# All-in at the River

## Standard Code Library

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# Contents

# 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:

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

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:

```
for (int i = 0; i <= k; i++)
    r[i] = f(i);
for (int j = 0; j < k; j++)
    for (int i = k; i > j; i--)
        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

```cpp
// 使用时一定要注意double的精度是否足够(极限大概是10 ^
    ↪ 14)

const double pi = acos((double)-1.0);

// 手写复数类
// 支持加减乘三种运算
// += 运算符如果用的不多可以不重载
struct Complex {
    double a, b; // 由于long double精度和double几乎相同,
        ↪ 通常没有必要用long double

    Complex(double a = 0.0, double b = 0.0) : a(a), b(b)
        ↪ {}

    Complex operator + (const Complex &x) const {
        return Complex(a + x.a, b + x.b);
    }

    Complex operator - (const Complex &x) const {
        return Complex(a - x.a, b - x.b);
    }

    Complex operator * (const Complex &x) const {
        return Complex(a * x.a - b * x.b, a * x.b + b *
            ↪ x.a);
    }

    Complex &operator += (const Complex &x) {
        return *this = *this + x;
    }
} w[maxn], w_inv[maxn];

// FFT初始化 O(n)
// 需要调用sin, cos函数
void FFT_init(int n) {
    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
        w[i] = w_inv[n - i - 1] = Complex(cos(2 * pi / n
            ↪ * i), sin(2 * pi / n * i));
    // 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
}

// FFT主过程 O(n\log n)
void FFT(Complex *A, int n, int tp) {
    for (int i = 1, j = 0, k; i < n - 1; i++) {
        k = n;
        do
            j ^= (k >>= 1);
        while (j < k);

        if (i < j)
            swap(A[i], A[j]);
    }

    for (int k = 2;k <= n; k *= 2)
        for (int i = 0; i < n; i += k)
            for (int j = 0; j < k * 2;j++) {
                Complex a = A[i + j], b = (tp > 0? w :
                    ↪ w_inv)[n / k * j] * A[i + j + (k /
                    ↪ 2)];

                A[i + j] = a + b;
                A[i + j + k / 2] = a - b;
            }

    if (tp < 0)
        for (int i = 0; i < n; i++)
            A[i].a /= n;
}
```

### 1.2.2 NTT

```cpp
constexpr int p = 998244353, g = 3; // p为模数, g为p的任
    ↪ 意一个原根

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
    for (int i = 1, j = 0, k; i < n - 1; i++) { // O(n)旋
        ↪ 转算法, 原理是模拟加1
        k = n;
        do
            j ^= (k >>= 1);
        while (j < k);

        if(i < j)
            swap(A[i], A[j]);
    }

    for (int k = 2; k <= n; k <<= 1) {
        int wn = qpow(g, (tp > 0 ? (p - 1) / k : (p - 1)
            ↪ / k * (long long)(p - 2) % (p - 1)));
        for (int i = 0; i < n; i += k) {
            int w = 1;
            for (int j = 0; j < (k >> 1); j++, w = (long
                ↪ long)w * wn % p){
```

```cpp
19              int a = A[i + j], b = (long long)w * A[i
    ↪ + j + (k >> 1)] % p;
20              A[i + j] = (a + b) % p;
21              A[i + j + (k >> 1)] = (a - b + p) % p;
22         } // 更好的写法是预处理单位根的次幂
23        }
24    }

26    if (tp < 0) {
27        int inv = qpow(n, p - 2); // 如果能预处理逆元更好
28        for (int i = 0; i < n; i++)
29            A[i] = (long long)A[i] * inv % p;
30    }
31 }
```

### 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.

```cpp
1 //以下为三模数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];

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);

13     while (N < n * 2)
14         N *= 2;

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]);

21     for (int i = 0; i < 3; i++)
22         mul(m[i], ans[i]);

24     for (int i = 0; i < n; i++)
25         printf("%d ", China(ans[0][i], ans[1][i], ans[2]
    ↪ [i]));

27     return 0;
28 }

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);

37     NTT(C, N, 1, p);
38     NTT(D, N, 1, p);
39
```

```cpp
40     for (int i = 0; i < N; i++)
41         ans[i] = (long long)C[i] * D[i] % p;

43     NTT(ans, N, -1, p);
44 }

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.

```cpp
1 constexpr int maxn = 262200, p = 23333333, M = 4830; //
    ↪ M取值要使得结果不超过10^14

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];

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);

13     int N = 1;
14     while (N < n * 2)
15         N *= 2;

17     for (int i = 0, x; i < n; i++) {
18         scanf("%d", &x);
19         A[i] = x / M;
20         B[i] = x % M;
21     }

23     for (int i = 0, x; i < n; i++) {
24         scanf("%d", &x);
25         C[i] = x / M;
26         D[i] = x % M;
27     }

29     FFT_init(N);

31     FFT(A, N, 1);
32     FFT(B, N, 1);
33     FFT(C, N, 1);
34     FFT(D, N, 1);

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     }

42     FFT(F, N, -1);
43     FFT(G, N, -1);
44     FFT(H, N, -1);

46     for (int i = 0; i < n; i++)
```

```
47          printf("%d ", (int)((M * M * ((long long)(F[i].a
            ↪ + 0.5) % p) % p + M * ((long long)(G[i].a +
            ↪ 0.5) % p) % p + (long long)(H[i].a + 0.5) %
            ↪ p) % p));
48
49      return 0;
50  }
```

### 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
            ↪ 为1就可以
8
9       for (int k = 2; k <= n; k <<= 1) {
10          memcpy(B, A, sizeof(int) * k);
11          memset(B + k, 0, sizeof(int) * k);
12
13          NTT(B, k * 2, 1);
14          NTT(C,k * 2, 1);
15
16          for (int i = 0; i < k * 2; i++) {
17              C[i] = (2 - (long long)B[i] * C[i]) % p *
                    ↪ C[i] % p;
18              if (C[i] < 0)
19                  C[i] += p;
20          }
21
22          NTT(C, k * 2, -1);
23
24          memset(C + k, 0, sizeof(int) * k);
25      }
26  }
27
28  // 开根
29  void get_sqrt(int *A, int *C, int n) {
30      static int B[maxn], D[maxn];
31
32      memset(C, 0, sizeof(int) * (n * 2));
33      C[0] = 1; // 如果不是1就要考虑二次剩余
34
35      for (int k = 2; k <= n; k *= 2) {
36          memcpy(B, A, sizeof(int) * k);
37          memset(B + k, 0, sizeof(int) * k);
38
39          get_inv(C, D, k);
40
41          NTT(B, k * 2, 1);
42          NTT(D, k * 2, 1);
43
44          for (int i = 0; i < k * 2; i++)
45              B[i] = (long long)B[i] * D[i]%p;
46
47          NTT(B, k * 2, -1);
48
49          for (int i = 0; i < k; i++)
50              C[i] = (long long)(C[i] + B[i]) * inv_2 %
                    ↪ p;//inv_2是2的逆元
51      }
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
        ↪ 都是1
72      static int B[maxn];
73
74      get_derivative(A, B, n);
75      memset(B + n, 0, sizeof(int) * n);
76
77      get_inv(A, C, n);
78
79      NTT(B, n * 2, 1);
80      NTT(C, n * 2, 1);
81
82      for (int i = 0;i < n * 2; i++)
83          B[i] = (long long)B[i] * C[i] % p;
84
85      NTT(B, n * 2, -1);
86
87      get_integrate(B, C, n);
88
89      memset(C+n,0,sizeof(int)*n);
90  }
91
92  // 多项式exp，要求A没有常数项
93  // 常数很大且总代码较长，一般来说最好替换为分治FFT
94  // 分治FFT依据：设G(x) = exp F(x)，则有 g_i = \sum_{k=1}
        ↪ ^{i-1} f_{i-k} * k * g_k
95  void get_exp(int *A, int *C, int n) {
96      static int B[maxn];
97
98      memset(C, 0, sizeof(int) * (n * 2));
99      C[0] = 1;
100
101     for (int k = 2; k <= n; k <<= 1) {
102         get_ln(C, B, k);
103
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
     ↪ 快速幂
125  void get_pow(int *A, int *C, int n, int k) {
126      static int B[maxn];
127
128      get_ln(A, B, n);
129
130      for (int i = 0; i < n; i++)
131          B[i] = (long long)B[i] * k % p;
132
133      get_exp(B, C, n);
134  }
135
136  // 多项式除法，A / B，结果输出在C
137  // A的次数为n，B的次数为m
138  void get_div(int *A, int *B, int *C, int n, int m) {
139      static int f[maxn], g[maxn], gi[maxn];
140
141      if (n < m) {
142          memset(C, 0, sizeof(int) * m);
143          return;
144      }
145
146      int N = 1;
147      while (N < (n - m + 1))
148          N <<= 1;
149
150      memset(f, 0, sizeof(int) * N * 2);
151      memset(g, 0, sizeof(int) * N * 2);
152      // memset(gi, 0, sizeof(int) * N);
153
154      for (int i = 0; i < n - m + 1; i++)
155          f[i] = A[n - i - 1];
156      for (int i = 0; i < m && i < n - m + 1; i++)
157          g[i] = B[m - i - 1];
158
159      get_inv(g, gi, N);
160
161      for (int i = n - m + 1; i < N; i++)
162          gi[i] = 0;
163
164      NTT(f, N * 2, 1);
165      NTT(gi, N * 2, 1);
166
167      for (int i = 0; i < N * 2; i++)
168          f[i] = (long long)f[i] * gi[i] % p;
169
170      NTT(f, N * 2, -1);
171
172      for (int i = 0; i < n - m + 1; i++)
173          C[i] = f[n - m - i];
174  }
175
176  // 多项式取模，余数输出到C，商输出到D
177  void get_mod(int *A, int *B, int *C, int *D, int n, int
     ↪ m) {
178      static int b[maxn], d[maxn];
179
180      if (n < m) {
181          memcpy(C, A, sizeof(int) * n);
182
183          if (D)
184              memset(D, 0, sizeof(int) * m);
185
186          return;
187      }
188
189      get_div(A, B, d, n, m);
190
191      if (D) { // D是商，可以选择不要
```

```
192      for (int i = 0; i < n - m + 1; i++)
193          D[i] = d[i];
194  }
195
196  int N = 1;
197  while (N < n)
198      N *= 2;
199
200  memcpy(b, B, sizeof(int) * m);
201
202  NTT(b, N, 1);
203  NTT(d, N, 1);
204
205  for (int i = 0; i < N; i++)
206      b[i] = (long long)d[i] * b[i] % p;
207
208  NTT(b, N, -1);
209
210  for (int i = 0; i < m - 1; i++)
211      C[i] = (A[i] - b[i] + p) % p;
212
213  memset(b, 0, sizeof(int) * N);
214  memset(d, 0, sizeof(int) * N);
215  }
216
217  // 多点求值要用的数组
218  int q[maxn], ans[maxn]; // q是要代入的各个系数，ans是求出
     ↪ 的值
219  int tg[25][maxn * 2], tf[25][maxn]; // 辅助数组，tg是预处
     ↪ 理乘积，
220  // tf是项数越来越少的f，tf[0]就是原来的函数
221
222  void pretreat(int l, int r, int k) { // 多点求值预处理
223      static int A[maxn], B[maxn];
224
225      int *g = tg[k] + l * 2;
226
227      if (r - l + 1 <= 200) {
228          g[0] = 1;
229
230          for (int i = l; i <= r; i++) {
231              for (int j = i - l + 1; j; j--) {
232                  g[j] = (g[j - 1] - (long long)g[j] *
                       ↪ q[i]) % p;
233                  if (g[j] < 0)
234                      g[j] += p;
235              }
236              g[0] = (long long)g[0] * (p - q[i]) % p;
237          }
238
239          return;
240      }
241
242      int mid = (l + r) / 2;
243
244      pretreat(l, mid, k + 1);
245      pretreat(mid + 1, r, k + 1);
246
247      if (!k)
248          return;
249
250      int N = 1;
251      while (N <= r - l + 1)
252          N *= 2;
253
254      int *gl = tg[k + 1] + l * 2, *gr = tg[k + 1] + (mid +
         ↪ 1) * 2;
255
256      memset(A, 0, sizeof(int) * N);
```

```
257        memset(B, 0, sizeof(int) * N);
258
259        memcpy(A, gl, sizeof(int) * (mid - l + 2));
260        memcpy(B, gr, sizeof(int) * (r - mid + 1));
261
262        NTT(A, N, 1);
263        NTT(B, N, 1);
264
265        for (int i = 0; i < N; i++)
266            A[i] = (long long)A[i] * B[i] % p;
267
268        NTT(A, N, -1);
269
270        for (int i = 0; i <= r - l + 1; i++)
271            g[i] = A[i];
272    }
273
274    void solve(int l, int r, int k) { // 多项式多点求值主过程
275        int *f = tf[k];
276
277        if (r - l + 1 <= 200) {
278            for (int i = l; i <= r; i++) {
279                int x = q[i];
280
281                for (int j = r - l; ~j; j--)
282                    ans[i] = ((long long)ans[i] * x + f[j]) %
                         ↪ p;
283            }
284
285            return;
286        }
287
288        int mid = (l + r) / 2;
289        int *ff = tf[k + 1], *gl = tg[k + 1] + l * 2, *gr =
            ↪ tg[k + 1] + (mid + 1) * 2;
290
291        get_mod(f, gl, ff, 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0-based, 当然改成1-based也很简
        ↪ 单
305    void get_value(int *f, int *x, int *a, int n, int m) {
306        if (m <= n)
307            m = n + 1;
308        if (n < m - 1)
309            n = m - 1; // 补零方便处理
310
311        memcpy(tf[0], f, sizeof(int) * n);
312        memcpy(q, x, sizeof(int) * m);
313
314        pretreat(0, m - 1, 0);
315        solve(0, m - 1, 0);
316
317        if (a) // 如果a是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,
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 - l + 1; i++)
53          g[i] = A[i];
54  }
55
56  void solve(int l, int r, int k) { // 主过程
57      static int a[maxn], b[maxn];
58
59      int *f = tf[k];
60
61      if (l == r) {
```

```
 62            ans[l] = f[0];
 63            return;
 64        }
 65
 66        int mid = (l + r) / 2;
 67        int *ff = tf[k + 1], *gl = tg[k + 1] + l * 2, *gr =
            ↪ tg[k + 1] + (mid + 1) * 2;
 68
 69        int N = 1;
 70        while (N < r - l + 2)
 71            N *= 2;
 72
 73        memcpy(a, f, sizeof(int) * (r - l + 2));
 74        memcpy(b, gr, sizeof(int) * (r - mid + 1));
 75        reverse(b, b + r - mid + 1);
 76
 77        NTT(a, N, 1);
 78        NTT(b, N, 1);
 79        for (int i = 0; i < N; i++)
 80            b[i] = (long long)a[i] * b[i] % p;
 81
 82        reverse(b + 1, b + N);
 83        NTT(b, N, 1);
 84        int n_inv = qpow(N, p - 2);
 85        for (int i = 0; i < N; i++)
 86            b[i] = (long long)b[i] * n_inv % p;
 87
 88        for (int i = 0; i < mid - l + 2; i++)
 89            ff[i] = b[i + r - mid];
 90
 91        memset(a, 0, sizeof(int) * N);
 92        memset(b, 0, sizeof(int) * N);
 93
 94        solve(l, mid, k + 1);
 95
 96        memset(ff, 0, sizeof(int) * (mid - l + 2));
 97
 98        memcpy(a, f, sizeof(int) * (r - l + 2));
 99        memcpy(b, gl, sizeof(int) * (mid - l + 2));
100        reverse(b, b + mid - l + 2);
101
102        NTT(a, N, 1);
103        NTT(b, N, 1);
104        for (int i = 0; i < N; i++)
105            b[i] = (long long)a[i] * b[i] % p;
106
107        reverse(b + 1, b + N);
108        NTT(b, N, 1);
109        for (int i = 0; i < N; i++)
110            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: $F(x) = \sum_{i=1}^{n} \frac{\prod_{i \neq j}(x - x_j)}{\prod_{i \neq j}(x_i - x_j)} y_i$.

对每个$i$先求出$\prod_{i \neq j}(x_i - x_j)$. 设$M(x) = \prod_{i=1}^{n}(x - x_i)$, 那么想要的是$\frac{M(x)}{x - x_i}$. 取$x = x_i$时, 上下都为0, 使用洛必达法则, 则原式化为$M'(x)$. 使用分治算出$M(x)$, 使用多点求值算出每个$\prod_{i \neq j}(x_i - x_j) = M'(x_i)$.

设$\frac{y_i}{\prod_{i \neq j}(x_i - x_j)} = v_i$, 现在要求出$\sum_{i=1}^{n} v_i \prod_{i \neq j}(x - x_j)$.

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$O(n \log^2 n)$.

