

# All-in at the River

Standard Code Library

Shanghai Jiao Tong University

Desprado2

fstqwq

AntiLeaf



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# 1. 数学

## 1.1 插值

### 1.1.1 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。

### 1.1.2 拉格朗日插值

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

## 1.2 多项式

### 1.2.1 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)-1.0);
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 = 0.0, double b = 0.0) : 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 += (const Complex &x) {
26         return *this = *this + x;
27     }
28 } omega[maxn], omega_inv[maxn];
29
30 int fft_n; // 要在主函数里初始化
31
32 // FFT初始化
33 void FFT_init(int n) {
34     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
35         omega[i] = Complex(cos(2 * pi / n * i), sin(2 *
   // pi / n * i));
36
37     omega_inv[0] = omega[0];
38     for (int i = 1; i < n; i++)
39         omega_inv[i] = omega[n - i];
40     // 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
41 }
42
43 // FFT主过程
44 void FFT(Complex *A, int n, int tp) {
45     for (int i = 1, j = 0, k; i < n - 1; i++) {
46         k = n;
47         do
48             j ^= (k >= 1);
49         while (j < k);
50
51         if (i < j)
52             swap(A[i], A[j]);
53     }
54
55     for (int k = 2, m = fft_n / 2; k <= n; k *= 2, m /=
   // 2)
56         for (int i = 0; i < n; i += k)
57             for (int j = 0; j < k * 2; j++) {
58                 Complex a = A[i + j], b = (tp > 0? omega
   // : omega_inv)[m * j] * A[i + j + (k /
   // 2)];
59
60                 A[i + j] = a + b;
61                 A[i + j + k / 2] = a - b;
62             }
63
64     if (tp < 0)
65         for (int i = 0; i < n; i++)
66             A[i].a /= n;
67 }
```

### 1.2.2 NTT

```
1 constexpr int p = 998244353; // p为模数
2
3 int ntt_n, omega[maxn], omega_inv[maxn]; // ntt_n要在主函
   // 数里初始化
4
5 void NTT_init(int n) {
6     int wn = qpow(3, (p - 1) / n); // 这里的3代表模数的任
   // 意一个原根
7
8     omega[0] = omega_inv[0] = 1;
9
10    for (int i = 1; i < n; i++)
11        omega_inv[n - i] = omega[i] = (long long)omega[i]
   // * wn % p;
12 }
13
14 void NTT(int *a, int n, int tp) { // n为变换长度,
   // tp为1或-1, 表示正/逆变换
```

```

15
16 for (int i = 1, j = 0, k; i < n - 1; i++) { // O(n)旋
    ↪ 转算法, 原理是模拟加1
17     k = n;
18     do
19         j ^= (k >= 1);
20     while (j < k);
21
22     if (i < j)
23         swap(a[i], a[j]);
24 }
25
26 for (int k = 2, m = ntt_n / 2; k <= n; k *= 2, m /=
    ↪ 2)
27     for (int i = 0; i < n; i += k)
28         for (int j = 0; j < k / 2; j++) {
29             int w = (tp > 0 ? omega : omega_inv)[m *
                ↪ j];
30
31             int u = a[i + j], v = (long long)w * a[i
                ↪ + j + k / 2] % p;
32             a[i + j] = u + v;
33             if (a[i + j] >= p)
34                 a[i + j] -= p;
35
36             a[i + j + k / 2] = u - v;
37             if (a[i + j + k / 2] < 0)
38                 a[i + j + k / 2] += p;
39         }
40
41     if (tp < 0) {
42         int inv = qpow(n, p - 2);
43         for (int i = 0; i < n; i++)
44             a[i] = (long long)a[i] * inv % p;
45     }
46 }

```

### 1.2.3 任意模数卷积

任意模数卷积有两种比较naive的做法, 三模数NTT和拆系数FFT. 一般来说后者常数比前者小一些.

但卷积答案不超过 $10^{18}$ 的时候可以改用双模数NTT, 比FFT是要快的.

#### 三模数NTT

原理是选取三个乘积大于结果的NTT模数, 最后中国剩余定理合并.

```

1 //以下三模数NTT, 原理是选取三个乘积大于结果的NTT模数,
    ↪ 最后中国剩余定理合并
2 //以对23333333(不是质数)取模为例
3 constexpr int maxn = 262200, Mod = 23333333, g = 3, m[] =
    ↪ {998244353, 1004535809, 1045430273}, m0_inv =
    ↪ 669690699, m1_inv = 332747959, M_inv = 942377029; //
    ↪ 这三个模数最小原根都是3
4 constexpr long long M = (long long)m[0] * m[1];
5
6 // 主函数(当然更多时候包装一下比较好)
7 // 用来卷积的是A和B
8 // 需要调用mul
9 int n, N = 1, A[maxn], B[maxn], C[maxn], D[maxn], ans[3]
    ↪ [maxn];
10 int main() {
11     scanf("%d", &n);
12
13     while (N < n * 2)
14         N *= 2;
15
16     for (int i = 0; i < n; i++)
17         scanf("%d", &A[i]);

```

```

18     for (int i = 0; i < n; i++)
19         scanf("%d", &B[i]);
20
21     for (int i = 0; i < 3; i++)
22         mul(m[i], ans[i]);
23
24     for (int i = 0; i < n; i++)
25         printf("%d ", China(ans[0][i], ans[1][i], ans[2]
            ↪ [i]));
26
27     return 0;
28 }
29
30 // mul O(n\log n)
31 // 包装了模NTT模数的卷积
32 // 需要调用NTT
33 void mul(int p, int *ans) {
34     copy(A, A + N, C);
35     copy(B, B + N, D);
36
37     NTT(C, N, 1, p);
38     NTT(D, N, 1, p);
39
40     for (int i = 0; i < N; i++)
41         ans[i] = (long long)C[i] * D[i] % p;
42
43     NTT(ans, N, -1, p);
44 }
45
46 // 中国剩余定理 O(1)
47 // 由于直接合并会爆Long Long, 采用神奇的方法合并
48 // 需要调用O(1)快速乘
49 inline int China(int a0, int a1, int a2) {
50     long long A = (mul((long long)a0 * m1_inv, m[1], M) +
        ↪ mul((long long)a1 * m0_inv, m[0], M)) % M;
51     int k = ((a2 - A) % m[2] + m[2]) % m[2] * M_inv %
        ↪ m[2];
52     return (k % Mod * (M % Mod) % Mod + A % Mod) % Mod;
53 }

```

#### 拆系数FFT

原理是选一个数 $M$ , 把每一项改写成 $aM + b$ 的形式再分别相乘.

```

1 constexpr int maxn = 262200, p = 23333333, M = 4830; //
    ↪ M取值要使得结果不超过 $10^{14}$ 
2
3 // 需要开的数组
4 struct Complex {
5     // 内容略
6 } w[maxn], w_inv[maxn], A[maxn], B[maxn], C[maxn],
    ↪ D[maxn], F[maxn], G[maxn], H[maxn];
7
8 // 主函数(当然更多时候包装一下比较好)
9 // 需要调用FFT初始化, FFT
10 int main() {
11     scanf("%d", &n);
12
13     int N = 1;
14     while (N < n * 2)
15         N *= 2;
16
17     for (int i = 0, x; i < n; i++) {
18         scanf("%d", &x);
19         A[i] = x / M;
20         B[i] = x % M;
21     }
22
23     for (int i = 0, x; i < n; i++) {
24         scanf("%d", &x);
25         C[i] = x / M;

```

```

26     D[i] = x % M;
27 }
28
29 FFT_init(N);
30
31 FFT(A, N, 1);
32 FFT(B, N, 1);
33 FFT(C, N, 1);
34 FFT(D, N, 1);
35
36 for (int i = 0; i < N; i++) {
37     F[i] = A[i] * C[i];
38     G[i] = A[i] * D[i] + B[i] * C[i];
39     H[i] = B[i] * D[i];
40 }
41
42 FFT(F, N, -1);
43 FFT(G, N, -1);
44 FFT(H, N, -1);
45
46 for (int i = 0; i < n; i++)
47     printf("%d ", (int)((M * M * ((long long)(F[i].a
48         ↪ + 0.5) % p) % p + M * ((long long)(G[i].a +
49         ↪ 0.5) % p) % p + (long long)(H[i].a + 0.5) %
50         ↪ p) % p));
51
52 return 0;
53 }

```

### 1.2.4 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, 直接赋值
8     ↪ 为1就可以
9
10    for (int k = 2; k <= n; k <= 1) {
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
24        NTT(C, k * 2, -1);
25
26        memset(C + k, 0, sizeof(int) * k);
27    }
28
29 // 开根
30 void get_sqrt(int *A, int *C, int n) {
31     static int B[maxn], D[maxn];
32
33     memset(C, 0, sizeof(int) * (n * 2));
34     C[0] = 1; // 如果不是1就要考虑二次剩余
35
36     for (int k = 2; k <= n; k *= 2) {
37         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) % p;
66
67     C[0] = 0; // 不定积分没有常数项
68 }
69
70 // 多项式ln, 要求A常数项不为0
71 void get_ln(int *A, int *C, int n) { // 通常情况下A常数项
72     ↪ 都是1
73     static int B[maxn];
74
75     get_derivative(A, B, n);
76     memset(B + n, 0, sizeof(int) * n);
77
78     get_inv(A, C, n);
79
80     NTT(B, n * 2, 1);
81     NTT(C, n * 2, 1);
82
83     for (int i = 0; i < n * 2; i++)
84         B[i] = (long long)B[i] * C[i] % p;
85
86     NTT(B, n * 2, -1);
87
88     get_integrate(B, C, n);
89
90     memset(C + n, 0, sizeof(int) * n);
91 }
92
93 // 多项式exp, 要求A没有常数项
94 // 常数很大且总代码较长, 一般来说最好替换为分治FFT
95 // 分治FFT依据: 设G(x) = exp F(x), 则有 g_i = \sum_{k=1}^i
96     ↪ f_{i-k} * k * g_k
97 void get_exp(int *A, int *C, int n) {
98     static int B[maxn];
99
100    memset(C, 0, sizeof(int) * (n * 2));
101    C[0] = 1;
102
103    for (int k = 2; k <= n; k <= 1) {
104        get_ln(C, B, k);

```

```

104     for (int i = 0; i < k; i++) {
105         B[i] = A[i] - B[i];
106         if (B[i] < 0)
107             B[i] += p;
108     }
109     (++B[0]) %= p;
110
111     NTT(B, k * 2, 1);
112     NTT(C, k * 2, 1);
113
114     for (int i = 0; i < k * 2; i++)
115         C[i] = (long long)C[i] * B[i] % p;
116
117     NTT(C, k * 2, -1);
118
119     memset(C + k, 0, sizeof(int) * k);
120 }
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
125 // 快速幂
126 void get_pow(int *A, int *C, int n, int k) {
127     static int B[maxn];
128
129     get_ln(A, B, n);
130
131     for (int i = 0; i < n; i++)
132         B[i] = (long long)B[i] * k % p;
133
134     get_exp(B, C, n);
135 }
136
137 // 多项式除法,  $A / B$ , 结果输出在 $C$ 
138 //  $A$ 的次数为 $n$ ,  $B$ 的次数为 $m$ 
139 void get_div(int *A, int *B, int *C, int n, int m) {
140     static int f[maxn], g[maxn], gi[maxn];
141
142     if (n < m) {
143         memset(C, 0, sizeof(int) * m);
144         return;
145     }
146
147     int N = 1;
148     while (N < (n - m + 1))
149         N <<= 1;
150
151     memset(f, 0, sizeof(int) * N * 2);
152     memset(g, 0, sizeof(int) * N * 2);
153     // memset(gi, 0, sizeof(int) * N);
154
155     for (int i = 0; i < n - m + 1; i++)
156         f[i] = A[n - i - 1];
157     for (int i = 0; i < m && i < n - m + 1; i++)
158         g[i] = B[m - i - 1];
159
160     get_inv(g, gi, N);
161
162     for (int i = n - m + 1; i < N; i++)
163         gi[i] = 0;
164
165     NTT(f, N * 2, 1);
166     NTT(gi, N * 2, 1);
167
168     for (int i = 0; i < N * 2; i++)
169         f[i] = (long long)f[i] * gi[i] % p;
170
171     NTT(f, N * 2, -1);
172
173     for (int i = 0; i < n - m + 1; i++)
174         C[i] = f[n - m - i];
175 }
176
177 // 多项式取模, 余数输出到 $C$ , 商输出到 $D$ 
178 void get_mod(int *A, int *B, int *C, int *D, int n, int
179 //  $m$ ) {
180     static int b[maxn], d[maxn];
181
182     if (n < m) {
183         memcpy(C, A, sizeof(int) * n);
184
185         if (D)
186             memset(D, 0, sizeof(int) * m);
187
188         return;
189     }
190
191     get_div(A, B, d, n, m);
192
193     if (D) { //  $D$ 是商, 可以选择不要
194         for (int i = 0; i < n - m + 1; i++)
195             D[i] = d[i];
196     }
197
198     int N = 1;
199     while (N < n)
200         N *= 2;
201
202     memcpy(b, B, sizeof(int) * m);
203
204     NTT(b, N, 1);
205     NTT(d, N, 1);
206
207     for (int i = 0; i < N; i++)
208         b[i] = (long long)d[i] * b[i] % p;
209
210     NTT(b, N, -1);
211
212     for (int i = 0; i < m - 1; i++)
213         C[i] = (A[i] - b[i] + p) % p;
214
215     memset(b, 0, sizeof(int) * N);
216     memset(d, 0, sizeof(int) * N);
217 }
218
219 // 多点求值要用的数组
220 int q[maxn], ans[maxn]; //  $q$ 是要代入的各个系数,  $ans$ 是求出
221 // 的值
222 int tg[25][maxn * 2], tf[25][maxn]; // 辅助数组,  $tg$ 是预处理
223 // 理乘积,
224 //  $tf$ 是项数越来越少的 $f$ ,  $tf[0]$ 就是原来的函数
225 void pretreat(int l, int r, int k) { // 多点求值预处理
226     static int A[maxn], B[maxn];
227
228     int *g = tg[k] + l * 2;
229
230     if (r - l + 1 <= 200) {
231         g[0] = 1;
232
233         for (int i = l; i <= r; i++) {
234             for (int j = i - l + 1; j; j--) {
235                 g[j] = (g[j - 1] - (long long)g[j] *
236 //  $q[i]$ ) % p;
237                 if (g[j] < 0)
238                     g[j] += p;
239             }
240             g[0] = (long long)g[0] * (p - q[i]) % p;
241         }
242     }

```

```

238     return;
239 }
240
241 int mid = (l + r) / 2;
242
243 pretreat(l, mid, k + 1);
244 pretreat(mid + 1, r, k + 1);
245
246 if (!k)
247     return;
248
249 int N = 1;
250 while (N <= r - l + 1)
251     N *= 2;
252
253 int *gl = tg[k + 1] + l * 2, *gr = tg[k + 1] + (mid +
    ↪ 1) * 2;
254
255 memset(A, 0, sizeof(int) * N);
256 memset(B, 0, sizeof(int) * N);
257
258 memcpy(A, gl, sizeof(int) * (mid - l + 2));
259 memcpy(B, gr, sizeof(int) * (r - mid + 1));
260
261 NTT(A, N, 1);
262 NTT(B, N, 1);
263
264 for (int i = 0; i < N; i++)
265     A[i] = (long long)A[i] * B[i] % p;
266
267 NTT(A, N, -1);
268
269 for (int i = 0; i <= r - l + 1; i++)
270     g[i] = A[i];
271 }
272
273 void solve(int l, int r, int k) { // 多项式多点求值主过程
274     int *f = tf[k];
275
276     if (r - l + 1 <= 200) {
277         for (int i = l; i <= r; i++) {
278             int x = q[i];
279
280             for (int j = r - 1; ~j; j--)
281                 ans[i] = ((long long)ans[i] * x + f[j]) %
                ↪ p;
282
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, NULL, 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, NULL, 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 $\theta$ -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NULL, 代表不复制答案, 直接用 $ans$ 数组
318         memcpy(a, ans, sizeof(int) * m);
319 }

```

### 1.2.5 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,
    ↪  $tf$ 是项数越来越少的 $f$ ,  $tf[0]$ 就是原来的函数
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) {
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 - 1 + 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] + 1 * 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     int n_inv = qpow(N, p - 2);
111     for (int i = 0; i < N; i++)
112         b[i] = (long long)b[i] * n_inv % p;

```

```

111
112 for (int i = 0; i < r - mid + 1; i++)
113     ff[i] = b[i + mid - l + 1];
114
115 memset(a, 0, sizeof(int) * N);
116 memset(b, 0, sizeof(int) * N);
117
118 solve(mid + 1, r, k + 1);
119
120 memset(gl, 0, sizeof(int) * (mid - l + 2));
121 memset(gr, 0, sizeof(int) * (r - mid + 1));
122 memset(ff, 0, sizeof(int) * (r - mid + 1));
123 }
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
136     pretreat(0, m - 1, 0);
137
138     int N = 1;
139     while (N < m)
140         N *= 2;
141
142     get_inv(tg[0], c, N);
143
144     fill(c + m, c + N, 0);
145     reverse(c, c + m);
146
147     memcpy(d, f, sizeof(int) * m);
148
149     NTT(c, N * 2, 1);
150     NTT(d, N * 2, 1);
151     for (int i = 0; i < N * 2; i++)
152         c[i] = (long long)c[i] * d[i] % p;
153     NTT(c, N * 2, -1);
154
155     for (int i = 0; i < m; i++)
156         tf[0][i] = c[i + n];
157
158     solve(0, m - 1, 0);
159
160     if (a) // 如果a是NULL, 代表不复制答案, 直接用ans数组
161         memcpy(a, ans, sizeof(int) * m);
162 }

```

### 1.2.6 多项式快速插值

快速插值: 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:

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

第一步要先对每个 $i$ 求出

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

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] + 1 * 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] + 1 * 2, *hr = th[k + 1] + (mid +
24        ↪ 1) * 2;
25
26    memset(A, 0, sizeof(int) * N);
27    memset(B, 0, sizeof(int) * N);
28
29    memcpy(A, hl, sizeof(int) * (mid - l + 2));
30    memcpy(B, hr, sizeof(int) * (r - mid + 1));
31
32    NTT(A, N, 1);
33    NTT(B, N, 1);

```

```

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] + 1 * 2, *hr = th[k + 1] + (mid +
55         ↪ 1) * 2;
56
57     int N = 1;
58
59     while (N < r - l + 1)
60         N *= 2;
61
62     memset(A, 0, sizeof(int) * N);
63     memset(B, 0, sizeof(int) * N);
64
65     memcpy(A, ansf + 1, sizeof(int) * (mid - l + 1));
66     memcpy(B, hr, sizeof(int) * (r - mid + 1));
67
68     NTT(A, N, 1);
69     NTT(B, N, 1);
70
71     for (int i = 0; i < N; i++)
72         t[i] = (long long)A[i] * B[i] % p;
73
74     memset(A, 0, sizeof(int) * N);
75     memset(B, 0, sizeof(int) * N);
76
77     memcpy(A, ansf + mid + 1, sizeof(int) * (r - mid));
78     memcpy(B, hl, sizeof(int) * (mid - l + 2));
79
80     NTT(A, N, 1);
81     NTT(B, N, 1);
82
83     for (int i = 0; i < N; i++)
84         t[i] = (t[i] + (long long)A[i] * B[i]) % p;
85
86     NTT(t, N, -1);
87
88     memcpy(ansf + 1, t, sizeof(int) * (r - l + 1));
89 }
90 // 主过程
91 // 如果x, y传NULL表示询问已经存在了qx, qy里
92 void interpolation(int *x, int *y, int n, int *f = NULL)
93     ↪ {
94     static int d[maxn];
95
96     if (x)
97         memcpy(qx, x, sizeof(int) * n);
98     if (y)
99         memcpy(qy, y, sizeof(int) * n);
100
101     pretreat2(0, n - 1, 0);

```

```

102 get_derivative(th[0], d, n + 1);
103
104 multipoint_eval(d, qx, NULL, n, n);
105
106 for (int i = 0; i < n; i++)
107     ansf[i] = (long long)qy[i] * qpow(ans[i], p - 2)
108         ↪ % p;
109
110 solve2(0, n - 1, 0);
111
112 if (f)
113     memcpy(f, ansf, sizeof(int) * n);
114 }

```

### 1.2.7 拉格朗日反演

如果 $f(x)$ 与 $g(x)$ 互为复合逆, 则有

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

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

### 1.2.8 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 = 1; i <= mid; i++)
14        B[i - 1] = (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 }

```

### 1.2.9 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 = 1, t = (long long)l * f[l] % p; i <=
12        ↪ n; i += 1)
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         B[i] = (c[i] + g[i]) % p;
26     }
27     NTT(A, r, 1);
28     NTT(B, r, 1);
29     for (int i = 0; i < r; i++)
30         A[i] = (long long)A[i] * B[i] % p;
31     NTT(A, r, -1);
32
33     for (int i = mid; i < r; i++)
34         f[i] = (f[i] + A[i]) % p;
35 }
36 else {
37     for (int i = 0; i < r - l; i++)
38         A[i] = f[i];
39     for (int i = l; i < mid; i++)
40         B[i - l] = (c[i] + g[i]) % p;
41     NTT(A, r - l, 1);
42     NTT(B, r - l, 1);
43     for (int i = 0; i < r - l; i++)
44         A[i] = (long long)A[i] * B[i] % p;
45     NTT(A, r - l, -1);
46
47     for (int i = mid; i < r; i++)
48         f[i] = (f[i] + A[i - l]) % p;
49
50     memset(A, 0, sizeof(int) * (r - l));
51     memset(B, 0, sizeof(int) * (r - l));
52
53     for (int i = l; i < mid; i++)
54         A[i - l] = f[i];
55     for (int i = 0; i < r - l; i++)
56         B[i] = (c[i] + g[i]) % p;
57     NTT(A, r - l, 1);
58     NTT(B, r - l, 1);
59     for (int i = 0; i < r - l; i++)
60         A[i] = (long long)A[i] * B[i] % p;
61     NTT(A, r - l, -1);
62
63     for (int i = mid; i < r; i++)
64         f[i] = (f[i] + A[i - l]) % p;
65 }
66
67 memset(A, 0, sizeof(int) * (r - l));
68 memset(B, 0, sizeof(int) * (r - l));
69
70 solve(mid, r);
71 }

```

### 1.2.10 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
   ↪ m) {
3     static int b[maxn], d[maxn];
4     static bool flag = false;
5
6     if (n < m) {
7         memcpy(C, A, sizeof(int) * n);
8
9         if (D)
10             memset(D, 0, sizeof(int) * m);
11
12         return;
13     }
14
15     get_div(A, B, d, n, m);
16
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         get_mod(t, g, f, NULL, n * 2 - 1, n);
70     }
71
72     for (int i = 0; i < N; i++)
73         a[i] = (long long)a[i] * a[i] % p;
74     NTT(a, N, -1);
75
76     memcpy(t, a, sizeof(int) * (n * 2 - 1));
77     get_mod(t, g, a, NULL, n * 2 - 1, n);
78     fill(a + n - 1, a + N, 0);
79
80     k >>= 1;
81 }
82
83     memset(a, 0, sizeof(int) * (n * 2));
84 }
85
86 // f_n = \sum_{i=1}^m f_{n-i} a_i
87 // f是0~m-1项的初值
88 int linear_recurrence(long long n, int m, int *f, int *a)
   ↪ {
89     static int g[maxn], c[maxn];
90
91     memset(g, 0, sizeof(int) * (m * 2 + 1));
92
93     for (int i = 0; i < m; i++)
94         g[i] = (p - a[m - i]) % p;
95     g[m] = 1;
96
97     pow_mod(n, g, m + 1, c);
98
99     int ans = 0;
100     for (int i = 0; i < m; i++)
101         ans = (ans + (long long)c[i] * f[i]) % p;
102
103     return ans;
104 }
105

```

### 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 /
25 |             ↪ 2] + p) % p;
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
40 |             ↪ 模时需要用每层除以2代替
41 |         for (int i = 0; i < n; i++)
42 |             A[i] = A[i] * inv % p;
43 |     }

```

## 1.4 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]);
12 |        id[i] = i;
13 |    }
14 |
15 |    for (int i = 1; i <= m; i++) {
16 |        for (int j = 1; j <= n; j++)
17 |            scanf("%lf", &A[i][j]);
18 |
19 |        scanf("%lf", &A[i][0]);
20 |    }
21 |
22 |    if (!inititalize())
23 |        printf("Infeasible"); // 无解
24 |    else if (!simplex())
25 |        printf("Unbounded"); // 最优解无限大
26 |
27 |    else {
28 |        printf("%.15lf\n", -A[0][0]);
29 |        if (t) {
30 |            for (int i = 1; i <= m; i++)
31 |                x[id[i + n]] = A[i][0];
32 |            for (int i = 1; i <= n; i++)
33 |                printf("%.15lf ", x[i]);
34 |        }
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 inititalize() {
42 |     while (true) {
43 |         double t = 0.0;
44 |         int l = 0, e = 0;

```

