y]; j++) {

```

```

42         v[x][h[x] - j - 1] += v[y][h[y] - j];
43
44         int t = v[x][h[x] - j - 1];
45         if (t > mx || (t == mx && h[x] - j - 1
46             ↪ > ans[x])) {
47             mx = t;
48             ans[x] = h[x] - j - 1;
49         }
50     }
51     v[y].clear();
52 }
53

```

4.11.1 梯子剖分

```

1 // 在线求一个点的第k祖先 O(n\log n)-O(1)
2 // 理论基础：任意一个点x的k级祖先y所在长链长度一定≥k
3
4 // 全局数组定义
5 vector<int> G[maxn], v[maxn];
6 int d[maxn], mxd[maxn], son[maxn], top[maxn],
7     ↪ len[maxn];
8 int f[19][maxn], log_tbl[maxn];
9
10 // 在主函数中两遍dfs之后加上如下预处理
11 log_tbl[0] = -1;
12 for (int i = 1; i ≤ n; i++)
13     log_tbl[i] = log_tbl[i / 2] + 1;
14 for (int j = 1; (1 << j) < n; j++)
15     for (int i = 1; i ≤ n; i++)
16         f[j][i] = f[j - 1][f[j - 1][i]];
17
18 // 第一遍dfs，用于计算深度和找出重儿子
19 void dfs1(int x) {
20     mxd[x] = d[x];
21
22     for (int y : G[x])
23         if (y != f[0][x]){
24             f[0][y] = x;
25             d[y] = d[x] + 1;
26             dfs1(y);
27
28             mxd[x] = max(mxd[x], mxd[y]);
29             if (mxd[y] > mxd[son[x]])
30                 son[x] = y;
31         }
32
33 // 第二遍dfs，用于进行剖分和预处理梯子剖分(每条链向上延伸
34 // → 一倍)数组
35 void dfs2(int x) {
36     top[x] = (x == son[f[0][x]] ? top[f[0][x]] : x);
37
38     for (int y : G[x])
39         if (y != f[0][x])
40             dfs2(y);
41
42     if (top[x] == x) {
43         int u = x;
44         while (top[son[u]] == x)
45             u = son[u];
46
47         len[x] = d[u] - d[x];
48         for (int i = 0; i < len[x]; i++, u = f[0][u])
49             v[x].push_back(u);
50     }
51     u = x;

```

```

52     for (int i = 0; i < len[x] && u; i++, u = f[0]
53         ↪ [u])
54         v[x].push_back(u);
55     }
56
57 // 在线询问x的k级祖先 O(1)
58 // 不存在时返回0
59 int query(int x, int k) {
60     if (!k)
61         return x;
62     if (k > d[x])
63         return 0;
64
65     x = f[log_tbl[k]][x];
66     k ≈ 1 << log_tbl[k];
67     return v[top[x]][d[top[x]] + len[top[x]] - d[x] +
68         ↪ k];
}

```

4.12 堆

4.12.1 左偏树

参见3.2.3.k短路(28页).

4.12.2 二叉堆

```

1 struct my_binary_heap {
2     static constexpr int maxn = 100005;
3
4     int a[maxn], size;
5
6     my_binary_heap() : size(0) {}
7
8     void push(int val) {
9         a[++size] = val;
10
11        for (int x = size; x > 1; x /= 2) {
12            if (a[x] < a[x / 2])
13                swap(a[x], a[x / 2]);
14            else
15                break;
16        }
17    }
18
19    int &top() {
20        return a[1];
21    }
22
23    int pop() {
24        int res = a[1];
25        a[1] = a[size--];
26
27        for (int x = 1, son; ; x = son) {
28            if (x * 2 == size)
29                son = x * 2;
30            else if (x * 2 > size)
31                break;
32            else if (a[x * 2] < a[x * 2 + 1])
33                son = x * 2;
34            else
35                son = x * 2 + 1;
36
37            if (a[son] < a[x])
38                swap(a[x], a[son]);
39            else
40                break;
41        }
}

```

```

42             ↪
43         return res;
44     }
45 }

```

4.13 莫队

注意如果 n 和 q 不平衡, 块大小应该设为 $\frac{n}{\sqrt{q}}$.

另外如果裸的莫队要卡常可以按块编号奇偶性分别对右端点正序或者倒序排序, 期望可以减少一半的移动次数.

4.13.1 莫队二次离线

适用范围: 询问的是点对相关(或者其它可以枚举每个点和区间算贡献)的信息, 并且可以离线; 更新时可以使用一些牺牲修改复杂度来改善询问复杂度的数据结构(如单点修改询问区间和).

先按照普通的莫队将区间排序. 考虑区间移动的情况, 以 (l, r) 向右移动右端点到 (l, t) 为例.

对于每个 $i \in (r, t]$ 来说, 它都要对区间 $[l, i]$ 算贡献. 可以拆成 $[1, i]$ 和 $[1, l]$ 两部分, 那么前一部分因为都是 i 和 $[1, i]$ 做贡献的形式所以可以直接预处理.

考虑后一部分, i 和 $[1, l]$ 做贡献, 因为莫队的性质我们可以保证这样的询问次数不超过 $O((n + m)\sqrt{n})$, 因此我们可以对每个 l 记录下来哪些 i 要和它询问. 并且每次移动时询问的 i 都是连续的, 所以对每个 l 开一个vector记录下对应的区间和编号就行了.

剩余的三种情况(右端点左移或者移动左端点)都是类似的, 具体可以看代码.

例: Yuno loves sqrt technology II (询问区间逆序对数)

```

1 #include <bits/stdc++.h>
2
3 using namespace std;
4
5 constexpr int maxn = 100005, B = 314;
6
7 struct Q {
8     int l, r, d, id;
9
10    Q() = default;
11
12    Q(int l, int r, int d, int id) : l(l), r(r), d(d),
13        ↪ id(id) {}
14
15    friend bool operator < (const Q &a, const Q &b) {
16        if (a.d != b.d)
17            return a.d < b.d;
18
19        return a.r < b.r;
20    }
21 } q[maxn]; // 结构体可以复用, d既可以作为左端点块编号, 也
22           ↪ 可以作为二次离线处理的倍数
23
24 int global_n, bid[maxn], L[maxn], R[maxn], cntb;
25
26 int sa[maxn], sb[maxn];
27
28 void addp(int x) { // sqrt(n)修改 O(1)查询
29     for (int k = bid[x]; k ≤ cntb; k++)
30         sb[k]++;
31
32     for (int i = x; i ≤ R[bid[x]]; i++)
33         sa[i]++;
34 }
35
36 int queryp(int x) {
37     if (!x)
38         return 0;
39
40     int res = 0;
41
42     for (int i = x; i ≤ R[bid[x]]; i++)
43         res += sb[i];
44
45     return res;
46 }

```

```

38     return sa[x] + sb[bid[x] - 1];
39 }
40
41 void adds(int x) {
42     for (int k = 1; k <= bid[x]; k++)
43         sb[k]++;
44
45     for (int i = L[bid[x]]; i <= x; i++)
46         sa[i]++;
47 }
48
49 int querys(int x) {
50     if (x > global_n)
51         return 0; // 为了防止越界就判一下
52     return sa[x] + sb[bid[x] + 1];
53 }
54
55 vector<Q> vp[maxn], vs[maxn]; // prefix, suffix
56 long long fp[maxn], fs[maxn]; // prefix, suffix
58 int a[maxn], b[maxn];
60 long long ta[maxn], ans[maxn];
62
63 int main() {
64
65     int n, m;
66     scanf("%d%d", &n, &m);
67
68     global_n = n;
69
70     for (int i = 1; i <= n; i++)
71         scanf("%d", &a[i]);
72
73     memcpy(b, a, sizeof(int) * (n + 1));
74     sort(b + 1, b + n + 1);
75
76     for (int i = 1; i <= n; i++)
77         a[i] = lower_bound(b + 1, b + n + 1, a[i]) - b;
78
79     for (int i = 1; i <= n; i++) {
80         bid[i] = (i - 1) / B + 1;
81
82         if (!L[bid[i]])
83             L[bid[i]] = i;
84
85         R[bid[i]] = i;
86         cntb = bid[i];
87     }
88
89     for (int i = 1; i <= m; i++) {
90         scanf("%d%d", &q[i].l, &q[i].r);
91
92         q[i].d = bid[q[i].l];
93         q[i].id = i;
94     }
95
96     sort(q + 1, q + m + 1);
97
98     int l = 2, r = 1; // l, r是上一个询问的端点
99
100    for (int i = 1; i <= m; i++) {
101        int s = q[i].l, t = q[i].r; // s, t是当前要调整
102        → 到的端点
103
104        if (s < l)
105            vs[r + 1].push_back(Q(s, l - 1, 1, i));
106        else if (s > l)
107            vs[r + 1].push_back(Q(l, s - 1, -1, i));

```

```

107
108     l = s;
109
110     if (t > r)
111         vp[l - 1].push_back(Q(r + 1, t, 1, i));
112     else if (t < r)
113         vp[l - 1].push_back(Q(t + 1, r, -1, i));
114
115     r = t;
116 }
117
118 for (int i = 1; i <= n; i++) { // 第一遍正着处理, 解
119     → 决关于前缀的询问
120     fp[i] = fp[i - 1] + querys(a[i] + 1);
121
122     adds(a[i]);
123
124     for (auto q : vp[i]) {
125         long long tmp = 0;
126         for (int k = q.l; k <= q.r; k++)
127             tmp += querys(a[k] + 1);
128
129         ta[q.id] -= q.d * tmp;
130     }
131
132     memset(sa, 0, sizeof(sa));
133     memset(sb, 0, sizeof(sb));
134
135     for (int i = n; i--){ // 第二遍倒着处理, 解决关
136     → 于后缀的询问
137     fs[i] = fs[i + 1] + queryp(a[i] - 1);
138
139     addp(a[i]);
140
141     for (auto q : vs[i]) {
142         long long tmp = 0;
143         for (int k = q.l; k <= q.r; k++)
144             tmp += queryp(a[k] - 1);
145
146         ta[q.id] -= q.d * tmp;
147     }
148
149     l = 2;
150     r = 1;
151
152     for (int i = 1; i <= m; i++) { // 求出fs和fp之后再加
153     → 上这部分的贡献
154         int s = q[i].l, t = q[i].r;
155
156         ta[i] += fs[s] - fs[l];
157         ta[i] += fp[t] - fp[r];
158
159         l = s;
160         r = t;
161
162         ta[i] += ta[i - 1]; // 因为算出来的是相邻两个询
163         → 问之间的贡献, 所以要前缀和
164         ans[q[i].id] = ta[i];
165
166         for (int i = 1; i <= m; i++)
167             printf("%lld\n", ans[i]);
168
169     }

```

4.13.2 带修莫队在线化 $O(n^{\frac{5}{3}})$

最简单的带修莫队：块大小设成 $n^{\frac{2}{3}}$ ，排序时第一关键字是左端点块编号，第二关键字是右端点块编号，第三关键字是时间。（记得把时间压缩成只有修改的时间。）

现在要求在线的同时支持修改，仍然以 $B = n^{\frac{2}{3}}$ 分一块，预处理出两块之间的贡献，那么预处理复杂度就是 $O(n^{\frac{5}{3}})$ 。

修改时最简单的方法是直接把 $n^{\frac{2}{3}}$ 个区间全更新一遍。嫌慢的话可以给每个区间打一个懒标记，询问的时候如果解了再更新区间的信息。

注意如果附加信息是可减的（比如每个数的出现次数），那么就只需要存 $O(n^{\frac{1}{3}})$ 个。

总复杂度仍然是 $O(n^{\frac{5}{3}})$ ，如果打懒标记的话是跑不太满的。如果附加信息可减则空间复杂度是 $O(n^{\frac{4}{3}})$ ，否则和时间复杂度同阶。

4.13.3 莫队二次离线 在线化 $O((n+m)\sqrt{n})$

和之前的道理是一样的， i 和 $[1, i]$ 的贡献这部分仍然可以预处理掉，而前后缀对区间的贡献那部分只保存块端点处的信息。

按照莫队二次离线的转移方法操作之后发现只剩两边散块的贡献没有解决。这时可以具体问题具体解决，例如求逆序对的话直接预处理出排序后的数组然后归并即可。

时空复杂度均为 $O(n\sqrt{n})$ 。

以下代码以强制在线求区间逆序对为例（洛谷上被卡常了，正常情况下极限数据应该在 1.5s 内。）

```

1 constexpr int maxn = 100005, B = 315, maxb = maxn / B +
2   ↪ 5;
3
4 int n, bid[maxn], L[maxb], R[maxb], cntb;
5
6 struct DS { // O(sqrt(n)) 修改 O(1) 查询
7     int total;
8     int sa[maxn], sb[maxb];
9
10    void init(const DS &o) {
11        total = o.total;
12        memcpy(sa, o.sa, sizeof(int) * (n + 1));
13        memcpy(sb, o.sb, sizeof(int) * (cntb + 1));
14    }
15
16    void add(int x) {
17        total++;
18        for (int k = 1; k ≤ bid[x]; k++)
19            sb[k]++;
20        for (int i = L[bid[x]]; i ≤ x; i++)
21            sa[i]++;
22    }
23
24    int querys(int x) {
25        if (x > n)
26            return 0;
27
28        return sb[bid[x] + 1] + sa[x];
29    }
30
31    int queryp(int x) {
32        return total - querys(x + 1);
33    }
34 } pr[maxb];
35
36 int c[maxn]; // 树状数组
37
38 void addc(int x, int d) {
39     while (x) {
40         c[x] += d;
41         x -= x & -x;
42     }
43 }
```

```

43
44 int queryc(int x) {
45     int ans = 0;
46     while (x ≤ n) {
47         ans += c[x];
48         x += x & -x;
49     }
50     return ans;
51 }
52
53 long long fp[maxn], fs[maxn];
54
55 int rk[maxn], val[maxn][B + 5];
56
57 long long dat[maxb][maxb];
58
59 int a[maxn];
60
61 int main() {
62     int m;
63     cin >> n >> m;
64
65     for (int i = 1; i ≤ n; i++) {
66         cin >> a[i];
67
68         bid[i] = (i - 1) / B + 1;
69         if (!L[bid[i]])
70             L[bid[i]] = i;
71         R[bid[i]] = i;
72         cntb = bid[i];
73
74         rk[i] = i;
75     }
76
77
78     for (int k = 1; k ≤ cntb; k++)
79         sort(rk + L[k], rk + R[k] + 1, [](int x, int
80           ↪ y) {return a[x] < a[y];}); // 每个块排序
81
82     for (int i = n; i; i--) {
83         for (int j = 2; i + j - 1 ≤ R[bid[i]]; j++) {
84             val[i][j] = val[i + 1][j - 1] + val[i][j -
85               ↪ 1] - val[i + 1][j - 2];
86             if (a[i] > a[i + j - 1])
87                 val[i][j]++; // 块内用二维前缀和预处理
88         }
89
90         for (int k = 1; k ≤ cntb; k++) {
91             for (int i = L[k]; i ≤ R[k]; i++) {
92                 dat[k][k] += queryc(a[i] + 1); // 单块内的逆
93                 addc(a[i], 1);
94
95                 for (int i = L[k]; i ≤ R[k]; i++)
96                     addc(a[i], -1);
97
98                 for (int i = 1; i ≤ n; i++) {
99                     if (i > 1 & i == L[bid[i]])
100                         pr[bid[i]].init(pr[bid[i] - 1]);
101
102                     fp[i] = fp[i - 1] + pr[bid[i]].querys(a[i] +
103                       ↪ 1);
104
105                     pr[bid[i]].addc(a[i]);
106
107                     for (int i = n; i; i--) {
108                         fs[i] = fs[i + 1] + (n - i - queryc(a[i] + 1));
109
110                     }
111
112                 }
113             }
114         }
115     }
116 }
```

```

109     addc(a[i], 1);
110 }
111
112 for (int s = 1; s <= cntb; s++) {
113     for (int t = s + 1; t <= cntb; t++) {
114         dat[s][t] = dat[s][t - 1] + dat[t][t];
115
116         for (int i = L[t]; i <= R[t]; i++) // 块间的
117             → 逆序对用刚才处理的块求出
118             dat[s][t] += pr[t - 1].querys(a[i] + 1)
119             → - pr[s - 1].querys(a[i] + 1);
120     }
121
122 long long ans = 0;
123
124 while (m--) {
125     long long s, t;
126     cin >> s >> t;
127
128     int l = s ^ ans, r = t ^ ans;
129
130     if (bid[l] == bid[r])
131         ans = val[l][r - l + 1];
132     else {
133         ans = dat[bid[l] + 1][bid[r] - 1];
134
135         ans += fp[r] - fp[L[bid[r]] - 1];
136         for (int i = L[bid[r]]; i <= r; i++)
137             ans -= pr[bid[l]].querys(a[i] + 1);
138
139         ans += fs[l] - fs[R[bid[l]] + 1];
140         for (int i = l; i <= R[bid[l]]; i++)
141             ans -= (a[i] - 1) - pr[bid[r] - 1].queryp(a[i] - 1);
142
143         int i = L[bid[l]], j = L[bid[r]], w = 0; // ← 手写归并
144
145         while (true) {
146             while (i <= R[bid[l]] && rnk[i] < l)
147                 i++;
148             while (j <= R[bid[r]] && rnk[j] > r)
149                 j++;
150
151             if (i > R[bid[l]] && j > R[bid[r]])
152                 break;
153
154             int x = (i <= R[bid[l]] ? a[rnk[i]] : (int)1e9), y = (j <= R[bid[r]] ?
155             a[rnk[j]] : (int)1e9);
156
157             if (x < y) {
158                 ans += w;
159                 i++;
160             } else {
161                 j++;
162                 w++;
163             }
164         }
165         cout << ans << '\n';
166     }
167
168     return 0;
169 }
```

4.14 常见根号思路

1. 通用

- 出现次数大于 \sqrt{n} 的数不会超过 \sqrt{n} 个
- 对于带修改问题, 如果不方便分治或者二进制分组, 可以考虑对操作分块, 每次查询时暴力最后的 \sqrt{n} 个修改并更正答案
- **根号分治:** 如果分治时每个子问题需要 $O(N)$ (N 是全局问题的大小)的时间, 而规模较小的子问题可以 $O(n^2)$ 解决, 则可以使用根号分治
 - 规模大于 \sqrt{n} 的子问题用 $O(N)$ 的方法解决, 规模小于 \sqrt{n} 的子问题用 $O(n^2)$ 暴力
 - 规模大于 \sqrt{n} 的子问题最多只有 \sqrt{n} 个
 - 规模不大于 \sqrt{n} 的子问题大小的平方和也必定不会超过 $n\sqrt{n}$
- 如果输入规模之和不大于 n (例如给定多个小字符串与大字符串进行询问), 那么规模超过 \sqrt{n} 的问题最多只有 \sqrt{n} 个

2. 序列

- 某些维护序列的问题可以用分块/块状链表维护
- 对于静态区间询问问题, 如果可以快速将左/右端点移动一位, 可以考虑莫队
 - 如果强制在线可以分块预处理, 但是一般空间需要 $n\sqrt{n}$
 - * 例题: 询问区间中有几种数出现次数恰好为 k , 强制在线
 - 如果带修改可以试着想一想带修莫队, 但是复杂度高达 $n^{\frac{5}{3}}$
- 线段树可以解决的问题也可以用分块来做到 $O(1)$ 询问或是 $O(1)$ 修改, 具体要看哪种操作更多

3. 树

- 与序列类似, 树上也有树分块和树上莫队
 - 树上带修莫队很麻烦, 常数也大, 最好不要先考虑
 - 树分块不要想当然
- 树分治也可以套根号分治, 道理是一样的

4. 字符串

- 循环节长度大于 \sqrt{n} 的子串最多只有 $O(n)$ 个, 如果是极长子串则只有 $O(\sqrt{n})$ 个

5 字符串

5.1 KMP

```

1 int fail[maxn];
2
3 void kmp(const char *s, int n) {
4     fail[0] = fail[1] = 0;
5
6     for (int i = 1; i < n; i++) {
7         int j = fail[i];
8
9         while (j && s[i + 1] != s[j + 1])
10            j = fail[j];
11
12         if (s[i + 1] == s[j + 1])
13             fail[i + 1] = j + 1;
14         else
15             fail[i + 1] = 0;
16     }
17 }
```

5.1.1 ex-KMP

```

1 void exkmp(const char *s, int *a, int n) {
2     int l = 0, r = 0;
3     a[0] = n;
4
5     for (int i = 1; i ≤ n; i++) {
6         a[i] = i > r ? 0 : min(r - i + 1, a[i - l]);
7
8         while (i + a[i] < n && s[a[i]] == s[i + a[i]])
9             a[i]++;
10
11         if (i + a[i] - 1 > r) {
12             l = i;
13             r = i + a[i] - 1;
14         }
15     }
16 }
```

5.2 AC自动机

```

1 int ch[maxm][26], f[maxm][26], q[maxm], sum[maxm], cnt
2     → = 0;
3
4 // 在字典树中插入一个字符串 O(n)
5 int insert(const char *c) {
6     int x = 0;
7     while (*c) {
8         if (!ch[x][*c - 'a'])
9             ch[x][*c - 'a'] = ++cnt;
10        x = ch[x][*c++ - 'a'];
11    }
12    return x;
13 }
14
15 // 建AC自动机 O(n * sigma)
16 void getfail() {
17     int x, head = 0, tail = 0;
18
19     for (int c = 0; c < 26; c++)
20         if (ch[0][c])
21             q[tail++] = ch[0][c]; // 把根节点的儿子加入
22             → 队列
23
24     while (head != tail) {
```

```

23         x = q[head++];
24
25         G[f[x][0]].push_back(x);
26         fill(f[x] + 1, f[x] + 26, cnt + 1);
27
28         for (int c = 0; c < 26; c++) {
29             if (ch[x][c]) {
30                 int y = f[x][0];
31
32                 f[ch[x][c]][0] = ch[y][c];
33                 q[tail++] = ch[x][c];
34             } else
35                 ch[x][c] = ch[f[x][0]][c];
36         }
37     }
38
39     fill(f[0], f[0] + 26, cnt + 1);
40 }
```

5.3 后缀数组

5.3.1 倍增

```

1 constexpr int maxn = 100005;
2
3 void get_sa(char *s, int n, int *sa, int *rnk, int
4     → *height) { // 1-base
5     static int buc[maxn], id[maxn], p[maxn], t[maxn *
6         → 2];
7
8     int m = 300;
9
10    for (int i = 1; i ≤ n; i++)
11        buc[rnk[i]] = s[i]++;
12    for (int i = 1; i ≤ m; i++)
13        buc[i] += buc[i - 1];
14    for (int i = n; i; i--)
15        sa[buc[rnk[i]]--] = i;
16
17    memset(buc, 0, sizeof(int) * (m + 1));
18
19    for (int k = 1, cnt = 0; cnt != n; k *= 2, m = cnt)
20        → {
21        cnt = 0;
22        for (int i = n; i > n - k; i--)
23            id[+cnt] = i;
24
25        for (int i = 1; i ≤ n; i++)
26            if (sa[i] > k)
27                id[+cnt] = sa[i] - k;
28
29        for (int i = 1; i ≤ n; i++)
30            buc[p[i]] = rnk[id[i]]++;
31        for (int i = 1; i ≤ m; i++)
32            buc[i] += buc[i - 1];
33        for (int i = n; i; i--)
34            sa[buc[p[i]]--] = id[i];
35
36        memset(buc, 0, sizeof(int) * (m + 1));
37
38        memcpy(t, rnk, sizeof(int) * (max(n, m) + 1));
39
40        cnt = 0;
41        for (int i = 1; i ≤ n; i++) {
42            if (t[sa[i]] != t[sa[i - 1]] || t[sa[i] +
43                → k] != t[sa[i - 1] + k])
44                cnt++;
45        }
46        rnk[sa[i]] = cnt;
47    }
48 }
```

```

43     }
44 }
45
46 for (int i = 1; i <= n; i++)
47     sa[rnk[i]] = i;
48
49 for (int i = 1, k = 0; i <= n; i++) { // 顺便
50     ←求height
51     if (k)
52         k--;
53
54     while (s[i + k] == s[sa[rnk[i] - 1] + k])
55         k++;
56
57     height[rnk[i]] = k; // height[i] = lcp(sa[i],
58     ←sa[i - 1])
59 }
60
61 char s[maxn];
62 int sa[maxn], rnk[maxn], height[maxn];
63
64 int main() {
65     cin >> s + 1;
66
67     int n = strlen(s + 1);
68
69     get_sa(s, n, sa, rnk, height);
70
71     for (int i = 1; i <= n; i++)
72         cout << sa[i] << (i < n ? ' ' : '\n');
73
74     for (int i = 2; i <= n; i++)
75         cout << height[i] << (i < n ? ' ' : '\n');
76
77     return 0;
}

```

5.3.2 SA-IS

```

1 // SA-IS求完的SA有效位只有1~n, 但它是0-based, 如果其他部
2     →分是1-based就抄一下封装
3
4 constexpr int maxn = 100005, l_type = 0, s_type = 1;
5
6 // 判断一个字符是否为LMS字符
7 bool is_lms(int *tp, int x) {
8     return x > 0 && tp[x] == s_type && tp[x - 1] ==
9         →l_type;
10
11 // 判断两个LMS子串是否相同
12 bool equal_substr(int *s, int x, int y, int *tp) {
13     do {
14         if (s[x] != s[y])
15             return false;
16         x++;
17     } while (!is_lms(tp, x) && !is_lms(tp, y));
18
19     return s[x] == s[y];
20 }
21
22 // 诱导排序(从*型诱导到L型, 从L型诱导到S型)
23 // 调用之前应将*型按要求放入SA中
24 void induced_sort(int *s, int *sa, int *tp, int *buc,
25     ←int *lbuc, int *sbuc, int n, int m) {
26     for (int i = 0; i < n; i++)
27         if (sa[i] > 0 && tp[sa[i] - 1] == l_type)

```

```

28     for (int i = 1; i <= m; i++)
29         sbuc[i] = buc[i] - 1;
30
31     for (int i = n; ~i; i--)
32         if (sa[i] > 0 && tp[sa[i] - 1] == s_type)
33             sa[sbuc[s[sa[i] - 1]]--] = sa[i] - 1;
34
35 }
36
37 // s是输入字符串, n是字符串的长度, m是字符集的大小
38 int *sa_is(int *s, int len, int m) {
39     int n = len - 1;
40
41     int *tp = new int[n + 1];
42     int *pos = new int[n + 1];
43     int *name = new int[n + 1];
44     int *sa = new int[n + 1];
45     int *buc = new int[m + 1];
46     int *lbuc = new int[m + 1];
47     int *sbuc = new int[m + 1];
48
49     memset(buc, 0, sizeof(int) * (m + 1));
50     memset(lbuc, 0, sizeof(int) * (m + 1));
51     memset(sbuc, 0, sizeof(int) * (m + 1));
52
53     for (int i = 0; i <= n; i++)
54         buc[s[i]]++;
55
56     for (int i = 1; i <= m; i++) {
57         buc[i] += buc[i - 1];
58
59         lbuc[i] = buc[i - 1];
60         sbuc[i] = buc[i] - 1;
61     }
62
63     tp[n] = s_type;
64     for (int i = n - 1; ~i; i--) {
65         if (s[i] < s[i + 1])
66             tp[i] = s_type;
67         else if (s[i] > s[i + 1])
68             tp[i] = l_type;
69         else
70             tp[i] = tp[i + 1];
71     }
72
73     int cnt = 0;
74     for (int i = 1; i <= n; i++)
75         if (tp[i] == s_type && tp[i - 1] == l_type)
76             pos[cnt++] = i;
77
78     memset(sa, -1, sizeof(int) * (n + 1));
79     for (int i = 0; i < cnt; i++)
80         sa[sbuc[s[pos[i]]]] = pos[i];
81     induced_sort(s, sa, tp, buc, lbuc, sbuc, n, m);
82
83     memset(name, -1, sizeof(int) * (n + 1));
84     int lastx = -1, namecnt = 1;
85     bool flag = false;
86
87     for (int i = 1; i <= n; i++) {
88         int x = sa[i];
89
90         if (is_lms(tp, x)) {
91             if (lastx >= 0 && !equal_substr(s, x,
92                 ←lastx, tp))
93                 namecnt++;
94
95             if (lastx >= 0 && namecnt == name[lastx])

```