### 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      int N = 1;
9      while (N <= r - l + 1)
10         N *= 2;
11
12
13     for (int i = l; i <= mid; i++)
14         B[i - l] = (long long)A[i] * fac_inv[i] % p;
15     fill(B + mid - l + 1, B + N, 0);
16     for (int i = 0; i < N; i++)
17         C[i] = fac_inv[i];
18
19     NTT(B, N, 1);
20     NTT(C, N, 1);
21
22     for (int i = 0; i < N; i++)
23         B[i] = (long long)B[i] * C[i] % p;
24
25     NTT(B, N, -1);
26
27     for (int i = mid + 1; i <= r; i++)
28         A[i] = (A[i] + B[i - l] * 2 % p * (long
                ↪ long)fac[i] % p) % p;
29
30     solve(mid + 1, r);
31 }
```

### 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 = l, t = (long long)l * f[l] % p; i <=
                ↪ n; i += l)
12             g[i] = (g[i] + t) % p;
13
14         return;
15     }
16
17     int mid = (l + r) / 2;
18
19     solve(l, mid);
20
21     if (l == 0) {
22         for (int i = 1; i < mid; i++) {
23             A[i] = f[i];
24             B[i] = (c[i] + g[i]) % p;
25         }
26         NTT(A, r, 1);
27         NTT(B, r, 1);
28         for (int i = 0; i < r; i++)
29             A[i] = (long long)A[i] * B[i] % p;
30         NTT(A, r, -1);
31
32         for (int i = mid; i < r; i++)
33             f[i] = (f[i] + A[i]) % p;
34     }
35     else {
36         for (int i = 0; i < r - l; i++)
37             A[i] = f[i];
38         for (int i = l; i < mid; i++)
39             B[i - l] = (c[i] + g[i]) % p;
40         NTT(A, r - l, 1);
```

```
41         NTT(B, r - l, 1);
42         for (int i = 0; i < r - l; i++)
43             A[i] = (long long)A[i] * B[i] %p;
44         NTT(A, r - l, -1);
45
46         for (int i = mid; i < r; i++)
47             f[i] = (f[i] + A[i - l]) % p;
48
49         memset(A, 0, sizeof(int) * (r - l));
50         memset(B, 0, sizeof(int) * (r - l));
51
52         for (int i = l; i < mid; i++)
53             A[i - l] = f[i];
54         for (int i = 0; i < r - l; i++)
55             B[i] = (c[i] + g[i]) % p;
56         NTT(A, r - l, 1);
57         NTT(B, r - l, 1);
58         for (int i = 0; i < r - l; i++)
59             A[i] = (long long)A[i] * B[i] % p;
60         NTT(A, r - l, -1);
61
62         for (int i = mid; i < r; i++)
63             f[i] = (f[i] + A[i - l]) % p;
64     }
65
66     memset(A, 0, sizeof(int) * (r - l));
67     memset(B, 0, sizeof(int) * (r - l));
68
69     solve(mid, r);
70 }
```

### 1.2.10 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像代码里一样加上一个只求一次逆的优化, 否则就乖乖每次做完整的除法和取模

```
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
70              get_mod(t, g, f, NULL, n * 2 - 1, n);
71          }
72
73          for (int i = 0; i < N; i++)
74              a[i] = (long long)a[i] * a[i] % p;
75          NTT(a, N, -1);
76
77          memcpy(t, a, sizeof(int) * (n * 2 - 1));
78          get_mod(t, g, a, NULL, n * 2 - 1, n);
79          fill(a + n - 1, a + N, 0);
80
81          k >>= 1;
82      }
83
84      memset(a, 0, sizeof(int) * (n * 2));
85  }
86
87  // f_n = \sum_{i = 1} ^ m  f_{n - i} a_i
88  // f是0~m-1项的初值
89  int linear_recurrence(long long n, int m, int *f, int *a)
        ↪ {
90      static int g[maxn], c[maxn];
91
92      memset(g, 0, sizeof(int) * (m * 2 + 1));
93
94      for (int i = 0; i < m; i++)
95          g[i] = (p - a[m - i]) % p;
96      g[m] = 1;
97
98      pow_mod(n, g, m + 1, c);
99
100     int ans = 0;
```

```
101     for (int i = 0; i < m; i++)
102         ans = (ans + (long long)c[i] * f[i]) % p;
103
104     return ans;
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 /
                          ↪ 2] + p) % p;
25              }
26  }
27
28  // 按位异或版本
29  void FWT_xor(int *A, int n, int tp) {
30      for (int k = 2; k <= n; k *= 2)
31          for (int i = 0; i < n; i += k)
32              for (int j = 0; j < k / 2; j++) {
33                  int a = A[i + j], b = A[i + j + k / 2];
34                  A[i + j] = (a + b) % p;
35                  A[i + j + k / 2] = (a - b + p) % p;
36              }
37
38      if (tp < 0) {
39          int inv = qpow(n % p, p - 2); // n的逆元，在不取
              ↪ 模时需要用每层除以2代替
40          for (int i = 0; i < n; i++)
41              A[i] = A[i] * inv % p;
42      }
43  }
```

## 1.4   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 (!initalize())
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 initalize() {
42      while (true) {
43          double t = 0.0;
44          int l = 0, e = 0;
45
46          for (int i = 1; i <= m; i++)
47              if (A[i][0] + eps < t) {
48                  t = A[i][0];
49                  l = i;
50              }
51
52          if (!l)
53              return true;
54
55          for (int i = 1; i <= n; i++)
56              if (A[l][i] < -eps && (!e || id[i] < 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:

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

## 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.

```cpp
void Gauss_Jordan(int A[][maxn], int n) {
    for (int i = 1; i <= n; i++) {
        int ii = i;
        for (int j = i + 1; j <= n; j++)
            if (fabs(A[j][i]) > fabs(A[ii][i]))
                ii = j;

        if (ii != i) // 这里没有判是否无解, 如果有可能无
                     // 解的话要判一下
            for (int j = i; j <= n + 1; j++)
                swap(A[i][j], A[ii][j]);

        for (int j = 1; j <= n; j++)
            if (j != i) // 消成对角
                for (int k = n + 1; k >= i; k--)
                    A[j][k] -= A[j][i] / A[i][i] * A[i]
                               [k];
    }
}
```

**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

```cpp
int p;

int Gauss(int A[maxn][maxn], int n) {
    int det = 1;

    for (int i = 1; i <= n; i++) {
        for (int j = i + 1; j <= n; j++)
            while (A[j][i]) {
                int t = (p - A[i][i] / A[j][i]) % p;
                for (int k = i; k <= n; k++)
                    A[i][k] = (A[i][k] + (long long)A[j]
                              [k] * t) % p;

                swap(A[i], A[j]);
                det = (p - det) % p; // 交换一次之后行列
                                     // 式取负
            }

        if (!A[i][i])
            return 0;

        det = (long long)det * A[i][i] % p;
    }

    return det;
}
```

### 1.5.4 线性基

```cpp
void add(unsigned long long x) {
    for (int i = 63; i >= 0; i--)
```

```cpp
        if (x >> i & 1) {
            if (b[i])
                x ^= b[i];
            else {
                b[i] = x;

                for (int j = i - 1; j >= 0; j--)
                    if (b[j] && (b[i] >> j & 1))
                        b[i] ^= b[j];

                for (int j = i + 1; j < 64; j++)
                    if (b[j] >> i & 1)
                        b[j] ^= b[i];

                break;
            }
        }
}
```

### 1.5.5 线性代数知识

行列式:
$$\det A = \sum_\sigma \operatorname{sgn}(\sigma) \prod_i a_{i,\sigma_i}$$

逆矩阵:
$$B = A^{-1} \iff AB = 1$$

代数余子式:
$$M_{i,j} = (-1)^{(i+j)} det A - \{i, j\}$$

也就是$A$去掉一行一列之后的行列式
同时我们有
$$M = \frac{A^{-1}}{\det A}$$

### 1.5.6 矩阵树定理

## 1.6 自适应Simpson积分

Forked from fstqwq's template.

```cpp
// Adaptive Simpson's method : double simpson::solve
// (double (*f) (double), double l, double r, double
// eps) : integrates f over (l, r) with error eps.
struct simpson {
double area (double (*f) (double), double l, double r) {
    double m = l + (r - l) / 2;
    return (f (l) + 4 * f (m) + f (r)) * (r - l) / 6;
}
double solve (double (*f) (double), double l, double r,
double eps, double a) {
    double m = l + (r - l) / 2;
    double left = area (f, l, m), right = area (f, m, r);
    if (fabs (left + right - a) <= 15 * eps) return left
        + right + (left + right - a) / 15.0;
    return solve (f, l, m, eps / 2, left) + solve (f, m,
    r, eps / 2, right);
}
double solve (double (*f) (double), double l, double r,
double eps) {
    return solve (f, l, r, eps, area (f, l, r));
}};
```

## 1.7 常见数列

### 1.7.1 伯努利数

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

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

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

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

### 1.7.2 分拆数

```
int b = sqrt(n);
ans[0] = tmp[0] = 1;

for (int i = 1; i <= b; ++i) {
    for (int rep = 0; rep < 2; ++rep)
        for (int j = i; j <= n - i * i; ++j)
            add(tmp[j], tmp[j - i]);

    for (int j = i * i; j <= n; ++j)
        add(ans[j], tmp[j - i * i]);
}
```

### 1.7.3 斯特林数

**第一类斯特林数**

$\left[ {n \atop k} \right]$ 表示 $n$ 个元素划分成 $k$ 个轮换的方案数.

求同一行: 分治FFT $O(n \log^2 n)$

求同一列: 用一个轮换的指数生成函数做 $k$ 次幂

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

**第二类斯特林数**

$\left\{ {n \atop k} \right\}$ 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

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

求同一行: FFT, 狗都会做

求同一列: 指数生成函数

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

普通生成函数

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

### 1.7.4 贝尔数

$$B_0 = 1, \ B_1 = 1, \ B_2 = 2, \ B_3 = 5,$$
$$B_4 = 15, \ B_5 = 52, \ B_6 = 203, \dots$$

$$B_n = \sum_{k=0}^{n} \left\{ {n \atop k} \right\}$$

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:

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

### 1.7.5 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:

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

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

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:

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

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 $g_{1 \dots n}$ 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 $\alpha_1, \cdots, \alpha_s$ 互异, $e_1 + \cdots + e_s = r$ 则 $u_n$ 有表达式

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

多项式 $p_1, \cdots, p_s$ 的共 $e_1 + \cdots + e_s = r$ 个系数可由初始

值 $u_0, \cdots, u_{r-1}$ 唯一确定。

# 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;
        ↪ // p为模数
6  // 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，
      ↪ 但f(p^k)可以递推时就可以省略了
8  // 这里没有记录最小质因子，但根据线性筛的性质，每个合数
      ↪ 只会被它最小的质因子筛掉
9  bool notp[maxn]; // 顾名思义
10
11 void get_table(int n) {
12     sigma_one[1] = 1; // 积性函数必有f(1) = 1
13     for (int i = 2; i <= n; i++) {
14         if (!notp[i]) { // 质数情况
15             prime[++prime[0]] = i;
16             sigma_one[i] = i + 1;
17             f[i] = g[i] = 1;
18         }
19
20         for (int j = 1; j <= prime[0] && i * prime[j] <=
             ↪ n; j++) {
21             notp[i * prime[j]] = true;
22
23             if (i % prime[j]) { // 加入一个新的质因子，这
                 ↪ 种情况很简单
24                 sigma_one[i * prime[j]] = (long
                     ↪ long)sigma_one[i] * (prime[j] + 1) %
                     ↪ p;
25                 f[i * prime[j]] = i;
26                 g[i * prime[j]] = 1;
27             }
```

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

## 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
      ↪ 缀和(有点绕)
2  // 有些题只要求n <= 10 ^ 9, 这时就没必要开long long了，但
      ↪ 记得乘法时强转
3
4  //常量/全局变量/数组定义
5  const int maxn = 5000005, table_size = 5000000, p =
      ↪ 1000000007, inv_2 = (p + 1) / 2;
6  bool notp[maxn];
7  int prime[maxn / 20], phi[maxn], tbl[100005];
8  // tbl用来顶替哈希表，其实开到n ^ {1 / 3}就够了，不过保
      ↪ 险起见开成\sqrt n比较好
9  long long N;
10
11 // 主函数前面加上这么一句
12 memset(tbl, -1, sizeof(tbl));
13
14 // 线性筛预处理部分略去
15
16 // 杜教筛主过程 总计O(n ^ {2 / 3})
17 // 递归调用自身
18 // 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
      ↪ 10 ^ 9 + 7)为例
19 int S(long long n) {
20     if (n <= table_size)
21         return phi[n];
22     else if (~tbl[N / n])
23         return tbl[N / n];
24     // 原理: n除以所有可能的数的结果一定互不相同
25
26     int ans = 0;
27     for (long long i = 2, last; i <= n; i = last + 1) {
28         last = n / (n / i);
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 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,
       ↪ 37}) {
14         if (i > n)
15             break;
16         if (!check(n, i))
17             return false;
18     }
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
       ↪ 写O(1)快速乘
35     if (t == 1 || t == n - 1)
36         return true;
37
38     while (k--) {
39         t = mul(t, t, n); // mul是O(1)快速乘函数
40         if(t == n - 1)
41             return true;
42     }
43
44     return false;
45 }
```

## 2.5 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
     ↪ 分解
3
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) { //
     ↪ v用于存分解出来的质因子, 重复的会放多个
8      for (int i : {2, 3, 5, 7, 11, 13, 17, 19})
9          while (n % i == 0) {
10             v.push_back(i);
11             n /= i;
```

```
12         }
13
14     solve(n, v);
15     sort(v.begin(), v.end()); // 从小到大排序后返回
16 }
17
18 // 递归过程
19 // 需要调用Pollard's Rho主过程, 同时递归调用自身
20 void solve(long long n, vector<long long> &v) {
21     if (n == 1)
22         return;
23
24     long long p;
25     do
26         p = Pollards_Rho(n);
27     while (!p); // p是任意一个非平凡因子
28
29     if (p == n) {
30         v.push_back(p); // 说明n本身就是质数
31         return;
32     }
33
34     solve(p, v); // 递归分解两半
35     solve(n / p, v);
36 }
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 =
       ↪ rand() % (n - 3) + 2, u = 2; // 注意这里rand函数
       ↪ 需要重定义一下
48     while (true) {
49         i++;
50         x = (mul(x, x, n) + c) % n; // mul是O(1)快速乘函
           ↪ 数
51
52         long long g = gcd((u - x + n) % n, n);
53         if (g > 1 && g < n)
54             return g;
55
56         if (u == x)
57             return 0; // 失败, 需要重新调用
58
59         if (i == k) {
60             u = x;
61             k *= 2;
62         }
63     }
64 }
```

## 2.6 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;
```

#### 2.6.1 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

$$p = p0 + b/\gcd(p, q) \times t \qquad q = q0 - a/\gcd(p, q) \times t$$

其中t为任意整数.

### 2.7 常用公式

#### 2.7.1 莫比乌斯反演

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

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

#### 2.7.2 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 = l; 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 = l; 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
115 // 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]=++cnt;
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
151 // Kruskal算法 O(mlogn)
152 // 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
177 // 以下是并查集相关函数
178 int findroot(int x) { // 因为需要撤销,不写路径压缩
179     while (p[x] != x)
180         x = p[x];
181
182     return x;
183 }
184
185 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:
$$f_{i,S} = \min_{T \subset S} \{f_{i,T} + f_{i,S \setminus T}\}$$

2. 新加一条边:
$$f_{i,S} = \min_{(i,j) \in E} \{f_{j,S} + w_{i,j}\}$$

第一种直接枚举子集DP就行了, 第二种可以用SPFA或者Dijkstra松弛(显然负边一开始全选就行了, 所以只需要处理非负边).
复杂度$O(n3^k + 2^k m \log n)$.

## 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$u \to v$的权值$w$修改为$w + h[u] - h[v]$即可, 由最短路的性质显然修改后边权非负.
然后对每个起点跑Dijkstra, 再修正距离$d_{u,v} = d'_{u,v} - h_u + h_v$即可, 复杂度$O(nm \log n)$, 在稀疏图上是要优于Floyd的.

### 3.2.3 k短路

```
1  // 注意这是个多项式算法, 在k比较大时很有优势, 但k比较小
   ↪ 时最好还是用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树上
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
50 // 以下是主函数中较关键的部分
51 for (int i = 0 ; i <= n; i++)
52     root[i] = null; // 一定要加上!!!
53
54 // (读入&建反向图)
55
56 Dijkstra();
57
58 // (清空G, W, id)
59
60 for (int i = 1; i <= n; i++)
61     if (p[i]) {
62         used[p[i]] = true; // 在最短路树上
63         G[v[p[i]]].push_back(i);
64     }
65
66 for (int i = 1; i <= m; i++) {
67     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
68     if (!used[i])
69         root[u[i]] = merge(root[u[i]], newnode(w[i], i));
70 }
71
72 dfs(t);
73
74 priority_queue<B> heap;
75 heap.push(B(s, root[s], 0)); // 初始状态是找贡献最小的边
   ↪ 加进去
76
77 printf("%d\n",d[s]); // 第1短路需要特判
```

```
78  while (--k) { // 其余k - 1短路径用二叉堆维护
79      if (heap.empty())
80          printf("-1\n");
81      else {
82          int x = heap.top().x, w = heap.top().w;
83          node *rt = heap.top().rt;
84          heap.pop();
85
86          printf("%d\n", d[s] + w + rt -> w);
87
88          if (rt -> lc != null || rt -> rc != null)
89              heap.push(B(x, merge(rt -> lc, rt -> rc),
                    ↪ w)); // pop掉当前边, 换成另一条贡献大一点
                    ↪ 的边
90          if (root[v[rt -> i]] != null)
91              heap.push(B(v[rt -> i], root[v[rt -> i]], w +
                    ↪ rt -> w)); // 保留当前边, 往后面再接上另
                    ↪ 一条边
92      }
93  }
94  // 主函数到此结束
95
96
97  // Dijkstra预处理最短路 O(m\log n)
98  void Dijkstra() {
99      memset(d, 63, sizeof(d));
100     d[t] = 0;
101     priority_queue<A> heap;
102     heap.push(A(t, 0));
103
104     while (!heap.empty()) {
105         int x = heap.top().x;
106         heap.pop();
107
108         if(vis[x])
109             continue;
110
111         vis[x] = true;
112         for (int i = 0; i < (int)G[x].size(); i++)
113             if (!vis[G[x][i]] && d[G[x][i]] > d[x] + W[x]
                    ↪ [i]) {
114                 d[G[x][i]] = d[x] + W[x][i];
115                 p[G[x][i]] = id[x][i];
116
117                 heap.push(A(G[x][i], d[G[x][i]]));
118             }
119     }
120 }
121
122 // dfs求出每个点的堆 总计O(m\log n)
123 // 需要调用merge, 同时递归调用自身
124 void dfs(int x) {
125     root[x] = merge(root[x], root[v[p[x]]]);
126
127     for (int i = 0; i < (int)G[x].size(); i++)
128         dfs(G[x][i]);
129 }
130
131 // 包装过的new node() O(1)
132 node *newnode(int w, int i) {
133     *++ptr = node(w, i);
134     ptr -> lc = ptr -> rc = null;
135     return ptr;
136 }
137
138 // 带可持久化的左偏树合并 总计O(\log n)
139 // 递归调用自身
140 node *merge(node *x, node *y) {
141     if (x == null)
142         return y;
```

```
143     if (y == null)
144         return x;
145
146     if (x -> w > y -> w)
147         swap(x, y);
148
149     node *z = newnode(x -> w, x -> i);
150     z -> lc = x -> lc;
151     z -> rc = merge(x -> rc, y);
152
153     if (z -> lc -> d > z -> rc -> d)
154         swap(z -> lc, z -> rc);
155     z -> refresh();
156
157     return z;
158 }
```

## 3.3　Tarjan算法

### 3.3.1　强连通分量

```
1   int dfn[maxn], low[maxn], tim = 0;
2   vector<int> G[maxn], scc[maxn];
3   int sccid[maxn], scc_cnt = 0, stk[maxn];
4   bool instk[maxn];
5
6   void dfs(int x) {
7       dfn[x] = low[x] = ++tim;
8
9       stk[++stk[0]] = x;
10      instk[x] = true;
11
12      for (int y : G[x]) {
13          if (!dfn[y]) {
14              dfs(y);
15              low[x] = min(low[x], low[y]);
16          }
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] +
                      ↪ w);
95          }
96      }
97      else {
98          f[x] = sum[x];
99          for (auto o : v[x]) {
100             int y = o.first;
101
102             f[x] += f[y];
103         }
104
105         g[x] = f[x];
106
107         for (int i = 0; i < (int)v[x].size(); i++) {
108             int y = v[x][i].first;
109
110             g[x] = min(g[x], f[x] - f[y] + g[y] +
                      ↪ min(d[x][i], sum[x] - d[x][i]));
111         }
112     }
113 }
```

## 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
       ↪ 边对0取max
6
7  bool visx[maxn], visy[maxn];
8
9  int boy[maxn], girl[maxn], p[maxn], q[maxn], head, tail;
       ↪ // p : pre
10
11 int n, m, N, e;
12
13 // 增广
14 bool check(int y) {
15     visy[y] = true;
16
17     if (boy[y]) {
18         visx[boy[y]] = true;
19         q[tail++] = boy[y];
20         return false;
21     }
22
23     while (y) {
24         boy[y] = p[y];
25         swap(y, girl[p[y]]);
26     }
27
28     return true;
29 }
30
31 // bfs每个点
32 void bfs(int x) {
33     memset(q, 0, sizeof(q));
34     head = tail = 0;
35
36     q[tail++] = x;
37     visx[x] = true;
38
39     while (true) {
40         while (head != tail) {
41             int x = q[head++];
42
43             for (int y = 1; y <= N; y++)
44                 if (!visy[y]) {
45                     long long d = lx[x] + ly[y] - w[x]
                          ↪ [y];
46
47                     if (d < slack[y]) {
48                         p[y] = x;
49                         slack[y] = d;
50
51                         if (!slack[y] && check(y))
52                             return;
53                     }
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]);
```

```
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**

- 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.