```

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] < id[e]))
57 |                 e = i;
58 |
59 |         if (!e)
60 |             return false;
61 |
62 |         pivot(l, e);
63 |     }
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 |                 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 |
91 | //转轴操作, 本质是在凸包上沿着一条棱移动
92 | void pivot(int l, int e) {
93 |     swap(id[e], id[n + l]);
94 |     double t = A[l][e];
95 |     A[l][e] = 1.0;
96 |
97 |     for (int i = 0; i <= n; i++)
98 |         A[l][i] /= t;
99 |
100 |    for (int i = 0; i <= m; i++)
101 |        if (i != l) {
102 |            t = A[i][e];
103 |            A[i][e] = 0.0;
104 |            for (int j = 0; j <= n; j++)
105 |                A[i][j] -= t * A[l][j];
106 |        }
107 | }

```

### 1.4.1 线性规划对偶原理

给定一个原始线性规划:

$$\text{Minimize} \quad \sum_{j=1}^n c_j x_j$$

$$\text{Where} \quad \sum_{j=1}^n a_{ij} x_j \geq b_i,$$

$$x_j \geq 0$$

定义它的对偶线性规划为:

$$\text{Maximize} \quad \sum_{i=1}^m b_i y_i$$

$$\text{Where} \quad \sum_{i=1}^m a_{ij} y_i \leq c_j,$$

$$y_i \geq 0$$

用矩阵可以更形象地表示为:

$$\begin{array}{ll} \text{Minimize} & \mathbf{c}^T \mathbf{x} \\ \text{Where} & \mathbf{Ax} \geq \mathbf{b}, \\ & \mathbf{x} \geq 0 \end{array} \iff \begin{array}{ll} \text{Maximize} & \mathbf{b}^T \mathbf{y} \\ \text{Where} & \mathbf{A}^T \mathbf{y} \leq \mathbf{c}, \\ & \mathbf{y} \geq 0 \end{array}$$

## 1.5 线性代数

### 1.5.1 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
```

### 1.5.2 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
9             解的话要判一下
10            for (int j = i; j <= n + 1; j++)
11                swap(A[i][j], A[ii][j]);
12
13        for (int j = 1; j <= n; j++)
14            if (j != i) // 消成对角
15                for (int k = n + 1; k >= i; k--)
16                    A[j][k] -= A[j][i] / A[i][i] * A[i][k];
17    }
18 }
```

#### 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。

### 1.5.3 行列式取模

```
1 int p;
2
3 int Gauss(int A[maxn][maxn], int n) {
4     int det = 1;
5
6     for (int i = 1; i <= n; i++) {
7         for (int j = i + 1; j <= n; j++)
8             while (A[j][i]) {
9                 int t = (p - A[i][i] / A[j][i]) % p;
10                for (int k = i; k <= n; k++)
11                    A[i][k] = (A[i][k] + (long long)A[j][k]
12                        * t) % p;
13
14                swap(A[i], A[j]);
15                det = (p - det) % p; // 交换一次之后行列
16                    式取负
17            }
18
19            if (!A[i][i])
20                return 0;
21
22            det = (long long)det * A[i][i] % p;
23        }
24    }
25    return det;
26 }
```

### 1.5.4 线性基

```
1 void add(unsigned long long x) {
2     for (int i = 63; i >= 0; i--)
3         if (x >> i & 1) {
4             if (b[i])
5                 x ^= b[i];
6             else {
7                 b[i] = x;
8
9                 for (int j = i - 1; j >= 0; j--)
10                    if (b[j] && (b[i] >> j & 1))
11                        b[i] ^= b[j];
12
13                for (int j = i + 1; j < 64; j++)
14                    if (b[j] >> i & 1)
15                        b[j] ^= b[i];
16
17                break;
18            }
19        }
20 }
```

### 1.5.5 线性代数知识

行列式:

$$\det A = \sum_{\sigma} \text{sgn}(\sigma) \prod_i a_{i, \sigma_i}$$

逆矩阵:

$$B = A^{-1} \iff AB = 1$$

代数余子式:

$$C_{i,j} = (-1)^{i+j} M_{i,j} = (-1)^{i+j} |A^{i,j}|$$

也就是 $A$ 去掉一行一列之后的行列式

伴随矩阵:

$$A^* = C^T$$

即代数余子式矩阵的转置  
同时我们有

$$A^* = |A|A^{-1}$$

### 1.5.6 矩阵树定理

## 1.6 自适应Simpson积分

Forked from fstqwq's template.

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

## 1.7 常见数列

### 1.7.1 斐波那契数

### 1.7.2 卢卡斯数

### 1.7.3 伯努利数

$$B(x) = \sum_{i \geq 0} \frac{B_i x^i}{i!} = \frac{x}{e^x - 1}$$

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

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

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

### 1.7.4 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];
```

```
16 long long p[50005]; // 欧拉五边形数定理
17
18 int main() {
19     p[0] = 1;
20     p[1] = 1;
21     p[2] = 2;
22     int i;
23     for (i = 1; i < 50005;
24         i++) /*递推系数1, 2, 5, 7, 12, 15, 22, 26...i*(3*i-1)/
  ↳ 2, i*(3*i+1)/2*/
25     {
26         a[2 * i] = i * (i * 3 - 1) / 2; /*五边形数
  ↳ 为1, 5, 12, 22...i*(3*i-1)/2*/
27         a[2 * i + 1] = i * (i * 3 + 1) / 2;
28     }
29     for (
30         i = 3; i < 50005;
31         i++) /*p[n]=p[n-1]+p[n-2]-p[n-5]-
  ↳ p[n-7]+p[12]+p[15]-...+p[n-i*[3i-1]/2]+p[n-
  ↳ i*[3i+1]/2]*/
32     {
33         p[i] = 0;
34         int j;
35         for (j = 2; a[j] <= i; j++) /*有可能为负数, 式中
  ↳ 加1000007*/
36         {
37             if (j & 2) {
38                 p[i] = (p[i] + p[i - a[j]] + 1000007) % 1000007;
39             } else {
40                 p[i] = (p[i] - p[i - a[j]] + 1000007) % 1000007;
41             }
42         }
43     }
44     int n;
45     while (~scanf("%d", &n))
46         printf("%lld\n", p[n]);
47 }
```

### 1.7.5 斯特林数

#### 第一类斯特林数

$\begin{Bmatrix} n \\ k \end{Bmatrix}$ 表示n个元素划分成k个轮换的方案数。

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)。

求同一列: 用一个轮换的指数生成函数做k次幂

$$\sum_{n=0}^{\infty} \begin{Bmatrix} n \\ k \end{Bmatrix} \frac{x^n}{n!} = \frac{(\ln(1-x))^k}{k!} = \frac{x^k}{k!} \left( \frac{\ln(1-x)}{x} \right)^k$$

#### 第二类斯特林数

$\begin{Bmatrix} n \\ k \end{Bmatrix}$ 表示n个元素划分成k个子集的方案数。

求一个: 容斥, 狗都会做

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

求同一行: FFT, 狗都会做

求同一列: 指数生成函数

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

普通生成函数

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

上升幂, 下降幂与普通幂的转换参见“常用公式及结论”部分。



## 1.7.6 贝尔数

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

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

$$B_n = \sum_{k=0}^n \left\{ \begin{matrix} n \\ k \end{matrix} \right\}$$

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:

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

## 1.7.7 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

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

## 1.8 常用公式及结论

## 1.8.1 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:  $D^2(x) = E(X^2) - E^2(x)$

## 1.8.2 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  $g_1 \dots g_n$  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  $\ln$ .

## 1.8.3 线性齐次线性常系数递推求通项

- **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

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

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

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

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。

## 1.8.4 上升幂, 下降幂与普通幂的转换

上升幂与普通幂的相互转化

$$x^{\bar{n}} = \sum_k \left[ \begin{matrix} n \\ k \end{matrix} \right] x^k$$

$$x^n = \sum_k \left\{ \begin{matrix} n \\ k \end{matrix} \right\} (-1)^{n-k} x^{\bar{k}}$$

下降幂与普通幂的相互转化

$$x^n = \sum_k \left[ \begin{matrix} n \\ k \end{matrix} \right] x^{\bar{k}}$$

$$x^{\bar{n}} = \sum_k \left\{ \begin{matrix} n \\ k \end{matrix} \right\} (-1)^{n-k} x^k$$

另外, 多项式的点值表示每项除以阶乘之后卷上  $e^{-x}$  就是牛顿插值表示, 或者乘上阶乘之后是下降幂系数表示. 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.

## 1.9 常用生成函数

$$\frac{1}{1-x} = \sum_{i \geq 0} x^i$$

$$\frac{1}{1-cx^k} = \sum_{i \geq 0} c^i x^{ki}$$

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

$$x^k \frac{d^k}{dx^k} \left( \frac{1}{1-x} \right) = \sum_{i \geq 0} i^k x^i$$

## 1.9.1 组合数

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

$$\frac{1}{\sqrt{1-4x}} = \sum_{i \geq 0} \binom{2i}{i} x^i$$

$$\frac{\text{Catalan}(x)^k}{\sqrt{1-4x}} = \sum_{i \geq 0} \binom{2i+k}{i} x^i$$



## 1.9.2 斐波那契数

见“常见数列”。

## 1.9.3 调和数

## 1.9.4 自然对数与幂

$$e^x = \sum_{i \geq 0} \frac{x^i}{i!}$$

$$\ln \frac{1}{1-x} = \sum_{i \geq 1} \frac{x^i}{i}$$

## 1.9.5 三角函数与反三角函数

$$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \cdots = \sum_{i \geq 0} (-1)^i \frac{x^{2i+1}}{(2i+1)!}$$

$$\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \cdots = \sum_{i \geq 0} (-1)^i \frac{x^{2i}}{(2i)!}$$

$$\cot x = x - \frac{x^3}{3} + \frac{x^5}{5} - \frac{x^7}{7} + \cdots = \sum_{i \geq 0} (-1)^i \frac{x^{2i+1}}{2i+1}$$

## 2. 数论

2.1  $O(n)$ 预处理逆元

```
1 // 要求p为质数
2
3 inv[0] = inv[1] = 1;
4 for (int i = 2; i <= n; i++)
5     inv[i] = (long long)(p - (p / i)) * inv[p % i] % p;
6     // 这里 p 为模数
7 // 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], g[maxn];
6 // f: 除掉最小质因子后剩下的部分
7 // g: 最小质因子的幂次, 在 f(p^k) 比较复杂时很有用,
8 // 但 f(p^k) 可以递推时就可以省掉了
9 // 这里没有记录最小质因子, 但根据线性筛的性质, 每个合数
10 // 只会被它最小的质因子筛掉
11 bool notp[maxn]; // 顾名思义
12
13 void get_table(int n) {
14     sigma_one[1] = 1; // 积性函数必有 f(1) = 1
15     for (int i = 2; i <= n; i++) {
16         if (!notp[i]) { // 质数情况
17             prime[++prime[0]] = i;
18             sigma_one[i] = i + 1;
19             f[i] = g[i] = 1;
20         }
21         for (int j = 1; j <= prime[0] && i * prime[j] <= n; j++) {
22             notp[i * prime[j]] = true;
23         }
24     }
25 }
```

```
23     if (i % prime[j]) { // 加入一个新的质因子, 这
24         // 种情况很简单
25         sigma_one[i * prime[j]] = (long
26             // long)sigma_one[i] * (prime[j] + 1) %
27             // p;
28         f[i * prime[j]] = i;
29         g[i * prime[j]] = 1;
30     }
31     else { // 再加入一次最小质因子, 需要再进行分
32         // 类讨论
33         f[i * prime[j]] = f[i];
34         g[i * prime[j]] = g[i] + 1;
35         // 对于 f(p^k) 可以直接递推的函数, 这里的判
36         // 断可以改成
37         // i / prime[j] % prime[j] != 0, 这样可以
38         // 省下 f[] 的空间,
39         // 但常数很可能会稍大一些
40
41         if (f[i] == 1) // 质数的幂次, 这
42             // 里 sigma_1 可以递推
43             sigma_one[i * prime[j]] =
44                 (sigma_one[i] + i * prime[j]) %
45                 p;
46         // 对于更一般的情况, 可以借助 g[] 计
47         // 算 f(p^k)
48         else sigma_one[i * prime[j]] = // 否则直
49             // 接利用积性, 两半乘起来
50             (long long)sigma_one[i * prime[j] /
51                 // f[i]] * sigma_one[f[i]] % p;
52             break;
53         }
54     }
55 }
```

## 2.3 杜教筛

```
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
2 // 缀和(有点绕)
3 // 有些题只要求 n <= 10 ^ 9, 这时就没必要开 long long 了, 但
4 // 记得乘法时强转
5
6 // 常量/全局变量/数组定义
7 const int maxn = 5000005, table_size = 5000000, p =
8     // 1000000007, inv_2 = (p + 1) / 2;
9 bool notp[maxn];
10 int prime[maxn / 20], phi[maxn], tbl[100005];
11 // tbl 用来顶替哈希表, 其实开到 n ^ {1 / 3} 就够了, 不过保
12 // 险起见开成 sqrt n 比较好
13 long long N;
14
15 // 主函数前面加上这么一句
16 memset(tbl, -1, sizeof(tbl));
17
18 // 线性筛预处理部分略去
19
20 // 杜教筛主过程 总计 O(n ^ {2 / 3})
21 // 递归调用自身
22 // 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
23 // 10 ^ 9 + 7) 为例
24 int S(long long n) {
25     if (n <= table_size)
26         return phi[n];
27     else if (~tbl[N / n])
28         return tbl[N / n];
29     // 原理: n 除以所有可能的数的结果一定互不相同
30
31     int ans = 0;
32     for (long long i = 2, last; i <= n; i = last + 1) {
33         last = n / (n / i);
34     }
35 }
```

```

29 |     ans = (ans + (last - i + 1) % p * S(n / i)) % p;
    |     ⇨ // 如果n是int范围的话记得强转
30 | }
31 |
32 | ans = (n % p * ((n + 1) % p) % p * inv_2 - ans + p) %
    | ⇨ p; // 同上
33 | return tbl[N / n] = ans;
34 | }

```

## 2.4 Powerful Number筛

注意Powerful Number筛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 min25筛

本质上其实还是类似于DP，不过计算方式比洲阁筛简单得多。

## 2.6 Miller-Rabin

```

1 // 复杂度可以认为是常数
2
3 // 封装好的函数体
4 // 需要调用check
5 bool Miller_Rabin(long long n) {
6     if (n == 1)
7         return false;
8     if (n == 2)
9         return true;
10    if (n % 2 == 0)
11        return false;
12
13    for (int i : {2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31,
14        ⇨ 37}) {
15        if (i > n)
16            break;
17        if (!check(n, i))
18            return false;
19    }
20    return true;

```

```

21 }
22
23 // 用一个数检测
24 // 需要调用Long Long快速幂和O(1)快速乘
25 bool check(long long n, long long b) { // b: base
26     long long a = n - 1;
27     int k = 0;
28
29     while (a % 2 == 0) {
30         a /= 2;
31         k++;
32     }
33
34     long long t = qpow(b, a, n); // 这里的快速幂函数需要
35     ⇨ 写O(1)快速乘
36     if (t == 1 || t == n - 1)
37         return true;
38
39     while (k-- > 0) {
40         t = mul(t, t, n); // mul是O(1)快速乘函数
41         if (t == n - 1)
42             return true;
43     }
44     return false;
45 }

```

## 2.7 Pollard's Rho

```

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函数
49     ↪ 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         long long g = gcd((u - x + n) % n, n);
55         if (g > 1 && g < n)
56             return g;
57
58         if (u == x)
59             return 0; // 失败, 需要重新调用
60
61         if (i == k) {
62             u = x;
63             k *= 2;
64         }
65     }
66 }

```

## 2.8 扩展欧几里德

```

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 }

```

### 2.8.1 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.

## 2.9 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 $a$ 在原根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             while n % i == 0:
8                 n /= i
9
10            i += 1
11
12    if n > 1:
13        a.append(n)
14
15    return a
16
17 def getg(p): # 找原根
18     def judge(g):
19         for i in d:
20             if pow(g, (p - 1) / i, p) == 1:
21                 return False
22         return True
23
24     d = split(p - 1)
25     g = 2
26
27     while not judge(g):
28         g += 1
29
30     return g
31
32 print(getg(int(input())))
33

```

## 2.10 常用公式

### 2.10.1 莫比乌斯反演

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

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

### 2.10.2 其他常用公式

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

$$\varphi * I = id$$

$$\mu * id = \varphi$$

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

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

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

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

## 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

```
1 // 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
2 // 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
3 // 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：
4 // - Reduction:待修改边标为+INF,跑MST后把非树边删掉，减少
  // 无用边
5 // - Contraction:待修改边标为-INF,跑MST后缩除待修改边之
  // 外的所有MST边，计算必须边
6 // 每轮分治需要Reduction-Contraction,借此减少不确定边，从
  // 而保证复杂度
7 // 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) -> (n, n + k - 1)
  // -> (k + 1, 2k)
8
9
10 // 全局结构体与数组定义
11 struct edge { //边的定义
12     int u, v, w, id; // id表示边在原图中的编号
13     bool vis; // 在Kruskal时,记录这条边是否是树边
14     bool operator < (const edge &e) const { return w <
        e.w; }
15 } e[20][maxn], t[maxn]; // 为了便于回滚,在每层分治存一个
  // 副本
16
17
18 // 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
19 struct A {
20     int id, u, v;
21 } a[maxn];
22
23
24 int id[20][maxn]; // 每条边在当前图中的编号
25 int p[maxn], size[maxn], stk[maxn], top; // p和size是并查
  // 集数组,stk是用来撤销的栈
26 int n, m, q; // 点数,边数,修改数
27
28
29 // 方便起见,附上可能需要用到的预处理代码
30 for (int i = 1; i <= n; i++) { // 并查集初始化
31     p[i] = i;
32     size[i] = 1;
33 }
34
35 for (int i = 1; i <= m; i++) { // 读入与预标号
36     scanf("%d%d%d", &e[0][i].u, &e[0][i].v, &e[0][i].w);
37     e[0][i].id = i;
38     id[0][i] = i;
39 }
40
41 for (int i = 1; i <= q; i++) { // 预处理出调用数组
42     scanf("%d%d", &a[i].id, &a[i].v);
43     a[i].u = e[0][a[i].id].w;
44     e[0][a[i].id].w = a[i].v;
```

```
45 }
46
47 for(int i = q; i; i--)
48     e[0][a[i].id].w = a[i].u;
49
50 CDQ(1, q, 0, m, 0); // 这是调用方法
51
52
53 // 分治主过程 O(nlog^2n)
54 // 需要调用Reduction和Contraction
55 void CDQ(int l, int r, int d, int m, long long ans) { //
  // CDQ分治
56     if (l == r) { // 区间长度已减小到1,输出答案,退出
57         e[d][id[d][a[l].id]].w = a[l].v;
58         printf("%lld\n", ans + Kruskal(m, e[d]));
59         e[d][id[d][a[l].id]].w = a[l].u;
60         return;
61     }
62
63     int tmp = top;
64
65     Reduction(l, r, d, m);
66     ans += Contraction(l, r, d, m); // R-C
67
68     int mid = (l + r) / 2;
69
70     copy(e[d] + 1, e[d] + m + 1, e[d + 1] + 1);
71     for (int i = 1; i <= m; i++)
72         id[d + 1][e[d][i].id] = i; // 准备好下一层要用的
        // 数组
73
74     CDQ(l, mid, d + 1, m, ans);
75
76     for (int i = 1; i <= mid; i++)
77         e[d][id[d][a[i].id]].w = a[i].v; // 进行左边的修
        // 改
78
79     copy(e[d] + 1, e[d] + m + 1, e[d + 1] + 1);
80     for (int i = 1; i <= m; i++)
81         id[d + 1][e[d][i].id] = i; // 重新准备下一层要用
        // 的数组
82
83     CDQ(mid + 1, r, d + 1, m, ans);
84
85     for (int i = top; i > tmp; i--)
86         cut(stk[i]); // 撤销所有操作
87     top = tmp;
88 }
89
90
91 // Reduction(减少无用边):待修改边标为+INF,跑MST后把非树
  // 边删掉,减少无用边
92 // 需要调用Kruskal
93 void Reduction(int l, int r, int d, int &m) {
94     for (int i = 1; i <= r; i++)
95         e[d][id[d][a[i].id]].w = INF; // 待修改的边标为INF
96
97     Kruskal(m, e[d]);
98
99     copy(e[d] + 1, e[d] + m + 1, t + 1);
100
101     int cnt = 0;
102     for (int i = 1; i <= m; i++)
103         if (t[i].w == INF || t[i].vis) { // 非树边扔掉
104             id[d][t[i].id] = ++cnt; // 给边重新编号
105             e[d][cnt] = t[i];
106         }
107
108     for (int i = r; i >= l; i--)
```

```

109 |     e[d][id[d][a[i].id]].w = a[i].u; // 把待修改的边
    |     ↪ 改回去
110 |
111 |     m=cnt;
112 | }
113 |
114 | // Contraction(缩必须边):待修改边标为-INF,跑MST后缩除待
    | ↪ 修改边之外的所有树边
116 | // 返回缩掉的边的总权值
117 | // 需要调用Kruskal
118 | long long Contraction(int l, int r, int d, int &m) {
119 |     long long ans = 0;
120 |
121 |     for (int i = l; i <= r; i++)
122 |         e[d][id[d][a[i].id]].w = -INF; // 待修改边标
    |         ↪ 为-INF
123 |
124 |     Kruskal(m, e[d]);
125 |     copy(e[d] + 1, e[d] + m + 1, t + 1);
126 |
127 |     int cnt = 0;
128 |     for (int i = 1; i <= m; i++) {
129 |
130 |         if (t[i].w != -INF && t[i].vis) { // 必须边
131 |             ans += t[i].w;
132 |             mergeset(t[i].u, t[i].v);
133 |         }
134 |         else { // 不确定边
135 |             id[d][t[i].id]++;
136 |             e[d][cnt]=t[i];
137 |         }
138 |     }
139 |
140 |     for (int i = r; i >= l; i--) {
141 |         e[d][id[d][a[i].id]].w = a[i].u; // 把待修改的边
    |         ↪ 改回去
142 |         e[d][id[d][a[i].id]].vis = false;
143 |     }
144 |
145 |     m = cnt;
146 |
147 |     return ans;
148 | }
149 |
150 | // Kruskal算法 O(mlogn)
151 | // 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
    | ↪ 撤销即可
153 | long long Kruskal(int m, edge *e) {
154 |     int tmp = top;
155 |     long long ans = 0;
156 |
157 |     sort(e + 1, e + m + 1); // 比较函数在结构体中定义过了
158 |
159 |     for (int i = 1; i <= m; i++) {
160 |         if (findroot(e[i].u) != findroot(e[i].v)) {
161 |             e[i].vis = true;
162 |             ans += e[i].w;
163 |             mergeset(e[i].u, e[i].v);
164 |         }
165 |         else
166 |             e[i].vis = false;
167 |     }
168 |
169 |     for(int i = top; i > tmp; i--)
170 |         cut(stk[i]); // 撤销所有操作
171 |     top = tmp;
172 |
173 |     return ans;

```