```

95     flag = true;
96
97     name[x] = namecnt;
98     lastx = x;
99 }
100 name[n] = 0;
101
102 int *t = new int[cnt];
103 int p = 0;
104 for (int i = 0; i <= n; i++)
105     if (name[i] >= 0)
106         t[p++] = name[i];
107
108 int *tsa;
109 if (!flag) {
110     tsa = new int[cnt];
111
112     for (int i = 0; i < cnt; i++)
113         tsa[t[i]] = i;
114 }
115 else
116     tsa = sais(t, cnt, namecnt);
117
118 lbuc[0] = sbuc[0] = 0;
119 for (int i = 1; i <= m; i++) {
120     lbuc[i] = buc[i - 1];
121     sbuc[i] = buc[i] - 1;
122 }
123
124 memset(sa, -1, sizeof(int) * (n + 1));
125 for (int i = cnt - 1; ~i; i--)
126     sa[sbuc[s[pos[tsa[i]]]]--] = pos[tsa[i]];
127 induced_sort(s, sa, tp, buc, lbuc, sbuc, n, m);
128
129 // 多组数据的时候最好 delete 掉
130 delete[] tp;
131 delete[] pos;
132 delete[] name;
133 delete[] buc;
134 delete[] lbuc;
135 delete[] sbuc;
136 delete[] t;
137 delete[] tsa;
138
139 return sa;
140 }
141
142 // 封装好的函数, 1-based
143 void get_sa(char *s, int n, int *sa, int *rnk, int
144     *height) {
145     static int a[maxn];
146
147     for (int i = 1; i <= n; i++)
148         a[i - 1] = s[i];
149
150     a[n] = '$';
151
152     int *t = sais(a, n + 1, 256);
153     memcpy(sa, t, sizeof(int) * (n + 1));
154     delete[] t;
155
156     sa[0] = 0;
157     for (int i = 1; i <= n; i++)
158         rnk[+sa[i]] = i;
159
160     for (int i = 1, k = 0; i <= n; i++) { // 求 height
161         if (k)
162             k--;
163     }
164     name[n] = 0;
165
166     int *tsa;
167     if (!flag) {
168         tsa = new int[cnt];
169         for (int i = 0; i < cnt; i++)
170             tsa[t[i]] = i;
171     }
172     else
173         tsa = sais(t, cnt, namecnt);
174
175     lbuc[0] = sbuc[0] = 0;
176     for (int i = 1; i <= m; i++) {
177         lbuc[i] = buc[i - 1];
178         sbuc[i] = buc[i] - 1;
179     }
180
181     memset(sa, -1, sizeof(int) * (n + 1));
182     for (int i = cnt - 1; ~i; i--)
183         sa[sbuc[s[pos[tsa[i]]]]--] = pos[tsa[i]];
184     induced_sort(s, sa, tp, buc, lbuc, sbuc, n, m);
185
186     delete[] tp;
187     delete[] pos;
188     delete[] name;
189     delete[] buc;
190     delete[] lbuc;
191     delete[] sbuc;
192     delete[] t;
193     delete[] tsa;
194
195     return sa;
196 }
197
198 // 封装好的函数, 1-based
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203     for (int i = 1; i <= n; i++)
204         a[i - 1] = s[i];
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206     a[n] = '$';
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208     int *t = sais(a, n + 1, 256);
209     memcpy(sa, t, sizeof(int) * (n + 1));
210     delete[] t;
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212     sa[0] = 0;
213     for (int i = 1; i <= n; i++)
214         rnk[+sa[i]] = i;
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220     name[n] = 0;
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237     memset(sa, -1, sizeof(int) * (n + 1));
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914     delete[] tp;
915     delete[] pos;
916     delete[] name;
917     delete[] buc;
918     delete[] lbuc;
919     delete[] sbuc;
920     delete[] t;
921     delete[] tsa;
922
923     return sa;
924 }
925
926 // 封装好的函数, 1-based
927 void get_sa(char *s, int n, int *sa, int *rnk, int
928     *height) {
929     static int a[maxn];
930
931     for (int i = 1; i <= n; i++)
932         a[i - 1] = s[i];
933
934     a[n] = '$';
935
936     int *t = sais(a, n + 1, 256);
937     memcpy(sa, t, sizeof(int) * (n + 1));
938     delete[] t;
939
940     sa[0] = 0;
941     for (int i = 1; i <= n; i++)
942         rnk[+sa[i]] = i;
943
944     for (int i = 1, k = 0; i <= n; i++) { // 求 height
945         if (k)
946             k--;
947     }
948     name[n] = 0;
949
950     int *tsa;
951     if (!flag) {
952         tsa = new int[cnt];
953         for (int i = 0; i < cnt; i++)
954             tsa[t[i]] = i;
955     }
956     else
957         tsa = sais(t, cnt, namecnt);
958
959     lbuc[0] = sbuc[0] = 0;
960     for (int i = 1; i <= m; i++) {
961         lbuc[i] = buc[i - 1];
962         sbuc[i] = buc[i] - 1;
963     }
964
965     memset(sa, -1, sizeof(int) * (n + 1));
966     for (int i = cnt - 1; ~i; i--)
967         sa[sbuc[s[pos[tsa[i]]]]--] = pos[tsa[i]];
968     induced_sort(s, sa, tp, buc, lbuc, sbuc, n, m);
969
970     delete[] tp;
971     delete[] pos;
972     delete[] name;
973     delete[] buc;
974     delete[] lbuc;
975     delete[] sbuc;
976     delete[] t;
977     delete[] tsa;
978
979     return sa;
980 }
981
982 // 封装好的函数, 1-based
983 void get_sa(char *s, int n, int *sa, int *rnk, int
984     *height) {
985     static int a[maxn];
986
987     for (int i = 1; i <= n; i++)
988         a[i - 1] = s[i];
989
990     a[n] = '$';
991
992     int *t = sais(a, n + 1, 256);
993     memcpy(sa, t, sizeof(int) * (n + 1));
994     delete[] t;
995
996     sa[0] = 0;
997     for (int i = 1; i <= n; i++)
998         rnk[+sa[i]] = i;
999
1000    for (int i = 1, k = 0; i <= n; i++) { // 求 height
1001        if (k)
1002            k--;
1003    }
1004    name[n] = 0;
1005
1006    int *tsa;
1007    if (!flag) {
1008        tsa = new int[cnt];
1009        for (int i = 0; i < cnt; i++)
1010            tsa[t[i]] = i;
1011    }
1012    else
1013        tsa = sais(t, cnt, namecnt);
1014
1015    lbuc[0] = sbuc[0] = 0;
1016    for (int i = 1; i <= m; i++) {
1017        lbuc[i] = buc[i - 1];
1018        sbuc[i] = buc[i] - 1;
1019    }
1020
1021    memset(sa, -1, sizeof(int) * (n + 1));
1022    for (int i = cnt - 1; ~i; i--)
1023        sa[sbuc[s[pos[tsa[i]]]]--] = pos[tsa[i]];
1024    induced_sort(s, sa, tp, buc, lbuc, sbuc, n, m);
1025
1026    delete[] tp;
1027    delete[] pos;
1028    delete[] name;
1029    delete[] buc;
1030    delete[] lbuc;
1031    delete[] sbuc;
1032    delete[] t;
1033    delete[] tsa;
1034
1035    return sa;
1036 }
1037
1038 // 封装好的函数, 1-based
1039 void get_sa(char *s, int n, int *sa, int *rnk, int
1040     *height) {
1041     static int a[maxn];
1042
1043     for (int i = 1; i <= n; i++)
1044         a[i - 1] = s[i];
1045
1046     a[n] = '$';
1047
1048     int *t = sais(a, n + 1, 256);
1049     memcpy(sa, t, sizeof(int) * (n + 1));
1050     delete[] t;
1051
1052     sa[0] = 0;
1053     for (int i = 1; i <= n; i++)
1054         rnk[+sa[i]] = i;
1055
1056     for (int i = 1, k = 0; i <= n; i++) { // 求 height
1057         if (k)
1058             k--;
1059     }
1060     name[n] = 0;
1061
1062     int *tsa;
1063     if (!flag) {
1064         tsa = new int[cnt];
1065         for (int i = 0; i < cnt; i++)
1066             tsa[t[i]] = i;
1067     }
1068     else
1069         tsa = sais(t, cnt, namecnt);
1070
1071     lbuc[0] = sbuc[0] = 0
```

57

5.4 后缀平衡树

如果不需要查询排名，只需要维护前驱后继关系的题目，可以直接用二分哈希+set去做。

一般的题目需要查询排名，这时候就需要写替罪羊树或者Treap维护tag。插入后缀时如果首字母相同只需比较各自删除首字母后的tag大小即可。

(Treap也具有重量平衡树的性质，每次插入后影响到的子树大小期望是 $O(\log n)$ 的，所以每次做完插入操作之后直接暴力重构子树内tag就行了。)

5.5 后缀自动机

```

1 // 在字符集比较小的时候可以直接开go数组，否则需要用map或
2 // →者哈希表替换
3 // 注意!!!结点数要开成串长的两倍
4 // 全局变量与数组定义
5 int last, val[maxn], par[maxn], go[maxn][26], sam_cnt;
6 int c[maxn], q[maxn]; // 用来桶排序
7
8 // 在主函数开头加上这句初始化
9 last = sam_cnt = 1;
10
11 // 以下是按val进行桶排序的代码
12 for (int i = 1; i ≤ sam_cnt; i++)
13     c[val[i] + 1]++;
14 for (int i = 1; i ≤ n; i++)
15     c[i] += c[i - 1]; // 这里n是串长
16 for (int i = 1; i ≤ sam_cnt; i++)
17     q[+c[val[i]]] = i;
18
19 // 加入一个字符 均摊O(1)
20 void extend(int c) {
21     int p = last, np = ++sam_cnt;
22     val[np] = val[p] + 1;
23
24     while (p && !go[p][c]) {
25         go[p][c] = np;
26         p = par[p];
27     }
28
29     if (!p)
30         par[np] = 1;
31     else {
32         int q = go[p][c];
33
34         if (val[q] == val[p] + 1)
35             par[np] = q;
36         else {
37             int nq = ++sam_cnt;
38             val[nq] = val[p] + 1;
39             memcpy(go[nq], go[q], sizeof(go[q]));
40
41             par[nq] = par[q];
42             par[np] = par[q] = nq;
43
44             while (p && go[p][c] == q)
45                 go[p][c] = nq;
46                 p = par[p];
47             }
48     }
49
50     last = np;
51 }

```

5.5.1 广义后缀自动机

下面的写法复杂度是 Σ 串长的，但是胜在简单。

如果建字典树然后BFS建自动机可以做到 $O(n|\Sigma|)$ (n 是字典树结点数)，但是后者写起来比较麻烦。

```

1 int extend(int p, int c) {
2     int np = 0;
3
4     if (!go[p][c]) {
5         np = ++sam_cnt;
6         val[np] = val[p] + 1;
7         while (p && !go[p][c]) {
8             go[p][c] = np;
9             p = par[p];
10        }
11    }
12
13    if (!p)
14        par[np] = 1;
15    else {
16        int q = go[p][c];
17
18        if (val[q] == val[p] + 1) {
19            if (np)
20                par[np] = q;
21            else
22                return q;
23        }
24        else {
25            int nq = ++sam_cnt;
26            val[nq] = val[p] + 1;
27            memcpy(go[nq], go[q], sizeof(go[q]));
28
29            par[nq] = par[q];
30            par[q] = nq;
31            if (np)
32                par[np] = nq;
33
34            while (p && go[p][c] == q) {
35                go[p][c] = nq;
36                p = par[p];
37            }
38
39            if (!np)
40                return nq;
41        }
42    }
43
44    return np;
45 }
46 // 调用的时候直接last = 1然后一路调用last = extend(last,
47 // → c)就行了

```

5.5.2 区间本质不同子串计数(后缀自动机+LCT+线段树)

问题: 给定一个字符串 s ，多次询问 $[l, r]$ 区间的本质不同的子串个数，可能强制在线。

做法: 考虑建出后缀自动机，然后枚举右端点，用线段树维护每个左端点的答案。

显然只有right集合在 $[l, r]$ 中的串才有可能有贡献，所以我们只考虑每个串最大的right。

每次右端点+1时找到它对应的结点 u ，则 u 到根节点路径上的每个点，它的right集合都会被 r 更新。

对于某个特定的左端点 l ，我们需要保证本质不同的子串左端点不能越过它；因此对于一个结点 p ，我们知道它对应的子串长

度(val_{par_p}, val_p)之后，在 p 的right集合最大值减去对应长度，这样对应的 l 内全部+1即可；这样询问时就只需要查询 r 对应的线段树中 $[l, r]$ 的区间和。(当然旧的right对应的区间也要减掉)实际上可以发现更新时都是把路径分成若干个整段更新right集合，因此可以用LCT维护这个过程。时间复杂度 $O(n \log^2 n)$ ，空间 $O(n)$ ，当然如果强制在线的话，就把线段树改成主席树，空间复杂度就和时间复杂度同阶了。

```

1 int tim; // tim实际上就是当前的右端点
2
3 node *access(node *x) {
4     node *y = null;
5
6     while (x != null) {
7         splay(x);
8
9         x → ch[1] = null;
10        x → refresh();
11
12        if (x → val) // val记录的是上次访问时间，也就
13            ↪是right集合最大值
14        update(x → val - val[x → r] + 1, x → val
15            ↪ - val[par[x → l]], -1);
16
17        x → val = tim;
18        x → lazy = true;
19
20        update(x → val - val[x → r] + 1, x → val -
21            ↪ val[par[x → l]], 1);
22
23        x → ch[1] = y;
24
25        (y = x) → refresh();
26
27        x = x → p;
28    }
29
30    return y;
31
32 // 以下是main函数中的用法
33 for (int i = 1; i ≤ n; i++) {
34     tim++;
35     access(null + id[i]);
36
37     if (i ≥ m) // 例题询问长度是固定的，如果不固定的话就
38         ↪按照右端点离线即可
39     ans[i - m + 1] = query(i - m + 1, i);
40 }
```

还有一份完整的代码，因为写起来确实细节挺多的。这份代码支持在尾部加一个字符或者询问区间有多少子串至少出现了两次，并且强制在线。

```

1 #include <bits/stdc++.h>
2
3 using namespace std;
4
5 constexpr int maxn = 200005, maxm = maxn * 17 * 15;
6
7 int mx[maxn][2], lc[maxn], rc[maxn], seg_cnt;
8 int root[maxn];
9
10 int s, t, d;
11
12 void modify_seg(int l, int r, int &o) {
13     int u = o;
14     o = ++seg_cnt;
15
16     mx[o][0] = max(mx[u][0], t);
```

```

17     mx[o][1] = max(mx[u][1], d);
18
19     if (l == r)
20         return;
21
22     lc[o] = lc[u];
23     rc[o] = rc[u];
24
25     int mid = (l + r) / 2;
26     if (s ≤ mid)
27         modify_seg(l, mid, lc[o]);
28     else
29         modify_seg(mid + 1, r, rc[o]);
30
31     int query_seg(int l, int r, int o, int k) {
32         if (s ≤ l && t ≥ r)
33             return mx[o][k];
34
35         int mid = (l + r) / 2, ans = 0;
36
37         if (s ≤ mid)
38             ans = max(ans, query_seg(l, mid, lc[o], k));
39         if (t > mid)
40             ans = max(ans, query_seg(mid + 1, r, rc[o],
41                 ↪ k));
42
43         return ans;
44     }
45
46 int N;
47
48 void modify(int pos, int u, int v, int &rt) {
49     s = pos;
50     t = u;
51     d = v;
52
53     modify_seg(1, N, rt);
54 }
55
56 int query(int l, int r, int rt) {
57     s = l;
58     t = r;
59     int ans = query_seg(1, N, rt, 0);
60
61     s = 1;
62     t = l;
63     return max(ans, query_seg(1, N, rt, 1) - l);
64 }
65
66 struct node {
67     int size, l, r, id, tim;
68     node *ch[2], *p;
69     bool tag;
70
71     node() = default;
72
73     void apply(int v) {
74         tim = v;
75         tag = true;
76     }
77
78     void pushdown() {
79         if (tag) {
80             ch[0] → tim = ch[1] → tim = tim;
81             ch[0] → tag = ch[1] → tag = true;
82
83             tag = false;
84         }
85     }
86 }
```

```

87 void update() {
88     size = ch[0] → size + ch[1] → size + 1;
89     l = (ch[0] → l ? ch[0] → l : id);
90     r = (ch[1] → r ? ch[1] → r : id);
91 }
92 } null[maxn];
93
94 inline bool isroot(node *x) {
95     return x != x → p → ch[0] && x != x → p → ch[1];
96 }
97
98 inline bool dir(node *x) {
99     return x == x → p → ch[1];
100 }
101
102 void init(node *x, int i) {
103     *x = node();
104     x → ch[0] = x → ch[1] = x → p = null;
105     x → size = 1;
106     x → id = x → l = x → r = i;
107 }
108
109 void rot(node *x, int d) {
110     node *y = x → ch[d ^ 1];
111
112     y → p = x → p;
113     if (!isroot(x))
114         x → p → ch[dir(x)] = y;
115
116     if ((x → ch[d ^ 1] = y → ch[d]) != null)
117         y → ch[d] → p = x;
118     (y → ch[d] = x) → p = y;
119
120     x → update();
121     y → update();
122 }
123
124 void splay(node *x) {
125     x → pushdown();
126
127     while (!isroot(x)) {
128         if (!isroot(x → p))
129             x → p → p → pushdown();
130         x → p → pushdown();
131         x → pushdown();
132
133         if (isroot(x → p)) {
134             rot(x → p, dir(x) ^ 1);
135             break;
136         }
137
138         if (dir(x) == dir(x → p))
139             rot(x → p → p, dir(x → p) ^ 1);
140         else
141             rot(x → p, dir(x) ^ 1);
142
143         rot(x → p, dir(x) ^ 1);
144     }
145 }
146
147 void splay(node *x, node *rt) {
148     x → pushdown();
149
150     while (x → p != rt) {
151         if (x → p → p != rt)
152             x → p → p → pushdown();
153         x → p → pushdown();
154         x → pushdown();

```

```

155     if (x → p → p == rt) {
156         rot(x → p, dir(x) ^ 1);
157         break;
158     }
159
160     if (dir(x) == dir(x → p))
161         rot(x → p → p, dir(x → p) ^ 1);
162     else
163         rot(x → p, dir(x) ^ 1);
164
165     rot(x → p, dir(x) ^ 1);
166 }
167 }
168 }
169
170 int val[maxn], par[maxn], go[maxn][26], sam_cnt,
171 → sam_last;
172
173 node *access(node *x, int r) {
174     root[r] = root[r - 1];
175
176     node *y = null;
177
178     while (x != null) {
179         splay(x);
180
181         x → pushdown();
182
183         x → ch[1] = null;
184         x → update();
185
186         if (x → tim && val[x → r]) { // last time
187             ← visited
188             int right = x → tim, left = right - val[x
189                 → r] + 1;
190             modify(left, val[x → r], right + 1,
191                 → root[r]);
192         }
193
194         x → apply(r);
195         x → pushdown();
196
197         x → ch[1] = y;
198         (y = x) → update();
199
200         x = x → p;
201     }
202
203     return y;
204 }
205
206 void new_leaf(node *x, node *par) {
207     x → p = par;
208 }
209
210 void new_node(node *x, node *y, node *par) {
211     splay(y);
212
213     if (isroot(y) && y → p == par) {
214         assert(y → ch[0] == null);
215
216         y → ch[0] = x;
217         x → p = y;
218         y → update();
219     }
220     else {
221         splay(par, y);
222
223         assert(y → ch[0] == par);
224     }
225 }

```

```

220     assert(par → ch[1] == null);
221     par → ch[1] = x;
222     x → p = par;
223
224     par → update();
225     y → update();
226 }
227
228 x → tim = y → tim;
229 }
230
231 void extend(int c) {
232     int p = sam_last, np = ++sam_cnt;
233     val[np] = val[p] + 1;
234
235     init(null + np, np);
236
237     while (p && !go[p][c]) {
238         go[p][c] = np;
239         p = par[p];
240     }
241
242     if (!p) {
243         par[np] = 1;
244         new_leaf(null + np, null + par[np]);
245     }
246     else {
247         int q = go[p][c];
248
249         if (val[q] == val[p] + 1) {
250             par[np] = q;
251             new_leaf(null + np, null + par[np]);
252         }
253         else {
254             int nq = ++sam_cnt;
255             val[nq] = val[p] + 1;
256             memcpy(go[nq], go[q], sizeof(go[q]));
257
258             init(null + nq, nq);
259
260             new_node(null + nq, null + q, null +
261                     ↪ par[q]);
262             new_leaf(null + np, null + nq);
263
264             par[nq] = par[q];
265             par[np] = par[q] = nq;
266
267             while (p && go[p][c] == q) {
268                 go[p][c] = nq;
269                 p = par[p];
270             }
271         }
272     }
273     sam_last = np;
274 }
275
276 char str[maxn];
277
278 int main() {
279
280     init(null, 0);
281
282     sam_last = sam_cnt = 1;
283     init(null + 1, 1);
284
285     int n, m;
286     scanf("%s%d", str + 1, &m);
287     n = strlen(str + 1);
288     N = n + m;

```

```

289
290     for (int i = 1; i ≤ n; i++) {
291         extend(str[i] - 'a');
292         access(null + sam_last, i);
293     }
294
295     int tmp = 0;
296
297     while (m--) {
298         int op;
299         scanf("%d", &op);
300
301         if (op == 1) {
302             scanf(" %c", &str[++n]);
303
304             str[n] = (str[n] - 'a' + tmp) % 26 + 'a';
305
306             extend(str[n] - 'a');
307             access(null + sam_last, n);
308         }
309         else {
310             int l, r;
311             scanf("%d%d", &l, &r);
312
313             l = (l - 1 + tmp) % n + 1;
314             r = (r - 1 + tmp) % n + 1;
315
316             printf("%d\n", tmp = query(l, r, root[r]));
317         }
318     }
319
320     return 0;
321 }

```

5.6 回文树

```

1 // 定理: 一个字符串本质不同的回文子串个数是 $O(n)$ 的
2 // 注意回文树只需要开一倍结点, 另外结点编号也是一个可用
3 // 的bfs序
4
5 // 全局数组定义
6 int val[maxn], par[maxn], go[maxn][26], last, cnt;
7 char s[maxn];
8
9 // 重要!在主函数最前面一定要加上以下初始化
10 par[0] = cnt = 1;
11 val[1] = -1;
12 // 这个初始化和广义回文树不一样, 写普通题可以用, 广义回文
13 // 树就不要乱搞了
14
15 // extend函数 均摊 $O(1)$ 
16 // 向后扩展一个字符
17 // 传入对应下标
18 void extend(int n) {
19     int p = last, c = s[n] - 'a';
20     while (s[n - val[p] - 1] != s[n])
21         p = par[p];
22
23     if (!go[p][c]) {
24         int q = ++cnt, now = p;
25         val[q] = val[p] + 2;
26
27         do
28             p = par[p];
29         while (s[n - val[p] - 1] != s[n]);
30
31         par[q] = go[p][c];
32         last = go[now][c] = q;
33     }
34 }

```

```

31     }
32     else
33     |   last = go[p][c];
34
35     // a[last]++;
36 }
```

5.6.1 广义回文树

(代码是梯子剖分的版本, 压力不大的题目换成直接倍增就好了, 常数只差不到一倍)

```

1 #include <bits/stdc++.h>
2
3 using namespace std;
4
5 constexpr int maxn = 1000005, mod = 1000000007;
6
7 int val[maxn], par[maxn], go[maxn][26], fail[maxn][26],
8     → pam_last[maxn], pam_cnt;
9 int weight[maxn], pow_26[maxn];
10
11 int trie[maxn][26], trie_cnt, d[maxn], mxd[maxn],
12     → son[maxn], top[maxn], len[maxn], sum[maxn];
13 char chr[maxn];
14 int f[25][maxn], log_tbl[maxn];
15 vector<int> v[maxn];
16
17 vector<int> queries[maxn];
18
19 char str[maxn];
20 int n, m, ans[maxn];
21
22 int add(int x, int c) {
23     if (!trie[x][c]) {
24         trie[x][c] = ++trie_cnt;
25         f[0][trie[x][c]] = x;
26         chr[trie[x][c]] = c + 'a';
27     }
28
29     return trie[x][c];
30 }
31
32 int del(int x) {
33     return f[0][x];
34 }
35
36 void dfs1(int x) {
37     mxd[x] = d[x] = d[f[0][x]] + 1;
38
39     for (int i = 0; i < 26; i++)
40         if (trie[x][i])
41             int y = trie[x][i];
42
43             dfs1(y);
44
45             mxd[x] = max(mxd[x], mxd[y]);
46             if (mxd[y] > mxd[son[x]])
47                 son[x] = y;
48 }
49
50 void dfs2(int x) {
51     if (x == son[f[0][x]])
52         top[x] = top[f[0][x]];
53     else
54         top[x] = x;
55
56     for (int i = 0; i < 26; i++)
57         if (trie[x][i])
58             int y = trie[x][i];
59             dfs2(y);
```