**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.)

## 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%d", &n, &m); // 点数和边数
21      while (m--) {
22          int x, y;
23          scanf("%d%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      Gauss(A, B, n);
44
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]
                        ↪ [i]) {
50                      // 注意上面那句if的写法，现在t是邻接
                            ↪ 矩阵的备份，
51                      // 逆矩阵j行i列不为0当且仅当这条边可
                            ↪ 行
52                      girl[a[i]] = a[j];
53                      girl[a[j]] = a[i];
54
55                      eliminate(i, j);
56                      eliminate(j, i);
57                      break;
58                  }
59
60      printf("%d\n", n / 2);
61      for (int i = 1; i <= m; i++)
62          printf("%d ", girl[i]);
63
64      return 0;
65  }
66
67  // 高斯消元 O(n^3)
68  // 在传入B时表示计算逆矩阵，传入NULL则只需计算矩阵的秩
69  void Gauss(int A[][maxn], int B[][maxn], int n) {
70      if(B) {
71          memset(B, 0, sizeof(t));
72          for (int i = 1; i <= n; i++)
73              B[i][i] = 1;
74      }
75
76      for (int i = 1; i <= n; i++) {
77          if (!A[i][i]) {
78              for (int j = i + 1; j <= n; j++)
79                  if (A[j][i]) {
80                      swap(id[i], id[j]);
81                      for (int k = i; k <= n; k++)
82                          swap(A[i][k], A[j][k]);
83
84                      if (B)
85                          for (int k = 1; k <= n; k++)
86                              swap(B[i][k], B[j][k]);
87                      break;
88                  }
89
90          if (!A[i][i])
91              continue;
92      }
93
94      int inv = qpow(A[i][i], p - 2);
95
96      for (int j = 1; j <= n; j++)
97          if (i != j && A[j][i]){
98              int t = (long long)A[j][i] * inv % p;
99
100             for (int k = i; k <= n; k++)
101                 if (A[i][k])
102                     A[j][k] = (A[j][k] - (long long)t
                        ↪ * A[i][k]) % p;
103
104             if (B)
105                 for (int k = 1; k <= n; k++)
106                     if (B[i][k])
107                         B[j][k] = (B[j][k] - (long
                            ↪ long)t * B[i][k])%p;
108                 }
109         }
110
111     if (B)
112         for (int i = 1; i <= n; i++) {
113             int inv = qpow(A[i][i], p - 2);
114
115             for (int j = 1; j <= n; j++)
116                 if (B[i][j])
117                     B[i][j] = (long long)B[i][j] * inv %
                        ↪ p;
118         }
119 }
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 *
                        ↪ B[r][j]) % p;
134         }
135 }
```

### 3.6.2 带花树

```
1   // 带花树通常比高斯消元快很多，但在只需要求最大匹配大小
        ↪ 的时候并没有高斯消元好写
2   // 当然输出方案要方便很多
3
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],
        ↪ tim, q[maxn], head, tail;
7   int n, m;
8
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
22  // bfs找增广路 O(m)
23  bool bfs(int s) {
24      memset(t, 0, sizeof(t));
25      memset(p, 0, sizeof(p));
26
27      for (int i = 1; i <= n; i++)
28          f[i] = i; // 并查集
29
30      head = tail = 0;
31      q[tail++] = s;
32      t[s] = 1;
33
```

```
34      while (head != tail) {
35          int x = q[head++];
36          for (int y : G[x]) {
37              if (findroot(y) == findroot(x) || t[y] == 2)
38                  continue;
39
40              if (!t[y]) {
41                  t[y] = 2;
42                  p[y] = x;
43
44                  if (!girl[y]) {
45                      for (int u = y, t; u; u = t) {
46                          t = girl[p[u]];
47                          girl[p[u]] = u;
48                          girl[u] = p[u];
49                      }
50                      return true;
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
68  //缩奇环 O(n)
69  void shrink(int x, int y, int z) {
70      while (findroot(x) != z) {
71          p[x] = y;
72          y = girl[x];
73
74          if (t[y] == 2) {
75              t[y] = 1;
76              q[tail++] = y;
77          }
78
79          if (findroot(x) == x)
80              f[x] = z;
81          if (findroot(y) == y)
82              f[y] = z;
83
84          x = p[y];
85      }
86  }
87
88  //暴力找LCA O(n)
89  int LCA(int x, int y) {
90      tim++;
91      while (true) {
92          if (x) {
93              x = findroot(x);
94
95              if (vis[x] == tim)
96                  return x;
97              else {
98                  vis[x] = tim;
99                  x = p[girl[x]];
100             }
101         }
102         swap(x, y);
```

```
103         }
104  }
105
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]
    ↪ [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
    ↪ 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
         ↪ 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]) <
             ↪ 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]] ==
                 ↪ 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();
             ↪ ++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(),
             ↪ xr) - flower[b].begin();
45          if(pr % 2 == 1){
46              reverse(flower[b].begin() + 1,
                 ↪ 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,
                    ↪ xr);
55              for(int i = 0;i < pr; ++i)
56                  set_match(flower[u][i], flower[u][i ^
                        ↪ 1]);
57              set_match(xr, v);
58              rotate(flower[u].begin(),
                    ↪ 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]
                ↪ [b].w = 0;
102         for(int x = 1; x <= n; ++x) flower_from[b][x] =
                ↪ 0;
103         for(size_t i = 0 ; i < flower[b].size(); ++i){
104             int xs = flower[b][i];
105             for(int x = 1; x <= n_x; ++x)
106                 if(g[b][x].w == 0 || e_delta(g[xs][x]) <
                        ↪ e_delta(g[b][x]))
107                     g[b][x] = g[xs][x], g[x][b] = g[x]
                            ↪ [xs];
108             for(int x = 1;x <= n; ++x)
109                 if(flower_from[xs][x]) flower_from[b][x]
                        ↪ = xs;
110         }
111         set_slack(b);
112     }
113     inline void expand_blossom(int b){ // S[b]  ==  1
114         for(size_t i = 0; i < flower[b].size(); ++i)
115             set_st(flower[b][i], flower[b][i]);
116         int xr = flower_from[b][g[b][pa[b]].u], pr =
                ↪ get_pr(b, xr);
117         for(int i = 0; i < pr; i += 2){
118             int xs = flower[b][i], xns = flower[b][i +
                    ↪ 1];
119             pa[xs] = g[xns][xs].u;
120             S[xs] = 1, S[xns] = 0;
121             slack[xs] = 0, set_slack(xns);
122             q_push(xns);
123         }
124         S[xr] = 1, pa[xr] = pa[b];
125         for(size_t i = pr + 1;i < flower[b].size(); ++i){
126             int xs = flower[b][i];
127             S[xs] = -1, set_slack(xs);
128         }
129         st[b] = 0;
130     }
131     inline bool on_found_edge(const edge &e){
132         int u = st[e.u], v = st[e.v];
133         if(S[v] == -1){
134             pa[v] = e.u, S[v] = 1;
135             int nu = st[match[v]];
136             slack[v] = slack[nu] = 0;
137             S[nu] = 0, q_push(nu);
138         }else if(S[v] == 0){
139             int lca = get_lca(u, v);
140             if(!lca) return augment(u, v), augment(v, u),
                    ↪ true;
141             else add_blossom(u, lca, v);
142         }
143         return false;
144     }
145     inline bool matching(){
146         memset(S + 1, -1, sizeof(int) * n_x);
147         memset(slack + 1, 0, sizeof(int) * n_x);
148         q = queue<int>();
149         for(int x = 1;x <= n_x; ++x)
150             if(st[x] == x && !match[x]) pa[x]=0, S[x]=0,
                    ↪ q_push(x);
151         if(q.empty())return false;
152         for(;;){
153             while(q.size()){
154                 int u = q.front();q.pop();
155                 if(S[st[u]] == 1)continue;
156                 for(int v = 1;v <= n; ++v)
157                     if(g[u][v].w > 0 && st[u] != st[v]){
158                         if(e_delta(g[u][v]) == 0){
159                             if(on_found_edge(g[u]
                                    ↪ [v]))return true;
160                         }else update_slack(u, st[v]);
161                     }
162             }
163             int d = INF;
164             for(int b = n + 1; b <= n_x;++b)
165                 if(st[b] == b && S[b] == 1)d = min(d,
                        ↪ lab[b]/2);
166             for(int x = 1; x <= n_x; ++x)
167                 if(st[x] == x && slack[x]){
168                     if(S[x] == -1)d = min(d,
                            ↪ e_delta(g[slack[x]][x]));
```

```
169                 else if(S[x] == 0)d = min(d,
                         ↪ e_delta(g[slack[x]][x])/2);
170            }
171            for(int u = 1; u <= n; ++u){
172                if(S[st[u]] == 0){
173                    if(lab[u] <= d)return 0;
174                    lab[u] -= d;
175                }else if(S[st[u]] == 1)lab[u] += d;
176            }
177            for(int b = n+1; b <= n_x; ++b)
178                if(st[b] == b){
179                    if(S[st[b]] == 0) lab[b] += d * 2;
180                    else if(S[st[b]] == 1) lab[b] -= d *
                         ↪ 2;
181                }
182            q=queue<int>();
183            for(int x = 1; x <= n_x; ++x)
184                if(st[x] == x && slack[x] && st[slack[x]]
                     ↪ != x && e_delta(g[slack[x]][x]) == 0)
185                    if(on_found_edge(g[slack[x]]
                         ↪ [x]))return true;
186            for(int b = n + 1; b <= n_x; ++b)
187                if(st[b] == b && S[b] == 1 && lab[b] ==
                     ↪ 0)expand_blossom(b);
188        }
189        return false;
190    }
191    inline pair<long long, int> solve(){
192        memset(match + 1, 0, sizeof(int) * n);
193        n_x = n;
194        int n_matches = 0;
195        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 $\frac{1}{2}\mathrm{rank}\tilde{A}$.

- $(\tilde{A}^{-1})_{i,j} \neq 0$ 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 $\tilde{A}^{-1}_{i,j} \neq 0$), 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
                ↪ = dfs(e[i].to, min(e[i].cap,a)))) {
50
51                e[i].cap -= f;
52                e[i^1].cap += f;
53                flow += f;
54                a -= f;
55
56                if (!a)
57                    break;
58            }
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
9   // 全局变量和数组定义
10  int last[maxn], cnte = 0, d[maxn], p[maxn], c[maxn],
    ↪ cur[maxn], q[maxn];
11  int n, m, s, t; // s, t一定要开成全局变量
12
13  void AddEdge(int x, int y, int z) {
14      e[cnte].to = y;
15      e[cnte].cap = z;
16      e[cnte].prev = last[x];
17      last[x] = cnte++;
18  }
19
20  void addedge(int x, int y, int z) {
21      AddEdge(x, y, z);
22      AddEdge(y, x, 0);
23  }
24
25  // 预处理到t的距离标号
26  // 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
27  void bfs() {
28      memset(d, -1, sizeof(d));
29
30      int head = 0, tail = 0;
31      d[t] = 0;
32      q[tail++] = t;
33
34      while (head != tail) {
35          int x = q[head++];
36          c[d[x]]++;
37
38          for (int i = last[x]; ~i; i = e[i].prev)
39              if (e[i ^ 1].cap && d[e[i].to] == -1) {
40                  d[e[i].to] = d[x] + 1;
41                  q[tail++] = e[i].to;
42              }
43      }
```

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

### 3.8.3 HLPP最高标号预流推进

```cpp
#include <bits/stdc++.h>

using namespace std;

constexpr int maxn = 1205, maxe = 120005, inf =
    ↪ 2147483647;

struct edge {
    int to, cap, prev;
} e[maxe * 2];

int n, m, s, t;
int last[maxn], cnte;
int h[maxn], ex[maxn], gap[maxn * 2];
bool inq[maxn];

struct cmp {
    bool operator() (int x, int y) const {
        return h[x] < h[y];
    }
};

priority_queue<int, vector<int>, cmp> heap;

void AddEdge(int x, int y, int z) {
    e[cnte].to = y;
    e[cnte].cap = z;
    e[cnte].prev = last[x];
    last[x] = cnte++;
}

void addedge(int x, int y, int z) {
    AddEdge(x, y, z);
    AddEdge(y, x, 0);
}

bool bfs() {
    static int q[maxn];

    fill(h, h + n + 1, 2 * n);
    int head = 0, tail = 0;
    q[tail++] = t;
    h[t] = 0;

    while (head < tail) {
        int x = q[head++];
        for (int i = last[x]; ~i; i = e[i].prev)
            if (e[i ^ 1].cap && h[e[i].to] > h[x] + 1) {
                h[e[i].to] = h[x] + 1;
                q[tail++] = e[i].to;
            }
    }

    return h[s] < 2 * n;
}

void push(int x) {
    for (int i = last[x]; ~i; i = e[i].prev)
        if (e[i].cap && h[x] == h[e[i].to] + 1) {
            int d = min(ex[x], e[i].cap);

            e[i].cap -= d;
            e[i ^ 1].cap += d;
            ex[x] -= d;
            ex[e[i].to] += d;

            if (e[i].to != s && e[i].to != t &&
                ↪ !inq[e[i].to]) {
                heap.push(e[i].to);
                inq[e[i].to] = true;
            }

            if (!ex[x])
                break;
        }
}

void relabel(int x) {
    h[x] = 2 * n;

    for (int i = last[x]; ~i; i = e[i].prev)
        if (e[i].cap)
            h[x] = min(h[x], h[e[i].to] + 1);
}

int hlpp() {
    if (!bfs())
        return 0;

    // memset(gap, 0, sizeof(int) * 2 * n);
    h[s] = n;

    for (int i = 1; i <= n; i++)
        gap[h[i]]++;

    for (int i = last[s]; ~i; i = e[i].prev)
        if (e[i].cap) {
            int d = e[i].cap;

            e[i].cap -= d;
            e[i ^ 1].cap += d;
            ex[s] -= d;
            ex[e[i].to] += d;

            if (e[i].to != s && e[i].to != t &&
                ↪ !inq[e[i].to]) {
                heap.push(e[i].to);
                inq[e[i].to] = true;
            }
        }

    while (!heap.empty()) {
        int x = heap.top();
        heap.pop();
        inq[x] = false;

        push(x);
        if (ex[x]) {
            if (!--gap[h[x]]) { // gap
                for (int i = 1; i <= n; i++)
                    if (i != s && i != t && h[i] > h[x])
                        h[i] = n + 1;
            }

            relabel(x);
            ++gap[h[x]];
            heap.push(x);
            inq[x] = true;
        }
    }

    return ex[t];
}

int main() {

    memset(last, -1, sizeof(last));
```

```cpp
135
136        scanf("%d%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

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

```cpp
53            e[p[x] ^ 1].cap += flow;
54        }
55    }
56
57    return ans;
58 }
59
60 void add(int x, int y, int c, int w) {
61     e[cnte].to = y;
62     e[cnte].cap = c;
63     e[cnte].w = w;
64
65     e[cnte].prev = last[x];
66     last[x] = cnte++;
67 }
68
69 void addedge(int x, int y, int c, int w) {
70     add(x, y, c, w);
71     add(y, x, 0, -w);
72 }
```

### 3.9.2 Dijkstra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$u \to v$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**

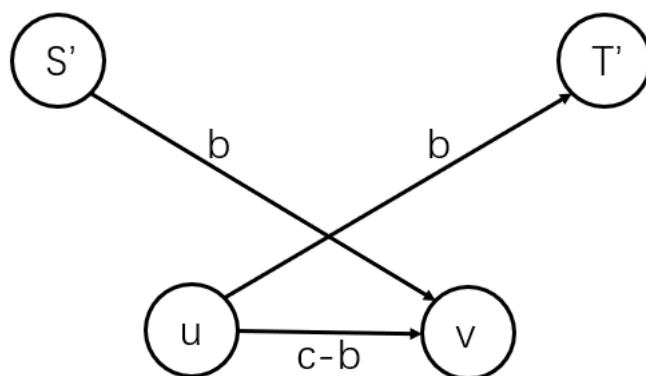在残量网络上从$S$开始floodfill, 源点可达的记为$S$集, 不可达的记为$T$, 如果一条边的起点在$S$集而终点在$T$集, 就将其加入最小割中.

**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!!

1. 团数 $\leq$ 色数 , 弦图团数 = 色数

2. 设 $next(v)$ 表示 $N(v)$ 中最前的点 . 令 w* 表示所有满足 $A \in B$ 的 w 中最后的一个点 , 判断 $v \cup N(v)$ 是否为极大团 , 只需判断是否存在一个 w, 满足 $Next(w) = v$ 且 $|N(v)| + 1 \leq |N(w)|$ 即可 .