```

174 | }
175 |
176 | // 以下是并查集相关函数
177 | int findroot(int x) { // 因为需要撤销,不写路径压缩
178 |     while (p[x] != x)
179 |         x = p[x];
180 |
181 |     return x;
182 | }
183 |
184 | void mergeset(int x, int y) { // 按size合并,如果想跑得更
    | ↪ 快就写一个按秩合并
186 |     x = findroot(x); // 但是按秩合并要再开一个栈记录合并
    | ↪ 之前的秩
187 |     y = findroot(y);
188 |
189 |     if (x == y)
190 |         return;
191 |
192 |     if (size[x] > size[y])
193 |         swap(x, y);
194 |
195 |     p[x] = y;
196 |     size[y] += size[x];
197 |     stk[++top] = x;
198 | }
199 |
200 | void cut(int x) { // 并查集撤销
201 |     int y = x;
202 |
203 |     do
204 |         size[y = p[y]] -= size[x];
205 |     while (p[y] != y);
206 |
207 |     p[x] = x;
208 | }

```

### 3.1.3 最小树形图(朱刘算法)

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.

### 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:

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

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 $O(n3^k + 2^k m \log n)$ .

## 3.2 最短路

### 3.2.1 Dijkstra

见k短路(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 $s$ , 跑一边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
  // 时最好还是用A*
2 // DAG和有环的情况都可以, 有重边或自环也无所谓, 但不能有
  // 零环
3 // 以下代码以Dijkstra + 可持久化左偏树为例
4
5 constexpr int maxn = 1005, maxe = 10005, maxm = maxe *
  // 30; // 点数, 边数, 左偏树结点数
6
7 // 结构体定义
8 struct A { // 用来求最短路
9     int x, d;
10
11     A(int x, int d) : x(x), d(d) {}
12
13     bool operator < (const A &a) const {
14         return d > a.d;
15     }
16 };
17
18 struct node { // 左偏树结点
19     int w, i, d; // i: 最后一条边的编号 d: 左偏树附加信息
20     node *lc, *rc;
21
22     node() {}
23
24     node(int w, int i) : w(w), i(i), d(0) {}
25
26     void refresh(){
27         d = rc -> d + 1;
28     }
29 } null[maxm], *ptr = null, *root[maxn];
30
31 struct B { // 维护答案用
32     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]; // 最开始要存反向
  // 图, 然后把G清空作为儿子列表
44 bool vis[maxn], used[maxe]; // used表示边是否在最短路上
45 int u[maxe], v[maxe], w[maxe]; // 存下每条边, 注意是有向边
46 int d[maxn], p[maxn]; // p表示最短路树上每个点的父边
47 int n, m, k, s, t; // s, t分别表示起点和终点
48
49 // 以下是主函数中较关键的部分
50 for (int i = 0; i <= n; i++)
51     root[i] = null; // 一定要加上!!!
52
53 // (读入&建反向图)
```

```
56 Dijkstra();
57
58 // (清空G, W, id)
59 for (int i = 1; i <= n; i++)
60     if (p[i]) {
61         used[p[i]] = true; // 在最短路树上
62         G[v[p[i]]].push_back(i);
63     }
64
65 for (int i = 1; i <= m; i++) {
66     w[i] -= d[u[i]] - d[v[i]]; // 现在的w[i]表示这条边能
      // 使路径长度增加多少
67     if (!used[i])
68         root[u[i]] = merge(root[u[i]], newnode(w[i], i));
69 }
70
71 dfs(t);
72
73 priority_queue<B> heap;
74 heap.push(B(s, root[s], 0)); // 初始状态是找贡献最小的边
  // 加进去
75
76 printf("%d\n", d[s]); // 第1短路需要特判
77 while (--k) { // 其余k - 1短路径用二叉堆维护
78     if (heap.empty())
79         printf("-1\n");
80     else {
81         int x = heap.top().x, w = heap.top().w;
82         node *rt = heap.top().rt;
83         heap.pop();
84
85         printf("%d\n", d[s] + w + rt -> w);
86
87         if (rt -> lc != null || rt -> rc != null)
88             heap.push(B(x, merge(rt -> lc, rt -> rc),
89                 // w)); // pop掉当前边, 换成另一条贡献大一点
90                 // 的边
91             if (root[v[rt -> i]] != null)
92                 heap.push(B(v[rt -> i], root[v[rt -> i]], w +
93                     // rt -> w)); // 保留当前边, 往后面再接上另
94                     // 一条边
95             }
96     }
97 }
98 // 主函数到此结束
99
100 // Dijkstra预处理最短路 O(m log n)
101 void Dijkstra() {
102     memset(d, 63, sizeof(d));
103     d[t] = 0;
104     priority_queue<A> heap;
105     heap.push(A(t, 0));
106
107     while (!heap.empty()) {
108         int x = heap.top().x;
109         heap.pop();
110
111         if (vis[x])
112             continue;
113
114         vis[x] = true;
115         for (int i = 0; i < (int)G[x].size(); i++)
116             if (!vis[G[x][i]] && d[G[x][i]] > d[x] + W[x][i]) {
117                 d[G[x][i]] = d[x] + W[x][i];
118                 p[G[x][i]] = id[x][i];
119                 heap.push(A(G[x][i], d[G[x][i]]));
120             }
121     }
122 }
```

```

119     }
120 }
121 // dfs求出每个点的堆 总计 $O(m \log n)$ 
122 // 需要调用merge, 同时递归调用自身
123 void dfs(int x) {
124     root[x] = merge(root[x], root[v[p[x]]]);
125
126     for (int i = 0; i < (int)G[x].size(); i++)
127         dfs(G[x][i]);
128 }
129
130 // 包装过的new node()  $O(1)$ 
131 node *newnode(int w, int i) {
132     *++ptr = node(w, i);
133     ptr -> lc = ptr -> rc = null;
134     return ptr;
135 }
136
137 // 带可持久化的左偏树合并 总计 $O(n \log n)$ 
138 // 递归调用自身
139 node *merge(node *x, node *y) {
140     if (x == null)
141         return y;
142     if (y == null)
143         return x;
144
145     if (x -> w > y -> w)
146         swap(x, y);
147
148     node *z = newnode(x -> w, x -> i);
149     z -> lc = x -> lc;
150     z -> rc = merge(x -> rc, y);
151
152     if (z -> lc -> d > z -> rc -> d)
153         swap(z -> lc, z -> rc);
154     z -> refresh();
155
156     return z;
157 }
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        }
17        else if (instk[y])
18            low[x] = min(low[x], dfn[y]);
19    }
20
21    if (dfn[x] == low[x]) {
22        scc_cnt++;
23
24        int u;

```

```

25        do {
26            u = stk[stk[0]--];
27            instk[u] = false;
28            sccid[u] = scc_cnt;
29            scc[scc_cnt].push_back(u);
30        } while (u != x);
31    }
32 }
33
34 void tarjan(int n) {
35     for (int i = 1; i <= n; i++)
36         if (!dfn[i])
37             dfs(i);
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 = 0;
3 bool iscut[maxn];
4
5 pair<int, int> stk[maxn];
6 int stk_cnt = 0;
7
8 void dfs(int x, int pr) {
9     int child = 0;
10    dfn[x] = low[x] = ++tim;
11
12    for (int y : G[x]) {
13        if (!dfn[y]) {
14            stk[++stk_cnt] = make_pair(x, y);
15            child++;
16            dfs(y, x);
17            low[x] = min(low[x], low[y]);
18
19            if (low[y] >= dfn[x]) {
20                iscut[x] = true;
21                bcc_cnt++;
22
23                while (true) {
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 == y)
36                        break;
37                }
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
46    if (!pr && child == 1)
47        iscut[x] = false;
48 }
49
50 void Tarjan(int n) {
51     for (int i = 1; i <= n; i++)

```

```

52     if (!dfn[i])
53         dfs(i, 0);
54 }

```

### 3.3.3 桥 边双

## 3.4 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。

### 3.4.1 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
7 vector<long long> d[maxn];
8
9 stack<int> stk;
10
11 int p[maxn];
12
13 bool vis[maxn], vise[maxn * 2];
14
15 int last[maxn], cnte;
16
17 long long f[maxn], g[maxn], sum[maxn];
18
19 int n, m, cnt;
20
21 void addedge(int x, int y, int w) {
22     v[x].push_back(make_pair(y, w));
23 }
24
25 void dfs(int x) {
26
27     vis[x] = true;
28
29     for (int i = last[x]; ~i; i = e[i].prev) {
30         if (vise[i ^ 1])
31             continue;
32
33         int y = e[i].to, w = e[i].w;
34
35         vise[i] = true;
36
37         if (!vis[y]) {
38             stk.push(i);
39             p[y] = x;
40             dfs(y);
41
42             if (!stk.empty() && stk.top() == i) {
43                 stk.pop();
44                 addedge(x, y, w);
45             }
46         }
47
48         else {
49             cnt++;
50
51             long long tmp = w;
52             while (!stk.empty()) {
53                 int i = stk.top();
54                 stk.pop();
55
56                 int yy = e[i].to, ww = e[i].w;
57

```

```

58         addedge(cnt, yy, 0);
59
60         d[cnt].push_back(tmp);
61
62         tmp += ww;
63
64         if (e[i ^ 1].to == y)
65             break;
66     }
67
68     addedge(y, cnt, 0);
69
70     sum[cnt] = tmp;
71 }
72
73 }
74
75 void dp(int x) {
76
77     for (auto o : v[x]) {
78         int y = o.first, w = o.second;
79         dp(y);
80     }
81
82     if (x <= n) {
83         for (auto o : v[x]) {
84             int y = o.first, w = o.second;
85
86             f[x] += 2 * w + f[y];
87         }
88
89         g[x] = f[x];
90
91         for (auto o : v[x]) {
92             int y = o.first, w = o.second;
93
94             g[x] = min(g[x], f[x] - f[y] - 2 * w + g[y] +
95                 ↪ w);
96         }
97     }
98     else {
99         f[x] = sum[x];
100         for (auto o : v[x]) {
101             int y = o.first;
102
103             f[x] += f[y];
104         }
105
106         g[x] = f[x];
107
108         for (int i = 0; i < (int)v[x].size(); i++) {
109             int y = v[x][i].first;
110
111             g[x] = min(g[x], f[x] - f[y] + g[y] +
112                 ↪ min(d[x][i], sum[x] - d[x][i]));
113         }
114     }
115 }

```

## 3.5 二分图

### 3.5.1 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 }

```

### 3.5.2 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], slack[maxn];
4 // 边权 顶标 slack
5 // 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
6 // 边对0取max
7 bool visx[maxn], visy[maxn];
8
9 int boy[maxn], girl[maxn], p[maxn], q[maxn], head, tail;
10 // p : pre
11
12 int n, m, N, e;
13
14 // 增广
15 bool check(int y) {
16     visy[y] = true;
17
18     if (boy[y]) {
19         visx[boy[y]] = true;
20         q[tail++] = boy[y];
21         return false;
22     }
23
24     while (y) {
25         boy[y] = p[y];
26         swap(y, girl[p[y]]);
27     }
28
29     return true;
30 }
31
32 // bfs每个点
33 void bfs(int x) {
34     memset(q, 0, sizeof(q));
35     head = tail = 0;
36
37     q[tail++] = x;
38     visx[x] = true;

```

```

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
78 // 主过程
79 long long KM() {
80     for (int i = 1; i <= N; i++) {
81         lx[i] = 0;
82         ly[i] = -INF;
83         // boy[i] = girl[i] = -1;
84
85         for (int j = 1; j <= N; j++)
86             ly[i] = max(ly[i], w[j][i]);
87     }
88
89     for (int i = 1; i <= N; i++) {
90         memset(slack, 0x3f, sizeof(slack));
91         memset(visx, 0, sizeof(visx));
92         memset(visy, 0, sizeof(visy));
93         bfs(i);
94     }
95
96     long long ans = 0;
97     for (int i = 1; i <= N; i++)
98         ans += w[i][girl[i]];
99     return ans;
100 }
101
102 // 为了方便贴上主函数
103 int main() {
104
105     scanf("%d%d%d", &n, &m, &e);

```

```

106 N = max(n, m);
107
108 while (e--) {
109     int x, y, c;
110     scanf("%d%d%d", &x, &y, &c);
111     w[x][y] = max(c, 0);
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 }

```

### 3.5.3 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.

## 3.6 一般图匹配

### 3.6.1 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,
  // 也更方便进行可行边的判定
2 // 注意这个算法复杂度是满的, 并且常数有点大, 而带花树通
  // 常是跑不满的
3 // 以及, 根据Tutte定理, 如果求最大匹配的大小的话直接输
  // 出Tutte矩阵的秩/2即可
4 // 需要输出方案时才需要再写后面那些乱七八糟的东西
5
6
7 // 复杂度和常数所限, 1s之内500已经是这个算法的极限了
8 const int maxn = 505, p = 1000000007; // p可以是任
  // 意10^9以内的质数
9
10 // 全局数组和变量定义

```

```

11 int A[maxn][maxn], B[maxn][maxn], t[maxn][maxn],
   // id[maxn], a[maxn];
12 bool row[maxn] = {false}, col[maxn] = {false};
13 int n, m, girl[maxn]; // girl是匹配点, 用来输出方案
14
15 // 为了方便使用, 贴上主函数
16 // 需要调用高斯消元和eliminate
17 int main() {
18     srand(19260817);
19
20     scanf("%d", &n, &m); // 点数和边数
21     while (m--) {
22         int x, y;
23         scanf("%d", &x, &y);
24         A[x][y] = rand() % p;
25         A[y][x] = -A[x][y]; // Tutte矩阵是反对称矩阵
26     }
27
28     for (int i = 1; i <= n; i++)
29         id[i] = i; // 输出方案用的, 因为高斯消元的时候会
   // 交换列
30     memcpy(t, A, sizeof(t));
31     Gauss(A, NULL, n);
32
33     m = n;
34     n = 0; // 这里变量复用纯属个人习惯
35
36     for (int i = 1; i <= m; i++)
37         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]] && B[j]
   // 注意上面那句if的写法, 现在t是邻接
   // 矩阵的备份,
   // 逆矩阵j行i列不为0当且仅当这条边可
   // 行
50                     && t[a[i]][a[j]] && B[j]
51                         && t[a[i]][a[j]] && B[j]
52                         && t[a[i]][a[j]] && B[j]
53                         && t[a[i]][a[j]] && B[j]
54                         && t[a[i]][a[j]] && B[j]
55                         && t[a[i]][a[j]] && B[j]
56                         && t[a[i]][a[j]] && B[j]
57                         && t[a[i]][a[j]] && B[j]
58                         && t[a[i]][a[j]] && B[j]
59                         && t[a[i]][a[j]] && B[j]
60                         && t[a[i]][a[j]] && B[j]
61                         && t[a[i]][a[j]] && B[j]
62                         && t[a[i]][a[j]] && B[j]
63                         && t[a[i]][a[j]] && B[j]
64                         && t[a[i]][a[j]] && B[j]
65                         && t[a[i]][a[j]] && B[j]
66                         && t[a[i]][a[j]] && B[j]
67                         && t[a[i]][a[j]] && B[j]
68                         && t[a[i]][a[j]] && B[j]
69                         && t[a[i]][a[j]] && B[j]
70                         && t[a[i]][a[j]] && B[j]
71                         && t[a[i]][a[j]] && B[j]
72                         && t[a[i]][a[j]] && B[j]
73                         && t[a[i]][a[j]] && B[j]
74                         && t[a[i]][a[j]] && B[j]
75                         && t[a[i]][a[j]] && B[j]
76                         && t[a[i]][a[j]] && B[j]
77                         && t[a[i]][a[j]] && B[j]
78                         && t[a[i]][a[j]] && B[j]
79                         && t[a[i]][a[j]] && B[j]
80                         && t[a[i]][a[j]] && B[j]
81                         && t[a[i]][a[j]] && B[j]
82                         && t[a[i]][a[j]] && B[j]
83                         && t[a[i]][a[j]] && B[j]
84                         && t[a[i]][a[j]] && B[j]
85                         && t[a[i]][a[j]] && B[j]
86                         && t[a[i]][a[j]] && B[j]
87                         && t[a[i]][a[j]] && B[j]
88                         && t[a[i]][a[j]] && B[j]
89                         && t[a[i]][a[j]] && B[j]
90                         && t[a[i]][a[j]] && B[j]
91                         && t[a[i]][a[j]] && B[j]
92                         && t[a[i]][a[j]] && B[j]
93                         && t[a[i]][a[j]] && B[j]
94                         && t[a[i]][a[j]] && B[j]
95                         && t[a[i]][a[j]] && B[j]
96                         && t[a[i]][a[j]] && B[j]
97                         && t[a[i]][a[j]] && B[j]
98                         && t[a[i]][a[j]] && B[j]
99                         && t[a[i]][a[j]] && B[j]
100                        && t[a[i]][a[j]] && B[j]

```

```

75 for (int i = 1; i <= n; i++) {
76     if (!A[i][i]) {
77         for (int j = i + 1; j <= n; j++)
78             if (A[j][i]) {
79                 swap(id[i], id[j]);
80                 for (int k = i; k <= n; k++)
81                     swap(A[i][k], A[j][k]);
82             }
83             if (B)
84                 for (int k = 1; k <= n; k++)
85                     swap(B[i][k], B[j][k]);
86             break;
87         }
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 long)t
102                     ↪ * 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
108                         ↪ long)t * B[i][k]) % p;
109     }
110 }
111
112 if (B)
113     for (int i = 1; i <= n; i++) {
114         int inv = qpow(A[i][i], p - 2);
115
116         for (int j = 1; j <= n; j++)
117             if (B[i][j])
118                 B[i][j] = (long long)B[i][j] * inv %
119                 ↪ p;
120     }
121 // 消去一行一列  $O(n^2)$ 
122 void eliminate(int r, int c) {
123     row[r] = col[c] = true; // 已经被消掉
124
125     int inv = qpow(B[r][c], p - 2);
126
127     for (int i = 1; i <= n; i++)
128         if (!row[i] && B[i][c]) {
129             int t = (long long)B[i][c] * inv % p;
130
131             for (int j = 1; j <= n; j++)
132                 if (!col[j] && B[r][j])
133                     B[i][j] = (B[i][j] - (long long)t *
134                         ↪ B[r][j]) % p;
135 }

```

## 3.6.2 带花树

```

1 // 带花树通常比高斯消元快很多, 但在只要求最大匹配大小
2 // 的时候并没有高斯消元好写
3 // 当然输出方案要方便很多
4 // 全局数组与变量定义
5 vector<int> G[maxn];
6 int girl[maxn], f[maxn], t[maxn], p[maxn], vis[maxn],
7     ↪ tim, q[maxn], head, tail;
8 int n, m;
9
10 // 封装好的主过程  $O(nm)$ 
11 int blossom() {
12     int ans = 0;
13
14     for (int i = 1; i <= n; i++)
15         if (!girl[i])
16             ans += bfs(i);
17
18     return ans;
19 }
20
21 // bfs找增广路  $O(m)$ 
22 bool bfs(int s) {
23     memset(t, 0, sizeof(t));
24     memset(p, 0, sizeof(p));
25
26     for (int i = 1; i <= n; i++)
27         f[i] = i; // 并查集
28
29     head = tail = 0;
30     q[tail++] = s;
31     t[s] = 1;
32
33     while (head != tail) {
34         int x = q[head++];
35         for (int y : G[x]) {
36             if (findroot(y) == findroot(x) || t[y] == 2)
37                 continue;
38
39             if (!t[y]) {
40                 t[y] = 2;
41                 p[y] = x;
42
43                 if (!girl[y]) {
44                     for (int u = y, t; u = t) {
45                         t = girl[p[u]];
46                         girl[p[u]] = u;
47                         girl[u] = p[u];
48                     }
49                     return true;
50                 }
51             }
52
53             t[girl[y]] = 1;
54             q[tail++] = girl[y];
55         }
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 //缩奇环  $O(n)$ 
68 void shrink(int x, int y, int z) {
69     while (findroot(x) != z) {
70         p[x] = y;
71         y = girl[x];
72
73         if (t[y] == 2) {
74             t[y] = 1;
75             q[tail++] = y;
76         }
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
106 //并查集的查找  $O(1)$ 
107 int findroot(int x) {
108     return x == f[x] ? x : (f[x] = findroot(f[x]));
109 }

```

### 3.6.3 带权带花树

(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  $INF - g[u]$ 
  //  $\hookrightarrow [v].w$  when minimum weight blossom is needed
2 //type of ans is Long Long
3 //replace all int to Long Long if weight of edge is Long
  //  $\hookrightarrow$  Long
4
5 struct WeightGraph {
6     static const int INF = INT_MAX;
7     static const int MAXN = 400;
8     struct edge {
9         int u, v, w;
10        edge() {}
11        edge(int u, int v, int w): u(u), v(v), w(w) {}
12    };
13    int n, n_x;
14    edge g[MAXN * 2 + 1][MAXN * 2 + 1];
15    int lab[MAXN * 2 + 1];
16    int match[MAXN * 2 + 1], slack[MAXN * 2 + 1], st[MAXN * 2 + 1], pa[MAXN * 2 + 1];
17    int flower_from[MAXN * 2 + 1][MAXN + 1], S[MAXN * 2 + 1], vis[MAXN * 2 + 1];

```

```

18 vector<int> flower[MAXN * 2 + 1];
19 queue<int> q;
20 inline int e_delta(const edge &e){ // does not work
  //  $\hookrightarrow$  inside blossoms
21     return lab[e.u] + lab[e.v] - g[e.u][e.v].w * 2;
22 }
23 inline void update_slack(int u, int x){
24     if(!slack[x] || e_delta(g[u][x]) <
  //  $\hookrightarrow$  e_delta(g[slack[x]][x]))
25         slack[x] = u;
26 }
27 inline void set_slack(int x){
28     slack[x] = 0;
29     for(int u = 1; u <= n; ++u)
30         if(g[u][x].w > 0 && st[u] != x && S[st[u]] ==
  //  $\hookrightarrow$  0)
31             update_slack(u, x);
32 }
33 void q_push(int x){
34     if(x <= n)q.push(x);
35     else for(size_t i = 0; i < flower[x].size(); i++)
36         q_push(flower[x][i]);
37 }
38 inline void set_st(int x, int b){
39     st[x]=b;
40     if(x > n) for(size_t i = 0; i < flower[x].size();
  //  $\hookrightarrow$  ++i)
41         set_st(flower[x][i], b);
42 }
43 inline int get_pr(int b, int xr){
44     int pr = find(flower[b].begin(), flower[b].end(),
  //  $\hookrightarrow$  xr) - flower[b].begin();
45     if(pr % 2 == 1){
46         reverse(flower[b].begin() + 1,
  //  $\hookrightarrow$  flower[b].end());
47         return (int)flower[b].size() - pr;
48     } else return pr;
49 }
50 inline void set_match(int u, int v){
51     match[u]=g[u][v].v;
52     if(u > n){
53         edge e=g[u][v];
54         int xr = flower_from[u][e.u], pr=get_pr(u,
  //  $\hookrightarrow$  xr);
55         for(int i = 0; i < pr; ++i)
56             set_match(flower[u][i], flower[u][i ^
  //  $\hookrightarrow$  1]);
57         set_match(xr, v);
58         rotate(flower[u].begin(),
  //  $\hookrightarrow$  flower[u].begin()+pr, flower[u].end());
59     }
60 }
61 inline void augment(int u, int v){
62     for(;;){
63         int xnv=st[match[u]];
64         set_match(u, v);
65         if(!xnv)return;
66         set_match(xnv, st[pa[xnv]]);
67         u=st[pa[xnv]], v=xnv;
68     }
69 }
70 inline int get_lca(int u, int v){
71     static int t=0;
72     for(++t; u || v; swap(u, v)){
73         if(u == 0)continue;
74         if(vis[u] == t)return u;
75         vis[u] = t;
76         u = st[match[u]];

```

```

77     if(u) u = st[pa[u]];
78 }
79 return 0;
80 }
81 inline void add_blossom(int u, int lca, int v){
82     int b = n + 1;
83     while(b <= n_x && st[b]) ++b;
84     if(b > n_x) ++n_x;
85     lab[b] = 0, S[b] = 0;
86     match[b] = match[lca];
87     flower[b].clear();
88     flower[b].push_back(lca);
89     for(int x = u, y; x != lca; x = st[pa[y]]) {
90         flower[b].push_back(x),
91         flower[b].push_back(y = st[match[x]]),
92         q_push(y);
93     }
94     reverse(flower[b].begin() + 1, flower[b].end());
95     for(int x = v, y; x != lca; x = st[pa[y]]) {
96         flower[b].push_back(x),
97         flower[b].push_back(y = st[match[x]]),
98         q_push(y);
99     }
100     set_st(b, b);
101     for(int x = 1; x <= n_x; ++x) g[b][x].w = g[x]
102     ↪ [b].w = 0;
103     for(int x = 1; x <= n; ++x) flower_from[b][x] =
104     ↪ 0;
105     for(size_t i = 0; i < flower[b].size(); ++i){
106         int xs = flower[b][i];
107         for(int x = 1; x <= n_x; ++x)
108             if(g[b][x].w == 0 || e_delta(g[xs][x]) <
109             ↪ e_delta(g[b][x]))
110                 g[b][x] = g[xs][x], g[x][b] = g[x]
111                 ↪ [xs];
112         for(int x = 1; x <= n; ++x)
113             if(flower_from[xs][x]) flower_from[b][x]
114             ↪ = xs;
115     }
116     set_slack(b);
117 }
118 inline void expand_blossom(int b){ // S[b] == 1
119     for(size_t i = 0; i < flower[b].size(); ++i)
120         set_st(flower[b][i], flower[b][i]);
121     int xr = flower_from[b][g[b][pa[b]].u], pr =
122     ↪ get_pr(b, xr);
123     for(int i = 0; i < pr; i += 2){
124         int xs = flower[b][i], xns = flower[b][i +
125         ↪ 1];
126         pa[xs] = g[xns][xs].u;
127         S[xs] = 1, S[xns] = 0;
128         slack[xs] = 0, set_slack(xns);
129         q_push(xns);
130     }
131     S[xr] = 1, pa[xr] = pa[b];
132     for(size_t i = pr + 1; i < flower[b].size(); ++i){
133         int xs = flower[b][i];
134         S[xs] = -1, set_slack(xs);
135     }
136     st[b] = 0;
137 }
138 inline bool on_found_edge(const edge &e){
139     int u = st[e.u], v = st[e.v];
140     if(S[v] == -1){
141         pa[v] = e.u, S[v] = 1;
142         int nu = st[match[v]];
143         slack[v] = slack[nu] = 0;
144         S[nu] = 0, q_push(nu);
145     }else if(S[v] == 0){

```