```

59     }
60
61     if (top[x] == x) {
62         int u = x;
63         while (top[son[u]] == x)
64             u = son[u];
65
66         len[x] = d[u] - d[x];
67
68         for (int i = 0; i < len[x]; i++) {
69             v[x].push_back(u);
70             u = f[0][u];
71         }
72
73         u = x;
74         for (int i = 0; i < len[x]; i++) { // 梯子剖
75             → 分, 要延长一倍
76             v[x].push_back(u);
77             u = f[0][u];
78         }
79     }
80
81     int get_anc(int x, int k) {
82         if (!k)
83             return x;
84         if (k > d[x])
85             return 0;
86
87         x = f[log_tbl[k]][x];
88         k ≈ 1 << log_tbl[k];
89
90         return v[top[x]][d[top[x]] + len[top[x]] - d[x] +
91             → k];
92
93     char get_char(int x, int k) { // 查询x前面k个的字符是哪
94         → ↑
95         return chr[get_anc(x, k)];
96
97     int getfail(int x, int p) {
98         if (get_char(x, val[p] + 1) == chr[x])
99             return p;
100        return fail[p][chr[x] - 'a'];
101    }
102
103    int extend(int x) {
104        int p = pam_last[f[0][x]], c = chr[x] - 'a';
105
106        p = getfail(x, p);
107
108        int new_last;
109
110        if (!go[p][c]) {
111            int q = ++pam_cnt, now = p;
112            val[q] = val[p] + 2;
113
114            p = getfail(x, par[p]);
115
116            par[q] = go[p][c];
117            new_last = go[now][c] = q;
118
119            for (int i = 0; i < 26; i++)
120                fail[q][i] = fail[par[q]][i];
121
122            if (get_char(x, val[par[q]]) ≥ 'a')
123                fail[q][get_char(x, val[par[q]]) - 'a'] =
124                    → par[q];
125        }
```

```

126     if (val[q] <= n)
127         weight[q] = (weight[par[q]] + (long long)(n
128             - val[q] + 1) * pow_26[n - val[q]]) % mod;
129     else
130         weight[q] = weight[par[q]];
131     else
132         new_last = go[p][c];
133
134     pam_last[x] = new_last;
135
136     return weight[pam_last[x]];
137 }
138
139 void bfs() {
140
141     queue<int> q;
142
143     q.push(1);
144
145     while (!q.empty()) {
146         int x = q.front();
147         q.pop();
148
149         sum[x] = sum[f[0][x]];
150         if (x > 1)
151             sum[x] = (sum[x] + extend(x)) % mod;
152
153         for (int i : queries[x])
154             ans[i] = sum[x];
155
156         for (int i = 0; i < 26; i++)
157             if (trie[x][i])
158                 q.push(trie[x][i]);
159     }
160 }
161
162 int main() {
163
164     pow_26[0] = 1;
165     log_tbl[0] = -1;
166
167     for (int i = 1; i <= 1000000; i++) {
168         pow_26[i] = 26ll * pow_26[i - 1] % mod;
169         log_tbl[i] = log_tbl[i / 2] + 1;
170     }
171
172     int T;
173     scanf("%d", &T);
174
175     while (T--) {
176         scanf("%d%d%s", &n, &m, str);
177
178         trie_cnt = 1;
179         chr[1] = '#';
180
181         int last = 1;
182         for (char *c = str; *c; c++)
183             last = add(last, *c - 'a');
184
185         queries[last].push_back(0);
186
187         for (int i = 1; i <= m; i++) {
188             int op;
189             scanf("%d", &op);
190
191             if (op == 1) {
192                 char c;
193                 scanf(" %c", &c);
194
195
196                     last = add(last, c - 'a');
197                 }
198                 else
199                     last = del(last);
200
201                 queries[last].push_back(i);
202             }
203
204             dfs1(1);
205             dfs2(1);
206
207             for (int j = 1; j <= log_tbl[trie_cnt]; j++)
208                 for (int i = 1; i <= trie_cnt; i++)
209                     f[j][i] = f[j - 1][f[j - 1][i]];
210
211             par[0] = pam_cnt = 1;
212
213             for (int i = 0; i < 26; i++)
214                 fail[0][i] = fail[1][i] = 1;
215
216             val[1] = -1;
217             pam_last[1] = 1;
218
219             bfs();
220
221             for (int i = 0; i <= m; i++)
222                 printf("%d\n", ans[i]);
223
224             for (int j = 0; j <= log_tbl[trie_cnt]; j++)
225                 memset(f[j], 0, sizeof(f[j]));
226
227             for (int i = 1; i <= trie_cnt; i++) {
228                 chr[i] = 0;
229                 d[i] = mxd[i] = son[i] = top[i] = len[i] =
230                     ->pam_last[i] = sum[i] = 0;
231                 v[i].clear();
232                 queries[i].clear();
233
234                 memset(trie[i], 0, sizeof(trie[i]));
235             }
236             trie_cnt = 0;
237
238             for (int i = 0; i <= pam_cnt; i++)
239                 val[i] = par[i] = weight[i];
240
241             memset(go[i], 0, sizeof(go[i]));
242             memset(fail[i], 0, sizeof(fail[i]));
243
244             pam_cnt = 0;
245
246         }
247
248         return 0;
249     }
}

```

5.7 Manacher马拉车

```

1 // n为串长, 回文半径输出到p数组中
2 // 数组要开串长的两倍
3 void manacher(const char *t, int n) {
4     static char s[maxn * 2];
5
6     for (int i = n; i; i--)
7         s[i * 2] = t[i];
8     for (int i = 0; i <= n; i++)
9         s[i * 2 + 1] = '#';
10
11    s[0] = '$';
12    s[(n + 1) * 2] = '\0';
13    n = n * 2 + 1;

```

```
14
15     int mx = 0, j = 0;
16
17     for (int i = 1; i <= n; i++) {
18         p[i] = (mx > i ? min(p[j * 2 - i], mx - i) :
19             → 1);
20         while (s[i - p[i]] == s[i + p[i]])
21             p[i]++;
22
23         if (i + p[i] > mx) {
24             mx = i + p[i];
25             j = i;
26         }
27 }
```

5.8 字符串原理

KMP和AC自动机的fail指针存储的都是它在串或者字典树上的最长后缀，因此要判断两个前缀是否互为后缀时可以直接用fail指针判断。当然它不能做子串问题，也不能做最长公共后缀。

后缀数组利用的主要是LCP长度可以按照字典序做RMQ的性质，与某个串的LCP长度 \geq 某个值的后缀形成一个区间。另外一个比较好用的性质是本质不同的子串个数 = 所有子串数 - 字典序相邻的串的height。

后缀自动机实际上可以接受的是所有后缀，如果把中间状态也算上的话就是所有子串。它的fail指针代表的也是当前串的后缀，不过注意每个状态可以代表很多状态，只要右端点在right集合中且长度处在 $(val_{par_p}, val_p]$ 中的串都被它代表。

后缀自动机的fail树也就是反串的后缀树。每个结点代表的串和后缀自动机同理，两个串的LCP长度也就是他们在后缀树上的LCA。

6 动态规划

6.1 决策单调性 $O(n \log n)$

```

1 int a[maxn], q[maxn], p[maxn], g[maxn]; // 存左端点, 右端
2   点就是下一个左端点 - 1
3
4 long long f[maxn], s[maxn];
5
6 int n, m;
7
8 long long calc(int l, int r) {
9     if (r < l)
10        return 0;
11
12     int mid = (l + r) / 2;
13     if ((r - l + 1) % 2 == 0)
14         return (s[r] - s[mid]) - (s[mid] - s[l - 1]);
15     else
16         return (s[r] - s[mid]) - (s[mid - 1] - s[l - 1]);
17
18 int solve(long long tmp) {
19     memset(f, 63, sizeof(f));
20     f[0] = 0;
21
22     int head = 1, tail = 0;
23
24     for (int i = 1; i ≤ n; i++) {
25         f[i] = calc(1, i);
26         g[i] = 1;
27
28         while (head < tail && p[head + 1] ≤ i)
29             head++;
30         if (head ≤ tail) {
31             if (f[q[head]] + calc(q[head] + 1, i) <
32                 → f[i]) {
33                 f[i] = f[q[head]] + calc(q[head] + 1,
34                               → i);
35                 g[i] = g[q[head]] + 1;
36             }
37             while (head < tail && p[head + 1] ≤ i + 1)
38                 head++;
39             if (head ≤ tail)
40                 p[head] = i + 1;
41         }
42         f[i] += tmp;
43
44         int r = n;
45
46         while (head ≤ tail) {
47             if (f[q[tail]] + calc(q[tail] + 1, p[tail]) →
48                 > f[i] + calc(i + 1, p[tail])) {
49                 r = p[tail] - 1;
50                 tail--;
51             }
52             else if (f[q[tail]] + calc(q[tail] + 1, r) →
53                 ≤ f[i] + calc(i + 1, r)) {
54                 if (r < n) {
55                     q[++tail] = i;
56                     p[tail] = r + 1;
57                 }
58                 break;
59             }
60             else {
61                 int L = p[tail], R = r;
62                 while (L < R) {
63                     int M = (L + R) / 2;
64
65                     if (f[q[tail]] + calc(q[tail] + 1, →
66                         M) ≤ f[i] + calc(i + 1, M))
67                         L = M + 1;
68                     else
69                         R = M;
70
71                     q[++tail] = i;
72                     p[tail] = L;
73
74                     break;
75                 }
76             }
77         }
78     }
79
80     return g[n];
81 }
```

```

if (f[q[tail]] + calc(q[tail] + 1, →
→ M) ≤ f[i] + calc(i + 1, M))
    L = M + 1;
else
    R = M;

q[++tail] = i;
p[tail] = L;

break;
}

if (head > tail) {
    q[++tail] = i;
    p[tail] = i + 1;
}

return g[n];
}
```

6.2 例题

6.2.1 103388A Assigning Prizes 容斥

题意 给定一个长为 n 的序列 a_i , 要求构造非严格递减序列 b_i , 满足 $a_i \leq b_i \leq R$, 求方案数. $n \leq 5 \times 10^3, R, a_i \leq 10^9$.

做法 a_i 的范围太大了, 不能简单地记录上一位的值.

考虑使用容斥. 方便起见把 a_i 直接变成 $R - a_i + 1$, 条件就变成了 $b_i \leq a_i$ 且 $b_i \geq b_{i-1}$.

这里有两个限制条件, 可以固定 $b_i \leq a_i$ 是必须满足的条件, 只对 $b_i \geq b_{i-1}$ 使用容斥, 枚举哪些位置是比上一位小的(违反限制), 其他位置随意.

枚举后的形态一定是有若干个区间是严格递减的, 其他位置随意. 考虑如果一个区间 $[l, r]$ 是严格递减的, 显然所有的数都 $< a_l$, 所以这段区间的方案数就是 $\binom{a_l}{r-l+1}$. 另外实际上 b_l 是没有违反限制的, 所以这里对系数的贡献是 $(-1)^{r-l}$.

考虑令 dp_i 表示只考虑前 i 个位置的答案, 转移时自然就是枚举一个 j , 然后计算 dp_{j-1} 乘上区间 $[j, i]$ 严格递减的方案数. 另外还有一种情况是 b_i 没有违反限制, 这时显然直接在 dp_{i-1} 的基础上乘上一个 a_i 就好了. (转移时还要注意, 由于枚举的是严格递减区间, 自然就不能枚举只有一个数的区间.)

```

1 constexpr int maxn = 5005, p = (int)1e9 + 7;
2
3 int inv[maxn];
4 int a[maxn], f[maxn][maxn], dp[maxn];
5
6 int main() {
7
8     int n, m;
9     scanf("%d%d", &n, &m);
10
11    inv[1] = 1;
12    for (int i = 2; i ≤ n; i++)
13        inv[i] = (long long)(p - p / i) * inv[p % i] %
14            → p;
15
16    for (int i = 1; i ≤ n; i++) {
17        scanf("%d", &a[i]);
18        a[i] = m - a[i] + 1;
19    }
20
21    if (any_of(a + 1, a + n + 1, [] (int x) {return x →
22        ≤ 0;})) {
23        printf("0\n");
24        return 0;
25    }
26
27    int ans = 0;
28    for (int i = 0; i < n; i++) {
29        for (int j = i + 1; j ≤ n; j++) {
30            if (a[i] > a[j])
31                ans += f[i][j];
32            else
33                ans -= f[i][j];
34        }
35    }
36
37    cout << ans;
38 }
```

```
23 }
24
25     for (int i = n - 1; i; i--)
26         a[i] = min(a[i], a[i + 1]);
27
28 // b_i ≥ b_{i - 1} && b_i ≤ a_i
29 // 我们可以假设 b_i ≤ a_i 是必定被满足的然后对 bi
30 // → 非严格递增的条件进行容斥枚举某一段是严格递减的
31 // 如果 [j, i] 严格递减显然它们都 ≤ a_j所以这个区
32 // → 间的方案数是 {a_j \choose i - j + 1}
33 // 如果 i 是合法的直接一个个转移即可因为这一部分的
34 // → 转移和区间长度没有关系
35
36     for (int i = 1; i ≤ n; i++) {
37         f[i][0] = 1;
38
39         for (int j = 1; j ≤ n - i + 1 && j ≤ a[i]; j+
40             → +)
41             f[i][j] = (long long)f[i][j - 1] * (a[i] -
42             → j + 1) % p * inv[j] % p;
43     }
44
45     dp[0] = 1;
46
47     for (int i = 1; i ≤ n; i++) {
48         dp[i] = (long long)dp[i - 1] * a[i] % p;
49
50         for (int j = 1; j < i; j++) {
51             int tmp = (long long)dp[j - 1] * f[j][i - j
52             → + 1] % p;
53
54             if ((i - j) % 2)
55                 tmp = p - tmp;
56
57             dp[i] = (dp[i] + tmp) % p;
58     }
59
60     printf("%d\n", dp[n]);
61
62     return 0;
63 }
```

7 计算几何

7.1 Delaunay三角剖分

只要两个点同在某个三角形上，它们就互为一对最近点。注意返回的三角形似乎不保证顺序，所以要加边的话还是要加双向边。

如果要建V图的话求出每个三角形的外心就行了，每个点控制的区域就是所在三角形的外心连起来。

```

1 #include <bits/stdc++.h>
2
3 using namespace std;
4
5 constexpr int maxn = 500005;
6
7 using ll = long long;
8
9 constexpr int INF = 0x3f3f3f3f;
10 constexpr ll LINF = 0x3f3f3f3f3f3f3f3fll;
11 constexpr double eps = 1e-8;
12
13 template <class T>
14 int sgn(T x) {
15     return x > 0 ? 1 : x < 0 ? -1 : 0;
16 }
17
18 struct point {
19     ll x, y;
20
21     point() = default;
22
23     point(ll x, ll y) : x(x), y(y) {}
24
25     point operator - (const point &p) const {
26         return point(x - p.x, y - p.y);
27     }
28
29     ll cross(const point &p) const {
30         return x * p.y - y * p.x;
31     }
32
33     ll cross(const point &a, const point &b) const {
34         return (a - *this).cross(b - *this);
35     }
36
37     ll dot(const point &p) const {
38         return x * p.x + y * p.y;
39     }
40
41     ll dot(const point &a, const point &b) const {
42         return (a - *this).dot(b - *this);
43     }
44
45     ll abs2() const {
46         return this -> dot(*this);
47     }
48
49     bool operator == (const point &p) const {
50         return x == p.x && y == p.y;
51     }
52
53     bool operator < (const point &p) const {
54         if (x != p.x) return x < p.x;
55         return y < p.y;
56     }
57 };
58
59
60 const point inf_point = point(1e18, 1e18);

```

```

62
63     struct quad_edge {
64         point origin;
65         quad_edge *rot = nullptr;
66         quad_edge *onext = nullptr;
67         bool used = false;
68
69         quad_edge *rev() const {
70             return rot -> rot;
71         }
72         quad_edge *lnext() const {
73             return rot -> rev() -> onext -> rot;
74         }
75         quad_edge *oprev() const {
76             return rot -> onext -> rot;
77         }
78         point dest() const {
79             return rev() -> origin;
80         }
81     };
82
83     quad_edge *make_edge(point from, point to) {
84         quad_edge *e1 = new quad_edge;
85         quad_edge *e2 = new quad_edge;
86         quad_edge *e3 = new quad_edge;
87         quad_edge *e4 = new quad_edge;
88
89         e1 -> origin = from;
90         e2 -> origin = to;
91         e3 -> origin = e4 -> origin = inf_point;
92
93         e1 -> rot = e3;
94         e2 -> rot = e4;
95         e3 -> rot = e2;
96         e4 -> rot = e1;
97
98         e1 -> onext = e1;
99         e2 -> onext = e2;
100        e3 -> onext = e4;
101        e4 -> onext = e3;
102
103        return e1;
104    }
105
106    void splice(quad_edge *a, quad_edge *b) { // 拼接
107        swap(a -> onext -> rot -> onext, b -> onext -> rot
108            -> onext);
109        swap(a -> onext, b -> onext);
110    }
111
112    void delete_edge(quad_edge *e) {
113        splice(e, e -> oprev());
114        splice(e -> rev(), e -> rev() -> oprev());
115
116        delete e -> rev() -> rot;
117        delete e -> rev();
118        delete e -> rot;
119        delete e;
120    }
121
122    quad_edge *connect(quad_edge *a, quad_edge *b) {
123        quad_edge *e = make_edge(a -> dest(), b -> origin);
124
125        splice(e, a -> lnext());
126        splice(e -> rev(), b);
127
128        return e;
129    }
130
131    bool left_of(point p, quad_edge *e) {

```

```

131     return p.cross(e → origin, e → dest()) > 0;
132 }
133
134 bool right_of(point p, quad_edge *e) {
135     return p.cross(e → origin, e → dest()) < 0;
136 }
137
138 template <class T>
139 T det3(T a1, T a2, T a3, T b1, T b2, T b3, T c1, T c2,
140        → T c3) {
141     return a1 * (b2 * c3 - c2 * b3) - a2 * (b1 * c3 -
142           → c1 * b3) +
143           a3 * (b1 * c2 - c1 * b2);
144 }
145
146 bool in_circle(point a, point b, point c, point d) { // → 如果有__int128就直接计算行列式, 否则算角度
147 #if defined(__LP64__) || defined(__WIN64__)
148     __int128 det = -det3<__int128>(b.x, b.y, b.abs2(),
149           → c.x, c.y, c.abs2(), d.x, d.y, d.abs2());
150     det += det3<__int128>(a.x, a.y, a.abs2(), c.x, c.y,
151           → c.abs2(), d.x, d.y, d.abs2());
152     det -= det3<__int128>(a.x, a.y, a.abs2(), b.x, b.y,
153           → b.abs2(), d.x, d.y, d.abs2());
154     det += det3<__int128>(a.x, a.y, a.abs2(), b.x, b.y,
155           → b.abs2(), c.x, c.y, c.abs2());
156
157     return det > 0;
158 #else
159     auto ang = [] (point l, point mid, point r) {
160         ll x = mid.dot(l, r);
161         ll y = mid.cross(l, r);
162         long double res = atan2((long double)x, (long
163             → double)y);
164         return res;
165     };
166
167     long double kek = ang(a, b, c) + ang(c, d, a) -
168           ang(b, c, d) - ang(d, a, b);
169
170     return kek > 1e-10;
171 #endif
172 }
173
174 pair<quad_edge*, quad_edge*> divide_and_conquer(int l,
175           → int r, vector<point> &p) {
176     if (r - l + 1 == 2) {
177         quad_edge *res = make_edge(p[l], p[r]);
178         return make_pair(res, res → rev());
179     }
180
181     if (r - l + 1 == 3) {
182         quad_edge *a = make_edge(p[l], p[l + 1]), *b =
183           → make_edge(p[l + 1], p[r]);
184         splice(a → rev(), b);
185
186         int sg = sgn(p[l].cross(p[l + 1], p[r]));
187
188         if (sg == 0)
189             return make_pair(a, b → rev());
190
191         quad_edge *c = connect(b, a);
192
193         if (sg == 1)
194             return make_pair(a, b → rev());
195         else
196             return make_pair(c → rev(), c);
197     }
198
199     int mid = (l + r) / 2;
200
201     quad_edge *ldo, *ldi, *rdo, *rdi;
202     tie(ldo, ldi) = divide_and_conquer(l, mid, p);
203     tie(rdi, rdo) = divide_and_conquer(mid + 1, r, p);
204
205     while (true) {
206         if (left_of(rdi → origin, ldi))
207             ldi = ldi → lnext();
208
209         else if (right_of(ldi → origin, rdi))
210             rdi = rdi → rev() → onext();
211
212         else
213             break;
214     }
215
216     quad_edge *basel = connect(rdi → rev(), ldi);
217     auto is_valid = [&basel] (quad_edge *e) {
218         return right_of(e → dest(), basel);
219     };
220
221     if (ldi → origin == ldo → origin)
222         ldo = basel → rev();
223     if (rdi → origin == rdo → origin)
224         rdo = basel;
225
226     while (true) {
227         quad_edge *lcand = basel → rev() → onext();
228         if (is_valid(lcand)) {
229             while (in_circle(basel → dest(), basel →
230                   → origin, lcand → dest(), lcand → onext(
231                   → → dest())))
232                 quad_edge *t = lcand → onext();
233                 delete_edge(lcand);
234                 lcand = t;
235         }
236
237         quad_edge *rcand = basel → oprev();
238         if (is_valid(rcand)) {
239             while (in_circle(basel → dest(), basel →
240                   → origin, rcand → dest(), rcand →
241                   → oprev() → dest()))
242                 quad_edge *t = rcand → oprev();
243                 delete_edge(rcand);
244                 rcand = t;
245         }
246
247         if (!is_valid(lcand) && !is_valid(rcand))
248             break;
249
250         if (!is_valid(lcand) || (is_valid(rcand) &&
251             → in_circle(lcand → dest(), lcand → origin,
252             → rcand → origin, rcand → dest())))
253             basel = connect(rcand, basel → rev());
254         else
255             basel = connect(basel → rev(), lcand →
256               → rev());
257
258         return make_pair(ldo, rdo);
259     }
260
261     vector<tuple<point, point, point> >
262     → delaunay(vector<point> p) { // Delaunay 三角剖分
263         sort(p.begin(), p.end(), [] (const point &a, const
264             → point &b) {

```

```

249     return a.x < b.x || (a.x == b.x && a.y < b.y);
250     // 实际上已经重载小于了，只是为了清晰
251 }
252 auto res = divide_and_conquer(0, (int)p.size() - 1,
253     ↪ p);
254 quad_edge *e = res.first;
255 vector<quad_edge*> edges = {e};
256
257 while (e → onext → dest().cross(e → dest(), e →
258     ↪ origin) < 0)
259     e = e → onext;
260
261 auto add = [&p, &e, &edges] () { // 修改 p, e, edges
262     quad_edge *cur = e;
263     do {
264         cur → used = true;
265         p.push_back(cur → origin);
266         edges.push_back(cur → rev());
267
268         cur = cur → lnext();
269     } while (cur != e);
270 };
271
272 add();
273 p.clear();
274
275 int kek = 0;
276 while (kek < (int)edges.size())
277     if (!(*e = edges[kek++]) → used)
278         add();
279
280 vector<tuple<point, point, point>> ans;
281 for (int i = 0; i < (int)p.size(); i += 3)
282     ans.push_back(make_tuple(p[i], p[i + 1], p[i +
283         ↪ 2]));
284
285 #define sq(x) ((x) * (ll)(x)) // 平方
286
287 ll dist(point p, point q) { // 两点间距离的平方
288     return (p - q).abs2();
289 }
290
291 ll sarea2(point p, point q, point r) { // 三角形面积的两
292     ↪ 倍(叉积)
293     return (q - p).cross(r - q);
294 }
295
296 point v[maxn];
297
298 int main() {
299     int n;
300     cin >> n;
301
302     // read the points, v[1 ~ n]
303
304     bool col_linear = true; // 如果给出的所有点都共线则
305     // 需要特判
306     for (int i = 3; i ≤ n; i++)
307         if (sarea2(v[1], v[2], v[i]))
308             col_linear = false;
309
310     if (col_linear) {
311         // do something
312         return 0;
313     }
314
315     auto triangles = delaunay(vector<point>(v + 1, v +
316         ↪ n + 1));
317
318     // do something
319
320     return 0;
321 }
```

7.2 最近点对

首先分治的做法是众所周知的.

有期望 $O(n)$ 的随机增量法: 首先将所有点随机打乱, 然后每次增加一个点, 更新答案.

假设当前最近点对距离为 s , 则把平面划分成 $s \times s$ 的方格, 用哈希表存储每个方格有哪些点.

加入一个新点时只需要枚举自身和周围共计9个方格中的点, 显然枚举到的点最多16个. 如果加入之后答案变小了就 $O(n)$ 暴力重构.

前 i 个点中 i 是最近点对中的点的概率至多为 $\frac{2}{i}$, 所以每个点的期望贡献都是 $O(1)$, 总的复杂度就是期望 $O(n)$.

如果对每个点都要求出距离最近的点的话, 也有随机化的 $O(n)$ 做法:

一个真的随机算法:

A simple randomized sieve algorithm for the closest-pair problem (<https://www.cs.umd.edu/~samir/grant/cp.pdf>)

1. 循环直到删完所有点:

- 随机选一个点, 计算它到所有点的最短距离 d 。
 - 将所有点划分到 $l = d/3$ 的网格里, 比如 $(\lfloor \frac{x}{l} \rfloor, \lfloor \frac{y}{l} \rfloor)$ 。
 - 将九宫格内孤立的点删除, 这意味着这些点的最近点对距离不小于 $\frac{2\sqrt{2}}{3}d$, 其中 $\frac{2\sqrt{2}}{3} < 1$ 。
2. 取最后一个 d , 将所有点划分到 $(\lfloor \frac{x}{d} \rfloor, \lfloor \frac{y}{d} \rfloor)$ 的网格里, 暴力计算九宫格内的答案。

第一部分每次期望会删掉至少一半的点, 因为有 $\geq 1/2$ 概率碰到一个最近点距离在中位数以下的点, 因此第一部分的复杂度是 $O(n)$ 的。

第二部分分析类似分治做法, 周围只有常数个点。

所以总复杂度是 $O(n)$ 的。

8 杂项

8.1 $O(1)$ 快速乘

如果对速度要求很高并且不能用指令集，可以去看fstqwq的模板。

```

1 // long double 快速乘
2 // 在两数直接相乘会爆long long时才有必要使用
3 // 常数比直接long long乘法 + 取模大很多，非必要时不建议使用
4 // → 用
5 long long mul(long long a, long long b, long long p) {
6     a %= p;
7     b %= p;
8     return ((a * b - p * (long long)((long double)a / p
9         → * b + 0.5)) % p + p) % p;
10 }
11
12 // 指令集快速乘
13 // 试机记得测试能不能过编译
14 inline long long mul(const long long a, const long long
15     → b, const long long p) {
16     long long ans;
17     __asm__ __volatile__ ("\\tmulq %%rbx\\n\\tdivq %
18     → %rcx\\n" : "=d"(ans) : "a"(a), "b"(b), "c"(p));
19     return ans;
20 }
21
22 // int乘法取模，大概比直接做快一倍
23 inline int mul_mod(int a, int b, int p) {
24     int ans;
25     __asm__ __volatile__ ("\\tmull %%ebx\\n\\tdivl %
26     → %ecx\\n" : "=d"(ans) : "a"(a), "b"(b), "c"(p));
27     return ans;
28 }
```

8.2 Kahan求和算法(减少浮点数累加的误差)

当然一般来说是用不到的，累加被卡精度了才有必要考虑。

```

1 double kahanSum(vector<double> vec) {
2     double sum = 0, c = 0;
3     for (auto x : vec) {
4         double y = x - c;
5         double t = sum + y;
6         c = (t - sum) - y;
7         sum = t;
8     }
9     return sum;
10 }
```

8.3 Python Decimal