3. 最小染色 : 完美消除序列从后往前依次给每个点染色 , 给每个点染上可以染的最小的颜色

4. 最大独立集 : 完美消除序列从前往后能选就选

5. 弦图最大独立集数 = 最小团覆盖数 , 最小团覆盖 : 设最大独立集为 $\{p_1, p_2, \ldots, p_t\}$, 则 $\{p_1 \cup N(p_1), \ldots, p_t \cup N(p_t)\}$ 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
           ↪ 两边分别实际修改的区间长度
3      for (l += n - 1, r += n + 1; l ^ r ^ 1; l >>= 1, r
           ↪ >>= 1, len <<= 1) {
4          tree[l] += cntl * d, tree[r] += cntr * d;
5          if (~l & 1) tree[l ^ 1] += d * len, mark[l ^ 1]
               ↪ += d, cntl += len;
6          if (r & 1) tree[r ^ 1] += d * len, mark[r ^ 1] +=
               ↪ d, cntr += len;
7      }
8
9      for (; l; l >>= 1, r >>= 1)
10         tree[l] += cntl * d, tree[r] += cntr * d;
11 }
12
13 int query(int l, int r) {
14     int ans = 0, len = 1, cntl = 0, cntr = 0;
15     for (l += n - 1, r += n + 1; l ^ r ^ 1; l >>= 1, r
           ↪ >>= 1, len <<= 1) {
16         ans += cntl * mark[l] + cntr * mark[r];
17         if (~l & 1) ans += tree[l ^ 1], cntl += len;
18         if (r & 1) ans += tree[r ^ 1], cntr += len;
19     }
20
21     for (; l; l >>= 1, r >>= 1)
22         ans += cntl * mark[l] + cntr * mark[r];
23
24     return ans;
25 }
```

**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
           ↪ >>= 1) {
3          if (l < N) {
4              tree[l] = max(tree[l << 1], tree[l << 1 | 1])
                   ↪ + mark[l];
5              tree[r] = max(tree[r << 1], tree[r << 1 | 1])
                   ↪ + mark[r];
6          }
7
8          if (~l & 1) {
9              tree[l ^ 1] += d;
10             mark[l ^ 1] += d;
11         }
12         if (r & 1) {
13             tree[r ^ 1] += d;
14             mark[r ^ 1] += d;
15         }
16     }
17
18     for (; l; l >>= 1, r >>= 1)
19         if (l < N) tree[l] = max(tree[l << 1], tree[l <<
               ↪ 1 | 1]) + mark[l],
20                 tree[r] = max(tree[r << 1], tree[r <<
                       ↪ 1 | 1]) + mark[r];
21 }
22
23 void query(int l, int r) {
24     int maxl = -INF, maxr = -INF;
25
26     for (l += N - 1, r += N + 1; l ^ r ^ 1; l >>= 1, r
           ↪ >>= 1) {
27         maxl += mark[l];
28         maxr += mark[r];
29
30         if (~l & 1)
```

```
31            maxl = max(maxl, tree[l ^ 1]);
32        if (r & 1)
33            maxr = max(maxr, tree[r ^ 1]);
34    }
35
36    while (l) {
37        maxl += mark[l];
38        maxr += mark[r];
39
40        l >>= 1;
41        r >>= 1;
42    }
43
44    return max(maxl, maxr);
45 }
```

### 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,
   ↪ seg_cnt;
8  int s, t, d;
9
10 void refresh(int l, int r, int o) {
11     if (cover[o])
12         sum[o] = r - l + 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 = l;
13
14     while (i <= mid && j <= r) {
15         if (a[i].x < a[j].x) {
16             a[i].ins = true;
17             b[k++] = a[i++];
18         }
19         else {
20             a[j].ins = false;
21             b[k++] = a[j++];
22         }
23     }
24
25     while (i <= mid) {
26         a[i].ins = true;
27         b[k++] = a[i++];
28     }
29
```

```
30        while (j <= r) {
31            a[j].ins = false;
32            b[k++] = a[j++];
33        }
34
35        copy(b + l, b + r + 1, a + l); // 后面的分治会破坏排
              ↪ 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 = l;
50
51      while (i <= mid && j <= r) {
52          if (b[i].y < b[j].y) {
53              if (b[i].ins)
54                  add(b[i].z, 1); // 树状数组
55
56              t[k++] = b[i++];
57          }
58          else{
59              if (!b[j].ins)
60                  ans += query(b[j].z - 1);
61
62              t[k++] = b[j++];
63          }
64      }
65
66      while (i <= mid) {
67          if (b[i].ins)
68              add(b[i].z, 1);
69
70          t[k++] = b[i++];
71      }
72
73      while (j <= r) {
74          if (!b[j].ins)
75              ans += query(b[j].z - 1);
76
77          t[k++] = b[j++];
78      }
79
80      for (i = l; i <= mid; i++)
81          if (b[i].ins)
82              add(b[i].z, -1);
83
84      copy(t + l, t + r + 1, b + l);
85  }
```

## 4.3  整体二分

修改和询问都要划分, 备份一下, 递归之前copy回去.

如果是满足可减性的问题(例如查询区间$k$小数)可以直接在划分的时候把询问的$k$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, 优先度
5       node *ch[2]; // 0表示左儿子, 1表示右儿子
6
7       node(int key = 0) : key(key), size(1), p(rand()) {}
8
9       void refresh() {
10          size = ch[0] -> size + ch[1] -> size + 1;
11      } // 更新子树大小(和附加信息, 如果有的话)
12  } null[maxn], *root = null, *ptr = null; // 数组名叫
       ↪ 做null是为了方便开哨兵节点
13  // 如果需要删除而空间不能直接开下所有结点, 则需要再写一
       ↪ 个垃圾回收
14  // 注意: 数组里的元素一定不能delete, 否则会导致RE
15
16  // 重要!在主函数最开始一定要加上以下预处理:
17  null -> ch[0] = null -> ch[1] = null;
18  null -> size = 0;
19
20  // 伪构造函数 O(1)
21  // 为了方便, 在结点类外面再定义一个伪构造函数
22  node *newnode(int x) { // 键值为x
23      *++ptr = node(x);
24      ptr -> ch[0] = ptr -> ch[1] = null;
25      return ptr;
26  }
27
28  // 插入键值 期望O(\log n)
29  // 需要调用旋转
30  void insert(int x, node *&rt) { // rt为当前结点, 建议调用
       ↪ 时传入root, 下同
31      if (rt == null) {
32          rt = newnode(x);
33          return;
34      }
35
36      int d = x > rt -> key;
37      insert(x, rt -> ch[d]);
38      rt -> refresh();
39
40      if (rt -> ch[d] -> p < rt -> p)
41          rot(rt, d ^ 1);
42  }
43
44  // 删除一个键值 期望O(\log n)
45  // 要求键值必须存在至少一个, 否则会导致RE
46  // 需要调用旋转
47  void erase(int x, node *&rt) {
48      if (x == rt -> key) {
49          if (rt -> ch[0] != null && rt -> ch[1] != null) {
50              int d = rt -> ch[0] -> p < rt -> ch[1] -> p;
51              rot(rt, d);
52              erase(x, rt -> ch[d]);
53          }
54          else
55              rt = rt -> ch[rt -> ch[0] == null];
56      }
57      else
58          erase(x, rt -> ch[x > rt -> key]);
59
60      if (rt != null)
61          rt -> refresh();
62  }
63
64  // 求元素的排名(严格小于键值的个数 + 1) 期望O(\log n)
```

```cpp
// 非递归
int rank(int x, node *rt) {
    int ans = 1, d;
    while (rt != null) {
        if ((d = x > rt -> key))
            ans += rt -> ch[0] -> size + 1;

        rt = rt -> ch[d];
    }

    return ans;
}

// 返回排名第k(从1开始)的键值对应的指针 期望O(\log n)
// 非递归
node *kth(int x, node *rt) {
    int d;
    while (rt != null) {
        if (x == rt -> ch[0] -> size + 1)
            return rt;

        if ((d = x > rt -> ch[0] -> size))
            x -= rt -> ch[0] -> size + 1;

        rt = rt -> ch[d];
    }

    return rt;
}

// 返回前驱(最大的比给定键值小的键值)对应的指针 期
// ↪ 望O(\log n)
// 非递归
node *pred(int x, node *rt) {
    node *y = null;
    int d;

    while (rt != null) {
        if ((d = x > rt -> key))
            y = rt;

        rt = rt -> ch[d];
    }

    return y;
}

// 返回后继(最小的比给定键值大的键值)对应的指针 期
// ↪ 望O(\log n)
// 非递归
node *succ(int x, node *rt) {
    node *y = null;
    int d;

    while (rt != null) {
        if ((d = x < rt -> key))
            y = rt;

        rt = rt -> ch[d ^ 1];
    }

    return y;
}

// 旋转(Treap版本) O(1)
// 平衡树基础操作
// 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
void rot(node *&x, int d) { // x为被转下去的结点，会被修
// ↪ 改以维护树结构
```

```cpp
    node *y = x -> ch[d ^ 1];

    x -> ch[d ^ 1] = y -> ch[d];
    y -> ch[d] = x;

    x -> refresh();
    (x = y) -> refresh();
}
```

### 4.4.2 无旋Treap/可持久化Treap

```cpp
struct node {
    int val, size;
    node *ch[2];

    node(int val) : val(val), size(1) {}

    inline void refresh() {
        size = ch[0] -> size + ch[1] -> size;
    }


} null[maxn];

node *copied(node *x) { // 如果不用可持久化的话，直接用就
// ↪ 行了
    return new node(*x);
}

node *merge(node *x, node *y) {
    if (x == null)
        return y;
    if (y == null)
        return x;

    node *z;
    if (rand() % (x -> size + y -> size) < x -> size) {
        z = copied(y);
        z -> ch[0] = merge(x, y -> ch[0]);
    }
    else {
        z = copied(x);
        z -> ch[1] = merge(x -> ch[1], y);
    }

    z -> refresh(); // 因为每次只有一边会递归到儿子，所
// ↪ 以z不可能取到null
    return z;
}

pair<node*, node*> split(node *x, int k) { // 左边大小为k
    if (x == null)
        return make_pair(null, null);

    pair<node*, node*> pi(null, null);

    if (k <= x -> ch[0] -> size) {
        pi = split(x -> ch[0], k);

        node *z = copied(x);
        z -> ch[0] = pi.second;
        z -> refresh();
        pi.second = z;
    }
    else {
        pi = split(x -> ch[1], k - x -> ch[0] -> size -
// ↪ 1);

        node *y = copied(x);
```

```
56        y -> ch[1] = pi.first;
57        y -> refresh();
58        pi.first = y;
59    }
60
61    return pi;
62 }
63
64 // 记得初始化null
65 int main() {
66    for (int i = 0; i <= n; i++)
67        null[i].ch[0] = null[i].ch[1] = null;
68    null -> size = 0;
69
70    // do something
71
72    return 0;
73 }
```

### 4.4.3  Splay

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

```
1  #define dir(x) ((x) == (x) -> p -> ch[1])
2
3  struct node {
4      int size;
5      bool rev;
6      node *ch[2],*p;
7
8      node() : size(1), rev(false) {}
9
10     void pushdown() {
11         if(!rev)
12             return;
13
14         ch[0] -> rev ^= true;
15         ch[1] -> rev ^= true;
16         swap(ch[0], ch[1]);
17
18         rev=false;
19     }
20
21     void refresh() {
22         size = ch[0] -> size + ch[1] -> size + 1;
23     }
24 } null[maxn], *root = null;
25
26 void rot(node *x, int d) {
27     node *y = x -> ch[d ^ 1];
28
29     if ((x -> ch[d ^ 1] = y -> ch[d]) != null)
30         y -> ch[d] -> p = x;
31     ((y -> p = x -> p) != null ? x -> p -> ch[dir(x)] :
       ↪ root) = y;
32     (y -> ch[d] = x) -> p = y;
33
34     x -> refresh();
35     y -> refresh();
36 }
37
38 void splay(node *x, node *t) {
39     while (x -> p != t) {
40         if (x -> p -> p == t) {
41             rot(x -> p, dir(x) ^ 1);
42             break;
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
       ↪ 果想减少常数也可以递归建一个平衡的树
97     root -> p = null + n + 2; // 总之记得建两个哨兵, 这
       ↪ 样splay起来不需要特判
98     (root = null + n + 2) -> refresh();
99
100    // Do something
101
102    return 0;
103 }
```

## 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
     ↪ 一半
2  // 以下以维护一个点到每个黑点的距离之和为例
```

```cpp
3
4    // 全局数组定义
5    vector<int> G[maxn], W[maxn];
6    int size[maxn], son[maxn], q[maxn];
7    int p[maxn], depth[maxn], id[maxn][20], d[maxn][20]; //
         ↪ id是对应层所在子树的根
8    int a[maxn], ca[maxn], b[maxn][20], cb[maxn][20]; // 维护
         ↪ 距离和用的
9    bool vis[maxn], col[maxn];
10
11   // 建树 总计O(n\log n)
12   // 需要调用找重心和预处理距离, 同时递归调用自身
13   void build(int x, int k, int s, int pr) { // 结点, 深度,
         ↪ 连通块大小, 点分树上的父亲
14       x = getcenter(x, s);
15       vis[x] = true;
16       depth[x] = k;
17       p[x] = pr;
18
19       for (int i = 0; i < (int)G[x].size(); i++)
20           if (!vis[G[x][i]]) {
21               d[G[x][i]][k] = W[x][i];
22               p[G[x][i]] = x;
23
24               getdis(G[x][i],k,G[x][i]); // bfs每个子树, 预
                     ↪ 处理距离
25           }
26
27       for (int i = 0; i < (int)G[x].size(); i++)
28           if (!vis[G[x][i]])
29               build(G[x][i], k + 1, size[G[x][i]], x); //
                     ↪ 递归建树
30   }
31
32   // 找重心 O(n)
33   int getcenter(int x, int s) {
34       int head = 0, tail = 0;
35       q[tail++] = x;
36
37       while (head != tail) {
38           x = q[head++];
39           size[x] = 1; // 这里不需要清空, 因为以后要用的话
                 ↪ 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
```

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

### 4.5.2 紫荆花之恋

```cpp
1    const int maxn = 100010;
2    const double alpha = 0.7;
3    struct node {
4        static int randint() {
```

```cpp
        static int a = 1213, b = 97818217, p = 998244353,
          ↪ x = 751815431;
        x = a * x + b;
        x %= p;
        return x < 0 ? (x += p) : x;
    }

    int data, size, p;
    node *ch[2];

    node(int d): data(d), size(1), p(randint()) {}

    inline void refresh() {
        size = ch[0]->size + ch[1]->size + 1;
    }
} *null = new node(0), *root[maxn], *root1[maxn][50];

void addnode(int, int);
void rebuild(int, int, int, int);
void dfs_getcenter(int, int, int &);
void dfs_getdis(int, int, int, int);
void dfs_destroy(int, int);
void insert(int, node *&);
int order(int, node *);
void destroy(node *&);
void rot(node *&, int);

vector<int>G[maxn], W[maxn];
int size[maxn] = {0}, siz[maxn][50] = {0}, son[maxn];
bool vis[maxn];
int depth[maxn], p[maxn], d[maxn][50], id[maxn][50];
int n, m, w[maxn], tmp;
long long ans = 0;

int main() {
    null->size = 0;
    null->ch[0] = null->ch[1] = null;

    scanf("%*d%d", &n);
    fill(vis, vis + n + 1, true);
    fill(root, root + n + 1, null);

    for (int i = 0; i <= n; i++)
        fill(root1[i], root1[i] + 50, null);

    scanf("%*d%*d%d", &w[1]);
    insert(-w[1], root[1]);
    size[1] = 1;
    printf("0\n");

    for (int i = 2; i <= n; i++) {
        scanf("%d%d%d", &p[i], &tmp, &w[i]);
        p[i] ^= (ans % (int)1e9);
        G[i].push_back(p[i]);
        W[i].push_back(tmp);
        G[p[i]].push_back(i);
        W[p[i]].push_back(tmp);
        addnode(i, tmp);
        printf("%lld\n", ans);
    }

    return 0;
}

void addnode(int x, int z) { //wj-dj>=di-wi
    depth[x] = depth[p[x]] + 1;
    size[x] = 1;
    insert(-w[x], root[x]);
    int rt = 0;

    for (int u = p[x], k = depth[p[x]]; u; u = p[u], k--)
      ↪ {
        if (u == p[x]) {
            id[x][k] = x;
            d[x][k] = z;
        }
        else {
            id[x][k] = id[p[x]][k];
            d[x][k] = d[p[x]][k] + z;
        }

        ans += order(w[x] - d[x][k], root[u]) -
          ↪ order(w[x] - d[x][k], root1[id[x][k]][k]);
        insert(d[x][k] - w[x], root[u]);
        insert(d[x][k] - w[x], root1[id[x][k]][k]);
        size[u]++;
        siz[id[x][k]][k]++;

        if (siz[id[x][k]][k] > size[u]*alpha + 5)
            rt = u;
    }

    id[x][depth[x]] = 0;
    d[x][depth[x]] = 0;

    if (rt) {
        dfs_destroy(rt, depth[rt]);
        rebuild(rt, depth[rt], size[rt], p[rt]);
    }
}

void rebuild(int x, int k, int s, int pr) {
    int u = 0;
    dfs_getcenter(x, s, u);
    vis[x = u] = true;
    p[x] = pr;
    depth[x] = k;
    size[x] = s;
    d[x][k] = id[x][k] = 0;
    destroy(root[x]);
    insert(-w[x], root[x]);

    if (s <= 1)
        return;

    for (int i = 0; i < (int)G[x].size(); i++)
        if (!vis[G[x][i]]) {
            p[G[x][i]] = 0;
            d[G[x][i]][k] = W[x][i];
            siz[G[x][i]][k] = p[G[x][i]] = 0;
            destroy(root1[G[x][i]][k]);
            dfs_getdis(G[x][i], x, G[x][i], k);
        }

    for (int i = 0; i < (int)G[x].size(); i++)
        if (!vis[G[x][i]])
            rebuild(G[x][i], k + 1, size[G[x][i]], x);
}

void dfs_getcenter(int x, int s, int &u) {
    size[x] = 1;
    son[x] = 0;

    for (int i = 0; i < (int)G[x].size(); i++)
        if (!vis[G[x][i]] && G[x][i] != p[x]) {
            p[G[x][i]] = x;
            dfs_getcenter(G[x][i], s, u);
            size[x] += size[G[x][i]];

            if (size[G[x][i]] > size[son[x]])
                son[x] = G[x][i];
        }
```