```

139     int lca = get_lca(u, v);
140     if(!lca) return augment(u, v), augment(v, u),
141     ↪ true;
142     else add_blossom(u, lca, v);
143 }
144 return false;
145 }
146 inline bool matching(){
147     memset(S + 1, -1, sizeof(int) * n_x);
148     memset(slack + 1, 0, sizeof(int) * n_x);
149     q = queue<int>();
150     for(int x = 1; x <= n_x; ++x)
151         if(st[x] == x && !match[x]) pa[x]=0, S[x]=0,
152         ↪ q_push(x);
153     if(q.empty())return false;
154     for(;;){
155         while(q.size()){
156             int u = q.front();q.pop();
157             if(S[st[u]] == 1)continue;
158             for(int v = 1; v <= n; ++v)
159                 if(g[u][v].w > 0 && st[u] != st[v]){
160                     if(e_delta(g[u][v]) == 0){
161                         if(on_found_edge(g[u]
162                         ↪ [v]))return true;
163                     }else update_slack(u, st[v]);
164                 }
165             int d = INF;
166             for(int b = n + 1; b <= n_x; ++b)
167                 if(st[b] == b && S[b] == 1)d = min(d,
168                 ↪ lab[b]/2);
169             for(int x = 1; x <= n_x; ++x)
170                 if(st[x] == x && slack[x]){
171                     if(S[x] == -1)d = min(d,
172                     ↪ e_delta(g[slack[x]][x]));
173                     else if(S[x] == 0)d = min(d,
174                     ↪ e_delta(g[slack[x]][x])/2);
175                 }
176             for(int u = 1; u <= n; ++u){
177                 if(S[st[u]] == 0){
178                     if(lab[u] <= d)return 0;
179                     lab[u] -= d;
180                     }else if(S[st[u]] == 1)lab[u] += d;
181             }
182             q=queue<int>();
183             for(int x = 1; x <= n_x; ++x)
184                 if(st[x] == x && slack[x] && st[slack[x]]
185                 ↪ != x && e_delta(g[slack[x]][x]) == 0)
186                     if(on_found_edge(g[slack[x]]
187                     ↪ [x]))return true;
188             for(int b = n + 1; b <= n_x; ++b)
189                 if(st[b] == b && S[b] == 1 && lab[b] ==
190                 ↪ 0)expand_blossom(b);
191             }
192             return false;
193 }
194 inline pair<long long, int> solve(){
195     memset(match + 1, 0, sizeof(int) * n);
196     n_x = n;
197     int n_matches = 0;
198     long long tot_weight = 0;

```

```

196     for(int u = 0; u <= n; ++u) st[u] = u,
        ↳ flower[u].clear();
197     int w_max = 0;
198     for(int u = 1; u <= n; ++u)
199         for(int v = 1; v <= n; ++v){
200             flower_from[u][v] = (u == v ? u : 0);
201             w_max = max(w_max, g[u][v].w);
202         }
203     for(int u = 1; u <= n; ++u) lab[u] = w_max;
204     while(matching()) ++n_matches;
205     for(int u = 1; u <= n; ++u)
206         if(match[u] && match[u] < u)
207             tot_weight += g[u][match[u]].w;
208     return make_pair(tot_weight, n_matches);
209 }
210 inline void init(){
211     for(int u = 1; u <= n; ++u)
212         for(int v = 1; v <= n; ++v)
213             g[u][v] = edge(u, v, 0);
214 }
215 };

```

### 3.6.4 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.

## 3.7 2-SAT

如果限制满足对称性, 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.

如果要字典序最小或者不满足对称性就用dfs, 注意可以压位优化.

## 3.8 最大流

### 3.8.1 Dinic

```

1 // 注意Dinic适用于二分图或分层图, 对于一般稀疏图ISAP更
  ↳ 优, 稠密图则HLPP更优
2
3 struct edge{
4     int to, cap, prev;
5 } e[maxe * 2];
6
7 int last[maxn], len, d[maxn], cur[maxn], q[maxn];

```

```

8
9 memset(last, -1, sizeof(last));
10
11 void AddEdge(int x, int y, int z) {
12     e[len].to = y;
13     e[len].cap = z;
14     e[len].prev = last[x];
15     last[x] = len++;
16 }
17
18 int Dinic() {
19     int flow = 0;
20     while (bfs(), ~d[t]) {
21         memcpy(cur, last, sizeof(int) * (t + 5));
22         flow += dfs(s, inf);
23     }
24     return flow;
25 }
26
27 void bfs() {
28     int head = 0, tail = 0;
29     memset(d, -1, sizeof(int) * (t + 5));
30     q[tail++] = s;
31     d[s] = 0;
32
33     while (head != tail){
34         int x = q[head++];
35         for (int i = last[x]; ~i; i = e[i].prev)
36             if (e[i].cap > 0 && d[e[i].to] == -1) {
37                 d[e[i].to] = d[x] + 1;
38                 q[tail++] = e[i].to;
39             }
40     }
41 }
42
43 int dfs(int x, int a) {
44     if (x == t || !a)
45         return a;
46
47     int flow = 0, f;
48     for (int &i = cur[x]; ~i; i = e[i].prev)
49         if (e[i].cap > 0 && d[e[i].to] == d[x] + 1 && (f
50             ↳ = dfs(e[i].to, min(e[i].cap, a)))) {
51
52             e[i].cap -= f;
53             e[i^1].cap += f;
54             flow += f;
55             a -= f;
56
57             if (!a)
58                 break;
59         }
60     return flow;
61 }

```

### 3.8.2 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
  ↳ 况Dinic比较优, 稠密图则HLPP更优
2
3 // 边的定义
4 // 这里没有记录起点和反向边, 因为反向边即为正向边xor 1,
  ↳ 起点即为反向边的终点
5 struct edge{
6     int to, cap, prev;
7 } e[maxe * 2];

```



```

8 // 全局变量和数组定义
9 int last[maxn], cnte = 0, d[maxn], p[maxn], c[maxn],
  ↪ cur[maxn], q[maxn];
10 int n, m, s, t; // s, t一定要开成全局变量
11
12 void AddEdge(int x, int y, int z) {
13     e[cnte].to = y;
14     e[cnte].cap = z;
15     e[cnte].prev = last[x];
16     last[x] = cnte++;
17 }
18
19 void addedge(int x, int y, int z) {
20     AddEdge(x, y, z);
21     AddEdge(y, x, 0);
22 }
23
24 // 预处理到t的距离标号
25 // 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
26 void bfs() {
27     memset(d, -1, sizeof(d));
28
29     int head = 0, tail = 0;
30     d[t] = 0;
31     q[tail++] = t;
32
33     while (head != tail) {
34         int x = q[head++];
35         c[d[x]]++;
36
37         for (int i = last[x]; ~i; i = e[i].prev)
38             if (e[i ^ 1].cap && d[e[i].to] == -1) {
39                 d[e[i].to] = d[x] + 1;
40                 q[tail++] = e[i].to;
41             }
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
  ↪ 变量记录下来并修改代码
62 int ISAP() {
63     bfs();
64
65     memcpy(cur, last, sizeof(cur));
66
67     int x = s, flow = 0;
68
69     while (d[s] < n) {
70         if (x == t) { // 如果走到了t就增广一次, 并返回s重
  ↪ 新找增广路
71             flow += augment();
72             x = s;
73         }
74     }

```

```

75     bool ok = false;
76     for (int &i = cur[x]; ~i; i = e[i].prev)
77         if (e[i].cap && d[x] == d[e[i].to] + 1) {
78             p[e[i].to] = i;
79             x = e[i].to;
80
81             ok = true;
82             break;
83         }
84
85     if (!ok) { // 修改距离标号
86         int tmp = n - 1;
87         for (int i = last[x]; ~i; i = e[i].prev)
88             if (e[i].cap)
89                 tmp = min(tmp, d[e[i].to] + 1);
90
91         if (!--c[d[x]])
92             break; // gap优化, 一定要加上
93
94         c[d[x] = tmp]++;
95         cur[x] = last[x];
96
97         if (x != s)
98             x = e[p[x] ^ 1].to;
99     }
100 }
101 return flow;
102 }
103
104 // 重要! main函数最前面一定要加上如下初始化
105 memset(last, -1, sizeof(last));
106

```

### 3.8.3 HLPP最高标号预流推进

```

1 #include <bits/stdc++.h>
2
3 using namespace std;
4
5 constexpr int maxn = 1205, maxe = 120005, inf =
  ↪ 2147483647;
6
7 struct edge {
8     int to, cap, prev;
9 } e[maxe * 2];
10
11 int n, m, s, t;
12 int last[maxn], cnte;
13 int h[maxn], ex[maxn], gap[maxn * 2];
14 bool inq[maxn];
15
16 struct cmp {
17     bool operator() (int x, int y) const {
18         return h[x] < h[y];
19     }
20 };
21
22 priority_queue<int, vector<int>, cmp> heap;
23
24 void AddEdge(int x, int y, int z) {
25     e[cnte].to = y;
26     e[cnte].cap = z;
27     e[cnte].prev = last[x];
28     last[x] = cnte++;
29 }
30
31 void addedge(int x, int y, int z) {
32     AddEdge(x, y, z);
33     AddEdge(y, x, 0);
34 }

```

```

34 }
35
36 bool bfs() {
37     static int q[maxn];
38
39     fill(h, h + n + 1, 2 * n);
40     int head = 0, tail = 0;
41     q[tail++] = t;
42     h[t] = 0;
43
44     while (head < tail) {
45         int x = q[head++];
46         for (int i = last[x]; ~i; i = e[i].prev)
47             if (e[i].cap && h[e[i].to] > h[x] + 1) {
48                 h[e[i].to] = h[x] + 1;
49                 q[tail++] = e[i].to;
50             }
51     }
52
53     return h[s] < 2 * n;
54 }
55
56 void push(int x) {
57     for (int i = last[x]; ~i; i = e[i].prev)
58         if (e[i].cap && h[x] == h[e[i].to] + 1) {
59             int d = min(ex[x], e[i].cap);
60
61             e[i].cap -= d;
62             e[i ^ 1].cap += d;
63             ex[x] -= d;
64             ex[e[i].to] += d;
65
66             if (e[i].to != s && e[i].to != t &&
67                 !inq[e[i].to]) {
68                 heap.push(e[i].to);
69                 inq[e[i].to] = true;
70             }
71
72             if (!ex[x])
73                 break;
74         }
75
76 void relabel(int x) {
77     h[x] = 2 * n;
78
79     for (int i = last[x]; ~i; i = e[i].prev)
80         if (e[i].cap)
81             h[x] = min(h[x], h[e[i].to] + 1);
82 }
83
84 int hlpp() {
85     if (!bfs())
86         return 0;
87
88     // memset(gap, 0, sizeof(int) * 2 * n);
89     h[s] = n;
90
91     for (int i = 1; i <= n; i++)
92         gap[h[i]]++;
93
94     for (int i = last[s]; ~i; i = e[i].prev)
95         if (e[i].cap) {
96             int d = e[i].cap;
97
98             e[i].cap -= d;
99             e[i ^ 1].cap += d;
100             ex[s] -= d;
101             ex[e[i].to] += d;
102

```

```

103         if (e[i].to != s && e[i].to != t &&
104             !inq[e[i].to]) {
105             heap.push(e[i].to);
106             inq[e[i].to] = true;
107         }
108     }
109
110     while (!heap.empty()) {
111         int x = heap.top();
112         heap.pop();
113         inq[x] = false;
114
115         push(x);
116         if (ex[x]) {
117             if (!--gap[h[x]]) { // gap
118                 for (int i = 1; i <= n; i++)
119                     if (i != s && i != t && h[i] > h[x])
120                         h[i] = n + 1;
121             }
122
123             relabel(x);
124             ++gap[h[x]];
125             heap.push(x);
126             inq[x] = true;
127         }
128     }
129
130     return ex[t];
131 }
132
133 int main() {
134     memset(last, -1, sizeof(last));
135
136     scanf("%d%d%d", &n, &m, &s, &t);
137
138     while (m--) {
139         int x, y, z;
140         scanf("%d%d%d", &x, &y, &z);
141         addedge(x, y, z);
142     }
143
144     printf("%d\n", hlpp());
145
146     return 0;
147 }

```

## 3.9 费用流

### 3.9.1 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
8     // 化成-1, 不然会死循环
9 bool inq[maxn];
10
11 void spfa(int s) {
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 int mcmf(int s, int t) {
41     int ans = 0;
42
43     while (spfa(s), d[t] > 0) {
44         int flow = 0x3f3f3f3f;
45         for (int x = t; x != s; x = e[p[x] ^ 1].to)
46             flow = min(flow, e[p[x]].cap);
47
48         ans += flow * d[t];
49
50         for (int x = t; x != s; x = e[p[x] ^ 1].to) {
51             e[p[x]].cap -= flow;
52             e[p[x] ^ 1].cap += flow;
53         }
54     }
55
56     return ans;
57 }
58
59 void add(int x, int y, int c, int w) {
60     e[cnte].to = y;
61     e[cnte].cap = c;
62     e[cnte].w = w;
63
64     e[cnte].prev = last[x];
65     last[x] = cnte++;
66 }
67
68 void addedge(int x, int y, int c, int w) {
69     add(x, y, c, w);
70     add(y, x, 0, -w);
71 }
72

```

### 3.9.2 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。

代码待补充

## 3.10 网络流原理

### 3.10.1 最小割

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

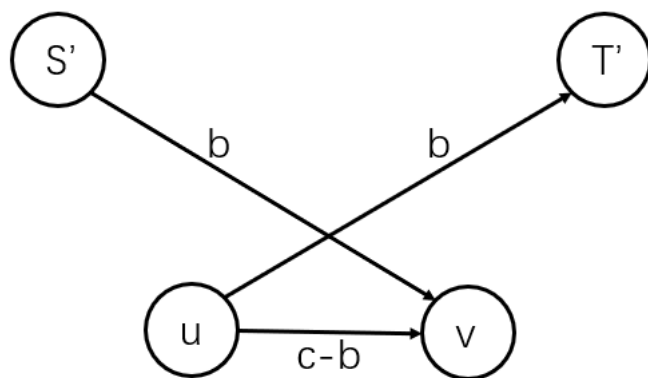
- 可行边：满流，且残量网络上不存在 $S$ 到 $T$ 的路径，也就是 $S$ 和 $T$ 不在同一SCC中。
- 必须边：满流，且残量网络上 $S$ 可达起点，终点可达 $T$ 。

### 3.10.2 费用流

### 3.10.3 上下界网络流

有源汇上下界最大流

新建超级源汇 $S', T'$ ，然后如图所示转化每一条边。



然后从 $S'$ 到 $S$ ，从 $T$ 到 $T'$ 分别连容量为正无穷的边即可。

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，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。

无源汇上下界可行流

转化方法和上面的图是一样的，只不过不需要考虑原有的源汇了。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。

### 3.10.4 常见建图方法

### 3.10.5 例题

## 3.11 弦图相关

From NEW CODE!!

- 团数  $\leq$  色数，弦图团数 = 色数
- 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。
- 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
- 最大独立集：完美消除序列从前往后能选就选
- 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

## 4. 数据结构

### 4.1 线段树

#### 4.1.1 非递归线段树

让fstqwq手撕

- 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
17 int query(int l, int r) {
18     int ans = 0, len = 1, cntl = 0, cntr = 0;
19     for (l += n - 1, r += n + 1; l ^ r ^ 1; l >>= 1, r
20         >>= 1, len <= 1) {
21         ans += cntl * mark[l] + cntr * mark[r];
22         if (~l & 1) ans += tree[l ^ 1], cntl += len;
23         if (r & 1) ans += tree[r ^ 1], cntr += len;
24    }
25
26    for (; l; l >>= 1, r >>= 1)
27        ans += cntl * mark[l] + cntr * mark[r];
28
29    return ans;
30 }
```

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 | 1])
6                 + mark[l];
7             tree[r] = max(tree[r << 1], tree[r << 1 | 1])
8                 + mark[r];
9         }
10
11        if (~l & 1) {
12            tree[l ^ 1] += d;
13            mark[l ^ 1] += d;
14        }
15
16        if (r & 1) {
17            tree[r ^ 1] += d;
18            mark[r ^ 1] += d;
19        }
20    }
21
22    for (; l; l >>= 1, r >>= 1)
23        if (l < N) tree[l] = max(tree[l << 1], tree[l <<
24            1 | 1]) + mark[l],
25            tree[r] = max(tree[r << 1], tree[r <<
26                1 | 1]) + mark[r];
27 }
28
29 void query(int l, int r) {
30     int maxl = -INF, maxr = -INF;
31
32     for (l += N - 1, r += N + 1; l ^ r ^ 1; l >>= 1, r
33         >>= 1) {
34         maxl += mark[l];
35         maxr += mark[r];
36
37         if (~l & 1)
38             maxl = max(maxl, tree[l ^ 1]);
39         if (r & 1)
40             maxr = max(maxr, tree[r ^ 1]);
41    }
42
43    while (l) {
44        maxl += mark[l];
45        maxr += mark[r];
46
47        l >>= 1;
48        r >>= 1;
49    }
50
51    return max(maxl, maxr);
52 }
```

#### 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 #include <bits/stdc++.h>
2
3 using namespace std;
4
5 constexpr int maxn = 100005, maxm = maxn * 70;
6
7 int lc[maxm], rc[maxm], cover[maxm], sum[maxm], root,
8     seg_cnt;
9 int s, t, d;
10 void refresh(int l, int r, int o) {
```

```

11     if (cover[o])
12         sum[o] = r - 1 + 1;
13     else
14         sum[o] = sum[lc[o]] + sum[rc[o]];
15 }
16
17 void modify(int l, int r, int &o) {
18     if (!o)
19         o = ++seg_cnt;
20
21     if (s <= l && t >= r) {
22         cover[o] += d;
23         refresh(l, r, o);
24
25         return;
26     }
27
28     int mid = (l + r) / 2;
29
30     if (s <= mid)
31         modify(l, mid, lc[o]);
32     if (t > mid)
33         modify(mid + 1, r, rc[o]);
34
35     refresh(l, r, o);
36 }
37
38 struct modi {
39     int x, l, r, d;
40
41     bool operator < (const modi &o) {
42         return x < o.x;
43     }
44 } a[maxn * 2];
45
46 int main() {
47
48     int n;
49     scanf("%d", &n);
50
51     for (int i = 1; i <= n; i++) {
52         int lx, ly, rx, ry;
53         scanf("%d%d%d%d", &lx, &ly, &rx, &ry);
54
55         a[i * 2 - 1] = {lx, ly + 1, ry, 1};
56         a[i * 2] = {rx, ly + 1, ry, -1};
57     }
58
59     sort(a + 1, a + n * 2 + 1);
60
61     int last = -1;
62     long long ans = 0;
63
64     for (int i = 1; i <= n * 2; i++) {
65         if (last != -1)
66             ans += (long long)(a[i].x - last) * sum[1];
67         last = a[i].x;
68
69         s = a[i].l;
70         t = a[i].r;
71         d = a[i].d;
72
73         modify(1, 1e9, root);
74     }
75
76     printf("%lld\n", ans);
77
78     return 0;
79 }

```

### 4.1.3 主席树

这种东西能不能手撕啊

## 4.2 陈丹琦分治

```

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 = 1;
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 + 1, b + r + 1, a + 1); // 后面的分治会破坏排
    → 序, 所以要复制一份
36
37    CDQ2(l, r);
38 }
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 = 1;
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             b[j].ins = true;
63             t[k++] = b[j++];
64         }
65     }
66
67     while (i <= mid) {
68         if (b[i].ins)
69             t[k++] = b[i++];
70     }
71
72     while (j <= r) {
73         b[j].ins = false;
74         t[k++] = b[j++];
75     }
76
77     copy(t + 1, t + r + 1, b + 1);
78 }

```

```

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 + 1);
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询问的 $k$ 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。

### 4.4 平衡树

pb\_ds平衡树在misc(倒数第二章)里。

#### 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, 优先级
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
15 // 个垃圾回收
16 // 注意: 数组里的元素一定不能delete, 否则会导致RE
17
18 // 重要!在主函数最开始一定要加上以下预处理:
19 null -> ch[0] = null -> ch[1] = null;
20 null -> size = 0;
21
22 // 伪构造函数  $O(1)$ 
23 // 为了方便, 在结点类外面再定义一个伪构造函数
24 node *newnode(int x) { // 键值为x
25     *++ptr = node(x);
26     ptr -> ch[0] = ptr -> ch[1] = null;
27     return ptr;
28 }
29
30 // 插入键值 期望 $O(\log n)$ 
31 // 需要调用旋转

```

```

30 void insert(int x, node *&rt) { // rt为当前结点, 建议调用
31     // 时传入root, 下同
32     if (rt == null) {
33         rt = newnode(x);
34         return;
35     }
36
37     int d = x > rt -> key;
38     insert(x, rt -> ch[d]);
39     rt -> refresh();
40
41     if (rt -> ch[d] -> p < rt -> p)
42         rot(rt, d ^ 1);
43 }
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             int d = rt -> ch[0] -> p < rt -> ch[1] -> p;
52             rot(rt, d);
53             erase(x, rt -> ch[d]);
54         }
55         else
56             rt = rt -> ch[rt -> ch[0] == null];
57     }
58     else
59         erase(x, rt -> ch[x > rt -> key]);
60
61     if (rt != null)
62         rt -> refresh();
63 }
64
65 // 求元素的排名(严格小于键值的个数 + 1) 期望 $O(\log n)$ 
66 // 非递归
67 int rank(int x, node *&rt) {
68     int ans = 1, d;
69     while (rt != null) {
70         if ((d = x > rt -> key))
71             ans += rt -> ch[0] -> size + 1;
72
73         rt = rt -> ch[d];
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     return rt;
92 }
93
94 // 返回前驱(最大的比给定键值小的键值)对应的指针 期
95 // 望 $O(\log n)$ 
96 // 非递归
97 node *pred(int x, node *&rt) {

```

```

98     node *y = null;
99     int d;
100
101     while (rt != null) {
102         if ((d = x > rt -> key))
103             y = rt;
104
105         rt = rt -> ch[d];
106     }
107
108     return y;
109 }
110
111 // 返回后继最小的比给定键值大的键值对应的指针 期
112 // 望  $O(\log n)$ 
113 // 非递归
114 node *succ(int x, node *rt) {
115     node *y = null;
116     int d;
117
118     while (rt != null) {
119         if ((d = x < rt -> key))
120             y = rt;
121
122         rt = rt -> ch[d ^ 1];
123     }
124
125     return y;
126 }
127
128 // 旋转(Treap版本)  $O(1)$ 
129 // 平衡树基础操作
130 // 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
131 // 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, 直接用就
14 // 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     node *z;
24     if (rand() % (x -> size + y -> size) < x -> size) {
25         z = copied(y);
26         z -> ch[0] = merge(x, y -> ch[0]);
27     }
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) { // 左边大小为k
39     if (x == null)
40         return make_pair(null, null);
41
42     pair<node*, node*> pi(null, null);
43
44     if (k <= x -> ch[0] -> size) {
45         pi = split(x -> ch[0], k);
46
47         node *z = copied(x);
48         z -> ch[0] = pi.second;
49         z -> refresh();
50         pi.second = z;
51     }
52     else {
53         pi = split(x -> ch[1], k - x -> ch[0] -> size -
54 // 1);
55
56         node *y = copied(x);
57         y -> ch[1] = pi.first;
58         y -> refresh();
59         pi.first = y;
60     }
61
62     return pi;
63 }
64
65 // 记得初始化null
66 int main() {
67     for (int i = 0; i <= n; i++)
68         null[i].ch[0] = null[i].ch[1] = null;
69     null -> size = 0;
70
71     // do something
72
73     return 0;
74 }

```

#### 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         }
44
45         if (dir(x) == dir(x -> p))
46             rot(x -> p -> p, dir(x -> p) ^ 1);
47         else
48             rot(x -> p, dir(x) ^ 1);
49         rot(x -> p, dir(x) ^ 1);
50     }
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, 如
97     ↪ 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
104     return 0;
105 }

```

## 4.5 树分治

### 4.5.1 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
2   ↪ 一半
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]; //
9   ↪ id是对应层所在子树的根
10 int a[maxn], ca[maxn], b[maxn][20], cb[maxn][20]; // 维护
11   ↪ 距离和用的
12 bool vis[maxn], col[maxn];
13
14 // 建树 总计O(n\log n)
15 // 需要调用找重心和预处理距离, 同时递归调用自身
16 void build(int x, int k, int s, int pr) { // 结点, 深度,
17   ↪ 连通块大小, 点分树上的父亲
18     x = getcenter(x, s);
19     vis[x] = true;
20     depth[x] = k;
21     p[x] = pr;
22
23     for (int i = 0; i < (int)G[x].size(); i++)
24         if (!vis[G[x][i]]) {
25             d[G[x][i]][k] = W[x][i];
26             p[G[x][i]] = x;
27
28             getdis(G[x][i], k, G[x][i]); // bfs每个子树, 预
29             ↪ 处理距离
30         }
31
32     for (int i = 0; i < (int)G[x].size(); i++)
33         if (!vis[G[x][i]])
34             build(G[x][i], k + 1, size[G[x][i]], x); //
35             ↪ 递归建树
36 }
37
38 // 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
           ↳ 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 }
63
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
           ↳ 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],
           ↳ k--) {
96         if (col[x]) {
97             a[u] -= d[x][k];
98             ca[u]--;