```

1 import decimal
2
3 decimal.getcontext().prec = 1234 # 有效数字位数
4
5 x = decimal.Decimal(2)
6 x = decimal.Decimal('50.5679') # 不要用float，因为float本身就不准确
7
8 x = decimal.Decimal('50.5679'). \
9     quantize(decimal.Decimal('0.00')) # 保留两位小数,
10    → 50.57
11 x = decimal.Decimal('50.5679'). \
12     quantize(decimal.Decimal('0.00'),           → decimal.ROUND_HALF_UP) # 四舍五入
13 # 第二个参数可选如下:
14 # ROUND_HALF_UP 四舍五入
```

```

14 # ROUND_HALF_DOWN 五舍六入
15 # ROUND_HALF_EVEN 银行家舍入法，舍入到最近的偶数
16 # ROUND_UP 向绝对值大的取整
17 # ROUND_DOWN 向绝对值小的取整
18 # ROUND_CEILING 向正无穷取整
19 # ROUND_FLOOR 向负无穷取整
20 # ROUND_05UP (away from zero if last digit after
21     → rounding towards zero would have been 0 or 5;
22     → otherwise towards zero)
23
24 print('%.f' % x) # 这样做只有float的精度
25 s = str(x)
26
27 decimal.is_finite(x) # x是否有穷(NaN也算)
28 decimal.is_infinite(x)
29 decimal.is_nan(x)
30 decimal.is_normal(x) # x是否正常
31 decimal.is_signed(x) # 是否为负数
32
33 decimal.fma(a, b, c) # a * b + c, 精度更高
34
35 x.exp(), x.ln(), x.sqrt(), x.log10()
```

8.4 $O(n^2)$ 高精度

```

1 // 注意如果只需要正数运算的话
2 // 可以只抄英文名的运算函数
3 // 按需自取
4 // 乘法O(n ^ 2), 除法O(10 * n ^ 2)
5
6 constexpr int maxn = 1005;
7
8 struct big_decimal {
9     int a[maxn];
10    bool negative;
11
12    big_decimal() {
13        memset(a, 0, sizeof(a));
14        negative = false;
15    }
16
17    big_decimal(long long x) {
18        memset(a, 0, sizeof(a));
19        negative = false;
20
21        if (x < 0) {
22            negative = true;
23            x = -x;
24        }
25
26        while (x) {
27            a[++a[0]] = x % 10;
28            x /= 10;
29        }
30
31    }
32
33    big_decimal(string s) {
34        memset(a, 0, sizeof(a));
35        negative = false;
36
37        if (s == "") {
38            return;
39        }
40
41        if (s[0] == '-') {
42            negative = true;
43            s = s.substr(1);
44        }
45        a[0] = s.size();
46    }
47
48    void print() {
49        cout << a[0];
50
51        for (int i = 1; i < a[0]; i++) {
52            cout << a[i];
53        }
54    }
55
56    void add(big_decimal b) {
57        int carry = 0;
58
59        for (int i = 0; i < a[0] || i < b.a[0]; i++) {
60            int sum = a[i] + b.a[i] + carry;
61            a[i] = sum % 10;
62            carry = sum / 10;
63        }
64
65        if (carry) {
66            a[a[0]] = carry;
67            a[0]++;
68        }
69    }
70
71    void sub(big_decimal b) {
72        int borrow = 0;
73
74        for (int i = 0; i < a[0] || i < b.a[0]; i++) {
75            int sum = a[i] - b.a[i] - borrow;
76            a[i] = sum % 10;
77            borrow = (sum < 0) ? 1 : 0;
78        }
79
80        if (borrow) {
81            a[a[0]] = borrow;
82            a[0]++;
83        }
84    }
85
86    void mult(big_decimal b) {
87        int carry = 0;
88
89        for (int i = 0; i < a[0]; i++) {
90            for (int j = 0; j < b.a[0]; j++) {
91                int sum = a[i] * b.a[j] + carry;
92                a[i + j + 1] += sum % 10;
93                carry = sum / 10;
94            }
95        }
96
97        if (carry) {
98            a[a[0] + 1] = carry;
99            a[0]++;
100       }
101   }
102
103   void div(big_decimal b) {
104       int quotient[1005];
105
106       int remainder = 0;
107
108       for (int i = 0; i < a[0]; i++) {
109           remainder *= 10;
110           remainder += a[i];
111
112           int q = remainder / b.a[0];
113           quotient[i] = q;
114
115           remainder -= q * b.a[0];
116       }
117
118       for (int i = 0; i < a[0]; i++) {
119           a[i] = quotient[i];
120       }
121   }
122
123   void pow(int n) {
124       big_decimal result;
125
126       for (int i = 0; i < n; i++) {
127           result *= *this;
128       }
129
130       *this = result;
131   }
132
133   void log() {
134       cout << "log not implemented";
135   }
136
137   void exp() {
138       cout << "exp not implemented";
139   }
140
141   void ln() {
142       cout << "ln not implemented";
143   }
144
145   void sqrt() {
146       cout << "sqrt not implemented";
147   }
148
149   void log10() {
150       cout << "log10 not implemented";
151   }
152
153   void abs() {
154       cout << "abs not implemented";
155   }
156
157   void floor() {
158       cout << "floor not implemented";
159   }
160
161   void ceil() {
162       cout << "ceil not implemented";
163   }
164
165   void round() {
166       cout << "round not implemented";
167   }
168
169   void trunc() {
170       cout << "trunc not implemented";
171   }
172
173   void mod() {
174       cout << "mod not implemented";
175   }
176
177   void gcd() {
178       cout << "gcd not implemented";
179   }
180
181   void lcm() {
182       cout << "lcm not implemented";
183   }
184
185   void modpow() {
186       cout << "modpow not implemented";
187   }
188
189   void modinv() {
190       cout << "modinv not implemented";
191   }
192
193   void modsqrt() {
194       cout << "modsqrt not implemented";
195   }
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197   void modgcd() {
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44     for (int i = 1; i <= a[0]; i++)
45         a[i] = s[a[0] - i] - '0';
46
47     while (a[0] && !a[a[0]])
48         a[0]--;
49 }
50
51 void input() {
52     string s;
53     cin >> s;
54     *this = s;
55 }
56
57 string str() const {
58     if (!a[0])
59         return "0";
60
61     string s;
62     if (negative)
63         s = "-";
64
65     for (int i = a[0]; i; i--)
66         s.push_back('0' + a[i]);
67
68     return s;
69 }
70
71 operator string() const {
72     return str();
73 }
74
75 big_decimal operator -() const {
76     big_decimal o = *this;
77     if (a[0])
78         o.negative = true;
79
80     return o;
81 }
82
83 friend big_decimal abs(const big_decimal &u) {
84     big_decimal o = u;
85     o.negative = false;
86     return o;
87 }
88
89 big_decimal &operator <= (int k) {
90     a[0] += k;
91
92     for (int i = a[0]; i > k; i--)
93         a[i] = a[i - k];
94
95     for (int i = k; i; i--)
96         a[i] = 0;
97
98     return *this;
99 }
100
101 friend big_decimal operator << (const big_decimal
102     &u, int k) {
103     big_decimal o = u;
104     return o <<= k;
105 }
106
107 big_decimal &operator >= (int k) {
108     if (a[0] < k)
109         return *this = big_decimal(0);
110
111     a[0] -= k;
112     for (int i = 1; i <= a[0]; i++)
113         a[i] = a[i + k];
114
115     for (int i = a[0] + 1; i <= a[0] + k; i++)
116         a[i] = 0;
117
118     return *this;
119 }
120
121 friend big_decimal operator >> (const big_decimal
122     &u, int k) {
123     big_decimal o = u;
124     return o >>= k;
125 }
126
127 friend int cmp(const big_decimal &u, const
128     &big_decimal &v) {
129     if (u.negative || v.negative) {
130         if (u.negative && v.negative)
131             return -cmp(-u, -v);
132
133         if (u.negative)
134             return -1;
135
136         if (v.negative)
137             return 1;
138
139     if (u.a[0] != v.a[0])
140         return u.a[0] < v.a[0] ? -1 : 1;
141
142     for (int i = u.a[0]; i; i--)
143         if (u.a[i] != v.a[i])
144             return u.a[i] < v.a[i] ? -1 : 1;
145
146     return 0;
147 }
148
149 friend bool operator < (const big_decimal &u, const
150     &big_decimal &v) {
151     return cmp(u, v) == -1;
152 }
153
154 friend bool operator > (const big_decimal &u, const
155     &big_decimal &v) {
156     return cmp(u, v) == 1;
157 }
158
159 friend bool operator == (const big_decimal &u,
160     &const big_decimal &v) {
161     return cmp(u, v) == 0;
162 }
163
164 friend bool operator <= (const big_decimal &u,
165     &const big_decimal &v) {
166     return cmp(u, v) <= 0;
167 }
168
169 friend big_decimal decimal_plus(const big_decimal
170     &u, const big_decimal &v) { // 保证u, v均为正数
171     big_decimal o;
172
173     o.a[0] = max(u.a[0], v.a[0]);

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172     for (int i = 1; i <= u.a[0] || i <= v.a[0]; i++)
173         o.a[i] += u.a[i] + v.a[i];
174
175         if (o.a[i] >= 10) {
176             o.a[i + 1]++;
177             o.a[i] -= 10;
178         }
179     }
180
181     if (o.a[o.a[0] + 1])
182         o.a[0]++;
183
184     return o;
185 }
186
187 friend big_decimal decimal_minus(const big_decimal
188     &u, const big_decimal &v) { // 保证u, v均为正数
189     // 的话可以直接调用
190     int k = cmp(u, v);
191
192     if (k == -1)
193         return -decimal_minus(v, u);
194     else if (k == 0)
195         return big_decimal(0);
196
197     big_decimal o;
198
199     o.a[0] = u.a[0];
200
201     for (int i = 1; i <= u.a[0]; i++) {
202         o.a[i] += u.a[i] - v.a[i];
203
204         if (o.a[i] < 0) {
205             o.a[i] += 10;
206             o.a[i + 1]--;
207         }
208     }
209
210     while (o.a[0] && !o.a[o.a[0]])
211         o.a[0]--;
212
213     return o;
214 }
215
216 friend big_decimal decimal_multi(const big_decimal
217     &u, const big_decimal &v) {
218     big_decimal o;
219
220     o.a[0] = u.a[0] + v.a[0] - 1;
221
222     for (int i = 1; i <= u.a[0]; i++)
223         for (int j = 1; j <= v.a[0]; j++)
224             o.a[i + j - 1] += u.a[i] * v.a[j];
225
226     for (int i = 1; i <= o.a[0]; i++)
227         if (o.a[i] >= 10) {
228             o.a[i + 1] += o.a[i] / 10;
229             o.a[i] %= 10;
230         }
231
232         if (o.a[o.a[0] + 1])
233             o.a[0]++;
234
235     friend pair<big_decimal, big_decimal>
236     decimal_divide(big_decimal u, big_decimal v) {
237         if (v > u)
238             return make_pair(big_decimal(0), u);
239
240         big_decimal o;
241         o.a[0] = u.a[0] - v.a[0] + 1;
242
243         int m = v.a[0];
244         v <= u.a[0] - m;
245
246         for (int i = u.a[0]; i >= m; i--) {
247             while (u >= v) {
248                 u = u - v;
249                 o.a[i - m + 1]++;
250             }
251             v >= 1;
252         }
253
254         while (o.a[0] && !o.a[o.a[0]])
255             o.a[0]--;
256
257         return make_pair(o, u);
258     }
259
260 friend big_decimal operator + (const big_decimal
261     &u, const big_decimal &v) {
262     if (u.negative || v.negative) {
263         if (u.negative && v.negative)
264             return -decimal_plus(-u, -v);
265
266         if (u.negative)
267             return v - (-u);
268
269         if (v.negative)
270             return u - (-v);
271     }
272
273     return decimal_plus(u, v);
274 }
275
276 friend big_decimal operator - (const big_decimal
277     &u, const big_decimal &v) {
278     if (u.negative || v.negative) {
279         if (u.negative && v.negative)
280             return -decimal_minus(-u, -v);
281
282         if (u.negative)
283             return -decimal_plus(-u, v);
284
285         if (v.negative)
286             return decimal_plus(u, -v);
287     }
288
289     return decimal_minus(u, v);
290 }
291
292 friend big_decimal operator * (const big_decimal
293     &u, const big_decimal &v) {
294     if (u.negative || v.negative) {
295         big_decimal o = decimal_multi(abs(u),
296             abs(v));
297
298         if (u.negative ^ v.negative)
299             return -o;
300         return o;
301     }
302
303     return decimal_multi(u, v);
304 }
```

```

300 }
301
302 big_decimal operator * (long long x) const {
303     if (x >= 10)
304         return *this * big_decimal(x);
305
306     if (negative)
307         return -(*this * x);
308
309     big_decimal o;
310
311     o.a[0] = a[0];
312
313     for (int i = 1; i <= a[0]; i++)
314         o.a[i] += a[i] * x;
315
316     if (o.a[i] >= 10) {
317         o.a[i + 1] += o.a[i] / 10;
318         o.a[i] %= 10;
319     }
320 }
321
322 if (o.a[a[0] + 1])
323     o.a[0]++;
324
325     return o;
326 }
327
328 friend pair<big_decimal, big_decimal>
329     decimal_div(const big_decimal &u, const
330     big_decimal &v) {
331     if (u.negative || v.negative) {
332         pair<big_decimal, big_decimal> o =
333             decimal_div(abs(u), abs(v));
334
335         if (u.negative ^ v.negative)
336             return make_pair(-o.first, -o.second);
337         return o;
338     }
339
340     return decimal_divide(u, v);
341 }
342
343 friend big_decimal operator / (const big_decimal
344     &u, const big_decimal &v) { // v不能是0
345     if (u.negative || v.negative) {
346         big_decimal o = abs(u) / abs(v);
347
348         if (u.negative ^ v.negative)
349             return -o;
350         return o;
351     }
352
353     return decimal_divide(u, v).first;
354 }
355
356 friend big_decimal operator % (const big_decimal
357     &u, const big_decimal &v) {
358     if (u.negative || v.negative) {
359         big_decimal o = abs(u) % abs(v);
360
361         if (u.negative ^ v.negative)
362             return -o;
363         return o;
364     }
365
366     return decimal_divide(u, v).second;
367 }
368

```

8.5 笛卡尔树

```

1 int s[maxn], root, lc[maxn], rc[maxn];
2
3 int top = 0;
4 s[++top] = root = 1;
5 for (int i = 2; i <= n; i++) {
6     s[top + 1] = 0;
7     while (top && a[i] < a[s[top]]) // 小根笛卡尔树
8         top--;
9
10    if (top)
11        rc[s[top]] = i;
12    else
13        root = i;
14
15    lc[i] = s[top + 1];
16    s[++top] = i;
17 }

```

8.6 GarsiaWachs算法($O(n \log n)$ 合并石子)

设序列是 $\{a_i\}$, 从左往右, 找到一个最小的且满足 $a_{k-1} \leq a_{k+1}$ 的 k , 找到后合并 a_k 和 a_{k-1} , 再从当前位置开始向左找最大的 j 满足 $a_j \geq a_k + a_{k-1}$ (当然是指合并前的), 然后把 $a_k + a_{k-1}$ 插到 j 的后面就行. 一直重复, 直到只剩下一堆石子就可以了.

另外在这个过程中, 可以假设 a_1 和 a_n 是正无穷的, 可省略边界的判别. 把 a_0 设为INF, a_{n+1} 设为INF-1, 可实现剩余一堆石子时自动结束.

8.7 常用NTT素数及原根

$p = r \times 2^k + 1$	r	k	最小原根
104857601	25	22	3
167772161	5	25	3
469762049	7	26	3
985661441	235	22	3
998244353	119	23	3
1004535809	479	21	3
1005060097*	1917	19	5
2013265921	15	27	31
2281701377	17	27	3
31525197391593473	7	52	3
180143985094819841	5	55	6
1945555039024054273	27	56	5
4179340454199820289	29	57	3

*注: 1005060097有点危险, 在变化长度大于 $524288 = 2^{19}$ 时不可用.

8.8 xorshift

```

1 ull k1, k2;
2 const int mod = 100000000;
3 ull xorShift128Plus() {
4     ull k3 = k1, k4 = k2;
5     k1 = k4;
6     k3 ^= (k3 << 23);
7     k2 = k3 ^ k4 ^ (k3 >> 17) ^ (k4 >> 26);
8     return k2 + k4;
9 }
10 void gen(ull _k1, ull _k2) {
11     k1 = _k1, k2 = _k2;
12     int x = xorShift128Plus() % threshold + 1;
13     // do sth
14 }

```

```

15
16
17 uint32_t xor128(void) {
18     static uint32_t x = 123456789;
19     static uint32_t y = 362436069;
20     static uint32_t z = 521288629;
21     static uint32_t w = 88675123;
22     uint32_t t;
23
24     t = x ^ (x << 11);
25     x = y; y = z; z = w;
26     return w = w ^ (w >> 19) ^ (t ^ (t >> 8));
27 }
```

8.9 枚举子集

(注意这是 $t \neq 0$ 的写法, 如果可以等于0需要在循环里手动break)

```

1 for (int t = s; t; (--t) &= s) {
2     // do something
3 }
```

8.10 STL

8.10.1 vector

- `vector(int nSize)`: 创建一个vector, 元素个数为nSize
- `vector(int nSize, const T &value)`: 创建一个vector, 元素个数为nSize, 且值均为value
- `vector(begin, end)`: 复制[begin, end)区间内另一个数组的元素到vector中
- `void assign(int n, const T &x)`: 设置向量中前n个元素的值为x
- `void assign(const_iterator first, const_iterator last)`: 向量中[first, last)中元素设置成当前向量元素
- `void emplace_back(Args&& ... args)`: 自动构造并push_back一个元素, 例如对一个存储pair的vector可以`v.emplace_back(x, y)`

8.10.2 list

- `assign()` 给list赋值
- `back()` 返回最后一个元素
- `begin()` 返回指向第一个元素的迭代器
- `clear()` 删除所有元素
- `empty()` 如果list是空的则返回true
- `end()` 返回末尾的迭代器
- `erase()` 删除一个元素
- `front()` 返回第一个元素
- `insert()` 插入一个元素到list中
- `max_size()` 返回list能容纳的最大元素数量
- `merge()` 合并两个list
- `pop_back()` 删除最后一个元素
- `pop_front()` 删除第一个元素
- `push_back()` 在list的末尾添加一个元素
- `push_front()` 在list的头部添加一个元素
- `rbegin()` 返回指向第一个元素的逆向迭代器
- `remove()` 从list删除元素
- `remove_if()` 按指定条件删除元素
- `rend()` 指向list末尾的逆向迭代器
- `resize()` 改变list的大小
- `reverse()` 把list的元素倒转
- `size()` 返回list中的元素个数
- `sort()` 给list排序
- `splice()` 合并两个list
- `swap()` 交换两个list
- `unique()` 删除list中重复的元

8.10.3 unordered_set/map

- `unordered_map<int, int, hash>`: 自定义哈希函数, 其中hash是一个带重载括号的类.

8.10.4 自定义 Hash

```

1 struct fuck_hash {
2     fuck_hash() = default;
3
4     size_t operator()(const fuck &f) const {
5         return (size_t)f[0] ^ ((size_t)f[1] << 7) ^
6             ((size_t)f[2] << 15) ^ ((size_t)f[3] <<
7                 23);
8     }
9 };
10
11 unordered_map<fuck, int, fuck_hash> cnt, sum;
```

8.11 Public Based DataStructure(PB_DS)

8.11.1 哈希表

```

1 #include<ext/pb_ds/assoc_container.hpp>
2 #include<ext/pb_ds/hash_policy.hpp>
3 using namespace __gnu_pbds;
4
5 cc_hash_table<string, int> mp1; // 拉链法
6 gp_hash_table<string, int> mp2; // 查探法(快一些)
```

8.11.2 堆

默认也是大根堆, 和`std::priority_queue`保持一致.

```

1 #include<ext/pb_ds/priority_queue.hpp>
2 using namespace __gnu_pbds;
3
4 __gnu_pbds::priority_queue<int> q;
5 __gnu_pbds::priority_queue<int, greater<int>,
6     → pairing_heap_tag> pq;
```

效率参考:

- * 共有五种操作: push、pop、modify、erase、join
- * pairing_heap_tag: push和join为 $O(1)$, 其余为均摊 $\Theta(\log n)$
- * binary_heap_tag: 只支持push和pop, 均为均摊 $\Theta(\log n)$
- * binomial_heap_tag: push为均摊 $O(1)$, 其余为 $\Theta(\log n)$
- * rc_binomial_heap_tag: push为 $O(1)$, 其余为 $\Theta(\log n)$
- * thin_heap_tag: push为 $O(1)$, 不支持join, 其余为 $\Theta(\log n)$; 如果只有increase_key, 那么modify为均摊 $O(1)$

* “不支持”不是不能用, 而是用起来很慢. csdn.net/TRiddle

常用操作:

- `push()`: 向堆中压入一个元素, 返回迭代器
- `pop()`: 将堆顶元素弹出
- `top()`: 返回堆顶元素
- `size()`: 返回元素个数
- `empty()`: 返回是否非空
- `modify(point_iterator, const key)`: 把迭代器位置的key修改为传入的key
- `erase(point_iterator)`: 把迭代器位置的键值从堆中删除
- `join(__gnu_pbds::priority_queue &other)`: 把other合并到*this, 并把other清空

8.11.3 平衡树

```
1 #include <ext/pb_ds/tree_policy.hpp>
2 #include <ext/pb_ds/assoc_container.hpp>
3 using namespace __gnu_pbds;
4
5 tree<int, null_type, less<int>, rb_tree_tag,
6     ↪ tree_order_statistics_node_update> t;
7
8 // rb_tree_tag 红黑树(还有splay_tree_tag和ov_tree_tag,
9     ↪ 后者不知道是什么)
```

注意第五个参数要填tree_order_statistics_node_update才能使用排名操作.

- `insert(x)`: 向树中插入一个元素x, 返回`pair<point_iterator, bool>`
 - `erase(x)`: 从树中删除一个元素/迭代器x, 返回一个 `bool` 表明是否删除成功
 - `order_of_key(x)`: 返回x的排名, 0-based
 - `find_by_order(x)`: 返回排名(0-based)所对应元素的迭代器
 - `lower_bound(x) / upper_bound(x)`: 返回第一个 \geq 或者 $>$ x的元素的迭代器
 - `join(x)`: 将x树并入当前树, 前提是两棵树的类型一样, 并且二者值域不能重叠, x树会被删除
 - `split(x, b)`: 分裂成两部分, 小于等于x的属于当前树, 其余的属于b树
 - `empty()`: 返回是否为空
 - `size()`: 返回大小

(注意平衡树不支持多重值，如果需要多重值，可以再开一个unordered_map来记录值出现的次数，将 $x \ll 32$ 后加上出现的次数后插入。注意此时应该为long long类型。)

8.12 rope

```
1 #include <ext/rope>
2 using namespace __gnu_cxx;
3
4 push_back(x); // 在末尾添加x
5 insert(pos, x); // 在pos插入x, 自然支持整个char数组的一
   ↪ 次插入
6 erase(pos, x); // 从pos开始删除x个, 不要只传一个参数, 有
   ↪ 毒
7 copy(pos, len, x); // 从pos开始到pos + len为止的部分, 赋
   ↪ 值给x
8 replace(pos, x); // 从pos开始换成x
9 substr(pos, x); // 提取pos开始x个
10 at(x) / [x]; // 访问第x个元素
```

8.13 其他C++相关

8.13.1 <cmath>

- `std::log1p(x)`: (注意是数字1)返回 $\ln(1 + x)$ 的值, x 非常接近0时比直接`exp`精确得多.
 - `std::hypot(x, y[, z])`: 返回平方和的平方根, 或者说到原点的欧几里德距离.

8.13.2 <algorithm>

- `std::all_of(begin, end, f)`: 检查范围内元素调用函数f后是否全返回真. 类似地还有`std::any_of`和`std::none_of`.
 - `std::for_each(begin, end, f)`: 对范围内所有元素调用一次f. 如果传入的是引用, 也可以用f修改. (例如`for_each(a, a + n, [](int &x){cout << ++x << "\n";})`)
 - `std::for_each_n(begin, n, f)`: 同上, 只不过范围改成了从begin开始的n个元素.

- `std::copy()`, `std::copy_n()`: 用法谁都会, 但标准里说如果元素是可平凡复制的(比如int), 那么它会避免批量赋值, 并且调用`std::memmove()`之类的快速复制函数. (一句话总结: 它跑得快)
 - `std::rotate(begin, mid, end)`: 循环移动, 移动后mid位置的元素会跑到first位置. C++11起会返回begin位置的元素移动后的位置.
 - `std::unique(begin, end)`: 去重, 返回去重后的end.
 - `std::partition(begin, end, f)`: 把f为true的放在前面, false的放在后面, 返回值是第二部分的开头, 不保持相对顺序. 如果要保留相对顺序可以用`std::stable_partition()`, 比如写整体二分.
 - `std::partition_copy(begin, end, begin_t, begin_f, f)`: 不修改原数组, 把true的扔到begin_t, false的扔到begin_f. 返回值是两部分结尾的迭代器的pair.
 - `std::equal_range(begin, end, x)`: 在已经排好序的数组里找到等于x的范围.
 - `std::minmax(a, b)`: 返回pair(`min(a, b)`, `max(a, b)`). 但是要注意返回的是引用, 所以不能直接用来交换 l, r .

8.13.3 std::tuple

- `std::make_tuple(...)`: 返回构造好的tuple
 - `std::get<i>(tup)`: 返回tuple的第i项
 - `std::tuple_cat(...)`: 传入几个tuple, 返回按顺序连起来的tuple
 - `std::tie(x, y, z, ...)`: 把传入的变量的左值引用绑起来作为tuple返回, 例如可以`std::tie(x, y, z) = std::make_tuple(a, b, c)`.

8.13.4 <complex>

- `complex<double> imaginary = 1i, x = 2 + 3i;` 可以这样直接构造复数.
 - `real/imag(x)`: 返回实部/虚部.
 - `conj(x)`: 返回共轭复数.
 - `arg(x)`: 返回辐角.
 - `norm(x)`: 返回模的平方. (直接求模用`abs(x)`.)
 - `polar(len, theta)`: 用绝对值和辐角构造复数.

8.14 一些游戏

8.14.1 德州扑克

一般来说德扑里Ace都是最大的，所以把Ace的点数规定为14会好写许多。

附一个高低奥马哈的参考代码，除了有四张底牌和需要比低之外和德州扑克区别不大。

```
1 struct Card {
2     int suit, value; // Ace is treated as 14
3
4     Card(string s) {
5         char a = s[0];
6
7         if (isdigit(a))
8             value = a - '0';
9         else if (a == 'T')
10            value = 10;
11        else if (a == 'A')
12            value = 14;
13        else if (a == 'J')
14            value = 11;
15        else if (a == 'Q')
16            value = 12;
17        else if (a == 'K')
18            value = 13;
19        else
```