```
145    if (!u || max(s - size[x], size[son[x]]) < max(s -
           ↪ size[u], size[son[u]]))
146        u = x;
147 }
148
149 void dfs_getdis(int x, int u, int rt, int k) {
150     insert(d[x][k] - w[x], root[u]);
151     insert(d[x][k] - w[x], root1[rt][k]);
152     id[x][k] = rt;
153     siz[rt][k]++;
154     size[x] = 1;
155
156     for (int i = 0; i < (int)G[x].size(); i++)
157         if (!vis[G[x][i]] && G[x][i] != p[x]) {
158             p[G[x][i]] = x;
159             d[G[x][i]][k] = d[x][k] + W[x][i];
160             dfs_getdis(G[x][i], u, rt, k);
161             size[x] += size[G[x][i]];
162         }
163 }
164
165 void dfs_destroy(int x, int k) {
166     vis[x] = false;
167
168     for (int i = 0; i < (int)G[x].size(); i++)
169         if (depth[G[x][i]] >= k && G[x][i] != p[x]) {
170             p[G[x][i]] = x;
171             dfs_destroy(G[x][i], k);
172         }
173 }
174
175 void insert(int x, node *&rt) {
176     if (rt == null) {
177         rt = new node(x);
178         rt->ch[0] = rt->ch[1] = null;
179         return;
180     }
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   不换根（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 initalize(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与其父亲的连边断掉
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
130 node *getmax(node *x, node *y) {
131     makeroot(x);
132     x = access(y);
133
134     while (x -> pushdown(), x -> pos != -1)
135         x = x -> ch[x -> pos];
136     splay(x);
137
138     return x;
139 }
140
141 // 以下为主函数示例
142 for (int i = 1; i <= m; i++) {
143     init(null + n + i, w[i]);
144     if (getroot(null + u[i]) != getroot(null + v[i])) {
145         ans[q + 1] -= k;
146         ans[q + 1] += w[i];
147
148         link(null + u[i], null + n + i);
149         link(null + v[i], null + n + i);
150         vis[i] = true;
151     }
152     else {
153         int ii = getmax(null + u[i], null + v[i]) - null
            ↪ - 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，
   ↪ 没必要的时候就不要用
2  // 如果维护子树最小值就需要套一个可删除的堆来维护，复杂
   ↪ 度会变成O(n\log^2 n)
3  // 注意由于这道题与边权有关，需要边权拆点变点权
4
5  // 宏定义
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  // 节点类定义
10 struct node { // 以维护子树中黑点到根距离和为例
11     int w, chain_cnt, tree_cnt;
12     long long sum, suml, sumr, tree_sum; // 由于换根需要
       ↪ 子树反转，需要维护两个方向的信息
13     bool rev, col;
14     node *ch[2], *p;
15
16     node() : w(0), chain_cnt(0),
       ↪ tree_cnt(0),sum(0),suml(0), sumr(0),
17         tree_sum(0), rev(false), col(false) {}
18
19     inline void pushdown() {
20         if (!rev)
21             return;
22
23         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
       ↪ 就pushdown一下
32         // pushdown();
33
34         sum = ch[0] -> sum + ch[1] -> sum + w;
35         suml = (ch[0] -> rev ? ch[0] -> sumr : ch[0] ->
            ↪ suml) + (ch[1] -> rev ? ch[1] -> sumr : ch[1]
            ↪ -> suml) + (tree_cnt + ch[1] -> chain_cnt) *
            ↪ (ch[0] -> sum + w) + tree_sum;
36         sumr = (ch[0] -> rev ? ch[0] -> suml : ch[0] ->
            ↪ sumr) + (ch[1] -> rev ? ch[1] -> suml : ch[1]
            ↪ -> sumr) + (tree_cnt + ch[0] -> chain_cnt) *
            ↪ (ch[1] -> sum + w) + tree_sum;
37         chain_cnt = ch[0] -> chain_cnt + ch[1] ->
            ↪ chain_cnt + tree_cnt;
38     }
39 } null[maxn * 2]; // 如果没有边权变点权就不用乘2了
40
41 // 封装构造函数
42 node *newnode(int w) {
43     node *x = nodes.front(); // 因为有删边加边，可以用一
       ↪ 个队列维护可用结点
44     nodes.pop();
45     initalize(x);
46     x -> w = w;
47     x -> refresh();
48     return x;
```

```
49   }
50
51   // 封装初始化函数
52   // 记得在进行操作之前对所有结点调用一遍
53   inline void initalize(node *x) {
54       *x = node();
55       x -> ch[0] = x -> ch[1] = x -> p = null;
56   }
57
58   // 注意一下在Access的同时更新子树信息的方法
59   node *access(node *x) {
60       node *y = null;
61
62       while (x != null) {
63           splay(x);
64
65           x -> tree_cnt += x -> ch[1] -> chain_cnt - y -> 
               ↪ chain_cnt;
66           x->tree_sum += (x -> ch[1] -> rev ? x -> ch[1] -> 
               ↪ sumr : x -> ch[1] -> suml) - y -> suml;
67           x -> ch[1] = y;
68
69           (y = x) -> refresh();
70           x = x -> p;
71       }
72
73       return y;
74   }
75
76   // 找到一个点所在连通块的根
77   // 对比原版没有变化
78   node *getroot(node *x) {
79       x = access(x);
80
81       while (x -> pushdown(), x -> ch[0] != null)
82           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 -> suml;
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 -> suml;
125  }
126
127  // Splay函数
128  // 对比原版没有变化
129  void splay(node *x) {
130      x -> pushdown();
131
132      while (!isroot(x)) {
133          if (!isroot(x -> p))
134              x -> p -> p -> pushdown();
135          x -> p -> pushdown();
136          x -> pushdown();
137
138          if (isroot(x -> p)) {
139              rot(x -> p,dir(x) ^ 1);
140              break;
141          }
142
143          if (dir(x) == dir(x -> p))
144              rot(x -> p -> p, dir(x -> p) ^ 1);
145          else
146              rot(x -> p, dir(x) ^ 1);
147
148          rot(x -> p, dir(x) ^ 1);
149      }
150  }
151
152  // 旋转函数
153  // 对比原版没有变化
154  void rot(node *x, int d) {
155      node *y = x -> ch[d ^ 1];
156
157      if ((x -> ch[d^1] = y -> ch[d]) != null)
158          y -> ch[d] -> p = x;
159
160      y -> p = x -> p;
161      if (!isroot(x))
162          x -> p -> ch[dir(x)] = y;
163
164      (y -> ch[d] = x) -> p = y;
165
166      x -> refresh();
167      y -> refresh();
168  }
```

### 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 = 1000000000000000001l;
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
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, 如果它是黑点的话还会包括自己
65      node *ch[2], *p;
66      bool rev;
67      node(int k = 0): sum(k), maxsum(-INF), 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 +
                          ↪ ch[1]->prefix);
90
91          if (!heap.empty()) {
92              prefix = max(prefix,
93                            ch[0]->sum + key + heap.top());
94              suffix = max(suffix,
95                            ch[1]->sum + key + heap.top());
96              maxsum = max(maxsum, max(ch[0]->suffix,
97                                        ch[1]->prefix) + key
                                          ↪ + heap.top());
98
99              if (heap.size() > 1) {
100                 maxsum = max(maxsum, heap.top2() + key);
101             }
102         }
103     }
104 } null[maxn << 1], *ptr = null;
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() :
            ↪ -1));
177    }
178
179    return 0;
180 }
181 void addedge(int x, int y, int z) {
182    node *tmp;
183    if (freenodes.empty())
184        tmp = newnode(z);
185    else {
186        tmp = freenodes.front();
187        freenodes.pop();
188        *tmp = node(z);
189    }
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            heap.push(x->ch[1]->maxsum);
264        }
265
266        x->heap.erase(y->prefix);
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
332    y->p = x->p;
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] ->
          ↪ l[0]));
16        l[1] = min(x[1], min(ch[0] -> l[1], ch[1] ->
          ↪ l[1]));
17        r[0] = max(x[0], max(ch[0] -> r[0], ch[1] ->
          ↪ r[0]));
```

```
18        r[1] = max(x[1], max(ch[0] -> r[1], ch[1] ->
          ↪ r[1]));
19    }
20 } null[maxn], *root = null;
21
22 void build(int l, int r, int k, node *&rt) {
23    if (l > r) {
24        rt = null;
25        return;
26    }
27
28    int mid = (l + r) / 2;
29
30    d = k;
31    nth_element(null + l, null + mid, null + r + 1);
32
33    rt = null + mid;
34    build(l, mid - 1, k ^ 1, rt -> ch[0]);
35    build(mid + 1, r, k ^ 1, rt -> ch[1]);
36
37    rt -> refresh();
38 }
39
40 void query(node *rt) {
41    if (l[0] <= rt -> l[0] && l[1] <= rt -> l[1] && rt ->
        ↪ r[0] <= r[0] && rt -> r[1] <= r[1]) {
42        ans += rt -> sum;
43        return;
44    }
45    else if (l[0] > rt -> r[0] || l[1] > rt -> r[1] ||
        ↪ r[0] < rt -> l[0] || r[1] < rt -> l[1])
46        return;
47
48    if (l[0] <= rt -> x[0] && l[1] <= rt -> x[1] && rt ->
        ↪ x[0] <= r[0] && rt -> x[1] <= r[1])
49        ans += rt -> w;
50
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],
              ↪ &w[tmp]);
67            x[tmp][0] ^= ans;
68            x[tmp][1] ^= ans;
69            w[tmp] ^= ans;
70
71            if (tmp == B) {
72                for (int i = 1; i <= tmp; i++) {
73                    null[cnt + i].x[0] = x[i][0];
74                    null[cnt + i].x[1] = x[i][1];
75                    null[cnt + i].w = w[i];
76                }
77
78                build(1, cnt += tmp, 0, root);
79                tmp = 0;
80            }
81        }
```

```
82          else {
83              scanf("%d%d%d%d", &l[0], &l[1], &r[0],
                    ↪ &r[1]);
84              l[0] ^= ans;
85              l[1] ^= ans;
86              r[0] ^= ans;
87              r[1] ^= ans;
88              ans = 0;
89
90              for (int i = 1; i <= tmp; i++)
91                  if (l[0] <= x[i][0] && l[1] <= x[i][1] &&
                        ↪ x[i][0] <= r[0] && x[i][1] <= r[1])
92                      ans += w[i];
93
94              query(root);
95              printf("%d\n", ans);
96          }
97      }
98
99      return 0;
100 }
```

## 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
13     void dfs(int x) {
14         size[x] = col[x];
15         mx[x] = (col[x] ? d[x] : -0x3f3f3f3f);
16         mn[x] = (col[x] ? d[x] : 0x3f3f3f3f);
17
18         for (int i = 0; i < (int)G[x].size(); i++) {
19             d[G[x][i]] = d[x] + W[x][i];
20             dfs(G[x][i]);
21             ans_sum += (long long)size[x] * size[G[x][i]]
                   ↪ * d[x];
22             ans_max = max(ans_max, mx[x] + mx[G[x][i]] -
                   ↪ (d[x] << 1));
23             ans_min = min(ans_min, mn[x] + mn[G[x][i]] -
                   ↪ (d[x] << 1));
24             size[x] += size[G[x][i]];
25             mx[x] = max(mx[x], mx[G[x][i]]);
26             mn[x] = min(mn[x], mn[G[x][i]]);
27         }
28     }
29
30     void clear(int x) {
31         G[x].clear();
32         W[x].clear();
33         col[x] = false;
34     }
35
36     void solve(int rt) {
37         ans_sum = 0;
38         ans_max = 1 << 31;
39         ans_min = (~0u) >> 1;
40         dfs(rt);
41         ans_sum <<= 1;
42     }
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                      virtree.add(s[top - 1], s[top],
                           ↪ d[s[top]] - d[s[top - 1]]);
100                     top--;
101                 }
102
103                 if (s[top] != u) {
104                     virtree.add(u, s[top], d[s[top]] -
                            ↪ d[u]);
105                     s[top] = v[++cnt] = u;
106                 }
107             }
108
109             s[++top] = a[i];
110         }
111
112         for (int i = top - 1; i; i--)
```

```
113            virtree.add(s[i], s[i + 1], d[s[i + 1]] -
               ↪ d[s[i]]);
114
115        virtree.solve(n + 1);
116        ans *= k - 1;
117        printf("%lld %d %d\n", ans - virtree.ans_sum,
           ↪ virtree.ans_min, virtree.ans_max);
118
119        for (int i = 1; i <= k; i++)
120            virtree.clear(a[i]);
121        for (int i = 1; i <= cnt; i++)
122            virtree.clear(v[i]);
123
124    }
125
126    return 0;
127 }
128
129 void dfs(int x) {
130    dfn[x] = ++tim;
131    d[x] = d[f[x][0]] + 1;
132
133    while ((1 << lgn) < d[x])
134        lgn++;
135
136    for (int i = 0; i < (int)G[x].size(); i++)
137        if (G[x][i] != f[x][0]) {
138            f[G[x][i]][0] = x;
139            dfs(G[x][i]);
140        }
141 }
142
143 int LCA(int x, int y) {
144    if (d[x] != d[y]) {
145        if (d[x] < d[y])
146            swap(x, y);
147
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 }
```

## 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
   ↪ 取最大深度
8  // 由于vector只能在后面加入元素，为了写代码方便，这里反
   ↪ 过来存
9  void dfs(int x) {
10    h[x] = 1;
11
12    for (int y : G[x])
13        if (y != p[x]){
```

```
14            p[y] = x;
15            dfs(y);
16
17            if (h[y] > h[son[x]])
18                son[x] = y;
19        }
20
21    if (!son[x]) {
22        v[x].push_back(1);
23        ans[x] = 0;
24        return;
25    }
26
27    h[x] = h[son[x]] + 1;
28    swap(v[x],v[son[x]]);
29
30    if (v[x][ans[son[x]]] == 1)
31        ans[x] = h[x] - 1;
32    else
33        ans[x] = ans[son[x]];
34
35    v[x].push_back(1);
36
37    int mx = v[x][ans[x]];
38    for (int y : G[x])
39        if (y != p[x] && y != son[x]) {
40            for (int j = 1; j <= h[y]; j++) {
41                v[x][h[x] - j - 1] += v[y][h[y] - j];
42
43                int t = v[x][h[x] - j - 1];
44                if (t > mx || (t == mx && h[x] - j - 1 >
                   ↪ ans[x])) {
45                    mx = t;
46                    ans[x] = h[x] - j - 1;
47                }
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祖先 O(n\Log n)-O(1)
2  // 理论基础：任意一个点x的k级祖先y所在长链长度一定>=k
3
4  // 全局数组定义
5  vector<int> G[maxn], v[maxn];
6  int d[maxn], mxd[maxn], son[maxn], top[maxn], 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                mxd[x] = max(mxd[x], mxd[y]);
28                if (mxd[y] > mxd[son[x]])
29                    son[x] = y;
30            }
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
         ↪ 伸一倍)数组
35    void dfs2(int x) {
36        top[x] = (x == son[f[0][x]] ? top[f[0][x]] : x);
37
38        for (int y : G[x])
39            if (y != f[0][x])
40                dfs2(y);
41
42        if (top[x] == x) {
43            int u = x;
44            while (top[son[u]] == x)
45                u = son[u];
46
47            len[x] = d[u] - d[x];
48            for (int i = 0; i < len[x]; i++, u = f[0][u])
49                v[x].push_back(u);
50
51            u = x;
52            for (int i = 0; i < len[x] && u; i++, u = f[0]
                 ↪ [u])
53                v[x].push_back(u);
54        }
55    }
56
57    // 在线询问x的k级祖先 O(1)
58    // 不存在时返回0
59    int query(int x, int k) {
60        if (!k)
61            return x;
62        if (k > d[x])
63            return 0;
64
65        x = f[log_tbl[k]][x];
66        k ^= 1 << log_tbl[k];
67        return v[top[x]][d[top[x]] + len[top[x]] - d[x] + 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于$n$(例如给定多个小字符串与大字符串进行询问), 那么规模超过$\sqrt{n}$的问题最多只有$\sqrt{n}$个

### 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      return cnt;
33  }
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
        ↪ 在nx中
7   // 0-based, s的长度是m, t的长度是n
8   void exKMP(const char *s, const char *t, int *a) {
9       static int nx[maxn];
10
11      memset(nx, 0, sizeof(nx));
12
13      int j = 0;
14      while (j + 1 < m && s[j] == s[j + 1])
15          j++;
16      nx[1] = j;
17
18      for (int i = 2, k = 1;i < m; i++) {
19          int pos = k + nx[k], len = nx[i - k];
20
21          if (i + len < pos)
22              nx[i] = len;
23          else {
24              j = max(pos - i, 0);
25              while (i + j < m && s[j] == s[i + j])
26                  j++;
27
28              nx[i] = j;
29              k = i;
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[s[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[s[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,
                    ↪ tp))
92                  namecnt++;
93
94              if (lastx >= 0 && namecnt == name[lastx])
95                  flag = true;
```

```
96
97              name[x] = namecnt;
98              lastx = x;
99          }
100      }
101      name[n] = 0;
102
103      int *t = new int[cnt];
104      int p = 0;
105      for (int i = 0; i <= n; i++)
106          if (name[i] >= 0)
107              t[p++] = name[i];
108
109      int *tsa;
110      if (!flag) {
111          tsa = new int[cnt];
112
113          for (int i = 0; i < cnt; i++)
114              tsa[t[i]] = i;
115      }
116      else
117          tsa = sais(t, cnt, namecnt);
118
119      lbuc[0] = sbuc[0] = 0;
120      for (int i = 1; i <= m; i++) {
121          lbuc[i] = buc[i - 1];
122          sbuc[i] = buc[i] - 1;
123      }
124
125      memset(sa, -1, sizeof(int) * (n + 1));
126      for (int i = cnt - 1; ~i; i--)
127          sa[sbuc[s[pos[tsa[i]]]]--] = pos[tsa[i]];
128      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,
         ↪ int n) {
135      for (int i = 0; i <= n; i++)
136          rnk[sa[i]] = i;
137
138      int k = 0;
139      for (int i = 0; i <= n; i++) {
140          if (!rnk[i])
141              continue;
142
143          if (k)
144              k--;
145
146          while (s[sa[rnk[i]] + k] == s[sa[rnk[i] - 1] +
               ↪ k])
147              k++;
148
149          height[rnk[i]] = k;
150      }
151  }
152
153  char str[maxn];
154  int n, s[maxn], sa[maxn], rnk[maxn], height[maxn];
155
156  // 方便起见附上主函数
157  int main() {
158      scanf("%s", str);
159      n = strlen(str);
160      str[n] = '$';
161
162      for (int i = 0; i <= n; i++)
```

```
163        s[i] = str[i];
164
165    memcpy(sa, sais(s, n + 1, 256), sizeof(int) * (n +
     ↪ 1));
166
167    get_height(s, sa, rnk, height, n);
168
169    return 0;
170 }
```