```

```

99         b[id[x][k]][k] -= d[x][k];
100         cb[id[x][k]][k]--;
101     }
102     else {
103         a[u] += d[x][k];
104         ca[u]++;
105
106         b[id[x][k]][k] += d[x][k];
107         cb[id[x][k]][k]++;
108     }
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],
           ↳ k--)
119         ans += a[u] - b[id[x][k]][k] + d[x][k] * (ca[u] -
           ↳ cb[id[x][k]][k]);
120
121     return ans;
122 }
123

```

#### 4.5.2 紫荆花之恋

```

1 const int maxn = 100010;
2 const double alpha = 0.7;
3 struct node {
4     static int randint() {
5         static int a = 1213, b = 97818217, p = 998244353,
           ↳ x = 751815431;
6         x = a * x + b;
7         x %= p;
8         return x < 0 ? (x += p) : x;
9     }
10
11     int data, size, p;
12     node *ch[2];
13
14     node(int d): data(d), size(1), p(randint()) {}
15
16     inline void refresh() {
17         size = ch[0]->size + ch[1]->size + 1;
18     }
19 } *null = new node(0), *root[maxn], *root1[maxn][50];
20
21 void addnode(int, int);
22 void rebuild(int, int, int, int);
23 void dfs_getcenter(int, int, int &);
24 void dfs_getdis(int, int, int, int);
25 void dfs_destroy(int, int);
26 void insert(int, node *&);
27 int order(int, node *);
28 void destroy(node *&);
29 void rot(node *&, int);
30
31 vector<int>G[maxn], W[maxn];
32 int size[maxn] = {0}, siz[maxn][50] = {0}, son[maxn];
33 bool vis[maxn];
34 int depth[maxn], p[maxn], d[maxn][50], id[maxn][50];
35 int n, m, w[maxn], tmp;
36 long long ans = 0;
37
38 int main() {
39     null->size = 0;

```



```

40 null->ch[0] = null->ch[1] = null;
41
42 scanf("%*d%d", &n);
43 fill(vis, vis + n + 1, true);
44 fill(root, root + n + 1, null);
45
46 for (int i = 0; i <= n; i++)
47     fill(root1[i], root1[i] + 50, null);
48
49 scanf("%*d%*d%d", &w[1]);
50 insert(-w[1], root[1]);
51 size[1] = 1;
52 printf("0\n");
53
54 for (int i = 2; i <= n; i++) {
55     scanf("%d%d%d", &p[i], &tmp, &w[i]);
56     p[i] ^= (ans % (int)1e9);
57     G[i].push_back(p[i]);
58     W[i].push_back(tmp);
59     G[p[i]].push_back(i);
60     W[p[i]].push_back(tmp);
61     addnode(i, tmp);
62     printf("%lld\n", ans);
63 }
64
65 return 0;
66 }
67
68 void addnode(int x, int z) { //wj-dj>=di-wi
69     depth[x] = depth[p[x]] + 1;
70     size[x] = 1;
71     insert(-w[x], root[x]);
72     int rt = 0;
73
74     for (int u = p[x], k = depth[p[x]]; u; u = p[u], k--)
75         ↪ {
76             if (u == p[x]) {
77                 id[x][k] = x;
78                 d[x][k] = z;
79             }
80             else {
81                 id[x][k] = id[p[x]][k];
82                 d[x][k] = d[p[x]][k] + z;
83             }
84
85             ans += order(w[x] - d[x][k], root[u]) -
86                 ↪ order(w[x] - d[x][k], root1[id[x][k]][k]);
87             insert(d[x][k] - w[x], root[u]);
88             insert(d[x][k] - w[x], root1[id[x][k]][k]);
89             size[u]++;
90             siz[id[x][k]][k]++;
91
92             if (siz[id[x][k]][k] > size[u]*alpha + 5)
93                 rt = u;
94
95             id[x][depth[x]] = 0;
96             d[x][depth[x]] = 0;
97
98             if (rt) {
99                 dfs_destroy(rt, depth[rt]);
100                 rebuild(rt, depth[rt], size[rt], p[rt]);
101             }
102
103 void rebuild(int x, int k, int s, int pr) {
104     int u = 0;
105     dfs_getcenter(x, s, u);
106     vis[x = u] = true;
107     p[x] = pr;
108     depth[x] = k;
109     size[x] = s;
110     d[x][k] = id[x][k] = 0;
111     destroy(root[x]);
112     insert(-w[x], root[x]);
113
114     if (s <= 1)
115         return;
116
117     for (int i = 0; i < (int)G[x].size(); i++)
118         if (!vis[G[x][i]]) {
119             p[G[x][i]] = 0;
120             d[G[x][i]][k] = W[x][i];
121             siz[G[x][i]][k] = p[G[x][i]] = 0;
122             destroy(root1[G[x][i]][k]);
123             dfs_getdis(G[x][i], x, G[x][i], k);
124         }
125
126     for (int i = 0; i < (int)G[x].size(); i++)
127         if (!vis[G[x][i]])
128             rebuild(G[x][i], k + 1, size[G[x][i]], x);
129 }
130
131 void dfs_getcenter(int x, int s, int &u) {
132     size[x] = 1;
133     son[x] = 0;
134
135     for (int i = 0; i < (int)G[x].size(); i++)
136         if (!vis[G[x][i]] && G[x][i] != p[x]) {
137             p[G[x][i]] = x;
138             dfs_getcenter(G[x][i], s, u);
139             size[x] += size[G[x][i]];
140
141             if (size[G[x][i]] > size[son[x]])
142                 son[x] = G[x][i];
143         }
144
145     if (!u || max(s - size[x], size[son[x]]) < max(s -
146         ↪ size[u], size[son[u]]))
147         u = x;
148 }
149
150 void dfs_getdis(int x, int u, int rt, int k) {
151     insert(d[x][k] - w[x], root[u]);
152     insert(d[x][k] - w[x], root1[rt][k]);
153     id[x][k] = rt;
154     siz[rt][k]++;
155     size[x] = 1;
156
157     for (int i = 0; i < (int)G[x].size(); i++)
158         if (!vis[G[x][i]] && G[x][i] != p[x]) {
159             p[G[x][i]] = x;
160             d[G[x][i]][k] = d[x][k] + W[x][i];
161             dfs_getdis(G[x][i], u, rt, k);
162             size[x] += size[G[x][i]];
163         }
164 }
165
166 void dfs_destroy(int x, int k) {
167     vis[x] = false;
168
169     for (int i = 0; i < (int)G[x].size(); i++)
170         if (depth[G[x][i]] >= k && G[x][i] != p[x]) {
171             p[G[x][i]] = x;
172             dfs_destroy(G[x][i], k);
173         }
174 }
175
176 void insert(int x, node *&rt) {
177     if (rt == null) {
178         rt = new node(x);
179         rt->ch[0] = rt->ch[1] = null;
180         return;
181     }

```



```

181
182     int d = x >= rt->data;
183     insert(x, rt->ch[d]);
184     rt->refresh();
185
186     if (rt->ch[d]->p < rt->p)
187         rot(rt, d ^ 1);
188 }
189
190 int order(int x, node *rt) {
191     int ans = 0, d;
192     x++;
193
194     while (rt != null) {
195         if ((d = x > rt->data))
196             ans += rt->ch[0]->size + 1;
197
198         rt = rt->ch[d];
199     }
200
201     return ans;
202 }
203
204 void destroy(node *&x) {
205     if (x == null)
206         return;
207
208     destroy(x->ch[0]);
209     destroy(x->ch[1]);
210     delete x;
211     x = null;
212 }
213
214 void rot(node *&x, int d) {
215     node *y = x->ch[d ^ 1];
216     x->ch[d ^ 1] = y->ch[d];
217     y->ch[d] = x;
218     x->refresh();
219     (x = y)->refresh();
220 }

```

## 4.6 LCT

### 4.6.1 不換根(弹飞绵羊)

```

1 #define isroot(x) ((x) != (x) -> p -> ch[0] && (x) != (x)
   ↳ -> p -> ch[1]) // 判断是不是Splay的根
2 #define dir(x) ((x) == (x) -> p -> ch[1]) // 判断它是它父
   ↳ 亲的左 / 右儿子
3
4 struct node { // 结点类定义
5     int size; // Splay的子树大小
6     node *ch[2], *p;
7
8     node() : size(1) {}
9     void refresh() {
10         size = ch[0] -> size + ch[1] -> size + 1;
11     } // 附加信息维护
12 } null[maxn];
13
14 // 在主函数开头加上这句初始化
15 null -> size = 0;
16
17 // 初始化结点
18 void initailize(node *x) {
19     x -> ch[0] = x -> ch[1] = x -> p = null;
20 }
21
22 // Access 均摊O(\log n)
23 // LCT核心操作, 把结点到根的路径打通, 顺便把与重儿子的连
   ↳ 边变成轻边

```

```

24 // 需要调用splay
25 node *access(node *x) {
26     node *y = null;
27
28     while (x != null) {
29         splay(x);
30
31         x -> ch[1] = y;
32         (y = x) -> refresh();
33
34         x = x -> p;
35     }
36
37     return y;
38 }
39
40 // Link 均摊O(\log n)
41 // 把x的父亲设为y
42 // 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
   ↳ 问题
43 // 需要调用splay
44 void link(node *x, node *y) {
45     splay(x);
46     x -> p = y;
47 }
48
49 // Cut 均摊O(\log n)
50 // 把x与其父亲的连边断开
51 // x可以是所在树的根节点, 这时此操作没有任何实质效果
52 // 需要调用access和splay
53 void cut(node *x) {
54     access(x);
55     splay(x);
56
57     x -> ch[0] -> p = null;
58     x -> ch[0] = null;
59
60     x -> refresh();
61 }
62
63 // 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 }

```

#### 4.6.2 换根/维护生成树

```

1  #define isroot(x) ((x) -> p == null || ((x) -> p -> ch[0]
    ↪ != (x) && (x) -> p -> ch[1] != (x)))
2  #define dir(x) ((x) == (x) -> p -> ch[1])
3
4  using namespace std;
5
6  const int maxn = 200005;
7
8  struct node{
9      int key, mx, pos;
10     bool rev;
11     node *ch[2], *p;
12
13     node(int key = 0): key(key), mx(key), pos(-1),
        ↪ rev(false) {}
14
15     void pushdown() {
16         if (!rev)
17             return;
18
19         ch[0] -> rev ^= true;
20         ch[1] -> rev ^= true;
21         swap(ch[0], ch[1]);
22
23         if (pos != -1)
24             pos ^= 1;
25
26         rev = false;
27     }
28
29     void refresh() {
30         mx = key;
31         pos = -1;
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
101 void makeroot(node *x) {
102     access(x);
103     splay(x);
104     x -> rev ^= true;
105 }
106
107 void link(node *x, node *y) {
108     makeroot(x);
109     x -> p = y;
110 }
111
112 void cut(node *x, node *y) {
113     makeroot(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 node *getmax(node *x, node *y) {
130     makeroot(x);
131     x = access(y);
132
133     while (x -> pushdown(), x -> pos != -1)
134         x = x -> ch[x -> pos];
135     splay(x);
136
137     return x;
138 }
139
140 // 以下为主函数示例
141 for (int i = 1; i <= m; i++) {
142     init(null + n + i, w[i]);
143     if (getroot(null + u[i]) != getroot(null + v[i])) {
144         ans[q + 1] -= k;
145         ans[q + 1] += w[i];
146
147         link(null + u[i], null + n + i);
148         link(null + v[i], null + n + i);
149         vis[i] = true;
150     }
151     else {
152         int ii = getmax(null + u[i], null + v[i]) - null
153             ↪ - n;
154         if (w[i] >= w[ii])
155             continue;
156
157         cut(null + u[ii], null + n + ii);
158         cut(null + v[ii], null + n + ii);
159
160         link(null + u[i], null + n + i);
161         link(null + v[i], null + n + i);
162
163         ans[q + 1] -= w[ii];
164         ans[q + 1] += w[i];
165     }
166 }

```

### 4.6.3 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
4   ↪ 度会变成  $O(n \log^2 n)$ 
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;

```

```

24         ch[1]->rev ^= true;
25         swap(ch[0], ch[1]);
26         swap(suml, sumr);
27
28         rev = false;
29     }
30
31     inline void refresh() { // 如果不想这样特判
32         ↪ 就pushdown一下
33         ↪ // pushdown();
34
35         sum = ch[0] -> sum + ch[1] -> sum + w;
36         suml = (ch[0] -> rev ? ch[0] -> sumr : ch[0] ->
37             ↪ suml) + (ch[1] -> rev ? ch[1] -> sumr : ch[1]
38             ↪ -> suml) + (tree_cnt + ch[1] -> chain_cnt) *
39             ↪ (ch[0] -> sum + w) + tree_sum;
40         sumr = (ch[0] -> rev ? ch[0] -> suml : ch[0] ->
41             ↪ sumr) + (ch[1] -> rev ? ch[1] -> suml : ch[1]
42             ↪ -> sumr) + (tree_cnt + ch[0] -> chain_cnt) *
43             ↪ (ch[1] -> sum + w) + tree_sum;
44         chain_cnt = ch[0] -> chain_cnt + ch[1] ->
45             ↪ chain_cnt + tree_cnt;
46     }
47 } null[maxn * 2]; // 如果没有边权变点权就不用乘2了
48
49 // 封装构造函数
50 node *newnode(int w) {
51     node *x = nodes.front(); // 因为有删边加边，可以用一
52     ↪ 个队列维护可用结点
53     nodes.pop();
54     initialize(x);
55     x -> w = w;
56     x -> refresh();
57     return x;
58 }
59
60 // 封装初始化函数
61 // 记得在进行操作之前对所有结点调用一遍
62 inline void initialize(node *x) {
63     *x = node();
64     x -> ch[0] = x -> ch[1] = x -> p = null;
65 }
66
67 // 注意一下在Access的同时更新子树信息的方法
68 node *access(node *x) {
69     node *y = null;
70
71     while (x != null) {
72         splay(x);
73
74         x -> tree_cnt += x -> ch[1] -> chain_cnt - y ->
75             ↪ chain_cnt;
76         x -> tree_sum += (x -> ch[1] -> rev ? x -> ch[1] ->
77             ↪ sumr : x -> ch[1] -> suml) - y -> suml;
78         x -> ch[1] = y;
79
80         (y = x) -> refresh();
81         x = x -> p;
82     }
83
84     return y;
85 }
86
87 // 找到一个点所在连通块的根
88 // 对比原版没有变化
89 node *getroot(node *x) {
90     x = access(x);
91
92     while (x -> pushdown(), x -> ch[0] != null)
93         x = x -> ch[0];

```

```

83     splay(x);
84
85     return x;
86 }
87
88 // 换根, 同样没有变化
89 void makeroot(node *x) {
90     access(x);
91     splay(x);
92     x -> rev ^= true;
93     x -> pushdown();
94 }
95
96 // 连接两个点
97 // !!! 注意这里必须把两者都变成根, 因为只能修改根结点
98 void link(node *x, node *y) {
99     makeroot(x);
100    makeroot(y);
101
102    x -> p = y;
103    y -> tree_cnt += x -> chain_cnt;
104    y -> tree_sum += x -> sum1;
105    y -> refresh();
106 }
107
108 // 删除一条边
109 // 对比原版没有变化
110 void cut(node *x, node *y) {
111     makeroot(x);
112     access(y);
113     splay(y);
114
115     y -> ch[0] -> p = null;
116     y -> ch[0] = null;
117     y -> refresh();
118 }
119
120 // 修改/询问一个点, 这里以询问为例
121 // 如果是修改就在换根之后搞一些操作
122 long long query(node *x) {
123     makeroot(x);
124     return x -> sum1;
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 }

```

#### 4.6.4 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->
    ↪ 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 const int maxn = 100010;
13 const long long INF = 1000000000000000000ll;
14
15 struct binary_heap {
16     __gnu_pbds::priority_queue<long long, less<long
    ↪ long>, binary_heap_tag>q1, q2;
17     binary_heap() {}
18
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
38         return q1.top();
39     }
40
41     long long top2() {
42         if (size() < 2)
43             return -INF;
44
45         long long a = top();
46         erase(a);
47         long long b = top();
48         push(a);
49         return a + b;
50     }
51 }

```

```

51
52     int size() {
53         return q1.size() - q2.size();
54     }
55
56     bool empty() {
57         return q1.size() == q2.size();
58     }
59 } heap; // 全局堆维护每条链的最大子段和
60
61 struct node {
62     long long sum, maxsum, prefix, suffix;
63     int key;
64     binary_heap heap; // 每个点的堆存的是它的子树中到它
        ↳ 的最远距离, 如果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), prefix(-INF),
68         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]->prefix);
86         suffix = max(ch[1]->suffix,
87             ch[1]->sum + key + ch[0]->suffix);
88         maxsum = max(max(ch[0]->maxsum, ch[1]->maxsum),
89             ch[0]->suffix + key +
90             ↳ ch[1]->prefix);
91
92         if (!heap.empty()) {
93             prefix = max(prefix,
94                 ch[0]->sum + key + heap.top());
95             suffix = max(suffix,
96                 ch[1]->sum + key + heap.top());
97             maxsum = max(maxsum, max(ch[0]->suffix,
98                 ch[1]->prefix) + key
99                 ↳ + heap.top());
100
101             if (heap.size() > 1) {
102                 maxsum = max(maxsum, heap.top2() + key);
103             }
104         }
105     }
106     void addedge(int, int, int);
107     void deledge(int, int);
108     void modify(int, int, int);
109     void modify_color(int);
110     node *newnode(int);
111     node *access(node *);
112     void makeroot(node *);
113     void link(node *, node *);
114     void cut(node *, node *);
115     void splay(node *);
116     void rot(node *, int);
117
118     queue<node *>freenodes;
119     tree<pair<int, int>, node *>mp;
120
121     bool col[maxn] = {false};
122     char c;
123     int n, m, k, x, y, z;
124
125     int main() {
126         null->ch[0] = null->ch[1] = null->p = null;
127         scanf("%d%d%d", &n, &m, &k);
128
129         for (int i = 1; i <= n; i++)
130             newnode(0);
131
132         heap.push(0);
133
134         while (k--) {
135             scanf("%d", &x);
136
137             col[x] = true;
138             null[x].heap.push(0);
139         }
140
141         for (int i = 1; i < n; i++) {
142             scanf("%d%d%d", &x, &y, &z);
143
144             if (x > y)
145                 swap(x, y);
146             addedge(x, y, z);
147         }
148
149         while (m--) {
150             scanf(" %c%d", &c, &x);
151
152             if (c == 'A') {
153                 scanf("%d", &y);
154
155                 if (x > y)
156                     swap(x, y);
157                 deledge(x, y);
158             }
159             else if (c == 'B') {
160                 scanf("%d%d", &y, &z);
161
162                 if (x > y)
163                     swap(x, y);
164                 addedge(x, y, z);
165             }
166             else if (c == 'C') {
167                 scanf("%d%d", &y, &z);
168
169                 if (x > y)
170                     swap(x, y);
171                 modify(x, y, z);
172             }
173             else
174                 modify_color(x);
175
176             printf("%lld\n", (heap.top() > 0 ? heap.top() :
177                 ↳ -1));
178         }
179
180         return 0;
181     }
182     void addedge(int x, int y, int z) {
183         node *tmp;
184         if (freenodes.empty())
185             tmp = newnode(z);
186         else {
187             tmp = freenodes.front();
188             freenodes.pop();
189             *tmp = node(z);
190         }

```

```

191     tmp->ch[0] = tmp->ch[1] = tmp->p = null;
192
193     heap.push(tmp->maxsum);
194     link(tmp, null + x);
195     link(tmp, null + y);
196     mp[make_pair(x, y)] = tmp;
197 }
198
199 void deledge(int x, int y) {
200     node *tmp = mp[make_pair(x, y)];
201
202     cut(tmp, null + x);
203     cut(tmp, null + y);
204
205     freenodes.push(tmp);
206     heap.erase(tmp->maxsum);
207     mp.erase(make_pair(x, y));
208 }
209
210 void modify(int x, int y, int z) {
211     node *tmp = mp[make_pair(x, y)];
212     makeroot(tmp);
213     tmp->pushdown();
214
215     heap.erase(tmp->maxsum);
216     tmp->key = z;
217     tmp->refresh();
218     heap.push(tmp->maxsum);
219 }
220
221 void modify_color(int x) {
222     makeroot(null + x);
223     col[x] ^= true;
224
225     if (col[x])
226         null[x].heap.push(0);
227     else
228         null[x].heap.erase(0);
229
230     heap.erase(null[x].maxsum);
231     null[x].refresh();
232     heap.push(null[x].maxsum);
233 }
234 node *newnode(int k) {
235     *(++ptr) = node(k);
236     ptr->ch[0] = ptr->ch[1] = ptr->p = null;
237     return ptr;
238 }
239 node *access(node *x) {
240     splay(x);
241     heap.erase(x->maxsum);
242     x->refresh();
243
244     if (x->ch[1] != null) {
245         x->ch[1]->pushdown();
246         x->heap.push(x->ch[1]->prefix);
247         x->refresh();
248         heap.push(x->ch[1]->maxsum);
249     }
250
251     x->ch[1] = null;
252     x->refresh();
253     node *y = x;
254     x = x->p;
255
256     while (x != null) {
257         splay(x);
258         heap.erase(x->maxsum);
259
260         if (x->ch[1] != null) {
261             x->ch[1]->pushdown();
262             x->heap.push(x->ch[1]->prefix);
263
264             heap.push(x->ch[1]->maxsum);
265         }
266
267         x->ch[1] = y;
268         (y = x)->refresh();
269         x = x->p;
270     }
271
272     heap.push(y->maxsum);
273     return y;
274 }
275 void makeroot(node *x) {
276     access(x);
277     splay(x);
278     x->rev ^= true;
279 }
280 void link(node *x, node *y) { // 新添一条虚边, 维护y对应
    ↳ 的堆
281     makeroot(x);
282     makeroot(y);
283
284     x->pushdown();
285     x->p = y;
286     heap.erase(y->maxsum);
287     y->heap.push(x->prefix);
288     y->refresh();
289     heap.push(y->maxsum);
290 }
291 void cut(node *x, node *y) { // 断开一条实边, 一条链变成
    ↳ 两条链, 需要维护全局堆
292     makeroot(x);
293     access(y);
294     splay(y);
295
296     heap.erase(y->maxsum);
297     heap.push(y->ch[0]->maxsum);
298     y->ch[0]->p = null;
299     y->ch[0] = null;
300     y->refresh();
301     heap.push(y->maxsum);
302 }
303 void splay(node *x) {
304     x->pushdown();
305
306     while (!isroot(x)) {
307         if (!isroot(x->p))
308             x->p->p->pushdown();
309
310         x->p->pushdown();
311         x->pushdown();
312
313         if (isroot(x->p)) {
314             rot(x->p, dir(x) ^ 1);
315             break;
316         }
317
318         if (dir(x) == dir(x->p))
319             rot(x->p->p, dir(x->p) ^ 1);
320         else
321             rot(x->p, dir(x) ^ 1);
322
323         rot(x->p, dir(x) ^ 1);
324     }
325 }
326 void rot(node *x, int d) {
327     node *y = x->ch[d ^ 1];
328
329     if ((x->ch[d ^ 1] = y->ch[d]) != null)
330         y->ch[d]->p = x;
331     y->p = x->p;
332

```

```

333
334     if (!isroot(x))
335         x->p->ch[dir(x)] = y;
336
337     (y->ch[d] = x)->p = y;
338
339     x->refresh();
340     y->refresh();
341 }

```

## 4.7 K-D树

### 4.7.1 动态K-D树

```

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
44 void query(node *rt) {
45     if (l[0] <= rt -> l[0] && l[1] <= rt -> l[1] && rt ->
46         ↪ r[0] <= r[0] && rt -> r[1] <= r[1]) {
47         ans += rt -> sum;
48         return;
49     }
50     else if (l[0] > rt -> r[0] || l[1] > rt -> r[1] ||
51         ↪ r[0] < rt -> l[0] || r[1] < rt -> l[1])
52         return;
53
54     if (l[0] <= rt -> x[0] && l[1] <= rt -> x[1] && rt ->
55         ↪ x[0] <= r[0] && rt -> x[1] <= r[1])
56         ans += rt -> w;

```

```

51     query(rt -> ch[0]);
52     query(rt -> ch[1]);
53 }
54
55 int main() {
56
57     null -> l[0] = null -> l[1] = 10000000;
58     null -> r[0] = null -> r[1] = -10000000;
59     null -> sum = 0;
60     null -> ch[0] = null -> ch[1] = null;
61     scanf("%d");
62
63     while (scanf("%d", &op) == 1 && op != 3) {
64         if (op == 1) {
65             tmp++;
66             scanf("%d%d%d", &x[tmp][0], &x[tmp][1],
67                 ↪ &w[tmp]);
68             x[tmp][0] ^= ans;
69             x[tmp][1] ^= ans;
70             w[tmp] ^= ans;
71
72             if (tmp == B) {
73                 for (int i = 1; i <= tmp; i++) {
74                     null[cnt + i].x[0] = x[i][0];
75                     null[cnt + i].x[1] = x[i][1];
76                     null[cnt + i].w = w[i];
77                 }
78                 build(1, cnt += tmp, 0, root);
79                 tmp = 0;
80             }
81         }
82         else {
83             scanf("%d%d%d", &l[0], &l[1], &r[0],
84                 ↪ &r[1]);
85             l[0] ^= ans;
86             l[1] ^= ans;
87             r[0] ^= ans;
88             r[1] ^= ans;
89             ans = 0;
90
91             for (int i = 1; i <= tmp; i++)
92                 if (l[0] <= x[i][0] && l[1] <= x[i][1] &&
93                     ↪ x[i][0] <= r[0] && x[i][1] <= r[1])
94                     ans += w[i];
95
96             query(root);
97             printf("%d\n", ans);
98         }
99     }
100     return 0;