```

20     value = -1; // error
21
22     char b = s[1];
23     suit = b; // Club, Diamond, Heart, Spade
24 }
25
26 friend bool operator < (const Card &a, const Card
27     &b) {
28     return a.value < b.value;
29 }
30
31 friend bool operator == (const Card &a, const Card
32     &b) {
33     return a.value == b.value;
34 }
35
36 constexpr int Highcard = 1, Pair = 2, TwoPairs = 3,
37     ThreeofaKind = 4, Straight = 5,
38 Flush = 6, FullHouse = 7, FourofaKind = 8,
39     StraightFlush = 9;
40
41 struct Hand {
42     vector<Card> v;
43     int type;
44
45     Hand() : type(0) {}
46
47     Hand(const Hand &o) : v(o.v), type(o.type) {}
48
49     Hand(const vector<Card> &v) : v(v), type(0) {}
50
51     void init_high() {
52         sort(v.begin(), v.end()); // 升序排序
53
54         bool straight = false;
55         if (v.back().value == 14) {
56             if (v[0].value == 2 && v[1].value == 3 &&
57                 v[2].value == 4 && v[3].value == 5) {
58                 straight = true;
59                 rotate(v.begin(), v.begin() + 1,
60                         v.end());
61             }
62         }
63
64         if (!straight) {
65             bool ok = true;
66             for (int i = 1; i < 5; i++)
67                 ok &= (v[i].value == v[i - 1].value +
68                         1);
69
70             if (ok)
71                 straight = true;
72         }
73
74         bool flush = all_of(v.begin(), v.end(), [&]
75             (const Card &a) {return a.suit ==
76             v.front().suit;});
77
78         if (flush && straight) { // 同花顺
79             type = StraightFlush;
80             reverse(v.begin(), v.end());
81             return;
82         }
83
84         vector<int> c;
85         c.assign(15, 0);
86
87         for (auto &o : v)
88             c[o.value]++;
89     }
90
91     void print() {
92         cout << "Hand Type: " << type << endl;
93         cout << "Hand Value: ";
94         for (const Card &c : v)
95             cout << c.value << " ";
96     }
97 }

```

```

81
82     vector<int> kind[5];
83
84     for (int i = 2; i <= 14; i++)
85         if (c[i] > 1)
86             kind[c[i]].push_back(i);
87
88     if (!kind[4].empty()) { // 四条
89         type = FourofaKind;
90
91         for (int i = 0; i < 4; i++)
92             if (v[i].value != kind[4].front())
93                 swap(v[i], v.back());
94             break;
95         }
96
97         return;
98     }
99
100    if (!kind[3].empty() && !kind[2].empty()) {
101        type = FullHouse;
102
103        sort(v.begin(), v.end(), [&] (const Card
104            &a, const Card &b) {
105            bool ta = (a.value == kind[3].front()),
106            tb = (b.value == kind[3].front());
107
108            return ta > tb;
109        });
110
111        return;
112    }
113
114    if (flush) {
115        type = Flush;
116        sort(v.begin(), v.end());
117        reverse(v.begin(), v.end());
118
119        return;
120    }
121
122    if (straight) {
123        type = Straight;
124        reverse(v.begin(), v.end());
125        return;
126    }
127
128    if (!kind[3].empty()) {
129        type = ThreeofaKind;
130
131        sort(v.begin(), v.end(), [&] (const Card
132            &a, const Card &b) {
133            bool ta = (a.value == kind[3].front()),
134            tb = (b.value == kind[3].front());
135
136            return ta > tb;
137        });
138
139        if (v[3] < v[4])
140            swap(v[3], v[4]);
141
142        return;
143    }
144
145    if ((int)kind[2].size() == 2) {
146        type = TwoPairs;
147
148        sort(v.begin(), v.end(), [&] (const Card
149            &a, const Card &b) {

```

```

145     bool ta = (c[a.value] == 2), tb =
146         ↪ (c[b.value] == 2);
147
148     if (ta != tb)
149         | return ta > tb;
150
151     return a.value > b.value;
152 };
153
154 return;
155 }

156 if ((int)kind[2].size() == 1) {
157     type = Pair;
158
159     sort(v.begin(), v.end(), [&] (const Card
160         ↪ &a, const Card &b) {
161         bool ta = (c[a.value] == 2), tb =
162             ↪ (c[b.value] == 2);
163
164         if (ta != tb)
165             | return ta > tb;
166
167         return a.value > b.value;
168 });
169
170 return;
171 }

172 type = Highcard;
173
174 sort(v.begin(), v.end());
175 reverse(v.begin(), v.end());
176 }

177 void init_low() {
178     for (auto &o : v)
179         if (o.value == 14)
180             o.value = 1;
181
182 sort(v.begin(), v.end());
183 reverse(v.begin(), v.end());
184 }

185 friend int cmp_high(const Hand &a, const Hand &b) {
186     if (a.type != b.type)
187         return a.type < b.type ? -1 : 1;
188
189     if (a.v != b.v)
190         return a.v < b.v ? -1 : 1;
191
192     return 0;
193 }

194 friend bool small_high(const Hand &a, const Hand
195     ↪ &b) {
196     return cmp_high(a, b) < 0;
197 }

198 friend int cmp_low(const Hand &a, const Hand &b) {
199     for (int i = 0; i < 5; i++)
200         if (a.v[i].value != b.v[i].value)
201             return a.v[i] < b.v[i] ? 1 : -1;
202
203     return 0;
204 }

205 friend bool small_low(const Hand &a, const Hand &b)
206     ↪ {
207     return cmp_low(a, b) < 0;
208 }

209

210     }
211
212     bool operator ! () const {
213         return v.empty();
214     }
215
216     string str() const {
217         stringstream ss;
218
219         for (auto &o : v)
220             ss << o.value << ' ';
221
222         return ss.str();
223     }
224 };

225 Hand get_max_high(vector<Card> u, vector<Card> v) { // private, public
226     Hand ans;
227
228     for (int i = 0; i < 4; i++)
229         for (int j = i + 1; j < 4; j++)
230             for (int k = 0; k < 5; k++)
231                 for (int p = k + 1; p < 5; p++)
232                     for (int q = p + 1; q < 5; q++) {
233                         Hand tmp({u[i], u[j], v[k],
234                             ↪ v[p], v[q]});
235
236                         tmp.init_high();
237
238                         if (!ans || cmp_high(tmp, ans)
239                             ↪ > 0)
240                             ans = tmp;
241
242     return ans;
243 }

244 Hand get_max_low(vector<Card> tu, vector<Card> tv) {
245     vector<Card> u, v;
246
247     for (auto o : tu)
248         if (o.value == 14 || o.value <= 8)
249             u.push_back(o);
250
251     for (auto o : tv)
252         if (o.value == 14 || o.value <= 8)
253             v.push_back(o);
254
255     Hand ans;
256
257     for (int i = 0; i < (int)u.size(); i++)
258         for (int j = i + 1; j < (int)u.size(); j++)
259             for (int k = 0; k < (int)v.size(); k++)
260                 for (int p = k + 1; p < (int)v.size();
261                     ↪ p++)
262                     for (int q = p + 1; q <
263                         ↪ (int)v.size(); q++) {
264                         vector<Card> vec = {u[i], u[j],
265                             ↪ v[k], v[p], v[q]};
266
267                         bool bad = false;
268
269                         for (int a = 0; a < 5; a++)
270                             for (int b = a + 1; b < 5;
271                                 ↪ b++)
272                                 if (vec[a].value ==
273                                     ↪ vec[b].value)
274                                     bad = true;
275
276                     }
277
278                 }
279
280             }
281
282         }
283
284     }

```

```

271         if (bad)
272             continue;
273
274         Hand tmp(vec);
275
276         tmp.init_low();
277
278         if (!ans || cmp_low(tmp, ans) >
279             ↪ 0)
280             ans = tmp;
281
282     }
283
284     return ans;
285 }
286
int main() {
287
    ios::sync_with_stdio(false);
288
    int T;
    cin >> T;
289
    while (T--) {
        int p;
        cin >> p;
290
        vector<Card> alice, bob, pub;
291
        for (int i = 0; i < 4; i++) {
            string s;
            cin >> s;
            alice.push_back(Card(s));
292
        }
293
        for (int i = 0; i < 4; i++) {
            string s;
            cin >> s;
            bob.push_back(Card(s));
294
        }
295
        for (int i = 0; i < 5; i++) {
            string s;
            cin >> s;
            pub.push_back(Card(s));
296
        }
297
        Hand alice_high = get_max_high(alice, pub),
298             ↪ bob_high = get_max_high(bob, pub);
299
        Hand alice_low = get_max_low(alice, pub),
300             ↪ bob_low = get_max_low(bob, pub);
301
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363
    int dh = cmp_high(alice_high, bob_high);
    int ans[2] = {0};

    if (!alice_low && !bob_low) {
        if (!dh) {
            ans[0] = p - p / 2;
            ans[1] = p / 2;
        }
        else
            ans[dh == -1] = p;
    }
    else if (!alice_low || !bob_low) {
        ans[!alice_low] += p / 2;

        if (!dh) {
            ans[0] += p - p / 2 - (p - p / 2) / 2;
            ans[1] += (p - p / 2) / 2;
        }
        else
            ans[dh == -1] += p / 2;
    }
    else
        ans[dh == -1] += p / 2;

    if (!dh) {
        ans[0] += p - p / 2 - (p - p / 2) / 2;
        ans[1] += (p - p / 2) / 2;
    }
    else
        ans[dh == -1] += p / 2;

    if (!dh) {
        ans[0] += p - p / 2 - (p - p / 2) / 2;
        ans[1] += (p - p / 2) / 2;
    }
    else
        ans[dh == -1] += p / 2;