### 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
   ↪ = 0;
4
5  void dfs(int x) {
6      if (id[x]) {
7          height[tim++] = val[last];
8          sa[tim] = id[x];
9
10         last = x;
11     }
12
13     for (int c = 0; c < 26; c++)
14         if (ch[x][c])
15             dfs(ch[x][c]);
16
17     last = par[x];
18 }
19
20 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 =
                ↪ par[x]) {
35                 vis[x] = true;
36                 pos -= val[x] - val[par[x]];
37                 ch[par[x]][s[pos + 1] - 'a'] = x;
38             }
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 }
```

## 5.4 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++)
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 }
```

## 5.5 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  }
```

### 5.5.1 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],
    ↪ pam_last[maxn], pam_cnt;
8   int weight[maxn], pow_26[maxn];
9
10  int trie[maxn][26], trie_cnt, d[maxn], mxd[maxn],
    ↪ son[maxn], top[maxn], len[maxn], sum[maxn];
11  char chr[maxn];
12  int f[25][maxn], log_tbl[maxn];
13  vector<int> v[maxn];
14
15  vector<int> queries[maxn];
16
17  char str[maxn];
18  int n, m, ans[maxn];
19
20  int add(int x, int c) {
21      if (!trie[x][c]) {
22          trie[x][c] = ++trie_cnt;
23          f[0][trie[x][c]] = x;
24          chr[trie[x][c]] = c + 'a';
25      }
26
27      return trie[x][c];
28  }
29
30  int del(int x) {
```

```
31      return f[0][x];
32  }
33
34  void dfs1(int x) {
35      mxd[x] = d[x] = d[f[0][x]] + 1;
36
37      for (int i = 0; i < 26; i++)
38          if (trie[x][i]) {
39              int y = trie[x][i];
40
41              dfs1(y);
42
43              mxd[x] = max(mxd[x], mxd[y]);
44              if (mxd[y] > mxd[son[x]])
45                  son[x] = y;
46          }
47  }
48
49  void dfs2(int x) {
50      if (x == son[f[0][x]])
51          top[x] = top[f[0][x]];
52      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
                ↪ 延长一倍
75              v[x].push_back(u);
76              u = f[0][u];
77          }
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'] =
                 ↪ par[q];
125
126          if (val[q] <= n)
127              weight[q] = (weight[par[q]] + (long long)(n -
                 ↪ val[q] + 1) * pow_26[n - val[q]]) % mod;
128          else
129              weight[q] = weight[par[q]];
130      }
131      else
132          new_last = go[p][c];
133
134      pam_last[x] = new_last;
135
136      return weight[pam_last[x]];
137  }
138
139  void bfs() {
140
141      queue<int> q;
142
143      q.push(1);
144
145      while (!q.empty()) {
146          int x = q.front();
147          q.pop();
148
149          sum[x] = sum[f[0][x]];
150          if (x > 1)
151              sum[x] = (sum[x] + extend(x)) % mod;
152
153          for (int i : queries[x])
154              ans[i] = sum[x];
155
156          for (int i = 0; i < 26; i++)
157              if (trie[x][i])
158                  q.push(trie[x][i]);
159      }
160
161  }
162
163  int main() {
164
165      pow_26[0] = 1;
166      log_tbl[0] = -1;
167
168      for (int i = 1; i <= 1000000; i++) {
169          pow_26[i] = 26ll * pow_26[i - 1] % mod;
170          log_tbl[i] = log_tbl[i / 2] + 1;
171      }
```

```
172
173      int T;
174      scanf("%d", &T);
175
176      while (T--) {
177          scanf("%d%d%s", &n, &m, str);
178
179          trie_cnt = 1;
180          chr[1] = '#';
181
182          int last = 1;
183          for (char *c = str; *c; c++)
184              last = add(last, *c - 'a');
185
186          queries[last].push_back(0);
187
188          for (int i = 1; i <= m; i++) {
189              int op;
190              scanf("%d", &op);
191
192              if (op == 1) {
193                  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
214          for (int i = 0; i < 26; i++)
215              fail[0][i] = fail[1][i] = 1;
216
217          val[1] = -1;
218          pam_last[1] = 1;
219
220          bfs();
221
222          for (int i = 0; i <= m; i++)
223              printf("%d\n", ans[i]);
224
225          for (int j = 0; j <= log_tbl[trie_cnt]; j++)
226              memset(f[j], 0, sizeof(f[j]));
227
228          for (int i = 1; i <= trie_cnt; i++) {
229              chr[i] = 0;
230              d[i] = mxd[i] = son[i] = top[i] = len[i] =
                 ↪ 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  }
```

## 5.6 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  }
```

## 5.7 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≥某个值的后缀形成一个区间. 另外一个比较好用的性质是本质不同的子串个数 = 所有子串数 - 字典序相邻的串的height.

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

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

# 6. 动态规划

## 6.1 决策单调性$O(n \log n)$

```
1   int a[maxn], q[maxn], p[maxn], g[maxn]; // 存左端点,右端
        ↪ 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          if (head <= tail) {
31              if (f[q[head]] + calc(q[head] + 1, i) < f[i])
                    ↪ {
32                  f[i] = f[q[head]] + calc(q[head] + 1, i);
33                  g[i] = g[q[head]] + 1;
34              }
35              while (head < tail && p[head + 1] <= i + 1)
36                  head++;
37              if (head <= tail)
38                  p[head] = i + 1;
39          }
40          f[i] += tmp;
41
42          int r = n;
43
44          while(head <= tail) {
45              if (f[q[tail]] + calc(q[tail] + 1, p[tail]) >
                    ↪ f[i] + calc(i + 1, p[tail])) {
46                  r = p[tail] - 1;
47                  tail--;
48              }
49              else if (f[q[tail]] + calc(q[tail] + 1, r) <=
                    ↪ f[i] + calc(i + 1, r)) {
50                  if (r < n) {
51                      q[++tail] = i;
52                      p[tail] = r + 1;
53                  }
54                  break;
55              }
56              else {
57                  int L = p[tail], R = r;
58                  while (L < R) {
59                      int M = (L + R) / 2;
60
61                      if (f[q[tail]] + calc(q[tail] + 1, M)
                            ↪ <= f[i] + calc(i + 1, M))
62                          L = M + 1;
63                      else
64                          R = M;
65                  }
66
67                  q[++tail] = i;
68                  p[tail] = L;
69
70                  break;
71              }
72          }
73          if (head > tail) {
74              q[++tail] = i;
```

```
75            p[tail] = i + 1;
76        }
77    }
78
79    return g[n];
80 }
```

## 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 }
```

## 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_finate(x) # x是否有穷(NaN也算)
26 decimal.is_infinate(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 {
```

```cpp
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,
        ↪ int k) {
102         big_decimal o = u;
103         return o <<= k;
104     }
105
106     big_decimal &operator >>= (int k) {
107         if (a[0] < k)
108             return *this = big_decimal(0);
109
110         a[0] -= k;
111         for (int i = 1; i <= a[0]; i++)
112             a[i] = a[i + k];
113
114         for (int i = a[0] + 1; i <= a[0] + k; i++)
115             a[i] = 0;
116
117         return *this;
118     }
119
120     friend big_decimal operator >> (const big_decimal &u,
        ↪ int k) {
121         big_decimal o = u;
122         return o >>= k;
123     }
124
125     friend int cmp(const big_decimal &u, const
        ↪ big_decimal &v) {
126         if (u.negative || v.negative) {
127             if (u.negative && v.negative)
128                 return -cmp(-u, -v);
129
130             if (u.negative)
131                 return -1;
132
133             if (v.negative)
134                 return 1;
135         }
136
137         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
        ↪ big_decimal &v) {
148         return cmp(u, v) == -1;
149     }
150
151     friend bool operator > (const big_decimal &u, const
        ↪ big_decimal &v) {
152         return cmp(u, v) == 1;
153     }
154
155     friend bool operator == (const big_decimal &u, const
        ↪ big_decimal &v) {
156         return cmp(u, v) == 0;
157     }
158
159     friend bool operator <= (const big_decimal &u, const
        ↪ big_decimal &v) {
160         return cmp(u, v) <= 0;
161     }
162
163     friend bool operator >= (const big_decimal &u, const
        ↪ big_decimal &v) {
164         return cmp(u, v) >= 0;
165     }
166
167     friend big_decimal decimal_plus(const big_decimal &u,
        ↪ const big_decimal &v) { // 保证u, v均为正数的话可
        ↪ 以直接调用
168         big_decimal o;
169
170         o.a[0] = max(u.a[0], v.a[0]);
171
172         for (int i = 1; i <= u.a[0] || i <= v.a[0]; i++)
          ↪ {
173             o.a[i] += u.a[i] + v.a[i];
174
175             if (o.a[i] >= 10) {
176                 o.a[i + 1]++;
177                 o.a[i] -= 10;
178             }
179         }
180
181         if (o.a[o.a[0] + 1])
182             o.a[0]++;
183
184         return o;
```

```
185        }
186
187        friend big_decimal decimal_minus(const big_decimal
           ↪ &u, const big_decimal &v) { // 保证u, v均为正数的
           ↪ 话可以直接调用
188            int k = cmp(u, v);
189
190            if (k == -1)
191                return -decimal_minus(v, u);
192            else if (k == 0)
193                return big_decimal(0);
194
195            big_decimal o;
196
197            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        if (o.a[i] >= 10) {
316            o.a[i + 1] += o.a[i] / 10;
317            o.a[i] %= 10;
318        }
319    }
320
321    if (o.a[a[0] + 1])
322        o.a[0]++;
323
324    return o;
325  }
326
327  friend pair<big_decimal, big_decimal>
328  ↪ decimal_div(const big_decimal &u, const
   ↪ big_decimal &v) {
329    if (u.negative || v.negative) {
330        pair<big_decimal, big_decimal> o =
           ↪ decimal_div(abs(u), abs(v));
331
332        if (u.negative ^ v.negative)
333            return make_pair(-o.first, -o.second);
334        return o;
335    }
336
337    return decimal_divide(u, v);
338  }
339
340  friend big_decimal operator / (const big_decimal &u,
   ↪ const big_decimal &v) { // v不能是0
341    if (u.negative || v.negative) {
342        big_decimal o = abs(u) / abs(v);
343
344        if (u.negative ^ v.negative)
345            return -o;
346        return o;
347    }
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 |
| **998244353** | 119 | 23 | 3 |
| **1004535809** | 479 | 21 | 3 |
| 1005060097* | 1917 | 19 | **5** |
| **2013265921** | 15 | 27 | **31** |
| 2281701377 | 17 | 27 | 3 |
| 315525197391593473 | 7 | 52 | 3 |
| 180143985094819841 | 5 | 55 | **6** |
| 1945555039024054273 | 27 | 56 | **5** |
| 4179340454199820289 | 29 | 57 | 3 |

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

## 7.6　xorshift

```
1  ull k1, k2;
2  const int mod = 10000000;
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

## 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

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≥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
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, 确定写对了吗**

### 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.

| Definitions | | Series |
|---|---|---|

**Definitions**

| | |
|---|---|
| $f(n) = O(g(n))$ | iff $\exists$ positive $c, n_0$ such that $0 \le f(n) \le cg(n)\ \forall n \ge n_0$. |
| $f(n) = \Omega(g(n))$ | iff $\exists$ positive $c, n_0$ such that $f(n) \ge cg(n) \ge 0\ \forall n \ge n_0$. |
| $f(n) = \Theta(g(n))$ | iff $f(n) = O(g(n))$ and $f(n) = \Omega(g(n))$. |
| $f(n) = o(g(n))$ | iff $\lim_{n\to\infty} f(n)/g(n) = 0$. |
| $\lim_{n\to\infty} a_n = a$ | iff $\forall \epsilon > 0$, $\exists n_0$ such that $|a_n - a| < \epsilon$, $\forall n \ge n_0$. |
| $\sup S$ | least $b \in \mathbb{R}$ such that $b \ge s$, $\forall s \in S$. |
| $\inf S$ | greatest $b \in \mathbb{R}$ such that $b \le s$, $\forall s \in S$. |
| $\liminf_{n\to\infty} a_n$ | $\lim_{n\to\infty} \inf\{a_i \mid i \ge n, i \in \mathbb{N}\}$. |
| $\limsup_{n\to\infty} a_n$ | $\lim_{n\to\infty} \sup\{a_i \mid i \ge n, i \in \mathbb{N}\}$. |
| $\binom{n}{k}$ | Combinations: Size $k$ subsets of a size $n$ set. |
| $\left[ {n \atop k} \right]$ | Stirling numbers (1st kind): Arrangements of an $n$ element set into $k$ cycles. |
| $\left\{ {n \atop k} \right\}$ | Stirling numbers (2nd kind): Partitions of an $n$ element set into $k$ non-empty sets. |
| $\left\langle {n \atop k} \right\rangle$ | 1st order Eulerian numbers: Permutations $\pi_1\pi_2\ldots\pi_n$ on $\{1,2,\ldots,n\}$ with $k$ ascents. |
| $\left\langle\!\!\left\langle {n \atop k} \right\rangle\!\!\right\rangle$ | 2nd order Eulerian numbers. |
| $C_n$ | Catalan Numbers: Binary trees with $n+1$ vertices. |

**Series**

$$\sum_{i=1}^{n} i = \frac{n(n+1)}{2}, \quad \sum_{i=1}^{n} i^2 = \frac{n(n+1)(2n+1)}{6}, \quad \sum_{i=1}^{n} i^3 = \frac{n^2(n+1)^2}{4}.$$

In general:

$$\sum_{i=1}^{n} i^m = \frac{1}{m+1}\left[(n+1)^{m+1} - 1 - \sum_{i=1}^{n}\left((i+1)^{m+1} - i^{m+1} - (m+1)i^m\right)\right]$$

$$\sum_{i=1}^{n-1} i^m = \frac{1}{m+1}\sum_{k=0}^{m}\binom{m+1}{k}B_k n^{m+1-k}.$$

Geometric series:

$$\sum_{i=0}^{n} c^i = \frac{c^{n+1}-1}{c-1}, \quad c \ne 1, \quad \sum_{i=0}^{\infty} c^i = \frac{1}{1-c}, \quad \sum_{i=1}^{\infty} c^i = \frac{c}{1-c}, \quad |c| < 1,$$

$$\sum_{i=0}^{n} ic^i = \frac{nc^{n+2} - (n+1)c^{n+1} + c}{(c-1)^2}, \quad c \ne 1, \quad \sum_{i=0}^{\infty} ic^i = \frac{c}{(1-c)^2}, \quad |c| < 1.$$

Harmonic series:

$$H_n = \sum_{i=1}^{n} \frac{1}{i}, \qquad \sum_{i=1}^{n} iH_i = \frac{n(n+1)}{2}H_n - \frac{n(n-1)}{4}.$$

$$\sum_{i=1}^{n} H_i = (n+1)H_n - n, \quad \sum_{i=1}^{n}\binom{i}{m}H_i = \binom{n+1}{m+1}\left(H_{n+1} - \frac{1}{m+1}\right).$$

**1.** $\binom{n}{k} = \dfrac{n!}{(n-k)!k!}$, **2.** $\sum_{k=0}^{n}\binom{n}{k} = 2^n$, **3.** $\binom{n}{k} = \binom{n}{n-k}$,

**4.** $\binom{n}{k} = \dfrac{n}{k}\binom{n-1}{k-1}$, **5.** $\binom{n}{k} = \binom{n-1}{k} + \binom{n-1}{k-1}$,

**6.** $\binom{n}{m}\binom{m}{k} = \binom{n}{k}\binom{n-k}{m-k}$, **7.** $\sum_{k=0}^{n}\binom{r+k}{k} = \binom{r+n+1}{n}$,

**8.** $\sum_{k=0}^{n}\binom{k}{m} = \binom{n+1}{m+1}$, **9.** $\sum_{k=0}^{n}\binom{r}{k}\binom{s}{n-k} = \binom{r+s}{n}$,

**10.** $\binom{n}{k} = (-1)^k\binom{k-n-1}{k}$, **11.** $\left\{ {n \atop 1} \right\} = \left\{ {n \atop n} \right\} = 1$,

**12.** $\left\{ {n \atop 2} \right\} = 2^{n-1} - 1$, **13.** $\left\{ {n \atop k} \right\} = k\left\{ {n-1 \atop k} \right\} + \left\{ {n-1 \atop k-1} \right\}$,

**14.** $\left[ {n \atop 1} \right] = (n-1)!$, **15.** $\left[ {n \atop 2} \right] = (n-1)!H_{n-1}$, **16.** $\left[ {n \atop n} \right] = 1$, **17.** $\left[ {n \atop k} \right] \ge \left\{ {n \atop k} \right\}$,

**18.** $\left[ {n \atop k} \right] = (n-1)\left[ {n-1 \atop k} \right] + \left[ {n-1 \atop k-1} \right]$, **19.** $\left\{ {n \atop n-1} \right\} = \left[ {n \atop n-1} \right] = \binom{n}{2}$, **20.** $\sum_{k=0}^{n}\left[ {n \atop k} \right] = n!$, **21.** $C_n = \dfrac{1}{n+1}\binom{2n}{n}$,

**22.** $\left\langle {n \atop 0} \right\rangle = \left\langle {n \atop n-1} \right\rangle = 1$, **23.** $\left\langle {n \atop k} \right\rangle = \left\langle {n \atop n-1-k} \right\rangle$, **24.** $\left\langle {n \atop k} \right\rangle = (k+1)\left\langle {n-1 \atop k} \right\rangle + (n-k)\left\langle {n-1 \atop k-1} \right\rangle$,

**25.** $\left\langle {0 \atop k} \right\rangle = \begin{cases} 1 & \text{if } k = 0, \\ 0 & \text{otherwise} \end{cases}$ **26.** $\left\langle {n \atop 1} \right\rangle = 2^n - n - 1$, **27.** $\left\langle {n \atop 2} \right\rangle = 3^n - (n+1)2^n + \binom{n+1}{2}$,

**28.** $x^n = \sum_{k=0}^{n}\left\langle {n \atop k} \right\rangle\binom{x+k}{n}$, **29.** $\left\langle {n \atop m} \right\rangle = \sum_{k=0}^{m}\binom{n+1}{k}(m+1-k)^n(-1)^k$, **30.** $m!\left\{ {n \atop m} \right\} = \sum_{k=0}^{n}\left\langle {n \atop k} \right\rangle\binom{k}{n-m}$,

**31.** $\left\langle {n \atop m} \right\rangle = \sum_{k=0}^{n}\left\{ {n \atop k} \right\}\binom{n-k}{m}(-1)^{n-k-m}k!$, **32.** $\left\langle\!\!\left\langle {n \atop 0} \right\rangle\!\!\right\rangle = 1$, **33.** $\left\langle\!\!\left\langle {n \atop n} \right\rangle\!\!\right\rangle = 0 \quad \text{for } n \ne 0$,

**34.** $\left\langle\!\!\left\langle {n \atop k} \right\rangle\!\!\right\rangle = (k+1)\left\langle\!\!\left\langle {n-1 \atop k} \right\rangle\!\!\right\rangle + (2n-1-k)\left\langle\!\!\left\langle {n-1 \atop k-1} \right\rangle\!\!\right\rangle$, **35.** $\sum_{k=0}^{n}\left\langle\!\!\left\langle {n \atop k} \right\rangle\!\!\right\rangle = \dfrac{(2n)^{\underline{n}}}{2^n}$,

**36.** $\left\{ {x \atop x-n} \right\} = \sum_{k=0}^{n}\left\langle\!\!\left\langle {n \atop k} \right\rangle\!\!\right\rangle\binom{x+n-1-k}{2n}$, **37.** $\left\{ {n+1 \atop m+1} \right\} = \sum_{k}\binom{n}{k}\left\{ {k \atop m} \right\} = \sum_{k=0}^{n}\left\{ {k \atop m} \right\}(m+1)^{n-k}$,

| Identities Cont. | | Trees |
|---|---|---|

**38.** $\begin{bmatrix} n+1 \\ m+1 \end{bmatrix} = \sum_k \begin{bmatrix} n \\ k \end{bmatrix} \binom{k}{m} = \sum_{k=0}^{n} \begin{bmatrix} k \\ m \end{bmatrix} n^{\underline{n-k}} = n! \sum_{k=0}^{n} \frac{1}{k!} \begin{bmatrix} k \\ m \end{bmatrix},$ **39.** $\begin{bmatrix} x \\ x-n \end{bmatrix} = \sum_{k=0}^{n} \left\langle\!\!\left\langle n \atop k \right\rangle\!\!\right\rangle \binom{x+k}{2n},$

**40.** $\begin{Bmatrix} n \\ m \end{Bmatrix} = \sum_k \binom{n}{k} \begin{Bmatrix} k+1 \\ m+1 \end{Bmatrix} (-1)^{n-k},$ **41.** $\begin{bmatrix} n \\ m \end{bmatrix} = \sum_k \begin{bmatrix} n+1 \\ k+1 \end{bmatrix} \binom{k}{m} (-1)^{m-k},$

**42.** $\begin{Bmatrix} m+n+1 \\ m \end{Bmatrix} = \sum_{k=0}^{m} k \begin{Bmatrix} n+k \\ k \end{Bmatrix},$ **43.** $\begin{bmatrix} m+n+1 \\ m \end{bmatrix} = \sum_{k=0}^{m} k(n+k) \begin{bmatrix} n+k \\ k \end{bmatrix},$

**44.** $\binom{n}{m} = \sum_k \begin{Bmatrix} n+1 \\ k+1 \end{Bmatrix} \begin{bmatrix} k \\ m \end{bmatrix} (-1)^{m-k},$ **45.** $(n-m)! \binom{n}{m} = \sum_k \begin{bmatrix} n+1 \\ k+1 \end{bmatrix} \begin{Bmatrix} k \\ m \end{Bmatrix} (-1)^{m-k}, \quad$ for $n \geq m,$

**46.** $\begin{Bmatrix} n \\ n-m \end{Bmatrix} = \sum_k \binom{m-n}{m+k} \binom{m+n}{n+k} \begin{bmatrix} m+k \\ k \end{bmatrix},$ **47.** $\begin{bmatrix} n \\ n-m \end{bmatrix} = \sum_k \binom{m-n}{m+k} \binom{m+n}{n+k} \begin{Bmatrix} m+k \\ k \end{Bmatrix},$

**48.** $\begin{Bmatrix} n \\ \ell+m \end{Bmatrix} \binom{\ell+m}{\ell} = \sum_k \begin{Bmatrix} k \\ \ell \end{Bmatrix} \begin{Bmatrix} n-k \\ m \end{Bmatrix} \binom{n}{k},$ **49.** $\begin{bmatrix} n \\ \ell+m \end{bmatrix} \binom{\ell+m}{\ell} = \sum_k \begin{bmatrix} k \\ \ell \end{bmatrix} \begin{bmatrix} n-k \\ m \end{bmatrix} \binom{n}{k}.$

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

Kraft inequality: If the depths of the leaves of a binary tree are $d_1, \ldots, d_n$:
$$\sum_{i=1}^{n} 2^{-d_i} \leq 1,$$
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
$$u_{i+1} = \tfrac{1}{2} + u_i, \qquad u_1 = \tfrac{1}{2},$$

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"

$$1\big(T(n) - 3T(n/2) = n\big)$$
$$3\big(T(n/2) - 3T(n/4) = n/2\big)$$
$$\vdots \quad \vdots \quad \vdots$$
$$3^{\log_2 n - 1}\big(T(2) - 3T(1) = 2\big)$$

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

Let $c = \tfrac{3}{2}$. Then we have
$$n \sum_{i=0}^{m-1} c^i = n \left(\frac{c^m - 1}{c - 1}\right)$$
$$= 2n(c^{\log_2 n} - 1)$$
$$= 2n(c^{(k-1)\log_c n} - 1)$$
$$= 2n^k - 2n,$$

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

So $g_i = 2^i - 1.$

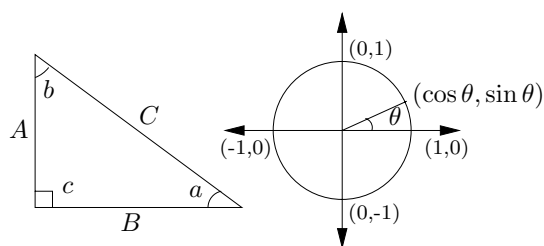| | | | | |
|---|---|---|---|---|
| | | | **Theoretical Computer Science Cheat Sheet** | |

$\pi \approx 3.14159,$ $\qquad e \approx 2.71828,$ $\qquad \gamma \approx 0.57721,$ $\qquad \phi = \frac{1+\sqrt{5}}{2} \approx 1.61803,$ $\qquad \hat{\phi} = \frac{1-\sqrt{5}}{2} \approx -.61803$

| $i$ | $2^i$ | $p_i$ | General | Probability |
|---|---|---|---|---|
| 1 | 2 | 2 | | |
| 2 | 4 | 3 | | |
| 3 | 8 | 5 | | |

**Left table (i, $2^i$, $p_i$):**

| $i$ | $2^i$ | $p_i$ |
|---|---|---|
| 1 | 2 | 2 |
| 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**