```

## 4.8 虚树

```

1  struct Tree {
2      vector<int> G[maxn], W[maxn];
3      int p[maxn], d[maxn], size[maxn], mn[maxn], mx[maxn];
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 void dfs(int x) {
13     size[x] = col[x];
14     mx[x] = (col[x] ? d[x] : -0x3f3f3f3f);
15     mn[x] = (col[x] ? d[x] : 0x3f3f3f3f);
16
17     for (int i = 0; i < (int)G[x].size(); i++) {
18         d[G[x][i]] = d[x] + W[x][i];
19         dfs(G[x][i]);
20         ans_sum += (long long)size[x] * size[G[x][i]]
21             ↳ * d[x];
22         ans_max = max(ans_max, mx[x] + mx[G[x][i]] -
23             ↳ (d[x] << 1));
24         ans_min = min(ans_min, mn[x] + mn[G[x][i]] -
25             ↳ (d[x] << 1));
26         size[x] += size[G[x][i]];
27         mx[x] = max(mx[x], mx[G[x][i]]);
28         mn[x] = min(mn[x], mn[G[x][i]]);
29     }
30
31 void clear(int x) {
32     G[x].clear();
33     W[x].clear();
34     col[x] = false;
35 }
36
37 void solve(int rt) {
38     ans_sum = 0;
39     ans_max = 1 << 31;
40     ans_min = (~0u) >> 1;
41     dfs(rt);
42     ans_sum <= 1;
43 } virtree;
44
45 void dfs(int);
46 int LCA(int, int);
47
48 vector<int>G[maxn];
49 int f[maxn][20], d[maxn], dfn[maxn], tim = 0;
50
51 bool cmp(int x, int y) {
52     return dfn[x] < dfn[y];
53 }
54
55 int n, m, lgn = 0, a[maxn], s[maxn], v[maxn];
56
57 int main() {
58     scanf("%d", &n);
59
60     for (int i = 1, x, y; i < n; i++) {
61         scanf("%d%d", &x, &y);
62         G[x].push_back(y);
63         G[y].push_back(x);
64     }
65
66     G[n + 1].push_back(1);
67     dfs(n + 1);
68
69     for (int i = 1; i <= n + 1; i++)
70         G[i].clear();
71
72     lgn--;
73
74     for (int j = 1; j <= lgn; j++)
75         for (int i = 1; i <= n; i++)
76             f[i][j] = f[f[i][j - 1]][j - 1];
77
78     scanf("%d", &m);
79
80     while (m--) {
81         int k;
82         scanf("%d", &k);
83
84         for (int i = 1; i <= k; i++)
85             scanf("%d", &a[i]);
86
87         sort(a + 1, a + k + 1, cmp);
88         int top = 0, cnt = 0;
89         s[++top] = v[++cnt] = n + 1;
90         long long ans = 0;
91
92         for (int i = 1; i <= k; i++) {
93             virtree.col[a[i]] = true;
94             ans += d[a[i]] - 1;
95             int u = LCA(a[i], s[top]);
96
97             if (s[top] != u) {
98                 while (top > 1 && d[s[top - 1]] >= d[u])
99                     ↳ {
100                         virtree.add(s[top - 1], s[top],
101                             ↳ d[s[top]] - d[s[top - 1]]);
102                         top--;
103                     }
104
105                 if (s[top] != u) {
106                     virtree.add(u, s[top], d[s[top]] -
107                         ↳ d[u]);
108                     s[top] = v[++cnt] = u;
109                 }
110             }
111
112             s[++top] = a[i];
113
114             for (int i = top - 1; i; i--)
115                 virtree.add(s[i], s[i + 1], d[s[i + 1]] -
116                     ↳ d[s[i]]);
117
118             virtree.solve(n + 1);
119             ans *= k - 1;
120             printf("%lld %d %d\n", ans - virtree.ans_sum,
121                 ↳ virtree.ans_min, virtree.ans_max);
122
123             for (int i = 1; i <= k; i++)
124                 virtree.clear(a[i]);
125             for (int i = 1; i <= cnt; i++)
126                 virtree.clear(v[i]);
127         }
128
129         return 0;
130     }
131
132 void dfs(int x) {
133     dfn[x] = ++tim;
134     d[x] = d[f[x][0]] + 1;
135
136     while ((1 << lgn) < d[x])
137         lgn++;
138
139     for (int i = 0; i < (int)G[x].size(); i++)
140         if (G[x][i] != f[x][0]) {
141             f[G[x][i]][0] = x;
142             dfs(G[x][i]);
143         }
144 }
145
146 int LCA(int x, int y) {
147     if (d[x] != d[y]) {
148         if (d[x] < d[y])
149             swap(x, y);
150     }

```

```

148     for (int i = lgn; i >= 0; i--)
149         if (((d[x] - d[y]) >> i) & 1)
150             x = f[x][i];
151     }
152
153     if (x == y)
154         return x;
155
156     for (int i = lgn; i >= 0; i--)
157         if (f[x][i] != f[y][i]) {
158             x = f[x][i];
159             y = f[y][i];
160         }
161
162     return f[x][0];
163 }

```

```

48     }
49
50     v[y].clear();
51 }
52 }

```

#### 4.9.1 梯子剖分

```

1 // 在线求一个点的第k级祖先  $O(n \log n) - O(1)$ 
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  $\geq k$ 
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], len[maxn];
7 int f[19][maxn], log_tbl[maxn];
8
9 // 在主函数中两遍dfs之后加上如下预处理
10 log_tbl[0] = -1;
11 for (int i = 1; i <= n; i++)
12     log_tbl[i] = log_tbl[i / 2] + 1;
13 for (int j = 1; (1 << j) < n; j++)
14     for (int i = 1; i <= n; i++)
15         f[j][i] = f[j - 1][f[j - 1][i]];
16
17 // 第一遍dfs, 用于计算深度和找出重儿子
18 void dfs1(int x) {
19     mxd[x] = d[x];
20
21     for (int y : G[x])
22         if (y != f[0][x]) {
23             f[0][y] = x;
24             d[y] = d[x] + 1;
25
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
34 // 第二遍dfs, 用于进行剖分和预处理梯子剖分(每条链向上延
35 // 伸一倍)数组
36 void dfs2(int x) {
37     top[x] = (x == son[f[0][x]]) ? top[f[0][x]] : x;
38
39     for (int y : G[x])
40         if (y != f[0][x])
41             dfs2(y);
42
43     if (top[x] == x) {
44         int u = x;
45         while (top[son[u]] == x)
46             u = son[u];
47
48         len[x] = d[u] - d[x];
49         for (int i = 0; i < len[x]; i++, u = f[0][u])
50             v[x].push_back(u);
51
52         u = x;
53         for (int i = 0; i < len[x] && u; i++, u = f[0][u])
54             v[x].push_back(u);
55     }
56 }
57
58 // 在线询问x的第k级祖先  $O(1)$ 
59 // 不存在时返回0
60 int query(int x, int k) {

```

## 4.9 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
10 // 过来存
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
23     if (!son[x]) {
24         v[x].push_back(1);
25         ans[x] = 0;
26         return;
27     }
28
29     h[x] = h[son[x]] + 1;
30     swap(v[x], v[son[x]]);
31
32     if (v[x][ans[son[x]]] == 1)
33         ans[x] = h[x] - 1;
34     else
35         ans[x] = ans[son[x]];
36
37     v[x].push_back(1);
38
39     int mx = v[x][ans[x]];
40     for (int y : G[x])
41         if (y != p[x] && y != son[x]) {
42             for (int j = 1; j <= h[y]; j++) {
43                 v[x][h[x] - j - 1] += v[y][h[y] - j];
44
45                 int t = v[x][h[x] - j - 1];
46                 if (t > mx || (t == mx && h[x] - j - 1 >
47                     // 取最大深度) {

```

```

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] + k];
68 }

```

## 4.10 左偏树

(参见k短路)

## 4.11 常见根号思路

### 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 $n$ (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

### 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

### 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

### 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 char s[maxn], t[maxn];
2 int fail[maxn];
3 int n, m;
4
5 void init() { // 注意字符串是0-based, 但是fail是1-based
6     // memset(fail, 0, sizeof(fail));
7
8     for (int i = 1; i < m; i++) {
9         int j = fail[i];
10        while (j && t[i] != t[j])
11            j = fail[j];
12
13        if (t[i] == t[j])
14            fail[i + 1] = j + 1;
15        else
16            fail[i + 1] = 0;
17    }
18 }
19
20 int KMP() {
21     int cnt = 0, j = 0;
22
23     for (int i = 0; i < n; i++) {
24         while (j && s[i] != t[j])
25             j = fail[j];
26
27         if (s[i] == t[j])
28             j++;
29         if (j == m)
30             cnt++;
31     }
32
33     return cnt;
34 }

```

#### 5.1.1 ex-KMP

```

1 //全局变量与数组定义
2 char s[maxn], t[maxn];
3 int n, m, a[maxn];
4
5 // 主过程  $O(n + m)$ 
6 // 把t的每个后缀与s的LCP输出到a中, s的后缀和自己的LCP存
7 // 在nx中
8 // 0-based, s的长度是m, t的长度是n
9 void exKMP(const char *s, const char *t, int *a) {
10     static int nx[maxn];
11
12     memset(nx, 0, sizeof(nx));
13
14     int j = 0;
15     while (j + 1 < m && s[j] == s[j + 1])
16         j++;
17     nx[1] = j;
18
19     for (int i = 2, k = 1; i < m; i++) {
20         int pos = k + nx[k], len = nx[i - k];
21
22         if (i + len < pos)
23             nx[i] = len;
24         else {
25             j = max(pos - i, 0);
26             while (i + j < m && s[j] == s[i + j])
27                 j++;
28         }
29     }
30 }

```

```

27     nx[i] = j;
28     k = i;
29 }
30 }
31 }
32
33 j = 0;
34 while (j < n && j < m && s[j] == t[j])
35     j++;
36 a[0] = j;
37
38 for (int i = 1, k = 0; i < n; i++) {
39     int pos = k + a[k], len = nx[i - k];
40     if (i + len < pos)
41         a[i] = len;
42     else {
43         j = max(pos - i, 0);
44         while (j < m && i + j < n && s[j] == t[i + j])
45             j++;
46
47         a[i] = j;
48         k = i;
49     }
50 }
51 }

```

## 5.2 AC自动机

```

1 int ch[maxm][26], f[maxm][26], q[maxm], sum[maxm], cnt =
   ↳ 0;
2
3 // 在字典树中插入一个字符串  $O(n)$ 
4 int insert(const char *c) {
5     int x = 0;
6     while (*c) {
7         if (!ch[x][*c - 'a'])
8             ch[x][*c - 'a'] = ++cnt;
9         x = ch[x][*c++ - 'a'];
10    }
11    return x;
12 }
13
14 // 建AC自动机  $O(n * \sigma)$ 
15 void getfail() {
16     int x, head = 0, tail = 0;
17
18     for (int c = 0; c < 26; c++)
19         if (ch[0][c])
20             q[tail++] = ch[0][c]; // 把根节点的儿子加入队
   ↳ 列
21
22     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             }
35             else
36                 ch[x][c] = ch[f[x][0]][c];
37         }
38     }
39     fill(f[0], f[0] + 26, cnt + 1);

```

```

40 }

```

## 5.3 后缀数组

### 5.3.1 SA-IS

```

1 // 注意求完的SA有效位只有1~n, 但它是0-based, 如果其他部
   ↳ 分是1-based记得+1再用
2
3 constexpr int maxn = 100005, l_type = 0, s_type = 1;
4
5 // 判断一个字符是否为LMS字符
6 bool is_lms(int *tp, int x) {
7     return x > 0 && tp[x] == s_type && tp[x - 1] ==
   ↳ l_type;
8 }
9
10 // 判断两个LMS子串是否相同
11 bool equal_substr(int *s, int x, int y, int *tp) {
12     do {
13         if (s[x] != s[y])
14             return false;
15         x++;
16         y++;
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, int
   ↳ *lbuc, int *sbuc, int n, int m) {
25     for (int i = 0; i <= n; i++)
26         if (sa[i] > 0 && tp[sa[i] - 1] == l_type)
27             sa[lbuc[sa[i] - 1]++] = sa[i] - 1;
28
29     for (int i = 1; i <= m; i++)
30         sbuc[i] = buc[i] - 1;
31
32     for (int i = n; ~i; i--)
33         if (sa[i] > 0 && tp[sa[i] - 1] == s_type)
34             sa[sbuc[sa[i] - 1]++] = sa[i] - 1;
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 *sais(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, lastx,
92                 ↪ tp))
93                 namecnt++;
94
95             if (lastx >= 0 && namecnt == name[lastx])
96                 flag = true;
97
98             name[x] = namecnt;
99             lastx = x;
100         }
101     }
102     name[n] = 0;
103
104     int *t = new int[cnt];
105     int p = 0;
106     for (int i = 0; i <= n; i++)
107         if (name[i] >= 0)
108             t[p++] = name[i];
109
110     int *tsa;
111     if (!flag) {
112         tsa = new int[cnt];
113
114         for (int i = 0; i < cnt; i++)
115             tsa[t[i]] = i;
116     }
117     else
118         tsa = sais(t, cnt, namecnt);
119
120     lbuc[0] = sbuc[0] = 0;
121     for (int i = 1; i <= m; i++) {
122         lbuc[i] = buc[i - 1];
123         sbuc[i] = buc[i] - 1;
124     }
125
126     memset(sa, -1, sizeof(int) * (n + 1));
127     for (int i = cnt - 1; ~i; i--)
128         sa[sbuc[s[pos[tsa[i]]]]--] = pos[tsa[i]];
129     induced_sort(s, sa, tp, buc, lbuc, sbuc, n, m);

```

```

129
130     return sa;
131 }
132
133 // O(n)求height数组, 注意是sa[i]与sa[i - 1]的LCP
134 void get_height(int *s, int *sa, int *rnk, int *height,
135     ↪ int n) {
136     for (int i = 0; i <= n; i++)
137         rnk[sa[i]] = i;
138
139     int k = 0;
140     for (int i = 0; i <= n; i++) {
141         if (!rnk[i])
142             continue;
143
144         if (k)
145             k--;
146
147         while (s[sa[rnk[i]] + k] == s[sa[rnk[i] - 1] +
148             ↪ k])
149             k++;
150
151         height[rnk[i]] = k;
152     }
153 }
154
155 char str[maxn];
156 int n, s[maxn], sa[maxn], rnk[maxn], height[maxn];
157
158 // 方便起见附上主函数
159 int main() {
160     scanf("%s", str);
161     n = strlen(str);
162     str[n] = '$';
163
164     for (int i = 0; i <= n; i++)
165         s[i] = str[i];
166
167     memcpy(sa, sais(s, n + 1, 256), sizeof(int) * (n +
168         ↪ 1));
169
170     get_height(s, sa, rnk, height, n);
171
172     return 0;
173 }

```

### 5.3.2 SAMSA

```

1 bool vis[maxn * 2];
2 char s[maxn];
3 int n, id[maxn * 2], ch[maxn * 2][26], height[maxn], tim
4     ↪ = 0;
5
6 void dfs(int x) {
7     if (id[x]) {
8         height[tim++] = val[last];
9         sa[tim] = id[x];
10
11         last = x;
12     }
13
14     for (int c = 0; c < 26; c++)
15         if (ch[x][c])
16             dfs(ch[x][c]);
17
18     last = par[x];
19 }
20
21 int main() {

```

```

21     last = ++cnt;
22
23     scanf("%s", s + 1);
24     n = strlen(s + 1);
25
26     for (int i = n; i; i--) {
27         expand(s[i] - 'a');
28         id[last] = i;
29     }
30
31     vis[1] = true;
32     for (int i = 1; i <= cnt; i++)
33         if (id[i])
34             for (int x = i, pos = n; x && !vis[x]; x =
35                 ↪ par[x]) {
36                 vis[x] = true;
37                 pos -= val[x] - val[par[x]];
38                 ch[par[x]][s[pos + 1] - 'a'] = x;
39             }
40     dfs(1);
41
42     for (int i = 1; i <= n; i++) {
43         if (i > 1)
44             printf(" ");
45         printf("%d", sa[i]); // 1-based
46     }
47     printf("\n");
48
49     for (int i = 1; i < n; i++) {
50         if (i > 1)
51             printf(" ");
52         printf("%d", height[i]);
53     }
54     printf("\n");
55
56     return 0;
57 }

```

```

15     c[i] += c[i - 1]; // 这里n是串长
16     for (int i = 1; i <= 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 = ++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 = ++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
51         last = np;
52     }

```

## 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

(广义后缀自动机复杂度就是 $O(n|\Sigma|)$ , 也没法做到更低了)

```

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
  ↪ 者哈希表替换
2 // 注意!!!结点数要开成串长的两倍
3
4 // 全局变量与数组定义
5 int last, val[maxn], par[maxn], go[maxn][26], 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 = cnt = 1;
10
11 // 以下是按val进行桶排序的代码
12 for (int i = 1; i <= cnt; i++)
13     c[val[i] + 1]++;
14 for (int i = 1; i <= n; i++)

```

## 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
  ↪ 的bfs序
3
4 // 全局数组定义
5 int val[maxn], par[maxn], go[maxn][26], last, cnt;
6 char s[maxn];
7
8 // 重要!在主函数最前面一定要加上以下初始化
9 par[0] = cnt = 1;
10 val[1] = -1;
11 // 这个初始化和广义回文树不一样, 写普通题可以用, 广义回
  ↪ 文树就不要乱搞了
12
13 // extend函数 均摊O(1)
14 // 向后扩展一个字符
15 // 传入对应下标
16 void extend(int n) {
17     int p = last, c = s[n] - 'a';
18     while (s[n - val[p] - 1] != s[n])
19         p = par[p];
20
21     if (!go[p][c]) {
22         int q = ++cnt, now = p;
23         val[q] = val[p] + 2;
24
25         do

```

```

26     p=par[p];
27     while (s[n - val[p] - 1] != s[n]);
28
29     par[q] = go[p][c];
30     last = go[now][c] = q;
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     return trie[x][c];
29 }
30
31 int del(int x) {
32     return f[0][x];
33 }
34
35 void dfs1(int x) {
36     mxd[x] = d[x] = d[f[0][x]] + 1;
37
38     for (int i = 0; i < 26; i++)
39         if (trie[x][i]) {
40             int y = trie[x][i];
41
42             dfs1(y);
43
44             mxd[x] = max(mxd[x], mxd[y]);
45             if (mxd[y] > mxd[son[x]])
46                 son[x] = y;
47         }
48 }
49
50 void dfs2(int x) {
51     if (x == son[f[0][x]])
52         top[x] = top[f[0][x]];
53     else

```

```

53     top[x] = x;
54
55     for (int i = 0; i < 26; i++)
56         if (trie[x][i]) {
57             int y = trie[x][i];
58             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++) { // 梯子剖分, 要
75             ↳ 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] + k];
91     }
92
93     char get_char(int x, int k) { // 查询x前面k个的字符是哪个
94         return chr[get_anc(x, k)];
95     }
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
105         int p = pam_last[f[0][x]], c = chr[x] - 'a';
106
107         p = getfail(x, p);
108
109         int new_last;
110
111         if (!go[p][c]) {
112             int q = ++pam_cnt, now = p;
113             val[q] = val[p] + 2;
114
115             p = getfail(x, par[p]);
116
117             par[q] = go[p][c];
118             new_last = go[now][c] = q;
119
120             for (int i = 0; i < 26; i++)
121                 fail[q][i] = fail[par[q]][i];
122
123             if (get_char(x, val[par[q]]) >= 'a')

```



```

124     fail[q][get_char(x, val[par[q]]) - 'a'] =
125         ↳ par[q];
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 }
132 else
133     new_last = go[p][c];
134 pam_last[x] = new_last;
135 return weight[pam_last[x]];
136 }
137
138 void bfs() {
139     queue<int> q;
140
141     q.push(1);
142
143     while (!q.empty()) {
144         int x = q.front();
145         q.pop();
146
147         sum[x] = sum[f[0][x]];
148         if (x > 1)
149             sum[x] = (sum[x] + extend(x)) % mod;
150
151         for (int i : queries[x])
152             ans[i] = sum[x];
153
154         for (int i = 0; i < 26; i++)
155             if (trie[x][i])
156                 q.push(trie[x][i]);
157     }
158 }
159
160 int main() {
161
162     pow_26[0] = 1;
163     log_tbl[0] = -1;
164
165     for (int i = 1; i <= 1000000; i++) {
166         pow_26[i] = 26ll * pow_26[i - 1] % mod;
167         log_tbl[i] = log_tbl[i / 2] + 1;
168     }
169
170     int T;
171     scanf("%d", &T);
172
173     while (T--) {
174         scanf("%d%d%s", &n, &m, str);
175
176         trie_cnt = 1;
177         chr[1] = '#';
178
179         int last = 1;
180         for (char *c = str; *c; c++)
181             last = add(last, *c - 'a');
182
183         queries[last].push_back(0);
184
185         for (int i = 1; i <= m; i++) {
186             int op;
187             scanf("%d", &op);
188
189             if (op == 1) {
190                 char c;

```

```

194         scanf("%c", &c);
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) : 1);
19     while (s[i - p[i]] == s[i + p[i]])
20         p[i]++;
21
22     if (i + p[i] > mx) {
23         mx = i + p[i];
24         j = i;
25     }
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 $(val_{par}, val_p]$ 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
   ↳ 点就是下一个左端点 - 1
2
3 long long f[maxn], s[maxn];
4
5 int n, m;
6
7 long long calc(int l, int r) {
8     if (r < l)
9         return 0;
10
11     int mid = (l + r) / 2;
12     if ((r - l + 1) % 2 == 0)
13         return (s[r] - s[mid]) - (s[mid] - s[l - 1]);
14     else
15         return (s[r] - s[mid]) - (s[mid - 1] - s[l - 1]);
16 }
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
31         if (head <= tail) {
32             if (f[q[head]] + calc(q[head] + 1, i) < f[i])
33                 ↳ {
34                     f[i] = f[q[head]] + calc(q[head] + 1, 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         }
61         else {
62             int L = p[tail], R = r;
63             while (L < R) {
64                 int M = (L + R) / 2;
65
66                 if (f[q[tail]] + calc(q[tail] + 1, M)
67                     ↳ <= f[i] + calc(i + 1, M))
68                     L = M + 1;
69                 else
70                     R = M;
71             }
72
73             q[++tail] = i;
74             p[tail] = L;
75
76             break;
77         }
78     }
79     return g[n];
80 }

```

```

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```

### 6.2 例题

## 7. Miscellaneous

### 7.1 $O(1)$ 快速乘

```

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 long long mul(long long a, long long b, long long p) {
5     a %= p;
6     b %= p;

```

```

7   return ((a * b - p * (long long)((long double)a / p *
    ↪ b + 0.5)) % p + p) % p;
8 }
9
10 // 指令集快速乘
11 // 试机记得测试能不能过编译
12 inline long long mul(const long long a, const long long
    ↪ b, const long long p) {
13     long long ans;
14     __asm__ __volatile__ ("\tmulq %%rbx\n\tdivq %%rcx\n"
    ↪ : "=d"(ans) : "a"(a), "b"(b), "c"(p));
15     return ans;
16 }
17
18 // int乘法取模, 大概比直接做快一倍
19 inline int mul_mod(int a, int b, int p) {
20     int ans;
21     __asm__ __volatile__ ("\tmull %%ebx\n\tdivl %%ecx\n"
    ↪ : "=d"(ans) : "a"(a), "b"(b), "c"(p));
22     return ans;
23 }

```

## 7.2 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,
    ↪ 50.57
10 x = decimal.Decimal('50.5679'). \
11     quantize(decimal.Decimal('0.00'),
    ↪ decimal.ROUND_HALF_UP) # 四舍五入
12 # 第二个参数可选如下:
13 # 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 rounding
    ↪ towards zero would have been 0 or 5; otherwise
    ↪ towards zero)
21
22 print('%f', x) # 这样做只有float的精度
23 s = str(x)
24
25 decimal.is_finite(x) # x是否有穷(NaN也算)
26 decimal.is_infinite(x)
27 decimal.is_nan(x)
28 decimal.is_normal(x) # x是否正常
29 decimal.is_signed(x) # 是否为负数
30
31 decimal.fma(a, b, c) # a * b + c, 精度更高
32
33 x.exp(), x.ln(), x.sqrt(), x.log10()
34
35 # 可以转复数, 前提是要import complex

```

## 7.3 $O(n^2)$ 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 const 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    big_decimal(string s) {
33        memset(a, 0, sizeof(a));
34        negative = false;
35
36        if (s == "")
37            return;
38
39        if (s[0] == '-') {
40            negative = true;
41            s = s.substr(1);
42        }
43        a[0] = s.size();
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 &u,
102     ↪ 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 &u,
122     ↪ 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
140     if (u.a[0] != v.a[0])