    cout << ans[0] << ' ' << ans[1] << '\n';
}
return 0;
}

```

8.14.2 炉石传说

两个随从 (a_i, h_i) 和 (a_j, h_j) 皇城PK, 最后只有 $a_i \times h_i$ 较大的一方才有可能活下来, 当然也有可能一起死.

8.15 OEIS

如果没有特殊说明, 那么以下数列都从第0项开始, 除非没有定义也没有好的办法解释第0项的意义.

8.15.1 计数相关

1. 卡特兰数(A000108)

1, 1, 2, 5, 14, 42, 132, 429, 1430, 4862, 16796, 58786, 208012, 742900, 2674440, 9694845, 35357670, ...

性质见1.10.7.卡特兰数, 施罗德数, 默慈金数(16页).

2. (大)施罗德数(A006318)

1, 2, 6, 22, 90, 394, 1806, 8558, 41586, 206098, 1037718, 5293446, 27297738, 142078746, 745387038, ... (0-based)

性质同样见1.10.7.卡特兰数, 施罗德数, 默慈金数(16页).

3. 小施罗德数(A001003)

1, 1, 3, 11, 45, 197, 903, 4279, 20793, 103049, 518859, 2646723, 13648869, 71039373, 372693519, ... (0-based)

性质位置同上.

小施罗德数除了第0项以外都是施罗德数的一半.

4. 默慈金数(Motzkin numbers, A001006)

1, 1, 2, 4, 9, 21, 51, 127, 323, 835, 2188, 5798, 15511, 41835, 113634, 310572, 853467, 2356779, ... (0-based)

性质位置同上.

5. 将点按顺序排成一圈后不自交的树的个数(A001764)

1, 1, 3, 12, 55, 273, 1428, 7752, 43263, 246675, 1430715, 8414640, 50067108, 300830572, 1822766520, ... (0-based)

$$a_n = \frac{\binom{3n}{n}}{2n+1}$$

也就是说, 在圆上按顺序排列的 n 个点之间连 $n - 1$ 条不相交(除端点外)的弦, 组成一棵树的方案数.

也等于每次只能向右或向上, 并且不能高于 $y = 2x$ 这条直线, 从 $(0, 0)$ 走到 $(n, 2n)$ 的方案数.

扩展: 如果改成不能高于 $y = kx$ 这条直线, 走到 (n, kn) 的方案数, 那么答案就是 $\frac{\binom{k+1}{n}}{kn+1}$.

6. n 个点的圆上画不相交的弦的方案数(A054726)

1, 1, 2, 8, 48, 352, 2880, 25216, 231168, 2190848, 21292032, 211044352, 2125246464, 21681954816, ... (0-based)

$a_n = 2^n s_{n-2}$ ($n > 2$), s_n 是上面的小施罗德数.

和上面的区别在于, 这里可以不连满 $n - 1$ 条边. 另外默慈金数画的弦不能共享端点, 但是这里可以.

7. Wedderburn-Etherington numbers(A001190)

0, 1, 1, 1, 2, 3, 6, 11, 23, 46, 98, 207, 451, 983, 2179, 4850, 10905, 24631, 56011, 127912, 293547, ... (0-based)

每个结点都有0或者2个儿子, 且总共有 n 个叶子结点的二叉树方案数. (无标号)

同时也是 $n - 1$ 个结点的无标号二叉树个数.

$$A(x) = x + \frac{A(x^2)^2 + A(x^2)}{2} = 1 - \sqrt{1 - 2x - A(x^2)}$$

8. 划分数(A000041)

1, 1, 2, 3, 5, 7, 11, 15, 22, 30, 42, 56, 77, 101, 135, 176, 231, 297, 385, 490, 627, 792, 1002, ... (0-based)

9. 贝尔数(A000110)

1, 1, 2, 5, 15, 52, 203, 877, 4140, 21147, 115975, 678570, 4213597, 27644437, 190899322, 1382958545, ... (0-based)

10. 错位排列数(A0000166)

1, 0, 1, 2, 9, 44, 265, 1854, 14833, 133496, 1334961, 14684570, 176214841, 2290792932, 32071101049, ... (0-based)

11. 交替阶乘(A005165)

0, 1, 1, 5, 19, 101, 619, 4421, 35899, 326981, 3301819, 36614981, 442386619, 5784634181, 81393657019, ...

$$n! - (n-1)! + (n-2)! - \dots 1! = \sum_{i=0}^{n-1} (-1)^i (n-i)!$$

$a_0 = 0$, $a_n = n! - a_{n-1}$.

8.15.2 线性递推数列

1. Lucas数(A000032)

2, 1, 3, 4, 7, 11, 18, 29, 47, 76, 123, 199, 322, 521, 843, 1364, 2207, 3571, 5778, 9349, 15127, ...

2. 斐波那契数(A000045)

0, 1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, 144, 233, 377, 610, 987, 1597, 2584, 4181, 6765, 10946, ...

3. 泰波那契数(Tribonacci, A000071)

0, 0, 1, 1, 2, 4, 7, 13, 24, 44, 81, 149, 274, 504, 927, 1705, 3136, 5768, 10609, 19513, 35890, ...

$a_0 = a_1 = 0$, $a_2 = 1$, $a_n = a_{n-1} + a_{n-2} + a_{n-3}$.

4. Pell数(A0000129)

0, 1, 2, 5, 12, 29, 70, 169, 408, 985, 2378, 5741, 13860, 33461, 80782, 195025, 470832, 1136689, ...

$a_0 = 0$, $a_1 = 1$, $a_n = 2a_{n-1} + a_{n-2}$.

5. 帕多万(Padovan)数(A0000931)

1, 0, 0, 1, 0, 1, 1, 1, 2, 2, 3, 4, 5, 7, 9, 12, 16, 21, 28, 37, 49, 65, 86, 114, 151, 200, 265, 351, 465, 616, 816, 1081, 1432, 1897, 2513, 3329, 4410, 5842, 7739, 10252, 13581, 17991, 23833, 31572, ...

$a_0 = 1$, $a_1 = a_2 = 0$, $a_n = a_{n-2} + a_{n-3}$.

6. Jacobsthal numbers(A001045)

0, 1, 1, 3, 5, 11, 21, 43, 85, 171, 341, 683, 1365, 2731, 5461, 10923, 21845, 43691, 87381, 174763, ...

$a_0 = 0$, $a_1 = 1$. $a_n = a_{n-1} + 2a_{n-2}$

同时也是最接近 $\frac{2^n}{3}$ 的整数.

7. 佩林数(A001608)

3, 0, 2, 3, 2, 5, 5, 7, 10, 12, 17, 22, 29, 39, 51, 68, 90, 119, 158, 209, 277, 367, 486, 644, 853, ...

$a_0 = 3$, $a_1 = 0$, $a_2 = 2$, $a_n = a_{n-2} + a_{n-3}$

8.15.3 数论相关

1. Carmichael数, 伪质数(A002997)

561, 1105, 1729, 2465, 2821, 6601, 8911, 10585, 15841, 29341, 41041, 46657, 52633, 62745, 63973, 75361, 101101, 115921, 126217, 162401, 172081, 188461, 252601, 278545, 294409, 314821, 334153, 340561, 399001, 410041, 449065, 488881, 512461, ...

满足 $\forall n$ 互质的 a , 都有 $a^{n-1} \equiv 1 \pmod{n}$ 的所有合数 n 被称为Carmichael数.

Carmichael数在 10^8 以内只有255个.

2. 反质数(A002182)

1, 2, 4, 6, 12, 24, 36, 48, 60, 120, 180, 240, 360, 720, 840, 1260, 1680, 2520, 5040, 7560, 10080, 15120, 20160, 25200, 27720, 45360, 50400, 55440, 83160, 110880, 166320, 221760, 277200, 332640, 498960, 554400, 665280, 720720, 1081080, 1441440, 2162160, ...

比所有更小的数的约数数量都更多的数.

3. 前 n 个质数的乘积(A002110)

1, 2, 6, 30, 210, 2310, 30030, 510510, 9699690, 223092870, 6469693230, 200560490130, 7420738134810, ...

4. 梅森质数(A000668)

3, 7, 31, 127, 8191, 131071, 524287, 2147483647, 2305843009213693951, 618970019642690137449562111, 162259276829213363391578010288127, 170141183460469231731687303715884105727

p 是质数, 同时 $2^p - 1$ 也是质数.

8.15.4 其他

1. 伯努利数(A027641)

见1.10.2. 伯努利数, 自然数幂次和(15页).

2. 四个柱子的汉诺塔(A007664)

0, 1, 3, 5, 9, 13, 17, 25, 33, 41, 49, 65, 81, 97, 113, 129, 161, 193, 225, 257, 289, 321, 385, 449, ...

差分之后可以发现其实就是1次+1, 2次+2, 3次+4, 4次+8...的规律.

3. 乌拉姆数(Ulam numbers, A002858)

1, 2, 3, 4, 6, 8, 11, 13, 16, 18, 26, 28, 36, 38, 47, 48, 53, 57, 62, 69, 72, 77, 82, 87, 97, 99, 102, 106, 114, 126, 131, 138, 145, 148, 155, 175, 177, 180, 182, 189, 197, 206, 209, 219, 221, 236, 238, 241, 243, 253, 258, 260, 273, 282, 309, 316, 319, 324, 339 ...

$a_1 = 1$, $a_2 = 2$, a_n 表示在所有 $> a_{n-1}$ 的数中, 最小的, 能被表示成(前面的两个不同的元素的和)的数.

8.16 编译选项

- `-O2 -g -std=c++17`: 狗都知道
- `-Wall -Wextra -Wshadow -Wconversion`: 更多警告
 - `-Werror`: 强制将所有Warning变成Error
- `-fsanitize=(address/undefined/ftrapv)`: 检查数组越界/有符号整数溢出(算ub)
 - 调试神器, 在遇到错误时会输出信息.
 - 注意无符号类型溢出不算ub.
- `-fno-ms-extensions`: 关闭一些和msvc保持一致的特性, 例如, 不标返回值类型的函数会报CE而不是默认为int.
 - 但是不写return的话它还是管不了.
- `#define debug(x) cout << #x << " = " << x << endl`

8.17 附录: VScode相关

8.17.1 插件

- Chinese (Simplified) (简体中文语言包)
- C/C++
- C++ Intellisense (前提是让用)
- Better C++ Syntax
- Python
- Pylance (前提是让用)
- Rainbow Brackets (前提是让用)

8.17.2 设置选项

- Editor: Insert Spaces (取消勾选, 改为tab缩进)
- Editor: Line Warp (开启折行)
- 改配色, “深色+：默认深色”
- 自动保存(F1 → “auto”)
- Terminal → Integrated: Cursor Style (修改终端光标形状)
- Terminal → Integrated: Cursor Blinking (终端光标闪烁)
- 字体改为Cascadia Code/Mono SemiLight (Windows可用)

8.17.3 快捷键

- F1 / Ctrl+Shift+P: 万能键, 打开命令面板
- F8: 下一个Error Shift+F8: 上一个Error
- Ctrl+\: 水平分栏, 最多3栏
- Ctrl+1/2/3: 切到对应栏
- Ctrl+[/: 当前行向左/右缩进
- Alt+F12: 查看定义的缩略图(显示小窗, 不跳过去)
- Ctrl+H: 查找替换
- Ctrl+D: 下一个匹配的也被选中(用于配合Ctrl+F)
- Ctrl+U: 回退上一个光标操作(防止光标飞了找不回去)
- Ctrl+/: 切换行注释
- Ctrl+` (键盘左上角的倒引号): 显示终端

更多快捷键参见最后两页, 分别是Windows和Linux下的快捷键列表.

8.18 附录：骂人的艺术—梁实秋

古今中外没有一个不骂人的人。骂人就是有道德观念的意思，因为在骂人的时候，至少在骂人者自己总觉得那人有该骂的地方。何者该骂，何者不该骂，这个抉择的标准，是极道德的。所以根本不骂人，大可不必。骂人是一种发泄感情的方法，尤其是那一种怨怒的感情。想骂人的时候而不骂，时常在身体上弄出毛病，所以想骂人时，骂骂何妨？

但是，骂人是一种高深的学问，不是人人都可以随便试的。有因为骂人挨嘴巴的，有因为骂人吃官司的，有因为骂人反被人骂的，这都是不会骂人的原故。今以研究所得，公诸同好，或可为骂人时之一助乎？

1. 知己知彼

骂人是和动手打架一样的，你如其敢打人一拳，你先要自己忖度下，你吃得起别人的一拳否。这叫做知己知彼。骂人也是一样。譬如你骂他是“屈死”，你先要反省，自己和“屈死”有无分别。你骂别人荒唐，你自己想想曾否吃喝嫖赌。否则别人回敬你一二句，你就受不了。所以别人有着某种短处，而足下也正有同病，那么你在骂他的时候只得割爱。

2. 无骂不如己者

要骂人须要挑比你大一点的人物，比你漂亮一点的或者比你坏得万倍而比你得势的人物，总之，你要骂人，那人无论在好的方面或坏的一方面都要能胜过你，你才不吃亏。你骂大人物，就怕他不理你，他一回骂，你就算骂着了。因为身份相同的人才肯对骂。在坏的一方面胜过你的，你骂他就如教训一般，他既便回骂，一般人仍不会理会他的。假如你骂一个无关痛痒的人，你越骂他他越得意，时常可以把一个无名小卒骂出名了，你看冤与不冤？

3. 适可而止

骂大人物骂到他回骂的时候，便不可再骂；再骂则一般人对你必无同情，以为你是无理取闹。骂小人物骂到他不能回骂的时候，便不可再骂；再骂下去则一般人对你也必无同情，以为你是欺负弱者。

4. 旁敲侧击

他偷东西，你骂他是贼；他抢东西，你骂他是盗，这是笨伯。骂人必须先明虚实掩映之法，须要烘托旁衬，旁敲侧击，于要紧处只一语便得，所谓杀于咽喉处着刀。越要骂他你越要原谅他，即便说些恭维话亦不为过，这样的骂法才能显得你所骂的句句是真实确凿，让旁人看起来也可见得你的度量。

5. 态度镇定

骂人最忌浮躁。一语不合，面红筋跳，暴躁如雷，此灌夫骂座，泼妇骂街之术，不足以言骂人。善骂者必须态度镇静，行若无事。普通一般骂人，谁的声音高便算谁占理，谁的来势猛便算谁骂赢，惟真善骂人者，乃能避其锋而击其懈。你等他骂得疲倦的时候，你只消轻轻的回敬他一句，让他再狂吼一阵。在他暴躁不堪的时候，你不妨对他冷笑几声，包管你不费力气，把他气得死去活来，骂得他针针见血。

6. 出言典雅

骂人要骂得微妙含蓄，你骂他一句要使他不甚觉得是骂，等到想

过一遍才慢慢觉悟这句话不是好话，让他笑着的面孔由白而红，由红而紫，由紫而灰，这才是骂人的上乘。欲达到此种目的，深刻之用意固不可少，而典雅之言词则尤为重要。言词典雅可使听者不致刺耳。如要骂人骂得典雅，则首先要在骂时万勿提起女人身上的某一部分，万勿不要涉及生理学范围。骂人一骂到生理学范围以内，底下再有什么话都不好说了。譬如你骂某甲，千万别提起他的令堂令妹。因为那样一来，便无是非可言，并且你自己也不免有令堂令妹，他若回敬起来，岂非势均力敌，半斤八两？再者骂人的时候，最好不要加入以种种难堪的名词，称呼起来总要客气，即使他是极卑鄙的小人，你也不妨称他先生，越客气，越骂得有力量。骂得时节最好引用他自己的词句，这不但可以使他难堪，还可以减轻他对你骂的力量。俗语少用，因为俗语一览无遗，不若典雅古文曲折含蓄。

7. 以退为进

两人对骂，而自己亦有理屈之处，则处于开骂伊始，特宜注意，最好是毅然将自己理屈之处完全承认下来，即使道歉认错均不妨事。先把自己理屈之处轻轻遮掩过去，然后你再重整旗鼓，着着逼人，方可无后顾之忧。即使自己没有理屈的地方，也绝不可自行夸张，务必要谦逊不遑，把自己的位置降到一个不可再降的位置，然后骂起人来，自有一种公正光明的态度。否则你骂他一两句，他便以你个人的事反唇相讥，一场对骂，会变成两人私下口角，是非曲直，无从判断。所以骂人者自己要低声下气，此所谓以退为进。

8. 预设埋伏

你把这句话骂过去，你便要想想看，他将用什么话骂回来。有眼光的骂人者，便处处留神，或是先将他要骂你的话替他说出来，或是预先安设埋伏，令他骂回来的话失去效力。他骂你的话，你替他说出来，这便等于缴了他的械一般。预设埋伏，便是在要攻击你的地方，你先轻轻的安下话根，然后他骂过来就等于枪弹打在沙包上，不能中伤。

9. 小题大做

如对方有该骂之处，而题目身小，不值一骂，或你所知不多，不足一骂，那时节你便可用小题大做的方法，来扩大题目。先用诚恳而怀疑的态度引申对方的意思，由不紧要之点引到大题目上去，处处用严谨的逻辑逼他说出不逻辑的话来，或是逼他说出合于逻辑但不合乎理的话来，然后你再大举骂他，骂到体无完肤为止，而原来惹动你的小题目，轻轻一提便了。

10. 远交近攻

一个时候，只能骂一个人，或一种人，或一派。决不宜多树敌。所以骂人的时候，万勿连累旁人，即使必须牵涉多人，你也要表示好意，否则回骂之声纷至沓来，使你无从应付。

骂人的艺术，一时所能想起来的有上面十条，信手拈来，并无条理。我做此文的用意，是助人骂人。同时也是想把骂人的技术揭破一点，供爱骂人者参考。挨骂的人看看，骂人的心理原来是这样的，也算是揭破一张黑幕给你瞧瞧！

8.19 附录：Cheat Sheet

见后面几页。

Theoretical Computer Science Cheat Sheet

Definitions		Series
$f(n) = O(g(n))$	iff \exists positive c, n_0 such that $0 \leq f(n) \leq cg(n) \forall n \geq n_0$.	$\sum_{i=1}^n i = \frac{n(n+1)}{2}, \quad \sum_{i=1}^n i^2 = \frac{n(n+1)(2n+1)}{6}, \quad \sum_{i=1}^n i^3 = \frac{n^2(n+1)^2}{4}$. In general: $\sum_{i=1}^n i^m = \frac{1}{m+1} \left[(n+1)^{m+1} - 1 - \sum_{i=1}^n ((i+1)^{m+1} - i^{m+1} - (m+1)i^m) \right]$ $\sum_{i=1}^{n-1} i^m = \frac{1}{m+1} \sum_{k=0}^m \binom{m+1}{k} B_k n^{m+1-k}.$
$f(n) = \Omega(g(n))$	iff \exists positive c, n_0 such that $f(n) \geq cg(n) \geq 0 \forall n \geq n_0$.	
$f(n) = \Theta(g(n))$	iff $f(n) = O(g(n))$ and $f(n) = \Omega(g(n))$.	
$f(n) = o(g(n))$	iff $\lim_{n \rightarrow \infty} f(n)/g(n) = 0$.	
$\lim_{n \rightarrow \infty} a_n = a$	iff $\forall \epsilon > 0, \exists n_0$ such that $ a_n - a < \epsilon, \forall n \geq n_0$.	
$\sup S$	least $b \in \mathbb{R}$ such that $b \geq s, \forall s \in S$.	Geometric series: $\sum_{i=0}^n c^i = \frac{c^{n+1} - 1}{c - 1}, \quad c \neq 1, \quad \sum_{i=0}^{\infty} c^i = \frac{1}{1 - c}, \quad \sum_{i=1}^{\infty} c^i = \frac{c}{1 - c}, \quad c < 1,$ $\sum_{i=0}^n i c^i = \frac{nc^{n+2} - (n+1)c^{n+1} + c}{(c-1)^2}, \quad c \neq 1, \quad \sum_{i=0}^{\infty} i c^i = \frac{c}{(1-c)^2}, \quad c < 1.$
$\inf S$	greatest $b \in \mathbb{R}$ such that $b \leq s, \forall s \in S$.	
$\liminf_{n \rightarrow \infty} a_n$	$\lim_{n \rightarrow \infty} \inf \{a_i \mid i \geq n, i \in \mathbb{N}\}$.	Harmonic series: $H_n = \sum_{i=1}^n \frac{1}{i}, \quad \sum_{i=1}^n i H_i = \frac{n(n+1)}{2} H_n - \frac{n(n-1)}{4}.$
$\limsup_{n \rightarrow \infty} a_n$	$\lim_{n \rightarrow \infty} \sup \{a_i \mid i \geq n, i \in \mathbb{N}\}$.	$\sum_{i=1}^n H_i = (n+1)H_n - n, \quad \sum_{i=1}^n \binom{i}{m} H_i = \binom{n+1}{m+1} \left(H_{n+1} - \frac{1}{m+1} \right).$
$\binom{n}{k}$	Combinations: Size k subsets of a size n set.	
$\begin{bmatrix} n \\ k \end{bmatrix}$	Stirling numbers (1st kind): Arrangements of an n element set into k cycles.	1. $\binom{n}{k} = \frac{n!}{(n-k)!k!}, \quad 2. \sum_{k=0}^n \binom{n}{k} = 2^n, \quad 3. \binom{n}{k} = \binom{n}{n-k},$
$\left\{ \begin{smallmatrix} n \\ k \end{smallmatrix} \right\}$	Stirling numbers (2nd kind): Partitions of an n element set into k non-empty sets.	4. $\binom{n}{k} = \frac{n}{k} \binom{n-1}{k-1}, \quad 5. \binom{n}{k} = \binom{n-1}{k} + \binom{n-1}{k-1},$
$\left\langle \begin{smallmatrix} n \\ k \end{smallmatrix} \right\rangle$	1st order Eulerian numbers: Permutations $\pi_1 \pi_2 \dots \pi_n$ on $\{1, 2, \dots, n\}$ with k ascents.	6. $\binom{n}{m} \binom{m}{k} = \binom{n}{k} \binom{n-k}{m-k}, \quad 7. \sum_{k=0}^n \binom{r+k}{k} = \binom{r+n+1}{n},$
$\left\langle \begin{smallmatrix} n \\ k \end{smallmatrix} \right\rangle$	2nd order Eulerian numbers.	8. $\sum_{k=0}^n \binom{k}{m} = \binom{n+1}{m+1}, \quad 9. \sum_{k=0}^n \binom{r}{k} \binom{s}{n-k} = \binom{r+s}{n},$
C_n	Catalan Numbers: Binary trees with $n+1$ vertices.	10. $\binom{n}{k} = (-1)^k \binom{k-n-1}{k}, \quad 11. \left\{ \begin{smallmatrix} n \\ 1 \end{smallmatrix} \right\} = \left\{ \begin{smallmatrix} n \\ n \end{smallmatrix} \right\} = 1,$
14. $\begin{bmatrix} n \\ 1 \end{bmatrix} = (n-1)!$	15. $\begin{bmatrix} n \\ 2 \end{bmatrix} = (n-1)!H_{n-1},$	12. $\left\{ \begin{smallmatrix} n \\ 2 \end{smallmatrix} \right\} = 2^{n-1} - 1, \quad 13. \left\{ \begin{smallmatrix} n \\ k \end{smallmatrix} \right\} = k \left\{ \begin{smallmatrix} n-1 \\ k \end{smallmatrix} \right\} + \left\{ \begin{smallmatrix} n-1 \\ k-1 \end{smallmatrix} \right\},$
18. $\begin{bmatrix} n \\ k \end{bmatrix} = (n-1) \begin{bmatrix} n-1 \\ k \end{bmatrix} + \begin{bmatrix} n-1 \\ k-1 \end{bmatrix},$	19. $\left\{ \begin{smallmatrix} n \\ n-1 \end{smallmatrix} \right\} = \left[\begin{smallmatrix} n \\ n-1 \end{smallmatrix} \right] = \binom{n}{2},$	16. $\begin{bmatrix} n \\ n \end{bmatrix} = 1, \quad 17. \begin{bmatrix} n \\ k \end{bmatrix} \geq \left\{ \begin{smallmatrix} n \\ k \end{smallmatrix} \right\},$
22. $\left\langle \begin{smallmatrix} n \\ 0 \end{smallmatrix} \right\rangle = \left\langle \begin{smallmatrix} n \\ n-1 \end{smallmatrix} \right\rangle = 1,$	23. $\left\langle \begin{smallmatrix} n \\ k \end{smallmatrix} \right\rangle = \left\langle \begin{smallmatrix} n \\ n-1-k \end{smallmatrix} \right\rangle,$	20. $\sum_{k=0}^n \begin{bmatrix} n \\ k \end{bmatrix} = n!, \quad 21. C_n = \frac{1}{n+1} \binom{2n}{n},$
25. $\left\langle \begin{smallmatrix} 0 \\ k \end{smallmatrix} \right\rangle = \begin{cases} 1 & \text{if } k=0, \\ 0 & \text{otherwise} \end{cases}$	26. $\left\langle \begin{smallmatrix} n \\ 1 \end{smallmatrix} \right\rangle = 2^n - n - 1,$	24. $\left\langle \begin{smallmatrix} n \\ k \end{smallmatrix} \right\rangle = (k+1) \left\langle \begin{smallmatrix} n-1 \\ k \end{smallmatrix} \right\rangle + (n-k) \left\langle \begin{smallmatrix} n-1 \\ k-1 \end{smallmatrix} \right\rangle,$
28. $x^n = \sum_{k=0}^n \left\langle \begin{smallmatrix} n \\ k \end{smallmatrix} \right\rangle \binom{x+k}{n},$	29. $\left\langle \begin{smallmatrix} n \\ m \end{smallmatrix} \right\rangle = \sum_{k=0}^m \binom{n+1}{k} (m+1-k)^n (-1)^k,$	27. $\left\langle \begin{smallmatrix} n \\ 2 \end{smallmatrix} \right\rangle = 3^n - (n+1)2^n + \binom{n+1}{2},$
31. $\left\langle \begin{smallmatrix} n \\ m \end{smallmatrix} \right\rangle = \sum_{k=0}^n \left\{ \begin{smallmatrix} n \\ k \end{smallmatrix} \right\} \binom{n-k}{m} (-1)^{n-k-m} k!,$	32. $\left\langle \begin{smallmatrix} n \\ 0 \end{smallmatrix} \right\rangle = 1,$	30. $m! \left\{ \begin{smallmatrix} n \\ m \end{smallmatrix} \right\} = \sum_{k=0}^n \left\langle \begin{smallmatrix} n \\ k \end{smallmatrix} \right\rangle \binom{k}{n-m},$
34. $\left\langle \begin{smallmatrix} n \\ k \end{smallmatrix} \right\rangle = (k+1) \left\langle \begin{smallmatrix} n-1 \\ k \end{smallmatrix} \right\rangle + (2n-1-k) \left\langle \begin{smallmatrix} n-1 \\ k-1 \end{smallmatrix} \right\rangle,$		33. $\left\langle \begin{smallmatrix} n \\ n \end{smallmatrix} \right\rangle = 0 \quad \text{for } n \neq 0,$
36. $\left\{ \begin{smallmatrix} x \\ x-n \end{smallmatrix} \right\} = \sum_{k=0}^n \left\langle \begin{smallmatrix} n \\ k \end{smallmatrix} \right\rangle \binom{x+n-1-k}{2n},$	37. $\left\{ \begin{smallmatrix} n+1 \\ m+1 \end{smallmatrix} \right\} = \sum_k \binom{n}{k} \left\{ \begin{smallmatrix} k \\ m \end{smallmatrix} \right\} = \sum_{k=0}^n \left\{ \begin{smallmatrix} k \\ m \end{smallmatrix} \right\} (m+1)^{n-k},$	35. $\sum_{k=0}^n \left\langle \begin{smallmatrix} n \\ k \end{smallmatrix} \right\rangle = \frac{(2n)^n}{2^n},$

Theoretical Computer Science Cheat Sheet

Identities Cont.	Trees
38. $\begin{bmatrix} n+1 \\ m+1 \end{bmatrix} = \sum_k \begin{bmatrix} n \\ k \end{bmatrix} \binom{k}{m} = \sum_{k=0}^n \begin{bmatrix} k \\ m \end{bmatrix} n^{n-k} = n! \sum_{k=0}^n \frac{1}{k!} \begin{bmatrix} k \\ m \end{bmatrix}$,	39. $\begin{bmatrix} x \\ x-n \end{bmatrix} = \sum_{k=0}^n \begin{Bmatrix} n \\ k \end{Bmatrix} \binom{x+k}{2n}$,
40. $\begin{Bmatrix} n \\ m \end{Bmatrix} = \sum_k \binom{n}{k} \begin{Bmatrix} k+1 \\ m+1 \end{Bmatrix} (-1)^{n-k}$,	41. $\begin{bmatrix} n \\ m \end{bmatrix} = \sum_k \begin{bmatrix} n+1 \\ k+1 \end{bmatrix} \binom{k}{m} (-1)^{m-k}$,
42. $\begin{Bmatrix} m+n+1 \\ m \end{Bmatrix} = \sum_{k=0}^m k \begin{Bmatrix} n+k \\ k \end{Bmatrix}$,	43. $\begin{bmatrix} m+n+1 \\ m \end{bmatrix} = \sum_{k=0}^m k(n+k) \begin{bmatrix} n+k \\ k \end{bmatrix}$,
44. $\binom{n}{m} = \sum_k \begin{Bmatrix} n+1 \\ k+1 \end{Bmatrix} \binom{k}{m} (-1)^{m-k}$,	45. $(n-m)! \binom{n}{m} = \sum_k \begin{bmatrix} n+1 \\ k+1 \end{bmatrix} \binom{k}{m} (-1)^{m-k}$, for $n \geq m$,
46. $\begin{Bmatrix} n \\ n-m \end{Bmatrix} = \sum_k \binom{m-n}{m+k} \binom{m+n}{n+k} \binom{m+k}{k}$,	47. $\begin{bmatrix} n \\ n-m \end{bmatrix} = \sum_k \binom{m-n}{m+k} \binom{m+n}{n+k} \binom{m+k}{k}$,
48. $\begin{Bmatrix} n \\ \ell+m \end{Bmatrix} \binom{\ell+m}{\ell} = \sum_k \begin{bmatrix} k \\ \ell \end{bmatrix} \binom{n-k}{m} \binom{n}{k}$,	49. $\begin{bmatrix} n \\ \ell+m \end{bmatrix} \binom{\ell+m}{\ell} = \sum_k \begin{bmatrix} k \\ \ell \end{bmatrix} \binom{n-k}{m} \binom{n}{k}$.

Recurrences

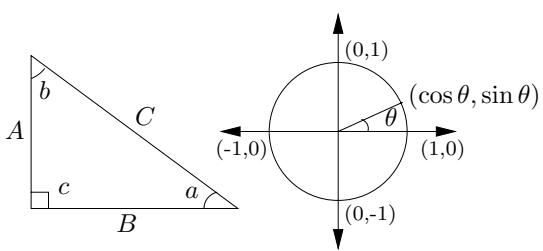
<p>Master method: $T(n) = aT(n/b) + f(n)$, $a \geq 1, b > 1$</p> <p>If $\exists \epsilon > 0$ such that $f(n) = O(n^{\log_b a - \epsilon})$ then $T(n) = \Theta(n^{\log_b a})$.</p> <p>If $f(n) = \Theta(n^{\log_b a})$ then $T(n) = \Theta(n^{\log_b a} \log_2 n)$.</p> <p>If $\exists \epsilon > 0$ such that $f(n) = \Omega(n^{\log_b a + \epsilon})$, and $\exists c < 1$ such that $af(n/b) \leq cf(n)$ for large n, then $T(n) = \Theta(f(n))$.</p> <p>Substitution (example): Consider the following recurrence $T_{i+1} = 2^{2^i} \cdot T_i^2$, $T_1 = 2$.</p> <p>Note that T_i is always a power of two. Let $t_i = \log_2 T_i$. Then we have $t_{i+1} = 2^i + 2t_i$, $t_1 = 1$.</p> <p>Let $u_i = t_i/2^i$. Dividing both sides of the previous equation by 2^{i+1} we get $\frac{t_{i+1}}{2^{i+1}} = \frac{2^i}{2^{i+1}} + \frac{t_i}{2^i}$.</p> <p>Substituting we find $u_{i+1} = \frac{1}{2} + u_i$, $u_1 = \frac{1}{2}$,</p> <p>which is simply $u_i = i/2$. So we find that T_i has the closed form $T_i = 2^{i^2/2^i}$.</p> <p>Summing factors (example): Consider the following recurrence $T(n) = 3T(n/2) + n$, $T(1) = 1$.</p> <p>Rewrite so that all terms involving T are on the left side $T(n) - 3T(n/2) = n$.</p> <p>Now expand the recurrence, and choose a factor which makes the left side “telescope”</p>	<p>$1(T(n) - 3T(n/2) = n)$ $3(T(n/2) - 3T(n/4) = n/2)$ $\vdots \quad \vdots \quad \vdots$ $3^{\log_2 n - 1}(T(2) - 3T(1) = 2)$</p> <p>Let $m = \log_2 n$. Summing the left side we get $T(n) - 3^m T(1) = T(n) - 3^m = T(n) - n^k$ where $k = \log_2 3 \approx 1.58496$. Summing the right side we get $\sum_{i=0}^{m-1} \frac{n}{2^i} 3^i = n \sum_{i=0}^{m-1} \left(\frac{3}{2}\right)^i$.</p> <p>Let $c = \frac{3}{2}$. Then we have $n \sum_{i=0}^{m-1} c^i = n \left(\frac{c^m - 1}{c - 1}\right)$ $= 2n(c^{\log_2 n} - 1)$ $= 2n(c^{(k-1)\log_2 n} - 1)$ $= 2n^k - 2n$,</p> <p>and so $T(n) = 3n^k - 2n$. Full history recurrences can often be changed to limited history ones (example): Consider $T_i = 1 + \sum_{j=0}^{i-1} T_j$, $T_0 = 1$.</p> <p>Note that $T_{i+1} = 1 + \sum_{j=0}^i T_j$.</p> <p>Subtracting we find $T_{i+1} - T_i = 1 + \sum_{j=0}^i T_j - 1 - \sum_{j=0}^{i-1} T_j$ $= T_i$.</p> <p>And so $T_{i+1} = 2T_i = 2^{i+1}$.</p>	<p>Generating functions:</p> <ol style="list-style-type: none"> Multiply both sides of the equation by x^i. Sum both sides over all i for which the equation is valid. Choose a generating function $G(x)$. Usually $G(x) = \sum_{i=0}^{\infty} x^i g_i$. Rewrite the equation in terms of the generating function $G(x)$. Solve for $G(x)$. The coefficient of x^i in $G(x)$ is g_i. <p>Example: $g_{i+1} = 2g_i + 1$, $g_0 = 0$.</p> <p>Multiply and sum: $\sum_{i \geq 0} g_{i+1} x^i = \sum_{i \geq 0} 2g_i x^i + \sum_{i \geq 0} x^i$.</p> <p>We choose $G(x) = \sum_{i \geq 0} x^i g_i$. Rewrite in terms of $G(x)$: $\frac{G(x) - g_0}{x} = 2G(x) + \sum_{i \geq 0} x^i$.</p> <p>Simplify: $\frac{G(x)}{x} = 2G(x) + \frac{1}{1-x}$.</p> <p>Solve for $G(x)$: $G(x) = \frac{x}{(1-x)(1-2x)}$.</p> <p>Expand this using partial fractions: $G(x) = x \left(\frac{2}{1-2x} - \frac{1}{1-x} \right)$ $= x \left(2 \sum_{i \geq 0} 2^i x^i - \sum_{i \geq 0} x^i \right)$ $= \sum_{i \geq 0} (2^{i+1} - 1)x^{i+1}$.</p> <p>So $g_i = 2^i - 1$.</p>