```
                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
```

**General**

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:
$$\log_b x = \frac{\log_a x}{\log_a b}, \qquad \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}.$$

Euler's number $e$:
$$e = 1 + \frac{1}{2} + \frac{1}{6} + \frac{1}{24} + \frac{1}{120} + \cdots$$
$$\lim_{n \to \infty} \left(1 + \frac{x}{n}\right)^n = e^x.$$
$$\left(1 + \frac{1}{n}\right)^n < e < \left(1 + \frac{1}{n}\right)^{n+1}.$$
$$\left(1 + \frac{1}{n}\right)^n = e - \frac{e}{2n} + \frac{11e}{24n^2} - O\left(\frac{1}{n^3}\right).$$

Harmonic numbers:
$$1, \frac{3}{2}, \frac{11}{6}, \frac{25}{12}, \frac{137}{60}, \frac{49}{20}, \frac{363}{140}, \frac{761}{280}, \frac{7129}{2520}, \cdots$$
$$\ln n < H_n < \ln n + 1,$$
$$H_n = \ln n + \gamma + O\left(\frac{1}{n}\right).$$

Factorial, Stirling's approximation:
$$1, 2, 6, 24, 120, 720, 5040, 40320, 362880, \ldots$$
$$n! = \sqrt{2\pi n}\left(\frac{n}{e}\right)^n \left(1 + \Theta\left(\frac{1}{n}\right)\right).$$

Ackermann's function and inverse:
$$a(i, j) = \begin{cases} 2^j & i = 1 \\ a(i-1, 2) & j = 1 \\ a(i-1, a(i, j-1)) & i, j \geq 2 \end{cases}$$
$$\alpha(i) = \min\{j \mid a(j, j) \geq i\}.$$

Binomial distribution:
$$\Pr[X = k] = \binom{n}{k} p^k q^{n-k}, \qquad q = 1 - p,$$
$$E[X] = \sum_{k=1}^{n} k \binom{n}{k} p^k q^{n-k} = np.$$

Poisson distribution:
$$\Pr[X = k] = \frac{e^{-\lambda} \lambda^k}{k!}, \quad E[X] = \lambda.$$

Normal (Gaussian) distribution:
$$p(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(x-\mu)^2/2\sigma^2}, \quad E[X] = \mu.$$

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
$$nH_n.$$

**Probability**

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
$$E[g(X)] = \sum_x g(x) \Pr[X = x].$$
If $X$ continuous then
$$E[g(X)] = \int_{-\infty}^{\infty} g(x) p(x)\, dx = \int_{-\infty}^{\infty} g(x)\, dP(x).$$

Variance, standard deviation:
$$\text{VAR}[X] = E[X^2] - E[X]^2,$$
$$\sigma = \sqrt{\text{VAR}[X]}.$$

For events $A$ and $B$:
$$\Pr[A \vee B] = \Pr[A] + \Pr[B] - \Pr[A \wedge B]$$
$$\Pr[A \wedge B] = \Pr[A] \cdot \Pr[B],$$
$$\text{iff } A \text{ and } B \text{ are independent.}$$
$$\Pr[A|B] = \frac{\Pr[A \wedge B]}{\Pr[B]}$$

For random variables $X$ and $Y$:
$$E[X \cdot Y] = E[X] \cdot E[Y],$$
$$\text{if } X \text{ and } Y \text{ are independent.}$$
$$E[X + Y] = E[X] + E[Y],$$
$$E[cX] = c\, E[X].$$

Bayes' theorem:
$$\Pr[A_i|B] = \frac{\Pr[B|A_i] \Pr[A_i]}{\sum_{j=1}^n \Pr[A_j] \Pr[B|A_j]}.$$

Inclusion-exclusion:
$$\Pr\left[\bigvee_{i=1}^n X_i\right] = \sum_{i=1}^n \Pr[X_i] +$$
$$\sum_{k=2}^n (-1)^{k+1} \sum_{i_i < \cdots < i_k} \Pr\left[\bigwedge_{j=1}^k X_{i_j}\right].$$

Moment inequalities:
$$\Pr\left[|X| \geq \lambda E[X]\right] \leq \frac{1}{\lambda},$$
$$\Pr\left[|X - E[X]| \geq \lambda \cdot \sigma\right] \leq \frac{1}{\lambda^2}.$$

Geometric distribution:
$$\Pr[X = k] = pq^{k-1}, \qquad q = 1 - p,$$
$$E[X] = \sum_{k=1}^{\infty} kpq^{k-1} = \frac{1}{p}.$$

## Theoretical Computer Science Cheat Sheet

### Trigonometry



Pythagorean theorem:
$$C^2 = A^2 + B^2.$$

Definitions:
$$\sin a = A/C, \quad \cos a = B/C,$$
$$\csc a = C/A, \quad \sec a = C/B,$$
$$\tan a = \frac{\sin a}{\cos a} = \frac{A}{B}, \quad \cot a = \frac{\cos a}{\sin a} = \frac{B}{A}.$$

Area, radius of inscribed circle:
$$\tfrac{1}{2}AB, \quad \frac{AB}{A+B+C}.$$

Identities:
$$\sin x = \frac{1}{\csc x}, \qquad\qquad \cos x = \frac{1}{\sec x},$$
$$\tan x = \frac{1}{\cot x}, \qquad\qquad \sin^2 x + \cos^2 x = 1,$$
$$1 + \tan^2 x = \sec^2 x, \qquad 1 + \cot^2 x = \csc^2 x,$$
$$\sin x = \cos\left(\tfrac{\pi}{2} - x\right), \qquad \sin x = \sin(\pi - x),$$
$$\cos x = -\cos(\pi - x), \qquad \tan x = \cot\left(\tfrac{\pi}{2} - x\right),$$
$$\cot x = -\cot(\pi - x), \qquad \csc x = \cot\tfrac{x}{2} - \cot x,$$
$$\sin(x \pm y) = \sin x \cos y \pm \cos x \sin y,$$
$$\cos(x \pm y) = \cos x \cos y \mp \sin x \sin y,$$
$$\tan(x \pm y) = \frac{\tan x \pm \tan y}{1 \mp \tan x \tan y},$$
$$\cot(x \pm y) = \frac{\cot x \cot y \mp 1}{\cot x \pm \cot y},$$
$$\sin 2x = 2 \sin x \cos x, \qquad \sin 2x = \frac{2\tan x}{1 + \tan^2 x},$$
$$\cos 2x = \cos^2 x - \sin^2 x, \qquad \cos 2x = 2\cos^2 x - 1,$$
$$\cos 2x = 1 - 2\sin^2 x, \qquad \cos 2x = \frac{1 - \tan^2 x}{1 + \tan^2 x},$$
$$\tan 2x = \frac{2\tan x}{1 - \tan^2 x}, \qquad \cot 2x = \frac{\cot^2 x - 1}{2\cot x},$$
$$\sin(x + y)\sin(x - y) = \sin^2 x - \sin^2 y,$$
$$\cos(x + y)\cos(x - y) = \cos^2 x - \sin^2 y.$$

Euler's equation:
$$e^{ix} = \cos x + i \sin x, \qquad e^{i\pi} = -1.$$

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

$2 \times 2$ and $3 \times 3$ determinant:
$$\begin{vmatrix} a & b \\ c & d \end{vmatrix} = ad - bc,$$
$$\begin{vmatrix} a & b & c \\ d & e & f \\ g & h & i \end{vmatrix} = g\begin{vmatrix} b & c \\ e & f \end{vmatrix} - h\begin{vmatrix} a & c \\ d & f \end{vmatrix} + i\begin{vmatrix} a & b \\ d & e \end{vmatrix}$$
$$= \begin{array}{l} aei + bfg + cdh \\ - ceg - fha - ibd. \end{array}$$

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

### Hyperbolic Functions

Definitions:
$$\sinh x = \frac{e^x - e^{-x}}{2}, \qquad \cosh x = \frac{e^x + e^{-x}}{2},$$
$$\tanh x = \frac{e^x - e^{-x}}{e^x + e^{-x}}, \qquad \operatorname{csch} x = \frac{1}{\sinh x},$$
$$\operatorname{sech} x = \frac{1}{\cosh x}, \qquad \coth x = \frac{1}{\tanh x}.$$

Identities:
$$\cosh^2 x - \sinh^2 x = 1, \qquad \tanh^2 x + \operatorname{sech}^2 x = 1,$$
$$\coth^2 x - \operatorname{csch}^2 x = 1, \qquad \sinh(-x) = -\sinh x,$$
$$\cosh(-x) = \cosh x, \qquad \tanh(-x) = -\tanh x,$$
$$\sinh(x + y) = \sinh x \cosh y + \cosh x \sinh y,$$
$$\cosh(x + y) = \cosh x \cosh y + \sinh x \sinh y,$$
$$\sinh 2x = 2 \sinh x \cosh x,$$
$$\cosh 2x = \cosh^2 x + \sinh^2 x,$$
$$\cosh x + \sinh x = e^x, \qquad \cosh x - \sinh x = e^{-x},$$
$$(\cosh x + \sinh x)^n = \cosh nx + \sinh nx, \quad n \in \mathbb{Z},$$
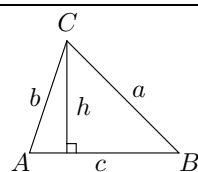$$2\sinh^2 \tfrac{x}{2} = \cosh x - 1, \qquad 2\cosh^2 \tfrac{x}{2} = \cosh x + 1.$$

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

. . . in mathematics you don't understand things, you just get used to them.
– J. von Neumann

### More Trig.



Law of cosines:
$$c^2 = a^2 + b^2 - 2ab\cos C.$$

Area:
$$A = \tfrac{1}{2}hc,$$
$$= \tfrac{1}{2}ab\sin C,$$
$$= \frac{c^2 \sin A \sin B}{2\sin C}.$$

Heron's formula:
$$A = \sqrt{s \cdot s_a \cdot s_b \cdot s_c},$$
$$s = \tfrac{1}{2}(a + b + c),$$
$$s_a = s - a,$$
$$s_b = s - b,$$
$$s_c = s - c.$$

More identities:
$$\sin\tfrac{x}{2} = \sqrt{\frac{1 - \cos x}{2}},$$
$$\cos\tfrac{x}{2} = \sqrt{\frac{1 + \cos x}{2}},$$
$$\tan\tfrac{x}{2} = \sqrt{\frac{1 - \cos x}{1 + \cos x}},$$
$$= \frac{1 - \cos x}{\sin x},$$
$$= \frac{\sin x}{1 + \cos x},$$
$$\cot\tfrac{x}{2} = \sqrt{\frac{1 + \cos x}{1 - \cos x}},$$
$$= \frac{1 + \cos x}{\sin x},$$
$$= \frac{\sin x}{1 - \cos x},$$
$$\sin x = \frac{e^{ix} - e^{-ix}}{2i},$$
$$\cos x = \frac{e^{ix} + e^{-ix}}{2},$$
$$\tan x = -i\frac{e^{ix} - e^{-ix}}{e^{ix} + e^{-ix}},$$
$$= -i\frac{e^{2ix} - 1}{e^{2ix} + 1},$$
$$\sin x = \frac{\sinh ix}{i},$$
$$\cos x = \cosh ix,$$
$$\tan x = \frac{\tanh ix}{i}.$$

| Number Theory | Graph Theory |
|---|---|

### Number Theory

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

$$C \equiv r_1 \bmod m_1$$
$$\vdots \quad \vdots \quad \vdots$$
$$C \equiv r_n \bmod m_n$$

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

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

Fermat's theorem:

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

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

$$(n-1)! \equiv -1 \bmod n.$$

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 $v_0 e_1 v_1 \ldots e_\ell v_\ell$. |
| *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 embeded 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 |
|---|---|
| $(x, y)$ | $(x, y, 1)$ |
| $y = mx + b$ | $(m, -1, b)$ |
| $x = c$ | $(1, 0, -c)$ |

Distance formula, $L_p$ and $L_\infty$ metric:
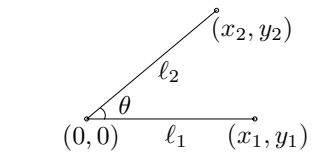
$$\sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2},$$
$$\left[|x_1 - x_0|^p + |y_1 - y_0|^p\right]^{1/p},$$
$$\lim_{p \to \infty} \left[|x_1 - x_0|^p + |y_1 - y_0|^p\right]^{1/p}.$$

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

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

Angle formed by three points:



$$\cos \theta = \frac{(x_1, y_1) \cdot (x_2, y_2)}{\ell_1 \ell_2}.$$

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:

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

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

<div align="center">

**Theoretical Computer Science Cheat Sheet**

</div>

| $\pi$ | Calculus |
|---|---|

## $\pi$

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

Gregrory'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. $\dfrac{d(cu)}{dx} = c\dfrac{du}{dx},$  2. $\dfrac{d(u+v)}{dx} = \dfrac{du}{dx} + \dfrac{dv}{dx},$  3. $\dfrac{d(uv)}{dx} = u\dfrac{dv}{dx} + v\dfrac{du}{dx},$

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

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

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

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

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

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

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

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

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

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

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

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

29. $\dfrac{d(\text{arctanh}\, u)}{dx} = \dfrac{1}{1-u^2}\dfrac{du}{dx},$  30. $\dfrac{d(\text{arccoth}\, u)}{dx} = \dfrac{1}{u^2-1}\dfrac{du}{dx},$

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

Integrals:

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

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

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

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

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