```

```

138     return u.a[0] < v.a[0] ? -1 : 1;
139
140     for (int i = u.a[0]; i; i--)
141         if (u.a[i] != v.a[i])
142             return u.a[i] < v.a[i] ? -1 : 1;
143
144     return 0;
145 }
146
147 friend bool operator < (const big_decimal &u, const
148     ↪ big_decimal &v) {
149     return cmp(u, v) == -1;
150 }
151
152 friend bool operator > (const big_decimal &u, const
153     ↪ big_decimal &v) {
154     return cmp(u, v) == 1;
155 }
156
157 friend bool operator == (const big_decimal &u, const
158     ↪ big_decimal &v) {
159     return cmp(u, v) == 0;
160 }
161
162 friend bool operator <= (const big_decimal &u, const
163     ↪ big_decimal &v) {
164     return cmp(u, v) <= 0;
165 }
166
167 friend bool operator >= (const big_decimal &u, const
168     ↪ big_decimal &v) {
169     return cmp(u, v) >= 0;
170 }
171
172 friend big_decimal decimal_plus(const big_decimal &u,
173     ↪ const big_decimal &v) { // 保证u, v均为正数的话可
174     ↪ 以直接调用
175     big_decimal o;
176
177     o.a[0] = max(u.a[0], v.a[0]);
178
179     for (int i = 1; i <= u.a[0] || i <= v.a[0]; i++)
180         ↪ {
181             o.a[i] += u.a[i] + v.a[i];
182
183             if (o.a[i] >= 10) {
184                 o.a[i + 1]++;
185                 o.a[i] -= 10;
186             }
187         }
188
189     if (o.a[o.a[0] + 1])
190         o.a[0]++;
191
192     return o;
193 }
194
195 friend big_decimal decimal_minus(const big_decimal
196     ↪ &u, const big_decimal &v) { // 保证u, v均为正数的
197     ↪ 话可以直接调用
198     int k = cmp(u, v);
199
200     if (k == -1)
201         return -decimal_minus(v, u);
202     else if (k == 0)
203         return big_decimal(0);
204
205     big_decimal o;
206
207     o.a[0] = u.a[0];

```

```

198
199     for (int i = 1; i <= u.a[0]; i++) {
200         o.a[i] += u.a[i] - v.a[i];
201
202         if (o.a[i] < 0) {
203             o.a[i] += 10;
204             o.a[i + 1]--;
205         }
206     }
207
208     while (o.a[0] && !o.a[o.a[0]])
209         o.a[0]--;
210
211     return o;
212 }
213
214 friend big_decimal decimal_multi(const big_decimal
    ↪ &u, const big_decimal &v) {
215     big_decimal o;
216
217     o.a[0] = u.a[0] + v.a[0] - 1;
218
219     for (int i = 1; i <= u.a[0]; i++)
220         for (int j = 1; j <= v.a[0]; j++)
221             o.a[i + j - 1] += u.a[i] * v.a[j];
222
223     for (int i = 1; i <= o.a[0]; i++)
224         if (o.a[i] >= 10) {
225             o.a[i + 1] += o.a[i] / 10;
226             o.a[i] %= 10;
227         }
228
229     if (o.a[o.a[0] + 1])
230         o.a[0]++;
231
232     return o;
233 }
234
235 friend pair<big_decimal, big_decimal>
    ↪ decimal_divide(big_decimal u, big_decimal v) { //
    ↪ 整除
236     if (v > u)
237         return make_pair(big_decimal(0), u);
238
239     big_decimal o;
240     o.a[0] = u.a[0] - v.a[0] + 1;
241
242     int m = v.a[0];
243     v <= u.a[0] - m;
244
245     for (int i = u.a[0]; i >= m; i--) {
246         while (u >= v) {
247             u = u - v;
248             o.a[i - m + 1]++;
249         }
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 &u,
    ↪ const big_decimal &v) {
261     if (u.negative || v.negative) {
262         if (u.negative && v.negative)
263             return -decimal_plus(-u, -v);
264
265         if (u.negative)
266             return v - (-u);
267
268         if (v.negative)
269             return u - (-v);
270     }
271
272     return decimal_plus(u, v);
273 }
274
275 friend big_decimal operator - (const big_decimal &u,
    ↪ const big_decimal &v) {
276     if (u.negative || v.negative) {
277         if (u.negative && v.negative)
278             return -decimal_minus(-u, -v);
279
280         if (u.negative)
281             return -decimal_plus(-u, v);
282
283         if (v.negative)
284             return decimal_plus(u, -v);
285     }
286
287     return decimal_minus(u, v);
288 }
289
290 friend big_decimal operator * (const big_decimal &u,
    ↪ const big_decimal &v) {
291     if (u.negative || v.negative) {
292         big_decimal o = decimal_multi(abs(u),
            ↪ abs(v));
293
294         if (u.negative ^ v.negative)
295             return -o;
296         return o;
297     }
298
299     return decimal_multi(u, v);
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>
    ↳ decimal_div(const big_decimal &u, const
329 ↳ big_decimal &v) {
330     if (u.negative || v.negative) {
331         pair<big_decimal, big_decimal> o =
332         ↳ decimal_div(abs(u), abs(v));
333
334         if (u.negative ^ v.negative)
335             return make_pair(-o.first, -o.second);
336         return o;
337     }
338     return decimal_divide(u, v);
339 }
340
341 friend big_decimal operator / (const big_decimal &u,
    ↳ const big_decimal &v) { // v不能是0
342     if (u.negative || v.negative) {
343         big_decimal o = abs(u) / abs(v);
344
345         if (u.negative ^ v.negative)
346             return -o;
347         return o;
348     }
349     return decimal_divide(u, v).first;
350 }
351
352 friend big_decimal operator % (const big_decimal &u,
    ↳ const big_decimal &v) {
353     if (u.negative || v.negative) {
354         big_decimal o = abs(u) % abs(v);
355
356         if (u.negative ^ v.negative)
357             return -o;
358         return o;
359     }
360
361     return decimal_divide(u, v).second;
362 }
363 };

```

## 7.4 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 (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 }

```

## 7.5 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
<b>998244353</b>	119	23	3
<b>1004535809</b>	479	21	3
1005060097*	1917	19	<b>5</b>
<b>2013265921</b>	15	27	<b>31</b>
2281701377	17	27	3
31525197391593473	7	52	3
180143985094819841	5	55	<b>6</b>
1945555039024054273	27	56	<b>5</b>
4179340454199820289	29	57	3

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

## 7.6 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 }

```

## 7.7 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 }

```

## 7.8 STL

### 7.8.1 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

### 7.8.2 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中重复的元素

## 7.9 pb\_ds

### 7.9.1 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)
```

### 7.9.2 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>,
   ↳ 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 $\Theta(\log n)$ ; 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](https://www.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

### 7.9.3 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,
   ↳ tree_order_statistics_node_update> t;
6
7 // rb_tree_tag 红黑树(还有splay_tree_tag和ov_tree_tag, 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<<32`后加上出现的次数后插入. 注意此时应该为`long long`类型.)