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Theoretical Computer Science Cheat Sheet

$\pi \approx 3.14159, e \approx 2.71828, \gamma \approx 0.57721, \phi = \frac{1+\sqrt{5}}{2} \approx 1.61803, \hat{\phi} = \frac{1-\sqrt{5}}{2} \approx -.61803$				
i	2^i	p_i	General	Probability
1	2	2	Bernoulli Numbers ($B_i = 0$, odd $i \neq 1$): $B_0 = 1, B_1 = -\frac{1}{2}, B_2 = \frac{1}{6}, B_4 = -\frac{1}{30}, B_6 = \frac{1}{42}, B_8 = -\frac{1}{30}, B_{10} = \frac{5}{66}.$	Continuous distributions: If $\Pr[a < X < b] = \int_a^b p(x) dx,$ then p is the probability density function of X . If $\Pr[X < a] = P(a),$ then P is the distribution function of X . If P and p both exist then $P(a) = \int_{-\infty}^a p(x) dx.$
2	4	3		
3	8	5		
4	16	7	Change of base, quadratic formula: $\log_b x = \frac{\log_a x}{\log_a b}, \quad \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}.$	
5	32	11		
6	64	13		
7	128	17	Euler's number e : $e = 1 + \frac{1}{2} + \frac{1}{6} + \frac{1}{24} + \frac{1}{120} + \dots$ $\lim_{n \rightarrow \infty} \left(1 + \frac{x}{n}\right)^n = e^x.$	Expectation: If X is discrete $E[g(X)] = \sum_x g(x) \Pr[X = x].$
8	256	19		If X continuous then $E[g(X)] = \int_{-\infty}^{\infty} g(x)p(x) dx = \int_{-\infty}^{\infty} g(x) dP(x).$
9	512	23		Variance, standard deviation: $\text{VAR}[X] = E[X^2] - E[X]^2,$ $\sigma = \sqrt{\text{VAR}[X]}.$
10	1,024	29		For events A and B : $\Pr[A \vee B] = \Pr[A] + \Pr[B] - \Pr[A \wedge B]$
11	2,048	31		$\Pr[A \wedge B] = \Pr[A] \cdot \Pr[B],$ iff A and B are independent.
12	4,096	37		$\Pr[A B] = \frac{\Pr[A \wedge B]}{\Pr[B]}$
13	8,192	41	Harmonic numbers: $1, \frac{3}{2}, \frac{11}{6}, \frac{25}{12}, \frac{137}{60}, \frac{49}{20}, \frac{363}{140}, \frac{761}{280}, \frac{7129}{2520}, \dots$	For random variables X and Y : $E[X \cdot Y] = E[X] \cdot E[Y],$ if X and Y are independent.
14	16,384	43		$E[X + Y] = E[X] + E[Y],$ $E[cX] = cE[X].$
15	32,768	47		Bayes' theorem:
16	65,536	53		$\Pr[A_i B] = \frac{\Pr[B A_i] \Pr[A_i]}{\sum_{j=1}^n \Pr[A_j] \Pr[B A_j]}.$
17	131,072	59		Inclusion-exclusion:
18	262,144	61		$\Pr\left[\bigvee_{i=1}^n X_i\right] = \sum_{i=1}^n \Pr[X_i] + \sum_{k=2}^n (-1)^{k+1} \sum_{i_1 < \dots < i_k} \Pr\left[\bigwedge_{j=1}^k X_{i_j}\right].$
19	524,288	67	Factorial, Stirling's approximation: $1, 2, 6, 24, 120, 720, 5040, 40320, 362880, \dots$	Moment inequalities:
20	1,048,576	71		$\Pr[X \geq \lambda E[X]] \leq \frac{1}{\lambda},$ $\Pr[X - E[X] \geq \lambda \cdot \sigma] \leq \frac{1}{\lambda^2}.$
21	2,097,152	73		Geometric distribution:
22	4,194,304	79		$\Pr[X = k] = pq^{k-1}, \quad q = 1 - p,$ $E[X] = \sum_{k=1}^{\infty} k \Pr[X = k] = \frac{p}{1-q}.$
23	8,388,608	83	Ackermann's function and inverse: $a(i, j) = \begin{cases} 2^j & i = 1 \\ a(i-1, 2) & j = 1 \\ a(i-1, a(i, j-1)) & i, j \geq 2 \end{cases}$ $\alpha(i) = \min\{j \mid a(j, j) \geq i\}.$	
24	16,777,216	89		
25	33,554,432	97		
26	67,108,864	101		
27	134,217,728	103		
28	268,435,456	107	Binomial distribution: $\Pr[X = k] = \binom{n}{k} p^k q^{n-k}, \quad q = 1 - p,$ $E[X] = \sum_{k=1}^n k \binom{n}{k} p^k q^{n-k} = np.$	
29	536,870,912	109		
30	1,073,741,824	113	Poisson distribution: $\Pr[X = k] = \frac{e^{-\lambda} \lambda^k}{k!}, \quad E[X] = \lambda.$	
31	2,147,483,648	127	Normal (Gaussian) distribution: $p(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(x-\mu)^2/2\sigma^2}, \quad E[X] = \mu.$	
32	4,294,967,296	131	The "coupon collector": We are given a random coupon each day, and there are n different types of coupons. The distribution of coupons is uniform. The expected number of days to pass before we collect all n types is $nH_n.$	
Pascal's Triangle				
	1			
	1 1			
	1 2 1			
	1 3 3 1			
	1 4 6 4 1			
	1 5 10 10 5 1			
	1 6 15 20 15 6 1			
	1 7 21 35 35 21 7 1			
	1 8 28 56 70 56 28 8 1			
	1 9 36 84 126 126 84 36 9 1			
	1 10 45 120 210 252 210 120 45 10 1			

Theoretical Computer Science Cheat Sheet

Trigonometry



Pythagorean theorem:

$$C^2 = A^2 + B^2.$$

Definitions:

$$\sin a = A/C, \quad \cos a = B/C,$$

$$\csc a = C/A, \quad \sec a = C/B,$$

$$\tan a = \frac{\sin a}{\cos a} = \frac{A}{B}, \quad \cot a = \frac{\cos a}{\sin a} = \frac{B}{A}.$$

Area, radius of inscribed circle:

$$\frac{1}{2}AB, \quad \frac{AB}{A+B+C}.$$

Identities:

$$\sin x = \frac{1}{\csc x},$$

$$\cos x = \frac{1}{\sec x},$$

$$\tan x = \frac{1}{\cot x},$$

$$\sin^2 x + \cos^2 x = 1,$$

$$1 + \tan^2 x = \sec^2 x,$$

$$1 + \cot^2 x = \csc^2 x,$$

$$\sin x = \cos(\frac{\pi}{2} - x),$$

$$\sin x = \sin(\pi - x),$$

$$\cos x = -\cos(\pi - x),$$

$$\tan x = \cot(\frac{\pi}{2} - x),$$

$$\cot x = -\cot(\pi - x),$$

$$\csc x = \cot \frac{x}{2} - \cot x,$$

$$\sin(x \pm y) = \sin x \cos y \pm \cos x \sin y,$$

$$\cos(x \pm y) = \cos x \cos y \mp \sin x \sin y,$$

$$\tan(x \pm y) = \frac{\tan x \pm \tan y}{1 \mp \tan x \tan y},$$

$$\cot(x \pm y) = \frac{\cot x \cot y \mp 1}{\cot x \pm \cot y},$$

$$\sin 2x = 2 \sin x \cos x, \quad \sin 2x = \frac{2 \tan x}{1 + \tan^2 x},$$

$$\cos 2x = \cos^2 x - \sin^2 x, \quad \cos 2x = 2 \cos^2 x - 1,$$

$$\cos 2x = 1 - 2 \sin^2 x, \quad \cos 2x = \frac{1 - \tan^2 x}{1 + \tan^2 x},$$

$$\tan 2x = \frac{2 \tan x}{1 - \tan^2 x}, \quad \cot 2x = \frac{\cot^2 x - 1}{2 \cot x},$$

$$\sin(x+y) \sin(x-y) = \sin^2 x - \sin^2 y,$$

$$\cos(x+y) \cos(x-y) = \cos^2 x - \sin^2 y.$$

Euler's equation:

$$e^{ix} = \cos x + i \sin x, \quad e^{i\pi} = -1.$$

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Matrices

Multiplication:

$$C = A \cdot B, \quad c_{i,j} = \sum_{k=1}^n a_{i,k} b_{k,j}.$$

Determinants: $\det A \neq 0$ iff A is non-singular.

$$\det A \cdot B = \det A \cdot \det B,$$

$$\det A = \sum_{\pi} \prod_{i=1}^n \text{sign}(\pi) a_{i,\pi(i)}.$$

2×2 and 3×3 determinant:

$$\begin{vmatrix} a & b \\ c & d \end{vmatrix} = ad - bc,$$

$$\begin{vmatrix} a & b & c \\ d & e & f \\ g & h & i \end{vmatrix} = g \begin{vmatrix} b & c \\ e & f \end{vmatrix} - h \begin{vmatrix} a & c \\ d & f \end{vmatrix} + i \begin{vmatrix} a & b \\ d & e \end{vmatrix}$$

$$= aei + bfg + cdh - ceg - fha - ibd.$$

Permanents:

$$\text{perm } A = \sum_{\pi} \prod_{i=1}^n a_{i,\pi(i)}.$$

Hyperbolic Functions

Definitions:

$$\sinh x = \frac{e^x - e^{-x}}{2}, \quad \cosh x = \frac{e^x + e^{-x}}{2},$$

$$\tanh x = \frac{e^x - e^{-x}}{e^x + e^{-x}}, \quad \operatorname{csch} x = \frac{1}{\sinh x},$$

$$\operatorname{sech} x = \frac{1}{\cosh x}, \quad \coth x = \frac{1}{\tanh x}.$$

Identities:

$$\cosh^2 x - \sinh^2 x = 1, \quad \tanh^2 x + \operatorname{sech}^2 x = 1,$$

$$\coth^2 x - \operatorname{csch}^2 x = 1, \quad \sinh(-x) = -\sinh x,$$

$$\cosh(-x) = \cosh x, \quad \tanh(-x) = -\tanh x,$$

$$\sinh(x+y) = \sinh x \cosh y + \cosh x \sinh y,$$

$$\cosh(x+y) = \cosh x \cosh y + \sinh x \sinh y,$$

$$\sinh 2x = 2 \sinh x \cosh x,$$

$$\cosh 2x = \cosh^2 x + \sinh^2 x,$$

$$\cosh x + \sinh x = e^x, \quad \cosh x - \sinh x = e^{-x},$$

$$(\cosh x + \sinh x)^n = \cosh nx + \sinh nx, \quad n \in \mathbb{Z},$$

$$2 \sinh^2 \frac{x}{2} = \cosh x - 1, \quad 2 \cosh^2 \frac{x}{2} = \cosh x + 1.$$

$$\theta \quad \sin \theta \quad \cos \theta \quad \tan \theta$$

$$0 \quad 0 \quad 1 \quad 0$$

$$\frac{\pi}{6} \quad \frac{1}{2} \quad \frac{\sqrt{3}}{2} \quad \frac{\sqrt{3}}{3}$$

$$\frac{\pi}{4} \quad \frac{\sqrt{2}}{2} \quad \frac{\sqrt{2}}{2} \quad 1$$

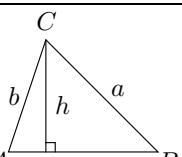
$$\frac{\pi}{3} \quad \frac{\sqrt{3}}{2} \quad \frac{1}{2} \quad \sqrt{3}$$

$$\frac{\pi}{2} \quad 1 \quad 0 \quad \infty$$

... in mathematics you don't understand things, you just get used to them.

– J. von Neumann

More Trig.



Law of cosines:

$$c^2 = a^2 + b^2 - 2ab \cos C.$$

Area:

$$A = \frac{1}{2}hc,$$

$$= \frac{1}{2}ab \sin C,$$

$$= \frac{c^2 \sin A \sin B}{2 \sin C}.$$

Heron's formula:

$$A = \sqrt{s \cdot s_a \cdot s_b \cdot s_c},$$

$$s = \frac{1}{2}(a+b+c),$$

$$s_a = s - a,$$

$$s_b = s - b,$$

$$s_c = s - c.$$

More identities:

$$\sin \frac{x}{2} = \sqrt{\frac{1 - \cos x}{2}},$$

$$\cos \frac{x}{2} = \sqrt{\frac{1 + \cos x}{2}},$$

$$\tan \frac{x}{2} = \sqrt{\frac{1 - \cos x}{1 + \cos x}},$$

$$= \frac{1 - \cos x}{\sin x},$$

$$= \frac{\sin x}{1 + \cos x},$$

$$\cot \frac{x}{2} = \sqrt{\frac{1 + \cos x}{1 - \cos x}},$$

$$= \frac{1 + \cos x}{\sin x},$$

$$= \frac{\sin x}{1 - \cos x},$$

$$\sin x = \frac{e^{ix} - e^{-ix}}{2i},$$

$$\cos x = \frac{e^{ix} + e^{-ix}}{2},$$

$$\tan x = -i \frac{e^{ix} - e^{-ix}}{e^{ix} + e^{-ix}},$$

$$= -i \frac{e^{2ix} - 1}{e^{2ix} + 1},$$

$$\sinh ix = \frac{e^{ix} - e^{-ix}}{2i},$$

$$\cosh ix = \frac{e^{ix} + e^{-ix}}{2},$$

$$\tanh ix = \frac{\sinh ix}{\cosh ix}.$$

Theoretical Computer Science Cheat Sheet

Theoretical Computer Science Cheat Sheet								
Number Theory	Graph Theory							
<p>The Chinese remainder theorem: There exists a number C such that:</p> $C \equiv r_1 \pmod{m_1}$ $\vdots \quad \vdots \quad \vdots$ $C \equiv r_n \pmod{m_n}$ <p>if m_i and m_j are relatively prime for $i \neq j$.</p> <p>Euler's function: $\phi(x)$ is the number of positive integers less than x relatively prime to x. If $\prod_{i=1}^n p_i^{e_i}$ is the prime factorization of x then</p> $\phi(x) = \prod_{i=1}^n p_i^{e_i-1} (p_i - 1).$ <p>Euler's theorem: If a and b are relatively prime then</p> $1 \equiv a^{\phi(b)} \pmod{b}.$ <p>Fermat's theorem:</p> $1 \equiv a^{p-1} \pmod{p}.$ <p>The Euclidean algorithm: if $a > b$ are integers then</p> $\gcd(a, b) = \gcd(a \bmod b, b).$ <p>If $\prod_{i=1}^n p_i^{e_i}$ is the prime factorization of x then</p> $S(x) = \sum_{d x} d = \prod_{i=1}^n \frac{p_i^{e_i+1} - 1}{p_i - 1}.$ <p>Perfect Numbers: x is an even perfect number iff $x = 2^{n-1}(2^n - 1)$ and $2^n - 1$ is prime.</p> <p>Wilson's theorem: n is a prime iff</p> $(n-1)! \equiv -1 \pmod{n}.$ <p>Möbius inversion:</p> $\mu(i) = \begin{cases} 1 & \text{if } i = 1. \\ 0 & \text{if } i \text{ is not square-free.} \\ (-1)^r & \text{if } i \text{ is the product of } r \text{ distinct primes.} \end{cases}$ <p>If</p> $G(a) = \sum_{d a} F(d),$ <p>then</p> $F(a) = \sum_{d a} \mu(d) G\left(\frac{a}{d}\right).$ <p>Prime numbers:</p> $p_n = n \ln n + n \ln \ln n - n + n \frac{\ln \ln n}{\ln n} + O\left(\frac{n}{\ln n}\right),$ $\pi(n) = \frac{n}{\ln n} + \frac{n}{(\ln n)^2} + \frac{2!n}{(\ln n)^3} + O\left(\frac{n}{(\ln n)^4}\right).$	<p>Definitions:</p> <ul style="list-style-type: none"> <i>Loop</i>: An edge connecting a vertex to itself. <i>Directed</i>: Each edge has a direction. <i>Simple</i>: Graph with no loops or multi-edges. <i>Walk</i>: A sequence $v_0 e_1 v_1 \dots e_\ell v_\ell$. <i>Trail</i>: A walk with distinct edges. <i>Path</i>: A trail with distinct vertices. <i>Connected</i>: A graph where there exists a path between any two vertices. <i>Component</i>: A maximal connected subgraph. <i>Tree</i>: A connected acyclic graph. <i>Free tree</i>: A tree with no root. <i>DAG</i>: Directed acyclic graph. <i>Eulerian</i>: Graph with a trail visiting each edge exactly once. <i>Hamiltonian</i>: Graph with a cycle visiting each vertex exactly once. <i>Cut</i>: A set of edges whose removal increases the number of components. <i>Cut-set</i>: A minimal cut. <i>Cut edge</i>: A size 1 cut. <i>k-Connected</i>: A graph connected with the removal of any $k-1$ vertices. <i>k-Tough</i>: $\forall S \subseteq V, S \neq \emptyset$ we have $k \cdot c(G-S) \leq S$. <i>k-Regular</i>: A graph where all vertices have degree k. <i>k-Factor</i>: A k-regular spanning subgraph. <i>Matching</i>: A set of edges, no two of which are adjacent. <i>Clique</i>: A set of vertices, all of which are adjacent. <i>Ind. set</i>: A set of vertices, none of which are adjacent. <i>Vertex cover</i>: A set of vertices which cover all edges. <i>Planar graph</i>: A graph which can be embedded in the plane. <i>Plane graph</i>: An embedding of a planar graph. 	<p>Notation:</p> <ul style="list-style-type: none"> $E(G)$: Edge set $V(G)$: Vertex set $c(G)$: Number of components $G[S]$: Induced subgraph $\deg(v)$: Degree of v $\Delta(G)$: Maximum degree $\delta(G)$: Minimum degree $\chi(G)$: Chromatic number $\chi_E(G)$: Edge chromatic number G^c: Complement graph K_n: Complete graph K_{n_1, n_2}: Complete bipartite graph $r(k, \ell)$: Ramsey number 						
		Geometry						
<p>Projective coordinates: triples (x, y, z), not all x, y and z zero.</p> $(x, y, z) = (cx, cy, cz) \quad \forall c \neq 0.$ <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 50%;">Cartesian</td><td style="width: 50%;">Projective</td></tr> <tr> <td>(x, y)</td><td>$(x, y, 1)$</td></tr> <tr> <td>$y = mx + b$</td><td>$(m, -1, b)$</td></tr> <tr> <td>$x = c$</td><td>$(1, 0, -c)$</td></tr> </table> <p>Distance formula, L_p and L_∞ metric:</p> $\sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2},$ $[x_1 - x_0 ^p + y_1 - y_0 ^p]^{1/p},$ $\lim_{p \rightarrow \infty} [x_1 - x_0 ^p + y_1 - y_0 ^p]^{1/p}.$ <p>Area of triangle (x_0, y_0), (x_1, y_1) and (x_2, y_2):</p> $\frac{1}{2} \operatorname{abs} \begin{vmatrix} x_1 - x_0 & y_1 - y_0 \\ x_2 - x_0 & y_2 - y_0 \end{vmatrix}.$ <p>Angle formed by three points:</p> $\cos \theta = \frac{(x_1 - x_0)(x_2 - x_0) + (y_1 - y_0)(y_2 - y_0)}{\ell_1 \ell_2}.$ <p>Line through two points (x_0, y_0) and (x_1, y_1):</p> $\begin{vmatrix} x & y & 1 \\ x_0 & y_0 & 1 \\ x_1 & y_1 & 1 \end{vmatrix} = 0.$ <p>Area of circle, volume of sphere:</p> $A = \pi r^2, \quad V = \frac{4}{3} \pi r^3.$	Cartesian	Projective	(x, y)	$(x, y, 1)$	$y = mx + b$	$(m, -1, b)$	$x = c$	$(1, 0, -c)$
Cartesian	Projective							
(x, y)	$(x, y, 1)$							
$y = mx + b$	$(m, -1, b)$							
$x = c$	$(1, 0, -c)$							
<p>If I have seen farther than others, it is because I have stood on the shoulders of giants. – Issac Newton</p>								

Theoretical Computer Science Cheat Sheet

π	Calculus
<p>Wallis' identity:</p> $\pi = 2 \cdot \frac{2 \cdot 2 \cdot 4 \cdot 4 \cdot 6 \cdot 6 \cdots}{1 \cdot 3 \cdot 3 \cdot 5 \cdot 5 \cdot 7 \cdots}$ <p>Brouncker's continued fraction expansion:</p> $\frac{\pi}{4} = 1 + \frac{1^2}{2 + \frac{3^2}{2 + \frac{5^2}{2 + \frac{7^2}{\cdots}}}}$ <p>Gregory's series:</p> $\frac{\pi}{4} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \cdots$ <p>Newton's series:</p> $\frac{\pi}{6} = \frac{1}{2} + \frac{1}{2 \cdot 3 \cdot 2^3} + \frac{1 \cdot 3}{2 \cdot 4 \cdot 5 \cdot 2^5} + \cdots$ <p>Sharp's series:</p> $\frac{\pi}{6} = \frac{1}{\sqrt{3}} \left(1 - \frac{1}{3^1 \cdot 3} + \frac{1}{3^2 \cdot 5} - \frac{1}{3^3 \cdot 7} + \cdots \right)$ <p>Euler's series:</p> $\begin{aligned}\frac{\pi^2}{6} &= \frac{1}{1^2} + \frac{1}{2^2} + \frac{1}{3^2} + \frac{1}{4^2} + \frac{1}{5^2} + \cdots \\ \frac{\pi^2}{8} &= \frac{1}{1^2} + \frac{1}{3^2} + \frac{1}{5^2} + \frac{1}{7^2} + \frac{1}{9^2} + \cdots \\ \frac{\pi^2}{12} &= \frac{1}{1^2} - \frac{1}{2^2} + \frac{1}{3^2} - \frac{1}{4^2} + \frac{1}{5^2} - \cdots\end{aligned}$	<p>Derivatives:</p> <ol style="list-style-type: none"> 1. $\frac{d(cu)}{dx} = c \frac{du}{dx},$ 2. $\frac{d(u+v)}{dx} = \frac{du}{dx} + \frac{dv}{dx},$ 3. $\frac{d(uv)}{dx} = u \frac{dv}{dx} + v \frac{du}{dx},$ 4. $\frac{d(u^n)}{dx} = nu^{n-1} \frac{du}{dx},$ 5. $\frac{d(u/v)}{dx} = \frac{v(\frac{du}{dx}) - u(\frac{dv}{dx})}{v^2},$ 6. $\frac{d(e^{cu})}{dx} = ce^{cu} \frac{du}{dx},$ 7. $\frac{d(c^u)}{dx} = (\ln c)c^u \frac{du}{dx},$ 8. $\frac{d(\ln u)}{dx} = \frac{1}{u} \frac{du}{dx},$ 10. $\frac{d(\cos u)}{dx} = -\sin u \frac{du}{dx},$ 12. $\frac{d(\cot u)}{dx} = \csc^2 u \frac{du}{dx},$ 14. $\frac{d(\csc u)}{dx} = -\cot u \csc u \frac{du}{dx},$ 16. $\frac{d(\arccos u)}{dx} = \frac{-1}{\sqrt{1-u^2}} \frac{du}{dx},$ 18. $\frac{d(\operatorname{arccot} u)}{dx} = \frac{-1}{1+u^2} \frac{du}{dx},$ 20. $\frac{d(\operatorname{arccsc} u)}{dx} = \frac{-1}{u\sqrt{1-u^2}} \frac{du}{dx},$ 22. $\frac{d(\cosh u)}{dx} = \sinh u \frac{du}{dx},$ 24. $\frac{d(\coth u)}{dx} = -\operatorname{csch}^2 u \frac{du}{dx},$ 26. $\frac{d(\operatorname{csch} u)}{dx} = -\operatorname{csch} u \coth u \frac{du}{dx},$ 28. $\frac{d(\operatorname{arccosh} u)}{dx} = \frac{1}{\sqrt{u^2-1}} \frac{du}{dx},$ 30. $\frac{d(\operatorname{arccoth} u)}{dx} = \frac{1}{u^2-1} \frac{du}{dx},$ 32. $\frac{d(\operatorname{arccsch} u)}{dx} = \frac{-1}{ u \sqrt{1+u^2}} \frac{du}{dx}.$ <p>Integrals:</p> <ol style="list-style-type: none"> 1. $\int cu \, dx = c \int u \, dx,$ 2. $\int (u+v) \, dx = \int u \, dx + \int v \, dx,$ 3. $\int x^n \, dx = \frac{1}{n+1} x^{n+1}, \quad n \neq -1,$ 4. $\int \frac{1}{x} \, dx = \ln x,$ 5. $\int e^x \, dx = e^x,$ 6. $\int \frac{dx}{1+x^2} = \arctan x,$ 7. $\int u \frac{dv}{dx} \, dx = uv - \int v \frac{du}{dx} \, dx,$ 8. $\int \sin x \, dx = -\cos x,$ 9. $\int \cos x \, dx = \sin x,$ 10. $\int \tan x \, dx = -\ln \cos x ,$ 11. $\int \cot x \, dx = \ln \cos x ,$ 12. $\int \sec x \, dx = \ln \sec x + \tan x ,$ 13. $\int \csc x \, dx = \ln \csc x + \cot x ,$ 14. $\int \arcsin \frac{x}{a} \, dx = \arcsin \frac{x}{a} + \sqrt{a^2 - x^2}, \quad a > 0,$
<p>The reasonable man adapts himself to the world; the unreasonable persists in trying to adapt the world to himself. Therefore all progress depends on the unreasonable. – George Bernard Shaw</p>	

Theoretical Computer Science Cheat Sheet

Calculus Cont.

15. $\int \arccos \frac{x}{a} dx = \arccos \frac{x}{a} - \sqrt{a^2 - x^2}, \quad a > 0,$
16. $\int \arctan \frac{x}{a} dx = x \arctan \frac{x}{a} - \frac{a}{2} \ln(a^2 + x^2), \quad a > 0,$
17. $\int \sin^2(ax) dx = \frac{1}{2a} (ax - \sin(ax) \cos(ax)),$
18. $\int \cos^2(ax) dx = \frac{1}{2a} (ax + \sin(ax) \cos(ax)),$
19. $\int \sec^2 x dx = \tan x,$
20. $\int \csc^2 x dx = -\cot x,$
21. $\int \sin^n x dx = -\frac{\sin^{n-1} x \cos x}{n} + \frac{n-1}{n} \int \sin^{n-2} x dx,$
22. $\int \cos^n x dx = \frac{\cos^{n-1} x \sin x}{n} + \frac{n-1}{n} \int \cos^{n-2} x dx,$
23. $\int \tan^n x dx = \frac{\tan^{n-1} x}{n-1} - \int \tan^{n-2} x dx, \quad n \neq 1,$
24. $\int \cot^n x dx = -\frac{\cot^{n-1} x}{n-1} - \int \cot^{n-2} x dx, \quad n \neq 1,$
25. $\int \sec^n x dx = \frac{\tan x \sec^{n-1} x}{n-1} + \frac{n-2}{n-1} \int \sec^{n-2} x dx, \quad n \neq 1,$
26. $\int \csc^n x dx = -\frac{\cot x \csc^{n-1} x}{n-1} + \frac{n-2}{n-1} \int \csc^{n-2} x dx, \quad n \neq 1,$
27. $\int \sinh x dx = \cosh x, \quad 28. \int \cosh x dx = \sinh x,$
29. $\int \tanh x dx = \ln |\cosh x|, \quad 30. \int \coth x dx = \ln |\sinh x|, \quad 31. \int \operatorname{sech} x dx = \arctan \sinh x, \quad 32. \int \operatorname{csch} x dx = \ln |\tanh \frac{x}{2}|,$
33. $\int \sinh^2 x dx = \frac{1}{4} \sinh(2x) - \frac{1}{2}x, \quad 34. \int \cosh^2 x dx = \frac{1}{4} \sinh(2x) + \frac{1}{2}x, \quad 35. \int \operatorname{sech}^2 x dx = \tanh x,$
36. $\int \operatorname{arcsinh} \frac{x}{a} dx = x \operatorname{arcsinh} \frac{x}{a} - \sqrt{x^2 + a^2}, \quad a > 0,$
37. $\int \operatorname{arctanh} \frac{x}{a} dx = x \operatorname{arctanh} \frac{x}{a} + \frac{a}{2} \ln |a^2 - x^2|,$
38. $\int \operatorname{arccosh} \frac{x}{a} dx = \begin{cases} x \operatorname{arccosh} \frac{x}{a} - \sqrt{x^2 + a^2}, & \text{if } \operatorname{arccosh} \frac{x}{a} > 0 \text{ and } a > 0, \\ x \operatorname{arccosh} \frac{x}{a} + \sqrt{x^2 + a^2}, & \text{if } \operatorname{arccosh} \frac{x}{a} < 0 \text{ and } a > 0, \end{cases}$
39. $\int \frac{dx}{\sqrt{a^2 + x^2}} = \ln \left(x + \sqrt{a^2 + x^2} \right), \quad a > 0,$
40. $\int \frac{dx}{a^2 + x^2} = \frac{1}{a} \arctan \frac{x}{a}, \quad a > 0,$
41. $\int \sqrt{a^2 - x^2} dx = \frac{x}{2} \sqrt{a^2 - x^2} + \frac{a^2}{2} \arcsin \frac{x}{a}, \quad a > 0,$
42. $\int (a^2 - x^2)^{3/2} dx = \frac{x}{8} (5a^2 - 2x^2) \sqrt{a^2 - x^2} + \frac{3a^4}{8} \arcsin \frac{x}{a}, \quad a > 0,$
43. $\int \frac{dx}{\sqrt{a^2 - x^2}} = \arcsin \frac{x}{a}, \quad a > 0,$
44. $\int \frac{dx}{a^2 - x^2} = \frac{1}{2a} \ln \left| \frac{a+x}{a-x} \right|, \quad 45. \int \frac{dx}{(a^2 - x^2)^{3/2}} = \frac{x}{a^2 \sqrt{a^2 - x^2}},$
46. $\int \sqrt{a^2 \pm x^2} dx = \frac{x}{2} \sqrt{a^2 \pm x^2} \pm \frac{a^2}{2} \ln \left| x + \sqrt{a^2 \pm x^2} \right|,$
47. $\int \frac{dx}{\sqrt{x^2 - a^2}} = \ln \left| x + \sqrt{x^2 - a^2} \right|, \quad a > 0,$
48. $\int \frac{dx}{ax^2 + bx} = \frac{1}{a} \ln \left| \frac{x}{a+bx} \right|,$
49. $\int x \sqrt{a+bx} dx = \frac{2(3bx - 2a)(a+bx)^{3/2}}{15b^2},$
50. $\int \frac{\sqrt{a+bx}}{x} dx = 2\sqrt{a+bx} + a \int \frac{1}{x\sqrt{a+bx}} dx,$
51. $\int \frac{x}{\sqrt{a+bx}} dx = \frac{1}{\sqrt{2}} \ln \left| \frac{\sqrt{a+bx} - \sqrt{a}}{\sqrt{a+bx} + \sqrt{a}} \right|, \quad a > 0,$
52. $\int \frac{\sqrt{a^2 - x^2}}{x} dx = \sqrt{a^2 - x^2} - a \ln \left| \frac{a + \sqrt{a^2 - x^2}}{x} \right|,$
53. $\int x \sqrt{a^2 - x^2} dx = -\frac{1}{3} (a^2 - x^2)^{3/2},$
54. $\int x^2 \sqrt{a^2 - x^2} dx = \frac{x}{8} (2x^2 - a^2) \sqrt{a^2 - x^2} + \frac{a^4}{8} \arcsin \frac{x}{a}, \quad a > 0,$
55. $\int \frac{dx}{\sqrt{a^2 - x^2}} = -\frac{1}{a} \ln \left| \frac{a + \sqrt{a^2 - x^2}}{x} \right|,$
56. $\int \frac{x dx}{\sqrt{a^2 - x^2}} = -\sqrt{a^2 - x^2},$
57. $\int \frac{x^2 dx}{\sqrt{a^2 - x^2}} = -\frac{x}{2} \sqrt{a^2 - x^2} + \frac{a^2}{2} \arcsin \frac{x}{a}, \quad a > 0,$
58. $\int \frac{\sqrt{a^2 + x^2}}{x} dx = \sqrt{a^2 + x^2} - a \ln \left| \frac{a + \sqrt{a^2 + x^2}}{x} \right|,$
59. $\int \frac{\sqrt{x^2 - a^2}}{x} dx = \sqrt{x^2 - a^2} - a \arccos \frac{a}{|x|}, \quad a > 0,$
60. $\int x \sqrt{x^2 \pm a^2} dx = \frac{1}{3} (x^2 \pm a^2)^{3/2},$
61. $\int \frac{dx}{x\sqrt{x^2 + a^2}} = \frac{1}{a} \ln \left| \frac{x}{a + \sqrt{a^2 + x^2}} \right|,$

Theoretical Computer Science Cheat Sheet

Calculus Cont.

- 62.** $\int \frac{dx}{x\sqrt{x^2 - a^2}} = \frac{1}{a} \arccos \frac{a}{|x|}, \quad a > 0,$ **63.** $\int \frac{dx}{x^2\sqrt{x^2 \pm a^2}} = \mp \frac{\sqrt{x^2 \pm a^2}}{a^2 x},$
64. $\int \frac{x dx}{\sqrt{x^2 \pm a^2}} = \sqrt{x^2 \pm a^2},$ **65.** $\int \frac{\sqrt{x^2 \pm a^2}}{x^4} dx = \mp \frac{(x^2 + a^2)^{3/2}}{3a^2 x^3},$
66. $\int \frac{dx}{ax^2 + bx + c} = \begin{cases} \frac{1}{\sqrt{b^2 - 4ac}} \ln \left| \frac{2ax + b - \sqrt{b^2 - 4ac}}{2ax + b + \sqrt{b^2 - 4ac}} \right|, & \text{if } b^2 > 4ac, \\ \frac{2}{\sqrt{4ac - b^2}} \arctan \frac{2ax + b}{\sqrt{4ac - b^2}}, & \text{if } b^2 < 4ac, \end{cases}$
67. $\int \frac{dx}{\sqrt{ax^2 + bx + c}} = \begin{cases} \frac{1}{\sqrt{a}} \ln \left| 2ax + b + 2\sqrt{a}\sqrt{ax^2 + bx + c} \right|, & \text{if } a > 0, \\ \frac{1}{\sqrt{-a}} \arcsin \frac{-2ax - b}{\sqrt{b^2 - 4ac}}, & \text{if } a < 0, \end{cases}$
68. $\int \sqrt{ax^2 + bx + c} dx = \frac{2ax + b}{4a} \sqrt{ax^2 + bx + c} + \frac{4ax - b^2}{8a} \int \frac{dx}{\sqrt{ax^2 + bx + c}},$
69. $\int \frac{x dx}{\sqrt{ax^2 + bx + c}} = \frac{\sqrt{ax^2 + bx + c}}{a} - \frac{b}{2a} \int \frac{dx}{\sqrt{ax^2 + bx + c}},$
70. $\int \frac{dx}{x\sqrt{ax^2 + bx + c}} = \begin{cases} \frac{-1}{\sqrt{c}} \ln \left| \frac{2\sqrt{c}\sqrt{ax^2 + bx + c} + bx + 2c}{x} \right|, & \text{if } c > 0, \\ \frac{1}{\sqrt{-c}} \arcsin \frac{bx + 2c}{|x|\sqrt{b^2 - 4ac}}, & \text{if } c < 0, \end{cases}$
71. $\int x^3 \sqrt{x^2 + a^2} dx = (\frac{1}{3}x^2 - \frac{2}{15}a^2)(x^2 + a^2)^{3/2},$
72. $\int x^n \sin(ax) dx = -\frac{1}{a} x^n \cos(ax) + \frac{n}{a} \int x^{n-1} \cos(ax) dx,$
73. $\int x^n \cos(ax) dx = \frac{1}{a} x^n \sin(ax) - \frac{n}{a} \int x^{n-1} \sin(ax) dx,$
74. $\int x^n e^{ax} dx = \frac{x^n e^{ax}}{a} - \frac{n}{a} \int x^{n-1} e^{ax} dx,$
75. $\int x^n \ln(ax) dx = x^{n+1} \left(\frac{\ln(ax)}{n+1} - \frac{1}{(n+1)^2} \right),$
76. $\int x^n (\ln ax)^m dx = \frac{x^{n+1}}{n+1} (\ln ax)^m - \frac{m}{n+1} \int x^n (\ln ax)^{m-1} dx.$

$$\begin{array}{llll}
x^1 & x^1 & = & x^{\bar{1}} \\
x^2 & x^2 + x^1 & = & x^{\bar{2}} - x^{\bar{1}} \\
x^3 & x^3 + 3x^2 + x^1 & = & x^{\bar{3}} - 3x^{\bar{2}} + x^{\bar{1}} \\
x^4 & x^4 + 6x^3 + 7x^2 + x^1 & = & x^{\bar{4}} - 6x^{\bar{3}} + 7x^{\bar{2}} - x^{\bar{1}} \\
x^5 & x^5 + 15x^4 + 25x^3 + 10x^2 + x^1 & = & x^{\bar{5}} - 15x^{\bar{4}} + 25x^{\bar{3}} - 10x^{\bar{2}} + x^{\bar{1}} \\
x^{\bar{1}} & x^1 & x^{\bar{1}} & x^1 \\
x^{\bar{2}} & x^2 + x^1 & x^{\bar{2}} & x^2 - x^1 \\
x^{\bar{3}} & x^3 + 3x^2 + 2x^1 & x^{\bar{3}} & x^3 - 3x^2 + 2x^1 \\
x^{\bar{4}} & x^4 + 6x^3 + 11x^2 + 6x^1 & x^{\bar{4}} & x^4 - 6x^3 + 11x^2 - 6x^1 \\
x^{\bar{5}} & x^5 + 10x^4 + 35x^3 + 50x^2 + 24x^1 & x^{\bar{5}} & x^5 - 10x^4 + 35x^3 - 50x^2 + 24x^1
\end{array}$$

Finite Calculus

Difference, shift operators:

$$\Delta f(x) = f(x+1) - f(x),$$

$$\mathrm{E} f(x) = f(x+1).$$

Fundamental Theorem:

$$f(x) = \Delta F(x) \Leftrightarrow \sum f(x) \delta x = F(x) + C.$$

$$\sum_a^b f(x) \delta x = \sum_{i=a}^{b-1} f(i).$$

Differences:

$$\Delta(cu) = c\Delta u, \quad \Delta(u+v) = \Delta u + \Delta v,$$

$$\Delta(uv) = u\Delta v + \mathrm{E} v \Delta u,$$

$$\Delta(x^n) = nx^{n-1},$$

$$\Delta(H_x) = x^{-1}, \quad \Delta(2^x) = 2^x,$$

$$\Delta(c^x) = (c-1)c^x, \quad \Delta(\binom{x}{m}) = \binom{x}{m-1}.$$

Sums:

$$\sum cu \delta x = c \sum u \delta x,$$

$$\sum(u+v) \delta x = \sum u \delta x + \sum v \delta x,$$

$$\sum u \Delta v \delta x = uv - \sum \mathrm{E} v \Delta u \delta x,$$

$$\sum x^n \delta x = \frac{x^{n+1}}{n+1}, \quad \sum x^{-1} \delta x = H_x,$$

$$\sum c^x \delta x = \frac{c^x}{c-1}, \quad \sum \binom{x}{m} \delta x = \binom{x}{m+1}.$$

Falling Factorial Powers:

$$x^{\underline{n}} = x(x-1) \cdots (x-n+1), \quad n > 0,$$

$$x^{\underline{0}} = 1,$$

$$x^{\bar{n}} = \frac{1}{(x+1) \cdots (x+|n|)}, \quad n < 0,$$

$$x^{\underline{n+m}} = x^{\underline{m}} (x-m)^{\underline{n}}.$$

Rising Factorial Powers:

$$x^{\overline{n}} = x(x+1) \cdots (x+n-1), \quad n > 0,$$

$$x^{\overline{0}} = 1,$$

$$x^{\overline{n}} = \frac{1}{(x-1) \cdots (x-|n|)}, \quad n < 0,$$

$$x^{\overline{n+m}} = x^{\overline{m}} (x+m)^{\overline{n}}.$$

Conversion:

$$x^{\underline{n}} = (-1)^n (-x)^{\overline{n}} = (x-n+1)^{\overline{n}}$$

$$= 1/(x+1)^{\overline{-n}},$$

$$x^{\overline{n}} = (-1)^n (-x)^{\underline{n}} = (x+n-1)^{\underline{n}}$$

$$= 1/(x-1)^{\underline{-n}},$$

$$x^n = \sum_{k=1}^n \binom{n}{k} x^k = \sum_{k=1}^n \binom{n}{k} (-1)^{n-k} x^{\bar{k}},$$

$$x^{\underline{n}} = \sum_{k=1}^n \binom{n}{k} (-1)^{n-k} x^k,$$

$$x^{\overline{n}} = \sum_{k=1}^n \binom{n}{k} x^k.$$

Theoretical Computer Science Cheat Sheet

Series

Taylor's series:

$$f(x) = f(a) + (x-a)f'(a) + \frac{(x-a)^2}{2}f''(a) + \dots = \sum_{i=0}^{\infty} \frac{(x-a)^i}{i!} f^{(i)}(a).$$

Expansions:

$\frac{1}{1-x}$	$= 1 + x + x^2 + x^3 + x^4 + \dots$	$= \sum_{i=0}^{\infty} x^i,$
$\frac{1}{1-cx}$	$= 1 + cx + c^2x^2 + c^3x^3 + \dots$	$= \sum_{i=0}^{\infty} c^i x^i,$
$\frac{1}{1-x^n}$	$= 1 + x^n + x^{2n} + x^{3n} + \dots$	$= \sum_{i=0}^{\infty} x^{ni},$
$\frac{x}{(1-x)^2}$	$= x + 2x^2 + 3x^3 + 4x^4 + \dots$	$= \sum_{i=0}^{\infty} ix^i,$
$x^k \frac{d^n}{dx^n} \left(\frac{1}{1-x} \right)$	$= x + 2^nx^2 + 3^nx^3 + 4^nx^4 + \dots$	$= \sum_{i=0}^{\infty} i^n x^i,$
e^x	$= 1 + x + \frac{1}{2}x^2 + \frac{1}{6}x^3 + \dots$	$= \sum_{i=0}^{\infty} \frac{x^i}{i!},$
$\ln(1+x)$	$= x - \frac{1}{2}x^2 + \frac{1}{3}x^3 - \frac{1}{4}x^4 - \dots$	$= \sum_{i=1}^{\infty} (-1)^{i+1} \frac{x^i}{i},$
$\ln \frac{1}{1-x}$	$= x + \frac{1}{2}x^2 + \frac{1}{3}x^3 + \frac{1}{4}x^4 + \dots$	$= \sum_{i=1}^{\infty} \frac{x^i}{i},$
$\sin x$	$= x - \frac{1}{3!}x^3 + \frac{1}{5!}x^5 - \frac{1}{7!}x^7 + \dots$	$= \sum_{i=0}^{\infty} (-1)^i \frac{x^{2i+1}}{(2i+1)!},$
$\cos x$	$= 1 - \frac{1}{2!}x^2 + \frac{1}{4!}x^4 - \frac{1}{6!}x^6 + \dots$	$= \sum_{i=0}^{\infty} (-1)^i \frac{x^{2i}}{(2i)!},$
$\tan^{-1} x$	$= x - \frac{1}{3}x^3 + \frac{1}{5}x^5 - \frac{1}{7}x^7 + \dots$	$= \sum_{i=0}^{\infty} (-1)^i \frac{x^{2i+1}}{(2i+1)},$
$(1+x)^n$	$= 1 + nx + \frac{n(n-1)}{2}x^2 + \dots$	$= \sum_{i=0}^{\infty} \binom{n}{i} x^i,$
$\frac{1}{(1-x)^{n+1}}$	$= 1 + (n+1)x + \binom{n+2}{2}x^2 + \dots$	$= \sum_{i=0}^{\infty} \binom{i+n}{i} x^i,$
$\frac{x}{e^x - 1}$	$= 1 - \frac{1}{2}x + \frac{1}{12}x^2 - \frac{1}{720}x^4 + \dots$	$= \sum_{i=0}^{\infty} \frac{B_i x^i}{i!},$
$\frac{1}{2x}(1 - \sqrt{1-4x})$	$= 1 + x + 2x^2 + 5x^3 + \dots$	$= \sum_{i=0}^{\infty} \frac{1}{i+1} \binom{2i}{i} x^i,$
$\frac{1}{\sqrt{1-4x}}$	$= 1 + x + 2x^2 + 6x^3 + \dots$	$= \sum_{i=0}^{\infty} \binom{2i}{i} x^i,$
$\frac{1}{\sqrt{1-4x}} \left(\frac{1 - \sqrt{1-4x}}{2x} \right)^n$	$= 1 + (2+n)x + \binom{4+n}{2}x^2 + \dots$	$= \sum_{i=0}^{\infty} \binom{2i+n}{i} x^i,$
$\frac{1}{1-x} \ln \frac{1}{1-x}$	$= x + \frac{3}{2}x^2 + \frac{11}{6}x^3 + \frac{25}{12}x^4 + \dots$	$= \sum_{i=1}^{\infty} H_i x^i,$
$\frac{1}{2} \left(\ln \frac{1}{1-x} \right)^2$	$= \frac{1}{2}x^2 + \frac{3}{4}x^3 + \frac{11}{24}x^4 + \dots$	$= \sum_{i=2}^{\infty} \frac{H_{i-1} x^i}{i},$
$\frac{x}{1-x-x^2}$	$= x + x^2 + 2x^3 + 3x^4 + \dots$	$= \sum_{i=0}^{\infty} F_i x^i,$
$\frac{F_n x}{1 - (F_{n-1} + F_{n+1})x - (-1)^n x^2}$	$= F_n x + F_{2n} x^2 + F_{3n} x^3 + \dots$	$= \sum_{i=0}^{\infty} F_{ni} x^i.$

Ordinary power series:

$$A(x) = \sum_{i=0}^{\infty} a_i x^i.$$

Exponential power series:

$$A(x) = \sum_{i=0}^{\infty} a_i \frac{x^i}{i!}.$$

Dirichlet power series:

$$A(x) = \sum_{i=1}^{\infty} \frac{a_i}{i^x}.$$

Binomial theorem:

$$(x+y)^n = \sum_{k=0}^n \binom{n}{k} x^{n-k} y^k.$$

Difference of like powers:

$$x^n - y^n = (x-y) \sum_{k=0}^{n-1} x^{n-1-k} y^k.$$

For ordinary power series:

$$\alpha A(x) + \beta B(x) = \sum_{i=0}^{\infty} (\alpha a_i + \beta b_i) x^i,$$

$$x^k A(x) = \sum_{i=k}^{\infty} a_{i-k} x^i,$$

$$\frac{A(x) - \sum_{i=0}^{k-1} a_i x^i}{x^k} = \sum_{i=0}^{\infty} a_{i+k} x^i,$$

$$A(cx) = \sum_{i=0}^{\infty} c^i a_i x^i,$$

$$A'(x) = \sum_{i=0}^{\infty} (i+1) a_{i+1} x^i,$$

$$xA'(x) = \sum_{i=1}^{\infty} i a_i x^i,$$

$$\int A(x) dx = \sum_{i=1}^{\infty} \frac{a_{i-1}}{i} x^i,$$

$$\frac{A(x) + A(-x)}{2} = \sum_{i=0}^{\infty} a_{2i} x^{2i},$$

$$\frac{A(x) - A(-x)}{2} = \sum_{i=0}^{\infty} a_{2i+1} x^{2i+1}.$$

Summation: If $b_i = \sum_{j=0}^i a_j$ then

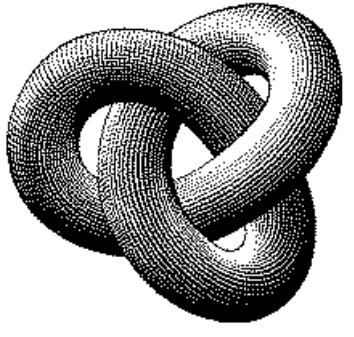
$$B(x) = \frac{1}{1-x} A(x).$$

Convolution:

$$A(x)B(x) = \sum_{i=0}^{\infty} \left(\sum_{j=0}^i a_j b_{i-j} \right) x^i.$$

God made the natural numbers;
all the rest is the work of man.
— Leopold Kronecker

Theoretical Computer Science Cheat Sheet

Series	Escher's Knot																																																																																																				
<p>Expansions:</p> $\frac{1}{(1-x)^{n+1}} \ln \frac{1}{1-x} = \sum_{i=0}^{\infty} (H_{n+i} - H_n) \binom{n+i}{i} x^i,$ $x^{\frac{n}{k}} = \sum_{i=0}^{\infty} \binom{n}{i} x^i,$ $\left(\ln \frac{1}{1-x}\right)^n = \sum_{i=0}^{\infty} \binom{i}{n} \frac{n! x^i}{i!},$ $\tan x = \sum_{i=1}^{\infty} (-1)^{i-1} \frac{2^{2i}(2^{2i}-1)B_{2i}x^{2i-1}}{(2i)!},$ $\frac{1}{\zeta(x)} = \sum_{i=1}^{\infty} \frac{\mu(i)}{i^x},$ $\zeta(x) = \prod_p \frac{1}{1-p^{-x}},$ $\zeta^2(x) = \sum_{i=1}^{\infty} \frac{d(i)}{i^x} \quad \text{where } d(n) = \sum_{d n} 1,$ $\zeta(x)\zeta(x-1) = \sum_{i=1}^{\infty} \frac{S(i)}{i^x} \quad \text{where } S(n) = \sum_{d n} d,$ $\zeta(2n) = \frac{2^{2n-1} B_{2n} }{(2n)!} \pi^{2n}, \quad n \in \mathbb{N},$ $\frac{x}{\sin x} = \sum_{i=0}^{\infty} (-1)^{i-1} \frac{(4^i - 2)B_{2i}x^{2i}}{(2i)!},$ $\left(\frac{1-\sqrt{1-4x}}{2x}\right)^n = \sum_{i=0}^{\infty} \frac{n(2i+n-1)!}{i!(n+i)!} x^i,$ $e^x \sin x = \sum_{i=1}^{\infty} \frac{2^{i/2} \sin \frac{i\pi}{4}}{i!} x^i,$ $\sqrt{\frac{1-\sqrt{1-x}}{x}} = \sum_{i=0}^{\infty} \frac{(4i)!}{16^i \sqrt{2}(2i)!(2i+1)!} x^i,$ $\left(\frac{\arcsin x}{x}\right)^2 = \sum_{i=0}^{\infty} \frac{4^i i!^2}{(i+1)(2i+1)!} x^{2i}.$																																																																																																					
	Stieltjes Integration																																																																																																				
	<p>If G is continuous in the interval $[a, b]$ and F is nondecreasing then</p> $\int_a^b G(x) dF(x)$ <p>exists. If $a \leq b \leq c$ then</p> $\int_a^c G(x) dF(x) = \int_a^b G(x) dF(x) + \int_b^c G(x) dF(x).$ <p>If the integrals involved exist</p> $\int_a^b (G(x) + H(x)) dF(x) = \int_a^b G(x) dF(x) + \int_a^b H(x) dF(x),$ $\int_a^b G(x) d(F(x) + H(x)) = \int_a^b G(x) dF(x) + \int_a^b G(x) dH(x),$ $\int_a^b c \cdot G(x) dF(x) = \int_a^b G(x) d(c \cdot F(x)) = c \int_a^b G(x) dF(x),$ $\int_a^b G(x) dF(x) = G(b)F(b) - G(a)F(a) - \int_a^b F(x) dG(x).$																																																																																																				
<p>Cramer's Rule</p> <p>If we have equations:</p> $a_{1,1}x_1 + a_{1,2}x_2 + \cdots + a_{1,n}x_n = b_1$ $a_{2,1}x_1 + a_{2,2}x_2 + \cdots + a_{2,n}x_n = b_2$ $\vdots \quad \vdots \quad \vdots$ $a_{n,1}x_1 + a_{n,2}x_2 + \cdots + a_{n,n}x_n = b_n$ <p>Let $A = (a_{i,j})$ and B be the column matrix (b_i). Then there is a unique solution iff $\det A \neq 0$. Let A_i be A with column i replaced by B. Then</p> $x_i = \frac{\det A_i}{\det A}.$	<p>Fibonacci Numbers</p> <table border="1" style="margin-left: auto; margin-right: auto;"> <tr><td>00</td><td>47</td><td>18</td><td>76</td><td>29</td><td>93</td><td>85</td><td>34</td><td>61</td><td>52</td></tr> <tr><td>86</td><td>11</td><td>57</td><td>28</td><td>70</td><td>39</td><td>94</td><td>45</td><td>02</td><td>63</td></tr> <tr><td>95</td><td>80</td><td>22</td><td>67</td><td>38</td><td>71</td><td>49</td><td>56</td><td>13</td><td>04</td></tr> <tr><td>59</td><td>96</td><td>81</td><td>33</td><td>07</td><td>48</td><td>72</td><td>60</td><td>24</td><td>15</td></tr> <tr><td>73</td><td>69</td><td>90</td><td>82</td><td>44</td><td>17</td><td>58</td><td>01</td><td>35</td><td>26</td></tr> <tr><td>68</td><td>74</td><td>09</td><td>91</td><td>83</td><td>55</td><td>27</td><td>12</td><td>46</td><td>30</td></tr> <tr><td>37</td><td>08</td><td>75</td><td>19</td><td>92</td><td>84</td><td>66</td><td>23</td><td>50</td><td>41</td></tr> <tr><td>14</td><td>25</td><td>36</td><td>40</td><td>51</td><td>62</td><td>03</td><td>77</td><td>88</td><td>99</td></tr> <tr><td>21</td><td>32</td><td>43</td><td>54</td><td>65</td><td>06</td><td>10</td><td>89</td><td>97</td><td>78</td></tr> <tr><td>42</td><td>53</td><td>64</td><td>05</td><td>16</td><td>20</td><td>31</td><td>98</td><td>79</td><td>87</td></tr> </table> <p>Definitions:</p> $F_i = F_{i-1} + F_{i-2}, \quad F_0 = F_1 = 1,$ $F_{-i} = (-1)^{i-1} F_i,$ $F_i = \frac{1}{\sqrt{5}} (\phi^i - \hat{\phi}^i),$ <p>Cassini's identity: for $i > 0$:</p> $F_{i+1}F_{i-1} - F_i^2 = (-1)^i.$ <p>Additive rule:</p> $F_{n+k} = F_k F_{n+1} + F_{k-1} F_n,$ $F_{2n} = F_n F_{n+1} + F_{n-1} F_n.$ <p>Calculation by matrices:</p> $\begin{pmatrix} F_{n-2} & F_{n-1} \\ F_{n-1} & F_n \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix}^n.$	00	47	18	76	29	93	85	34	61	52	86	11	57	28	70	39	94	45	02	63	95	80	22	67	38	71	49	56	13	04	59	96	81	33	07	48	72	60	24	15	73	69	90	82	44	17	58	01	35	26	68	74	09	91	83	55	27	12	46	30	37	08	75	19	92	84	66	23	50	41	14	25	36	40	51	62	03	77	88	99	21	32	43	54	65	06	10	89	97	78	42	53	64	05	16	20	31	98	79	87
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<p>Improvement makes strait roads, but the crooked roads without Improvement, are roads of Genius. – William Blake (The Marriage of Heaven and Hell)</p>	<p>The Fibonacci number system: Every integer n has a unique representation</p> $n = F_{k_1} + F_{k_2} + \cdots + F_{k_m},$ <p>where $k_i \geq k_{i+1} + 2$ for all i, $1 \leq i < m$ and $k_m \geq 2$.</p>																																																																																																				



File management

Ctrl+M Toggle Tab moves focus

Search and replace

Ctrl+N	New File
Ctrl+O	Open File...
Ctrl+S	Save
Ctrl+Shift+S	Save As...
Ctrl+K S	Save All
Ctrl+F4	Close
Ctrl+K Ctrl+W	Close All
Ctrl+Shift+T	Reopen closed editor
Ctrl+K Enter	Keep preview mode editor open
Ctrl+Tab	Open next
Ctrl+Shift+Tab	Open previous
Ctrl+P	Copy path of active file
Ctrl+K R	Copy active file in Explorer
Ctrl+K O	Show active file in new window/instance

Display

F11	Toggle full screen
Shift+Alt+0	Toggle editor layout (horizontal/vertical)
Ctrl+= - / -	Zoom in/out
Ctrl+B	Toggle Sidebar visibility
Ctrl+Shift+E	Show Explorer / Toggle focus
Ctrl+Shift+F	Show Search
Ctrl+Shift+G	Show Source Control
Ctrl+Shift+D	Show Debug
Ctrl+Shift+X	Show Extensions
Ctrl+Shift+H	Replace in files
Ctrl+Shift+J	Toggle Search details
Ctrl+Shift+U	Show Output panel
Ctrl+Shift+V	Open Markdown preview
Ctrl+K V	Open Markdown preview to the side
Ctrl+K Z	Zen Mode (Esc Esc to exit)

Multi-cursor and selection

Alt+Click	Insert cursor
Ctrl+Alt+ 1 / 1	Insert cursor above / below
Ctrl+U	Undo last cursor operation
Shift+Alt+I	Insert cursor at end of each line selected
Ctrl+L	Select current line
Ctrl+Shift+L	Select all occurrences of current selection
Ctrl+F2	Select all occurrences of current word
Shift+Alt+→	Expand selection
Shift+Alt+←	Shrink selection
Shift+Alt+ (drag mouse)	Column (box) selection
Ctrl+Shift+Alt + (arrow key)	Column (box) selection
Ctrl+Shift+Alt +PgUp/PgDn	Column (box) selection page up/down

Rich languages editing

Ctrl+Space, Ctrl+I	Trigger suggestion
Ctrl+Shift+Space	Trigger parameter hints
Shift+Alt+F	Format document
Ctrl+K Ctrl+F	Format selection
F12	Go to Definition
Alt+F12	Peek Definition
Ctrl+K F12	Open Definition to the side
Ctrl+.	Quick Fix
Shift+F12	Show References
F2	Rename Symbol
Ctrl+K Ctrl+X	Trim trailing whitespace
Ctrl+K M	Change file language

Navigation

Ctrl+T	Show all Symbols
Ctrl+G	Go to Line...
Ctrl+P	Go to File...
Ctrl+Shift+O	Go to Symbol...
Ctrl+Shift+M	Show Problems panel
F8	Go to next error or warning
Shift+F8	Navigate editor group history
Ctrl+Shift+Tab	Move active editor group
Alt+ ← / →	Go back / forward

Other operating systems' keyboard shortcuts and additional unassigned shortcuts available at aka.ms/vscodetkeybindings



Multi-cursor and selection

Editor management

General

Ctrl+Shift+P	Show Command Palette
F1	Quick Open, Go to File...
Ctrl+Shift+N	New window/instance
Ctrl+W	Close window/instance
Ctrl+,	User Settings
Ctrl+K Ctrl+S	Keyboard Shortcuts
Basic editing	
Ctrl+X	Cut line (empty selection)
Ctrl+C	Copy line (empty selection)
Alt+ ↴ / ↑	Move line down/up
Ctrl+Shift+K	Delete line
Ctrl+Enter /	Insert line below/ above
Ctrl+Shift+Enter	
Ctrl+Shift+\`	Jump to matching bracket
Ctrl+] / Ctrl+[Indent/Outdent line
Home / End	Go to beginning/end of line
Ctrl+Home / End	Go to beginning/end of file
Ctrl+↑ / ↓	Scroll line up/down
Alt+ PgUp / PgDn	Scroll page up/down
Ctrl+Shift+ [/]	Fold/unfold region
Ctrl+K Ctrl+ [/]	Fold/unfold all subregions
Ctrl+K Ctrl+0 /	Fold/Unfold all regions
Ctrl+K Ctrl+I	Add line comment
Ctrl+K Ctrl+U	Remove line comment
Ctrl+/-	Toggle line comment
Ctrl+Shift+A	Toggle block comment
Alt+Z	Toggle word wrap
Rich languages editing	
Ctrl+Space, Ctrl+I	Trigger suggestion
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Display

F11	Shift+Alt+0	Toggle full screen
Ctrl+ / -		Toggle editor layout (horizontal)/vertical)
Ctrl+B		Zoom in/out
Ctrl+Shift+E		Toggle Sidebar visibility
Ctrl+Shift+F		Show Explorer / Toggle focus
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Ctrl+Shift+H		Replace in files
Ctrl+Shift+J		Toggle Search details
Ctrl+Shift+C		Open new command prompt/terminal
Ctrl+K Ctrl+H		Show Output panel
Ctrl+Shift+V		Open Markdown preview
Ctrl+K V		Zen Mode (Esc Esc to exit)
Ctrl+K Z		
Search and replace		
Ctrl+F	Find	
Ctrl+H	Replace	
F3 / Shift+F3	Find next/previous	
Alt+Enter	Select all occurrences of Find match	
Ctrl+D	Add selection to next Find match	
Ctrl+K Ctrl+D	Move last selection to next Find match	
Navigation		
Ctrl+T	Show all Symbols	
Ctrl+G	Go to Line...	
Ctrl+P	Go to File...	
Ctrl+Shift+O	Go to Symbol...	
Ctrl+Shift+M	Show Problems panel	
F8	Go to next error or warning	
Shift+F8	Go to previous error or warning	
Ctrl+Shift+Tab	Navigate editor group history	
Ctrl+Alt+-	Go back	
Ctrl+Shift+-	Go forward	
Ctrl+M	Toogle Tab moves focus	

File management

Ctrl+N	New File
Ctrl+O	Open File...
Ctrl+S	Save
Ctrl+Shift+S	Save As...
Ctrl+W	Close
Ctrl+K Ctrl+W	Close All
Ctrl+Shift+T	Reopen closed editor
Ctrl+K Enter	Keep preview mode editor open
Ctrl+Tab	Open next
Ctrl+Shift+Tab	Open previous
Ctrl+K P	Copy path of active file
Ctrl+K R	Reveal active file in Explorer
Ctrl+K O	Show active file in new window/instance
<hr/>	
Debug	
F9	Toggle breakpoint
F5	Start / Continue
F11 / Shift+F11	Step into/out
F10	Step over
Shift+F5	Stop
Ctrl+K Ctrl+I	Show hover
<hr/>	
Integrated terminal	
Ctrl+`	Show integrated terminal
Ctrl+Shift+`	Create new terminal
Ctrl+Shift+C	Copy selection
Ctrl+Shift+V	Paste into active terminal
Ctrl+Shift+↑ ↓	Scroll up/down
Shift+ PgUp / PgDn	Scroll page up/down
Shift+ Home / End	Scroll to top/bottom

* The Alt+Click gesture may not work on some Linux distributions. You can change the modifier key for the Insert cursor command to Ctrl+Click with the “`editor.multiCursorModifier`” setting.