## 7.10 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
```

## 7.11 编译选项

- `-O2 -g -std=c++11`: 狗都知道
- `-Wall -Wextra -Wconversion`: 更多警告
- `-fsanitize=(address/undefined)`: 检查有符号整数溢出(算ub)/数组越界  
注意无符号类型溢出不算ub

## 7.12 注意事项

### 7.12.1 常见下毒手法

- 高精度高低位搞反了吗
- 线性筛抄对了吗
- 快速乘抄对了吗
- `i <= n, j <= m`
- `sort`比较函数是不是比了个寂寞
- 该取模的地方都取模了吗
- 边界情况(+1-1之类的)有没有想清楚
- 特判是否有必要, 确定写对了没

### 7.12.2 场外相关

- 安顿好之后查一下附近的咖啡店,打印店,便利店之类的位置,以备不时之需
- 热身赛记得检查一下编译注意事项中的代码能否过编译,还有熟悉比赛场地,清楚洗手间在哪儿,测试打印机(如果可以)
- 比赛前至少要翻一遍板子,尤其要看原理与例题

- 比赛前一两天不要摸鱼,要早睡,有条件最好洗个澡;比赛当天不要起太晚,维持好的状态
- 赛前记得买咖啡,最好直接安排三人份,记得要咖啡因比较足的;如果主办方允许,就带些巧克力之类的高热量零食
- 入场之后记得检查机器,尤其要逐个检查键盘按键有没有坏的;如果可以的话,调一下gedit设置
- 开赛之前调整好心态,比赛而已,不必心急.

### 7.12.3 做题策略与心态调节

- 拿到题后立刻按照商量好的顺序读题, 前半小时最好跳过题意太复杂的题(除非被过穿了)
- 签到题写完不要激动, 稍微检查一下最可能的下毒点再交, 避免无谓的罚时  
一两行的那种傻逼题就算了
- 读完题及时输出题意, 一方面避免重复读题, 一方面也可以让队友有一个初步印象, 方便之后决定开题顺序
- 如果不能确定题意就不要贸然输出甚至上机, 尤其是签到题, 因为样例一般都很弱
- 一个题如果卡了很久又有其他题可以写, 那不妨先放掉写更容易的题, 不要在一棵树上吊死

不要被一两道题搞得心态爆炸, 一方面急也没有意义, 一方面你很可能真的离AC就差一步

- 榜是不会骗人的, 一个题如果被不少人过了就说明这个题很可能并没有那么难;如果不是有十足的把握就不要轻易开没什么人交的题;另外不要忘记最后一小时会封榜
- 想不出题/找不出毒自然容易犯困, 一定不要放任自己昏昏欲睡, 最好去洗手间冷静一下, 没有条件就站起来踱步
- 思考的时候不要挂机, 一定要在草稿纸上画一画, 最好说出声来最不容易断掉思路
- 出完算法一定要check一下样例和一些trivial的情况, 不然容易写了半天发现写了个假算法
- 上机前有时间就提前给需要思考怎么写的地方打草稿, 不要浪费机时
- 查毒时如果最难的地方反复check也没有问题, 就从头到脚仔仔细细查一遍, 不要放过任何细节, 即使是并查集和sort这种东西也不能想当然
- 后半场如果时间不充裕就不要冒险开难题, 除非真的无事可做  
如果是没写过的东西也不要轻举妄动, 在有其他好写的题的时候就等一会再说
- 大多数时候都要听队长安排, 虽然不一定最正确但可以保持组织性
- 任何时候都不要着急, 着急不能解决问题, 不要当喆国王
- 输了游戏, 还有人生;赢了游戏, 还有人生.

## 7.13 附录: Cheat Sheet

见最后几页.

# Theoretical Computer Science Cheat Sheet

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

# Theoretical Computer Science Cheat Sheet

## Identities Cont.

$$\begin{aligned}
 38. \quad \binom{n+1}{m+1} &= \sum_k \binom{n}{k} \binom{k}{m} = \sum_{k=0}^n \binom{k}{m} n^{\overline{n-k}} = n! \sum_{k=0}^n \frac{1}{k!} \binom{k}{m}, & 39. \quad \begin{bmatrix} x \\ x-n \end{bmatrix} &= \sum_{k=0}^n \left\langle \begin{matrix} n \\ k \end{matrix} \right\rangle \begin{pmatrix} x+k \\ 2n \end{pmatrix}, \\
 40. \quad \left\{ \begin{matrix} n \\ m \end{matrix} \right\} &= \sum_k \binom{n}{k} \left\{ \begin{matrix} k+1 \\ m+1 \end{matrix} \right\} (-1)^{n-k}, & 41. \quad \begin{bmatrix} n \\ m \end{bmatrix} &= \sum_k \begin{bmatrix} n+1 \\ k+1 \end{bmatrix} \binom{k}{m} (-1)^{m-k}, \\
 42. \quad \left\{ \begin{matrix} m+n+1 \\ m \end{matrix} \right\} &= \sum_{k=0}^m k \left\{ \begin{matrix} n+k \\ k \end{matrix} \right\}, & 43. \quad \begin{bmatrix} m+n+1 \\ m \end{bmatrix} &= \sum_{k=0}^m k(n+k) \begin{bmatrix} n+k \\ k \end{bmatrix}, \\
 44. \quad \binom{n}{m} &= \sum_k \left\{ \begin{matrix} n+1 \\ k+1 \end{matrix} \right\} \begin{bmatrix} k \\ m \end{bmatrix} (-1)^{m-k}, & 45. \quad (n-m)! \binom{n}{m} &= \sum_k \begin{bmatrix} n+1 \\ k+1 \end{bmatrix} \left\{ \begin{matrix} k \\ m \end{matrix} \right\} (-1)^{m-k}, \quad \text{for } n \geq m, \\
 46. \quad \left\{ \begin{matrix} n \\ n-m \end{matrix} \right\} &= \sum_k \binom{m-n}{m+k} \binom{m+n}{n+k} \begin{bmatrix} m+k \\ k \end{bmatrix}, & 47. \quad \begin{bmatrix} n \\ n-m \end{bmatrix} &= \sum_k \binom{m-n}{m+k} \binom{m+n}{n+k} \left\{ \begin{matrix} m+k \\ k \end{matrix} \right\}, \\
 48. \quad \left\{ \begin{matrix} n \\ \ell+m \end{matrix} \right\} \binom{\ell+m}{\ell} &= \sum_k \left\{ \begin{matrix} k \\ \ell \end{matrix} \right\} \left\{ \begin{matrix} n-k \\ m \end{matrix} \right\} \binom{n}{k}, & 49. \quad \begin{bmatrix} n \\ \ell+m \end{bmatrix} \binom{\ell+m}{\ell} &= \sum_k \begin{bmatrix} k \\ \ell \end{bmatrix} \begin{bmatrix} n-k \\ m \end{bmatrix} \binom{n}{k}.
 \end{aligned}$$

## Trees

Every tree with  $n$  vertices has  $n-1$  edges.

Kraft inequality: If the depths of the leaves of a binary tree are  $d_1, \dots, d_n$ :

$$\sum_{i=1}^n 2^{-d_i} \leq 1,$$

and equality holds only if every internal node has 2 sons.

## Recurrences

Master method:

$$T(n) = aT(n/b) + f(n), \quad a \geq 1, b > 1$$

If  $\exists \epsilon > 0$  such that  $f(n) = O(n^{\log_b a - \epsilon})$  then

$$T(n) = \Theta(n^{\log_b a}).$$

If  $f(n) = \Theta(n^{\log_b a})$  then

$$T(n) = \Theta(n^{\log_b a} \log_2 n).$$

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

$$T(n) = \Theta(f(n)).$$

Substitution (example): Consider the following recurrence

$$T_{i+1} = 2^{2^i} \cdot T_i^2, \quad T_1 = 2.$$

Note that  $T_i$  is always a power of two.

Let  $t_i = \log_2 T_i$ . Then we have

$$t_{i+1} = 2^i + 2t_i, \quad t_1 = 1.$$

Let  $u_i = t_i/2^i$ . Dividing both sides of the previous equation by  $2^{i+1}$  we get

$$\frac{t_{i+1}}{2^{i+1}} = \frac{2^i}{2^{i+1}} + \frac{t_i}{2^i}.$$

Substituting we find

$$u_{i+1} = \frac{1}{2} + u_i, \quad u_1 = \frac{1}{2},$$

which is simply  $u_i = i/2$ . So we find that  $T_i$  has the closed form  $T_i = 2^{i2^{i-1}}$ .

Summing factors (example): Consider the following recurrence

$$T(n) = 3T(n/2) + n, \quad T(1) = 1.$$

Rewrite so that all terms involving  $T$  are on the left side

$$T(n) - 3T(n/2) = n.$$

Now expand the recurrence, and choose a factor which makes the left side “telescope”

$$1(T(n) - 3T(n/2)) = n$$

$$3(T(n/2) - 3T(n/4)) = n/2$$

$$\vdots \quad \vdots \quad \vdots$$

$$3^{\log_2 n - 1} (T(2) - 3T(1)) = 2$$

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

$$\sum_{i=0}^{m-1} \frac{n}{2^i} 3^i = n \sum_{i=0}^{m-1} \left(\frac{3}{2}\right)^i.$$

Let  $c = \frac{3}{2}$ . Then we have

$$n \sum_{i=0}^{m-1} c^i = n \left( \frac{c^m - 1}{c - 1} \right)$$

$$= 2n(c^{\log_2 n} - 1)$$

$$= 2n(c^{(k-1)\log_2 n} - 1)$$

$$= 2n^k - 2n,$$

and so  $T(n) = 3n^k - 2n$ . Full history recurrences can often be changed to limited history ones (example): Consider

$$T_i = 1 + \sum_{j=0}^{i-1} T_j, \quad T_0 = 1.$$

Note that

$$T_{i+1} = 1 + \sum_{j=0}^i T_j.$$

Subtracting we find

$$T_{i+1} - T_i = 1 + \sum_{j=0}^i T_j - 1 - \sum_{j=0}^{i-1} T_j$$

$$= T_i.$$

And so  $T_{i+1} = 2T_i = 2^{i+1}$ .

Generating functions:

1. Multiply both sides of the equation by  $x^i$ .
2. Sum both sides over all  $i$  for which the equation is valid.
3. Choose a generating function  $G(x)$ . Usually  $G(x) = \sum_{i=0}^{\infty} x^i g_i$ .
3. Rewrite the equation in terms of the generating function  $G(x)$ .
4. Solve for  $G(x)$ .
5. The coefficient of  $x^i$  in  $G(x)$  is  $g_i$ .

Example:

$$g_{i+1} = 2g_i + 1, \quad g_0 = 0.$$

Multiply and sum:

$$\sum_{i \geq 0} g_{i+1} x^i = \sum_{i \geq 0} 2g_i x^i + \sum_{i \geq 0} x^i.$$

We choose  $G(x) = \sum_{i \geq 0} x^i g_i$ . Rewrite in terms of  $G(x)$ :

$$\frac{G(x) - g_0}{x} = 2G(x) + \sum_{i \geq 0} x^i.$$

Simplify:

$$\frac{G(x)}{x} = 2G(x) + \frac{1}{1-x}.$$

Solve for  $G(x)$ :

$$G(x) = \frac{x}{(1-x)(1-2x)}.$$

Expand this using partial fractions:

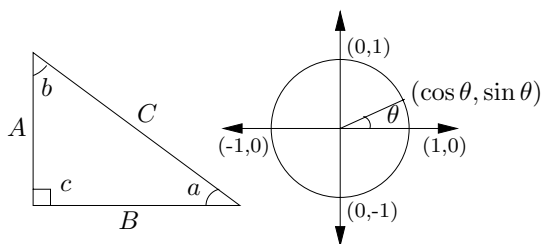
$$\begin{aligned}
 G(x) &= x \left( \frac{2}{1-2x} - \frac{1}{1-x} \right) \\
 &= x \left( 2 \sum_{i \geq 0} 2^i x^i - \sum_{i \geq 0} x^i \right) \\
 &= \sum_{i \geq 0} (2^{i+1} - 1) x^{i+1}.
 \end{aligned}$$

So  $g_i = 2^i - 1$ .

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 $i \neq 1$ ): $B_0 = 1, B_1 = -\frac{1}{2}, B_2 = \frac{1}{6}, B_4 = -\frac{1}{30},$ $B_6 = \frac{1}{42}, B_8 = -\frac{1}{30}, B_{10} = \frac{5}{66}.$ Change of base, quadratic formula: $\log_b x = \frac{\log_a x}{\log_a b}, \quad \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}.$ Euler's number $e$ : $e = 1 + \frac{1}{2} + \frac{1}{6} + \frac{1}{24} + \frac{1}{120} + \cdots$ $\lim_{n \rightarrow \infty} \left(1 + \frac{x}{n}\right)^n = e^x.$ $\left(1 + \frac{1}{n}\right)^n < e < \left(1 + \frac{1}{n}\right)^{n+1}.$ $\left(1 + \frac{1}{n}\right)^n = e - \frac{e}{2n} + \frac{11e}{24n^2} - O\left(\frac{1}{n^3}\right).$ Harmonic numbers: $1, \frac{3}{2}, \frac{11}{6}, \frac{25}{12}, \frac{137}{60}, \frac{49}{20}, \frac{363}{140}, \frac{761}{280}, \frac{7129}{2520}, \dots$ $\ln n < H_n < \ln n + 1,$ $H_n = \ln n + \gamma + O\left(\frac{1}{n}\right).$ Factorial, Stirling's approximation: $1, 2, 6, 24, 120, 720, 5040, 40320, 362880, \dots$ $n! = \sqrt{2\pi n} \left(\frac{n}{e}\right)^n \left(1 + \Theta\left(\frac{1}{n}\right)\right).$ Ackermann's function and inverse: $a(i, j) = \begin{cases} 2^j & i = 1 \\ a(i-1, 2) & j = 1 \\ a(i-1, a(i, j-1)) & i, j \geq 2 \end{cases}$ $\alpha(i) = \min\{j \mid a(j, j) \geq i\}.$	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 $P(a) = \int_{-\infty}^a p(x) dx.$ Expectation: If $X$ is discrete $\mathbb{E}[g(X)] = \sum_x g(x) \Pr[X = x].$ If $X$ continuous then $\mathbb{E}[g(X)] = \int_{-\infty}^{\infty} g(x)p(x) dx = \int_{-\infty}^{\infty} g(x) dP(x).$ Variance, standard deviation: $\text{VAR}[X] = \mathbb{E}[X^2] - \mathbb{E}[X]^2,$ $\sigma = \sqrt{\text{VAR}[X]}.$ For events $A$ and $B$ : $\Pr[A \vee B] = \Pr[A] + \Pr[B] - \Pr[A \wedge B]$ $\Pr[A \wedge B] = \Pr[A] \cdot \Pr[B],$ iff $A$ and $B$ are independent. $\Pr[A B] = \frac{\Pr[A \wedge B]}{\Pr[B]}$ For random variables $X$ and $Y$ : $\mathbb{E}[X \cdot Y] = \mathbb{E}[X] \cdot \mathbb{E}[Y],$ if $X$ and $Y$ are independent. $\mathbb{E}[X + Y] = \mathbb{E}[X] + \mathbb{E}[Y],$ $\mathbb{E}[cX] = c \mathbb{E}[X].$ Bayes' theorem: $\Pr[A_i B] = \frac{\Pr[B A_i] \Pr[A_i]}{\sum_{j=1}^n \Pr[B A_j] \Pr[A_j]}.$ Inclusion-exclusion: $\Pr\left[\bigvee_{i=1}^n X_i\right] = \sum_{i=1}^n \Pr[X_i] +$ $\sum_{k=2}^n (-1)^{k+1} \sum_{i_1 < \cdots < i_k} \Pr\left[\bigwedge_{j=1}^k X_{i_j}\right].$ Moment inequalities: $\Pr\left[ X  \geq \lambda \mathbb{E}[X]\right] \leq \frac{1}{\lambda},$ $\Pr\left[ X - \mathbb{E}[X]  \geq \lambda \cdot \sigma\right] \leq \frac{1}{\lambda^2}.$ Geometric distribution: $\Pr[X = k] = pq^{k-1}, \quad q = 1 - p,$ $\mathbb{E}[X] = \sum_{k=1}^{\infty} kpq^{k-1} = \frac{1}{p}.$	
2	4	3			
3	8	5			
4	16	7			
5	32	11			
6	64	13			
7	128	17			
8	256	19			
9	512	23			
10	1,024	29			
11	2,048	31			
12	4,096	37			
13	8,192	41			
14	16,384	43			
15	32,768	47			
16	65,536	53			
17	131,072	59			
18	262,144	61			
19	524,288	67			
20	1,048,576	71			
21	2,097,152	73			
22	4,194,304	79			
23	8,388,608	83			
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			
29	536,870,912	109			
30	1,073,741,824	113			
31	2,147,483,648	127			
32	4,294,967,296	131			
Pascal's Triangle			Binomial distribution: $\Pr[X = k] = \binom{n}{k} p^k q^{n-k}, \quad q = 1 - p,$ $\mathbb{E}[X] = \sum_{k=1}^n k \binom{n}{k} p^k q^{n-k} = np.$ Poisson distribution: $\Pr[X = k] = \frac{e^{-\lambda} \lambda^k}{k!}, \quad \mathbb{E}[X] = \lambda.$ Normal (Gaussian) distribution: $p(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(x-\mu)^2/2\sigma^2}, \quad \mathbb{E}[X] = \mu.$ 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 to collect all $n$ types is $nH_n.$		
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:

$$\begin{aligned} \sin a &= A/C, & \cos a &= B/C, \\ \csc a &= C/A, & \sec a &= C/B, \\ \tan a &= \frac{\sin a}{\cos a} = \frac{A}{B}, & \cot a &= \frac{\cos a}{\sin a} = \frac{B}{A}. \end{aligned}$$

Area, radius of inscribed circle:

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

Identities:

$$\sin x = \frac{1}{\csc x}, \quad \cos x = \frac{1}{\sec x},$$

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

$$1 + \tan^2 x = \sec^2 x, \quad 1 + \cot^2 x = \csc^2 x,$$

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

$$\cos x = -\cos(\pi - x), \quad \tan x = \cot\left(\frac{\pi}{2} - x\right),$$

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

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

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

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

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

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

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

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

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

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

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

Euler's equation:

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

## 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.

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

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

$2 \times 2$  and  $3 \times 3$  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:

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

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

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

Identities:

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

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

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

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

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

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

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

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

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

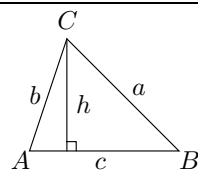
$$2 \sinh^2 \frac{x}{2} = \cosh x - 1, \quad 2 \cosh^2 \frac{x}{2} = \cosh x + 1.$$

$\theta$	$\sin \theta$	$\cos \theta$	$\tan \theta$
0	0	1	0
$\frac{\pi}{6}$	$\frac{1}{2}$	$\frac{\sqrt{3}}{2}$	$\frac{\sqrt{3}}{3}$
$\frac{\pi}{4}$	$\frac{\sqrt{2}}{2}$	$\frac{\sqrt{2}}{2}$	1
$\frac{\pi}{3}$	$\frac{\sqrt{3}}{2}$	$\frac{1}{2}$	$\sqrt{3}$
$\frac{\pi}{2}$	1	0	$\infty$

... in mathematics  
you don't under-  
stand 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:

$$\begin{aligned} A &= \frac{1}{2}hc, \\ &= \frac{1}{2}ab \sin C, \\ &= \frac{c^2 \sin A \sin B}{2 \sin C}. \end{aligned}$$

Heron's formula:

$$\begin{aligned} A &= \sqrt{s \cdot s_a \cdot s_b \cdot s_c}, \\ s &= \frac{1}{2}(a + b + c), \\ s_a &= s - a, \\ s_b &= s - b, \\ s_c &= s - c. \end{aligned}$$

More identities:

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

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

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

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

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

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

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

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

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

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

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

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

$$\sin x = \frac{\sinh ix}{i},$$

$$\cos x = \cosh ix,$$

$$\tan x = \frac{\tanh ix}{i}.$$

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# Theoretical Computer Science Cheat Sheet

## Number Theory

The Chinese remainder theorem: There exists a number  $C$  such that:

$$C \equiv r_1 \pmod{m_1}$$

$$\vdots \quad \vdots \quad \vdots$$

$$C \equiv r_n \pmod{m_n}$$

if  $m_i$  and  $m_j$  are relatively prime for  $i \neq j$ .

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

$$\phi(x) = \prod_{i=1}^n p_i^{e_i-1} (p_i - 1).$$

Euler's theorem: If  $a$  and  $b$  are relatively prime then

$$1 \equiv a^{\phi(b)} \pmod{b}.$$

Fermat's theorem:

$$1 \equiv a^{p-1} \pmod{p}.$$

The Euclidean algorithm: if  $a > b$  are integers then

$$\gcd(a, b) = \gcd(a \bmod b, b).$$

If  $\prod_{i=1}^n p_i^{e_i}$  is the prime factorization of  $x$  then

$$S(x) = \sum_{d|x} d = \prod_{i=1}^n \frac{p_i^{e_i+1} - 1}{p_i - 1}.$$

Perfect Numbers:  $x$  is an even perfect number iff  $x = 2^{n-1}(2^n - 1)$  and  $2^n - 1$  is prime.

Wilson's theorem:  $n$  is a prime iff

$$(n - 1)! \equiv -1 \pmod{n}.$$

Möbius inversion:

$$\mu(i) = \begin{cases} 1 & \text{if } i = 1. \\ 0 & \text{if } i \text{ is not square-free.} \\ (-1)^r & \text{if } i \text{ is the product of } r \text{ distinct primes.} \end{cases}$$

If

$$G(a) = \sum_{d|a} F(d),$$

then

$$F(a) = \sum_{d|a} \mu(d) G\left(\frac{a}{d}\right).$$

Prime numbers:

$$p_n = n \ln n + n \ln \ln n - n + n \frac{\ln \ln n}{\ln n}$$

$$+ O\left(\frac{n}{\ln n}\right),$$

$$\pi(n) = \frac{n}{\ln n} + \frac{n}{(\ln n)^2} + \frac{2!n}{(\ln n)^3}$$

$$+ O\left(\frac{n}{(\ln n)^4}\right).$$

## Graph Theory

### Definitions:

*Loop* An edge connecting a vertex to itself.

*Directed* Each edge has a direction.

*Simple* Graph with no loops or multi-edges.

*Walk* A sequence  $v_0 e_1 v_1 \dots e_\ell v_\ell$ .

*Trail* A walk with distinct edges.

*Path* A trail with distinct vertices.

*Connected* A graph where there exists a path between any two vertices.

*Component* A maximal connected subgraph.

*Tree* A connected acyclic graph.

*Free tree* A tree with no root.

*DAG* Directed acyclic graph.

*Eulerian* Graph with a trail visiting each edge exactly once.

*Hamiltonian* Graph with a cycle visiting each vertex exactly once.

*Cut* A set of edges whose removal increases the number of components.

*Cut-set* A minimal cut.

*Cut edge* A size 1 cut.

*k-Connected* A graph connected with the removal of any  $k - 1$  vertices.

*k-Tough*  $\forall S \subseteq V, S \neq \emptyset$  we have  $k \cdot c(G - S) \leq |S|$ .

*k-Regular* A graph where all vertices have degree  $k$ .

*k-Factor* A  $k$ -regular spanning subgraph.

*Matching* A set of edges, no two of which are adjacent.

*Clique* A set of vertices, all of which are adjacent.

*Ind. set* A set of vertices, none of which are adjacent.

*Vertex cover* A set of vertices which cover all edges.

*Planar graph* A graph which can be embedded in the plane.

*Plane graph* An embedding of a planar graph.

$$\sum_{v \in V} \deg(v) = 2m.$$

If  $G$  is planar then  $n - m + f = 2$ , so

$$f \leq 2n - 4, \quad m \leq 3n - 6.$$

Any planar graph has a vertex with degree  $\leq 5$ .

### Notation:

$E(G)$  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

Projective coordinates: triples  $(x, y, z)$ , not all  $x, y$  and  $z$  zero.

$$(x, y, z) = (cx, cy, cz) \quad \forall c \neq 0.$$

Cartesian Projective

$$(x, y) \quad (x, y, 1)$$

$$y = mx + b \quad (m, -1, b)$$

$$x = c \quad (1, 0, -c)$$

Distance formula,  $L_p$  and  $L_\infty$  metric:

$$\sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2},$$

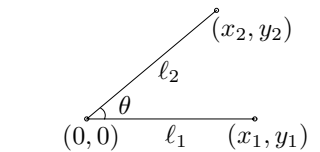
$$[|x_1 - x_0|^p + |y_1 - y_0|^p]^{1/p},$$

$$\lim_{p \rightarrow \infty} [|x_1 - x_0|^p + |y_1 - y_0|^p]^{1/p}.$$

Area of triangle  $(x_0, y_0), (x_1, y_1)$  and  $(x_2, y_2)$ :

$$\frac{1}{2} \text{abs} \begin{vmatrix} x_1 - x_0 & y_1 - y_0 \\ x_2 - x_0 & y_2 - y_0 \end{vmatrix}.$$

Angle formed by three points:



$$\cos \theta = \frac{(x_1, y_1) \cdot (x_2, y_2)}{l_1 l_2}.$$

Line through two points  $(x_0, y_0)$  and  $(x_1, y_1)$ :

$$\begin{vmatrix} x & y & 1 \\ x_0 & y_0 & 1 \\ x_1 & y_1 & 1 \end{vmatrix} = 0.$$

Area of circle, volume of sphere:

$$A = \pi r^2, \quad V = \frac{4}{3} \pi r^3.$$

If I have seen farther than others, it is because I have stood on the shoulders of giants.

– Issac Newton

# Theoretical Computer Science Cheat Sheet

$\pi$

Wallis' identity:

$$\pi = 2 \cdot \frac{2 \cdot 2 \cdot 4 \cdot 4 \cdot 6 \cdot 6 \cdots}{1 \cdot 3 \cdot 3 \cdot 5 \cdot 5 \cdot 7 \cdots}$$

Brouncker's continued fraction expansion:

$$\frac{\pi}{4} = 1 + \frac{1^2}{2 + \frac{3^2}{2 + \frac{5^2}{2 + \frac{7^2}{2 + \cdots}}}}$$

Gregory's series:

$$\frac{\pi}{4} = 1 - \frac{1}{3} + \frac{1}{5} - \frac{1}{7} + \frac{1}{9} - \cdots$$

Newton's series:

$$\frac{\pi}{6} = \frac{1}{2} + \frac{1}{2 \cdot 3 \cdot 2^3} + \frac{1 \cdot 3}{2 \cdot 4 \cdot 5 \cdot 2^5} + \cdots$$

Sharp's series:

$$\frac{\pi}{6} = \frac{1}{\sqrt{3}} \left( 1 - \frac{1}{3^1 \cdot 3} + \frac{1}{3^2 \cdot 5} - \frac{1}{3^3 \cdot 7} + \cdots \right)$$

Euler's series:

$$\frac{\pi^2}{6} = \frac{1}{1^2} + \frac{1}{2^2} + \frac{1}{3^2} + \frac{1}{4^2} + \frac{1}{5^2} + \cdots$$

$$\frac{\pi^2}{8} = \frac{1}{1^2} + \frac{1}{3^2} + \frac{1}{5^2} + \frac{1}{7^2} + \frac{1}{9^2} + \cdots$$

$$\frac{\pi^2}{12} = \frac{1}{1^2} - \frac{1}{2^2} + \frac{1}{3^2} - \frac{1}{4^2} + \frac{1}{5^2} - \cdots$$

## Partial Fractions

Let  $N(x)$  and  $D(x)$  be polynomial functions of  $x$ . We can break down  $N(x)/D(x)$  using partial fraction expansion. First, if the degree of  $N$  is greater than or equal to the degree of  $D$ , divide  $N$  by  $D$ , obtaining

$$\frac{N(x)}{D(x)} = Q(x) + \frac{N'(x)}{D(x)},$$

where the degree of  $N'$  is less than that of  $D$ . Second, factor  $D(x)$ . Use the following rules: For a non-repeated factor:

$$\frac{N(x)}{(x-a)D(x)} = \frac{A}{x-a} + \frac{N'(x)}{D(x)},$$

where

$$A = \left[ \frac{N(x)}{D(x)} \right]_{x=a}.$$

For a repeated factor:

$$\frac{N(x)}{(x-a)^m D(x)} = \sum_{k=0}^{m-1} \frac{A_k}{(x-a)^{m-k}} + \frac{N'(x)}{D(x)},$$

where

$$A_k = \frac{1}{k!} \left[ \frac{d^k}{dx^k} \left( \frac{N(x)}{D(x)} \right) \right]_{x=a}.$$

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

## Calculus

Derivatives:

$$1. \frac{d(cu)}{dx} = c \frac{du}{dx}, \quad 2. \frac{d(u+v)}{dx} = \frac{du}{dx} + \frac{dv}{dx}, \quad 3. \frac{d(uv)}{dx} = u \frac{dv}{dx} + v \frac{du}{dx},$$

$$4. \frac{d(u^n)}{dx} = nu^{n-1} \frac{du}{dx}, \quad 5. \frac{d(u/v)}{dx} = \frac{v \left( \frac{du}{dx} \right) - u \left( \frac{dv}{dx} \right)}{v^2}, \quad 6. \frac{d(e^{cu})}{dx} = ce^{cu} \frac{du}{dx},$$

$$7. \frac{d(c^u)}{dx} = (\ln c) c^u \frac{du}{dx}, \quad 8. \frac{d(\ln u)}{dx} = \frac{1}{u} \frac{du}{dx},$$

$$9. \frac{d(\sin u)}{dx} = \cos u \frac{du}{dx}, \quad 10. \frac{d(\cos u)}{dx} = -\sin u \frac{du}{dx},$$

$$11. \frac{d(\tan u)}{dx} = \sec^2 u \frac{du}{dx}, \quad 12. \frac{d(\cot u)}{dx} = -\csc^2 u \frac{du}{dx},$$

$$13. \frac{d(\sec u)}{dx} = \tan u \sec u \frac{du}{dx}, \quad 14. \frac{d(\csc u)}{dx} = -\cot u \csc u \frac{du}{dx},$$

$$15. \frac{d(\arcsin u)}{dx} = \frac{1}{\sqrt{1-u^2}} \frac{du}{dx}, \quad 16. \frac{d(\arccos u)}{dx} = \frac{-1}{\sqrt{1-u^2}} \frac{du}{dx},$$

$$17. \frac{d(\arctan u)}{dx} = \frac{1}{1+u^2} \frac{du}{dx}, \quad 18. \frac{d(\operatorname{arccot} u)}{dx} = \frac{-1}{1+u^2} \frac{du}{dx},$$

$$19. \frac{d(\operatorname{arcsec} u)}{dx} = \frac{1}{u\sqrt{1-u^2}} \frac{du}{dx}, \quad 20. \frac{d(\operatorname{arccsc} u)}{dx} = \frac{-1}{u\sqrt{1-u^2}} \frac{du}{dx},$$

$$21. \frac{d(\sinh u)}{dx} = \cosh u \frac{du}{dx}, \quad 22. \frac{d(\cosh u)}{dx} = \sinh u \frac{du}{dx},$$

$$23. \frac{d(\tanh u)}{dx} = \operatorname{sech}^2 u \frac{du}{dx}, \quad 24. \frac{d(\coth u)}{dx} = -\operatorname{csch}^2 u \frac{du}{dx},$$

$$25. \frac{d(\operatorname{sech} u)}{dx} = -\operatorname{sech} u \tanh u \frac{du}{dx}, \quad 26. \frac{d(\operatorname{csch} u)}{dx} = -\operatorname{csch} u \coth u \frac{du}{dx},$$

$$27. \frac{d(\operatorname{arcsinh} u)}{dx} = \frac{1}{\sqrt{1+u^2}} \frac{du}{dx}, \quad 28. \frac{d(\operatorname{arccosh} u)}{dx} = \frac{1}{\sqrt{u^2-1}} \frac{du}{dx},$$

$$29. \frac{d(\operatorname{arctanh} u)}{dx} = \frac{1}{1-u^2} \frac{du}{dx}, \quad 30. \frac{d(\operatorname{arcoth} u)}{dx} = \frac{1}{u^2-1} \frac{du}{dx},$$

$$31. \frac{d(\operatorname{arcsech} u)}{dx} = \frac{-1}{u\sqrt{1-u^2}} \frac{du}{dx}, \quad 32. \frac{d(\operatorname{arccsch} u)}{dx} = \frac{-1}{|u|\sqrt{1+u^2}} \frac{du}{dx}.$$

Integrals:

$$1. \int cu \, dx = c \int u \, dx, \quad 2. \int (u+v) \, dx = \int u \, dx + \int v \, dx,$$

$$3. \int x^n \, dx = \frac{1}{n+1} x^{n+1}, \quad n \neq -1, \quad 4. \int \frac{1}{x} \, dx = \ln x, \quad 5. \int e^x \, dx = e^x,$$

$$6. \int \frac{dx}{1+x^2} = \arctan x, \quad 7. \int u \frac{dv}{dx} \, dx = uv - \int v \frac{du}{dx} \, dx,$$

$$8. \int \sin x \, dx = -\cos x, \quad 9. \int \cos x \, dx = \sin x,$$

$$10. \int \tan x \, dx = -\ln |\cos x|, \quad 11. \int \cot x \, dx = \ln |\cos x|,$$

$$12. \int \sec x \, dx = \ln |\sec x + \tan x|, \quad 13. \int \csc x \, dx = \ln |\csc x + \cot x|,$$

$$14. \int \arcsin \frac{x}{a} \, dx = \arcsin \frac{x}{a} + \sqrt{a^2 - x^2}, \quad a > 0,$$



# 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.  $\int \sinh x dx = \cosh x,$
28.  $\int \cosh x dx = \sinh x,$
29.  $\int \tanh x dx = \ln |\cosh x|,$
30.  $\int \coth x dx = \ln |\sinh x|,$
31.  $\int \operatorname{sech} x dx = \arctan \sinh x,$
32.  $\int \operatorname{csch} x dx = \ln \left| \tanh \frac{x}{2} \right|,$
33.  $\int \sinh^2 x dx = \frac{1}{4} \sinh(2x) - \frac{1}{2} x,$
34.  $\int \cosh^2 x dx = \frac{1}{4} \sinh(2x) + \frac{1}{2} x,$
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.  $\int \frac{dx}{a^2 - x^2} = \frac{1}{2a} \ln \left| \frac{a+x}{a-x} \right|,$
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.

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

## Finite Calculus

Difference, shift operators:

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

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

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:

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

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

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

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

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

Sums:

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

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

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

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

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

Falling Factorial Powers:

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

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

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

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

Rising Factorial Powers:

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

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

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

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

Conversion:

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

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

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

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

$$x^n = \sum_{k=1}^n \left\{ \begin{matrix} n \\ k \end{matrix} \right\} x^{\underline{k}} = \sum_{k=1}^n \left\{ \begin{matrix} n \\ k \end{matrix} \right\} (-1)^{n-k} x^{\overline{k}},$$

$$x^{\underline{n}} = \sum_{k=1}^n \left[ \begin{matrix} n \\ k \end{matrix} \right] (-1)^{n-k} x^k,$$

$$x^{\overline{n}} = \sum_{k=1}^n \left[ \begin{matrix} n \\ k \end{matrix} \right] x^k.$$

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

# 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:

$$\begin{aligned} \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^n x^2 + 3^n x^3 + 4^n x^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. \end{aligned}$$

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:

$$\alpha A(x) + \beta B(x) = \sum_{i=0}^{\infty} (\alpha a_i + \beta b_i) x^i,$$

$$x^k A(x) = \sum_{i=k}^{\infty} a_{i-k} x^i,$$

$$\frac{A(x) - \sum_{i=0}^{k-1} a_i x^i}{x^k} = \sum_{i=0}^{\infty} a_{i+k} x^i,$$

$$A(cx) = \sum_{i=0}^{\infty} c^i a_i x^i,$$

$$A'(x) = \sum_{i=0}^{\infty} (i+1) a_{i+1} x^i,$$

$$x A'(x) = \sum_{i=1}^{\infty} i a_i x^i,$$

$$\int A(x) dx = \sum_{i=1}^{\infty} \frac{a_{i-1}}{i} x^i,$$

$$\frac{A(x) + A(-x)}{2} = \sum_{i=0}^{\infty} a_{2i} x^{2i},$$

$$\frac{A(x) - A(-x)}{2} = \sum_{i=0}^{\infty} a_{2i+1} x^{2i+1}.$$

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

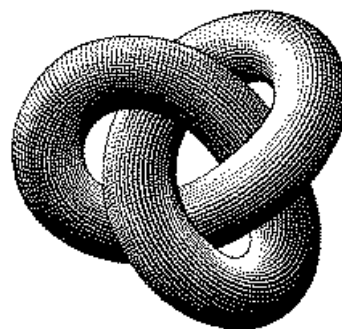
## Series

Expansions:

$$\begin{aligned}\frac{1}{(1-x)^{n+1}} \ln \frac{1}{1-x} &= \sum_{i=0}^{\infty} (H_{n+i} - H_n) \binom{n+i}{i} x^i, \\ x^{\overline{n}} &= \sum_{i=0}^{\infty} \left[ \begin{matrix} n \\ i \end{matrix} \right] x^i, \\ \left( \ln \frac{1}{1-x} \right)^n &= \sum_{i=0}^{\infty} \left[ \begin{matrix} i \\ n \end{matrix} \right] \frac{n! x^i}{i!}, \\ \tan x &= \sum_{i=1}^{\infty} (-1)^{i-1} \frac{2^{2i} (2^{2i} - 1) B_{2i} x^{2i-1}}{(2i)!}, \\ \frac{1}{\zeta(x)} &= \sum_{i=1}^{\infty} \frac{\mu(i)}{i^x}, \\ \zeta(x) &= \prod_p \frac{1}{1 - p^{-x}}, \\ \zeta^2(x) &= \sum_{i=1}^{\infty} \frac{d(i)}{x^i} \quad \text{where } d(n) = \sum_{d|n} 1, \\ \zeta(x) \zeta(x-1) &= \sum_{i=1}^{\infty} \frac{S(i)}{x^i} \quad \text{where } S(n) = \sum_{d|n} d, \\ \zeta(2n) &= \frac{2^{2n-1} |B_{2n}|}{(2n)!} \pi^{2n}, \quad n \in \mathbb{N}, \\ \frac{x}{\sin x} &= \sum_{i=0}^{\infty} (-1)^{i-1} \frac{(4^i - 2) B_{2i} x^{2i}}{(2i)!}, \\ \left( \frac{1 - \sqrt{1-4x}}{2x} \right)^n &= \sum_{i=0}^{\infty} \frac{n(2i+n-1)!}{i!(n+i)!} x^i, \\ e^x \sin x &= \sum_{i=1}^{\infty} \frac{2^{i/2} \sin \frac{i\pi}{4}}{i!} x^i, \\ \sqrt{\frac{1 - \sqrt{1-x}}{x}} &= \sum_{i=0}^{\infty} \frac{(4i)!}{16^i \sqrt{2} (2i)! (2i+1)!} x^i, \\ \left( \frac{\arcsin x}{x} \right)^2 &= \sum_{i=0}^{\infty} \frac{4^i i!^2}{(i+1)(2i+1)!} x^{2i}.\end{aligned}$$

$$\begin{aligned}\left( \frac{1}{x} \right)^{\overline{-n}} &= \sum_{i=0}^{\infty} \left\{ \begin{matrix} i \\ n \end{matrix} \right\} x^i, \\ (e^x - 1)^n &= \sum_{i=0}^{\infty} \left\{ \begin{matrix} i \\ n \end{matrix} \right\} \frac{n! x^i}{i!}, \\ x \cot x &= \sum_{i=0}^{\infty} \frac{(-4)^i B_{2i} x^{2i}}{(2i)!}, \\ \zeta(x) &= \sum_{i=1}^{\infty} \frac{1}{i^x}, \\ \frac{\zeta(x-1)}{\zeta(x)} &= \sum_{i=1}^{\infty} \frac{\phi(i)}{i^x},\end{aligned}$$

## Escher's Knot



## Stieltjes Integration

If  $G$  is continuous in the interval  $[a, b]$  and  $F$  is nondecreasing then

$$\int_a^b G(x) dF(x)$$

exists. If  $a \leq b \leq c$  then

$$\int_a^c G(x) dF(x) = \int_a^b G(x) dF(x) + \int_b^c G(x) dF(x).$$

If the integrals involved exist

$$\int_a^b (G(x) + H(x)) dF(x) = \int_a^b G(x) dF(x) + \int_a^b H(x) dF(x),$$

$$\int_a^b G(x) d(F(x) + H(x)) = \int_a^b G(x) dF(x) + \int_a^b G(x) dH(x),$$

$$\int_a^b c \cdot G(x) dF(x) = \int_a^b G(x) d(c \cdot F(x)) = c \int_a^b G(x) dF(x),$$

$$\int_a^b G(x) dF(x) = G(b)F(b) - G(a)F(a) - \int_a^b F(x) dG(x).$$

If the integrals involved exist, and  $F$  possesses a derivative  $F'$  at every point in  $[a, b]$  then

$$\int_a^b G(x) dF(x) = \int_a^b G(x) F'(x) dx.$$

## Cramer's Rule

If we have equations:

$$a_{1,1}x_1 + a_{1,2}x_2 + \cdots + a_{1,n}x_n = b_1$$

$$a_{2,1}x_1 + a_{2,2}x_2 + \cdots + a_{2,n}x_n = b_2$$

$$\vdots \quad \quad \quad \vdots$$

$$a_{n,1}x_1 + a_{n,2}x_2 + \cdots + a_{n,n}x_n = b_n$$

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

$$x_i = \frac{\det A_i}{\det A}.$$

Improvement makes strait roads, but the crooked roads without Improvement, are roads of Genius.  
– William Blake (The Marriage of Heaven and Hell)

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

The Fibonacci number system:  
Every integer  $n$  has a unique representation

$$n = F_{k_1} + F_{k_2} + \cdots + F_{k_m},$$

where  $k_i \geq k_{i+1} + 2$  for all  $i$ ,  
 $1 \leq i < m$  and  $k_m \geq 2$ .

## Fibonacci Numbers

1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89, ...

Definitions:

$$F_i = F_{i-1} + F_{i-2}, \quad F_0 = F_1 = 1,$$

$$F_{-i} = (-1)^{i-1} F_i,$$

$$F_i = \frac{1}{\sqrt{5}} \left( \phi^i - \hat{\phi}^i \right),$$

Cassini's identity: for  $i > 0$ :

$$F_{i+1}F_{i-1} - F_i^2 = (-1)^i.$$

Additive rule:

$$F_{n+k} = F_k F_{n+1} + F_{k-1} F_n,$$

$$F_{2n} = F_n F_{n+1} + F_{n-1} F_n.$$

Calculation by matrices:

$$\begin{pmatrix} F_{n-2} & F_{n-1} \\ F_{n-1} & F_n \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix}^n.$$