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

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

## 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.** $\int \sin^2(ax) dx = \frac{1}{2a}\big(ax - \sin(ax)\cos(ax)\big),$      **18.** $\int \cos^2(ax) dx = \frac{1}{2a}\big(ax + \sin(ax)\cos(ax)\big),$

**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.** $\int \operatorname{arccosh} \frac{x}{a} dx = \begin{cases} x \operatorname{arccosh} \dfrac{x}{a} - \sqrt{x^2 + a^2}, & \text{if } \operatorname{arccosh} \frac{x}{a} > 0 \text{ and } a > 0, \\ x \operatorname{arccosh} \dfrac{x}{a} + \sqrt{x^2 + a^2}, & \text{if } \operatorname{arccosh} \frac{x}{a} < 0 \text{ and } a > 0, \end{cases}$

**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.** $\int \frac{dx}{x\sqrt{x^2 + a^2}} = \frac{1}{a} \ln\left|\frac{x}{a + \sqrt{a^2 + x^2}}\right|,$

| Calculus Cont. | Finite Calculus |
|---|---|

## Calculus Cont.

**62.** $\int \dfrac{dx}{x\sqrt{x^2-a^2}} = \frac{1}{a}\arccos\frac{a}{|x|}, \quad a > 0,$ **63.** $\int \dfrac{dx}{x^2\sqrt{x^2 \pm a^2}} = \mp\dfrac{\sqrt{x^2 \pm a^2}}{a^2 x},$

**64.** $\int \dfrac{x\,dx}{\sqrt{x^2 \pm a^2}} = \sqrt{x^2 \pm a^2},$ **65.** $\int \dfrac{\sqrt{x^2 \pm a^2}}{x^4}\,dx = \mp\dfrac{(x^2 + a^2)^{3/2}}{3a^2 x^3},$

**66.** $\int \dfrac{dx}{ax^2+bx+c} = \begin{cases} \dfrac{1}{\sqrt{b^2-4ac}}\ln\left|\dfrac{2ax+b-\sqrt{b^2-4ac}}{2ax+b+\sqrt{b^2-4ac}}\right|, & \text{if } b^2 > 4ac, \\[2ex] \dfrac{2}{\sqrt{4ac-b^2}}\arctan\dfrac{2ax+b}{\sqrt{4ac-b^2}}, & \text{if } b^2 < 4ac, \end{cases}$

**67.** $\int \dfrac{dx}{\sqrt{ax^2+bx+c}} = \begin{cases} \dfrac{1}{\sqrt{a}}\ln\left|2ax+b+2\sqrt{a}\sqrt{ax^2+bx+c}\right|, & \text{if } a > 0, \\[2ex] \dfrac{1}{\sqrt{-a}}\arcsin\dfrac{-2ax-b}{\sqrt{b^2-4ac}}, & \text{if } a < 0, \end{cases}$

**68.** $\int \sqrt{ax^2+bx+c}\,dx = \dfrac{2ax+b}{4a}\sqrt{ax^2+bx+c} + \dfrac{4ax-b^2}{8a}\int \dfrac{dx}{\sqrt{ax^2+bx+c}},$

**69.** $\int \dfrac{x\,dx}{\sqrt{ax^2+bx+c}} = \dfrac{\sqrt{ax^2+bx+c}}{a} - \dfrac{b}{2a}\int \dfrac{dx}{\sqrt{ax^2+bx+c}},$

**70.** $\int \dfrac{dx}{x\sqrt{ax^2+bx+c}} = \begin{cases} \dfrac{-1}{\sqrt{c}}\ln\left|\dfrac{2\sqrt{c}\sqrt{ax^2+bx+c}+bx+2c}{x}\right|, & \text{if } c > 0, \\[2ex] \dfrac{1}{\sqrt{-c}}\arcsin\dfrac{bx+2c}{|x|\sqrt{b^2-4ac}}, & \text{if } c < 0, \end{cases}$

**71.** $\int x^3\sqrt{x^2+a^2}\,dx = (\frac{1}{3}x^2 - \frac{2}{15}a^2)(x^2+a^2)^{3/2},$

**72.** $\int x^n\sin(ax)\,dx = -\frac{1}{a}x^n\cos(ax) + \frac{n}{a}\int x^{n-1}\cos(ax)\,dx,$

**73.** $\int x^n\cos(ax)\,dx = \frac{1}{a}x^n\sin(ax) - \frac{n}{a}\int x^{n-1}\sin(ax)\,dx,$

**74.** $\int x^n e^{ax}\,dx = \dfrac{x^n e^{ax}}{a} - \dfrac{n}{a}\int x^{n-1}e^{ax}\,dx,$

**75.** $\int x^n\ln(ax)\,dx = x^{n+1}\left(\dfrac{\ln(ax)}{n+1} - \dfrac{1}{(n+1)^2}\right),$

**76.** $\int x^n(\ln ax)^m\,dx = \dfrac{x^{n+1}}{n+1}(\ln ax)^m - \dfrac{m}{n+1}\int x^n(\ln ax)^{m-1}\,dx.$

$$
\begin{aligned}
x^1 &= & x^{\underline{1}} & &=& & x^{\overline{1}} \\
x^2 &= & x^{\underline{2}} + x^{\underline{1}} & &=& & x^{\overline{2}} - x^{\overline{1}} \\
x^3 &= & x^{\underline{3}} + 3x^{\underline{2}} + x^{\underline{1}} & &=& & x^{\overline{3}} - 3x^{\overline{2}} + x^{\overline{1}} \\
x^4 &= & x^{\underline{4}} + 6x^{\underline{3}} + 7x^{\underline{2}} + x^{\underline{1}} & &=& & x^{\overline{4}} - 6x^{\overline{3}} + 7x^{\overline{2}} - x^{\overline{1}} \\
x^5 &= & x^{\underline{5}} + 15x^{\underline{4}} + 25x^{\underline{3}} + 10x^{\underline{2}} + x^{\underline{1}} & &=& & x^{\overline{5}} - 15x^{\overline{4}} + 25x^{\overline{3}} - 10x^{\overline{2}} + x^{\overline{1}}
\end{aligned}
$$

$$
\begin{aligned}
x^{\overline{1}} &= & x^1 & \qquad & x^{\underline{1}} &= & x^1 \\
x^{\overline{2}} &= & x^2 + x^1 & & x^{\underline{2}} &= & x^2 - x^1 \\
x^{\overline{3}} &= & x^3 + 3x^2 + 2x^1 & & x^{\underline{3}} &= & x^3 - 3x^2 + 2x^1 \\
x^{\overline{4}} &= & x^4 + 6x^3 + 11x^2 + 6x^1 & & x^{\underline{4}} &= & x^4 - 6x^3 + 11x^2 - 6x^1 \\
x^{\overline{5}} &= & x^5 + 10x^4 + 35x^3 + 50x^2 + 24x^1 & & x^{\underline{5}} &= & x^5 - 10x^4 + 35x^3 - 50x^2 + 24x^1
\end{aligned}
$$

## Finite Calculus

Difference, shift operators:
$$\Delta f(x) = f(x+1) - f(x),$$
$$\mathrm{E}\,f(x) = f(x+1).$$

Fundamental Theorem:
$$f(x) = \Delta F(x) \Leftrightarrow \sum f(x)\delta x = F(x) + C.$$
$$\sum_a^b f(x)\delta x = \sum_{i=a}^{b-1} f(i).$$

Differences:
$$\Delta(cu) = c\Delta u, \qquad \Delta(u+v) = \Delta u + \Delta v,$$
$$\Delta(uv) = u\Delta v + \mathrm{E}\,v\Delta u,$$
$$\Delta(x^{\underline{n}}) = nx^{\underline{n-1}},$$
$$\Delta(H_x) = x^{\underline{-1}}, \qquad \Delta(2^x) = 2^x,$$
$$\Delta(c^x) = (c-1)c^x, \qquad \Delta\binom{x}{m} = \binom{x}{m-1}.$$

Sums:
$$\sum cu\,\delta x = c\sum u\,\delta x,$$
$$\sum(u+v)\,\delta x = \sum u\,\delta x + \sum v\,\delta x,$$
$$\sum u\Delta v\,\delta x = uv - \sum \mathrm{E}\,v\Delta u\,\delta x,$$
$$\sum x^{\underline{n}}\,\delta x = \tfrac{x^{\underline{n+1}}}{m+1}, \qquad \sum x^{\underline{-1}}\,\delta x = H_x,$$
$$\sum c^x\,\delta x = \tfrac{c^x}{c-1}, \qquad \sum \binom{x}{m}\,\delta x = \binom{x}{m+1}.$$

Falling Factorial Powers:
$$x^{\underline{n}} = x(x-1)\cdots(x-n+1), \quad n > 0,$$
$$x^{\underline{0}} = 1,$$
$$x^{\underline{n}} = \dfrac{1}{(x+1)\cdots(x+|n|)}, \quad n < 0,$$
$$x^{\underline{n+m}} = x^{\underline{m}}(x-m)^{\underline{n}}.$$

Rising Factorial Powers:
$$x^{\overline{n}} = x(x+1)\cdots(x+n-1), \quad n > 0,$$
$$x^{\overline{0}} = 1,$$
$$x^{\overline{n}} = \dfrac{1}{(x-1)\cdots(x-|n|)}, \quad n < 0,$$
$$x^{\overline{n+m}} = x^{\overline{m}}(x+m)^{\overline{n}}.$$

Conversion:
$$x^{\underline{n}} = (-1)^n(-x)^{\overline{n}} = (x-n+1)^{\overline{n}}$$
$$= 1/(x+1)^{\overline{-n}},$$
$$x^{\overline{n}} = (-1)^n(-x)^{\underline{n}} = (x+n-1)^{\underline{n}}$$
$$= 1/(x-1)^{\underline{-n}},$$
$$x^n = \sum_{k=1}^n \left\{{n \atop k}\right\} x^{\underline{k}} = \sum_{k=1}^n \left\{{n \atop k}\right\}(-1)^{n-k}x^{\overline{k}},$$
$$x^{\underline{n}} = \sum_{k=1}^n \left[{n \atop k}\right](-1)^{n-k}x^k,$$
$$x^{\overline{n}} = \sum_{k=1}^n \left[{n \atop k}\right] x^k.$$

## Series

Taylor's series:

$$f(x) = f(a) + (x-a)f'(a) + \frac{(x-a)^2}{2}f''(a) + \cdots = \sum_{i=0}^{\infty} \frac{(x-a)^i}{i!} f^{(i)}(a).$$

Expansions:

$$\frac{1}{1-x} = 1 + x + x^2 + x^3 + x^4 + \cdots = \sum_{i=0}^{\infty} x^i,$$

$$\frac{1}{1-cx} = 1 + cx + c^2x^2 + c^3x^3 + \cdots = \sum_{i=0}^{\infty} c^i x^i,$$

$$\frac{1}{1-x^n} = 1 + x^n + x^{2n} + x^{3n} + \cdots = \sum_{i=0}^{\infty} x^{ni},$$

$$\frac{x}{(1-x)^2} = x + 2x^2 + 3x^3 + 4x^4 + \cdots = \sum_{i=0}^{\infty} i x^i,$$

$$x^k \frac{d^n}{dx^n}\left(\frac{1}{1-x}\right) = x + 2^n x^2 + 3^n x^3 + 4^n x^4 + \cdots = \sum_{i=0}^{\infty} i^n x^i,$$

$$e^x = 1 + x + \tfrac{1}{2}x^2 + \tfrac{1}{6}x^3 + \cdots = \sum_{i=0}^{\infty} \frac{x^i}{i!},$$

$$\ln(1+x) = x - \tfrac{1}{2}x^2 + \tfrac{1}{3}x^3 - \tfrac{1}{4}x^4 - \cdots = \sum_{i=1}^{\infty} (-1)^{i+1} \frac{x^i}{i},$$

$$\ln\frac{1}{1-x} = x + \tfrac{1}{2}x^2 + \tfrac{1}{3}x^3 + \tfrac{1}{4}x^4 + \cdots = \sum_{i=1}^{\infty} \frac{x^i}{i},$$

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

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

$$\tan^{-1} x = x - \tfrac{1}{3}x^3 + \tfrac{1}{5}x^5 - \tfrac{1}{7}x^7 + \cdots = \sum_{i=0}^{\infty} (-1)^i \frac{x^{2i+1}}{(2i+1)},$$

$$(1+x)^n = 1 + nx + \tfrac{n(n-1)}{2}x^2 + \cdots = \sum_{i=0}^{\infty} \binom{n}{i} x^i,$$

$$\frac{1}{(1-x)^{n+1}} = 1 + (n+1)x + \binom{n+2}{2}x^2 + \cdots = \sum_{i=0}^{\infty} \binom{i+n}{i} x^i,$$

$$\frac{x}{e^x-1} = 1 - \tfrac{1}{2}x + \tfrac{1}{12}x^2 - \tfrac{1}{720}x^4 + \cdots = \sum_{i=0}^{\infty} \frac{B_i x^i}{i!},$$

$$\frac{1}{2x}(1 - \sqrt{1-4x}) = 1 + x + 2x^2 + 5x^3 + \cdots = \sum_{i=0}^{\infty} \frac{1}{i+1}\binom{2i}{i} x^i,$$

$$\frac{1}{\sqrt{1-4x}} = 1 + x + 2x^2 + 6x^3 + \cdots = \sum_{i=0}^{\infty} \binom{2i}{i} x^i,$$

$$\frac{1}{\sqrt{1-4x}}\left(\frac{1-\sqrt{1-4x}}{2x}\right)^n = 1 + (2+n)x + \binom{4+n}{2}x^2 + \cdots = \sum_{i=0}^{\infty} \binom{2i+n}{i} x^i,$$

$$\frac{1}{1-x}\ln\frac{1}{1-x} = x + \tfrac{3}{2}x^2 + \tfrac{11}{6}x^3 + \tfrac{25}{12}x^4 + \cdots = \sum_{i=1}^{\infty} H_i x^i,$$

$$\frac{1}{2}\left(\ln\frac{1}{1-x}\right)^2 = \tfrac{1}{2}x^2 + \tfrac{3}{4}x^3 + \tfrac{11}{24}x^4 + \cdots = \sum_{i=2}^{\infty} \frac{H_{i-1} x^i}{i},$$

$$\frac{x}{1-x-x^2} = x + x^2 + 2x^3 + 3x^4 + \cdots = \sum_{i=0}^{\infty} F_i x^i,$$

$$\frac{F_n x}{1-(F_{n-1}+F_{n+1})x - (-1)^n x^2} = F_n x + F_{2n}x^2 + F_{3n}x^3 + \cdots = \sum_{i=0}^{\infty} F_{ni} x^i.$$

Ordinary power series:

$$A(x) = \sum_{i=0}^{\infty} a_i x^i.$$

Exponential power series:

$$A(x) = \sum_{i=0}^{\infty} a_i \frac{x^i}{i!}.$$

Dirichlet power series:

$$A(x) = \sum_{i=1}^{\infty} \frac{a_i}{i^x}.$$

Binomial theorem:

$$(x+y)^n = \sum_{k=0}^{n} \binom{n}{k} x^{n-k} y^k.$$

Difference of like powers:

$$x^n - y^n = (x-y) \sum_{k=0}^{n-1} x^{n-1-k} y^k.$$

For ordinary power series:

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

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

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

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

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

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

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

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

$$\frac{A(x) - A(-x)}{2} = \sum_{i=0}^{\infty} a_{2i+1} x^{2i+1}.$$
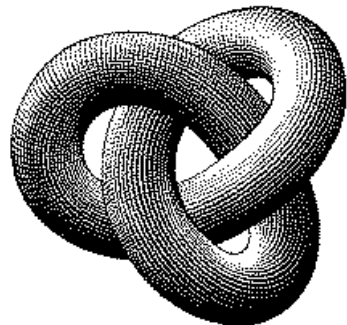
Summation: If $b_i = \sum_{j=0}^{i} a_i$ then

$$B(x) = \frac{1}{1-x} A(x).$$

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:

$$\frac{1}{(1-x)^{n+1}}\ln\frac{1}{1-x} = \sum_{i=0}^{\infty}(H_{n+i}-H_n)\binom{n+i}{i}x^i,$$

$$x^{\overline{n}} = \sum_{i=0}^{\infty}\begin{bmatrix}n\\i\end{bmatrix}x^i,$$

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

$$\tan x = \sum_{i=1}^{\infty}(-1)^{i-1}\frac{2^{2i}(2^{2i}-1)B_{2i}x^{2i-1}}{(2i)!},$$

$$\frac{1}{\zeta(x)} = \sum_{i=1}^{\infty}\frac{\mu(i)}{i^x},$$

$$\zeta(x) = \prod_{p}\frac{1}{1-p^{-x}},$$

$$\zeta^2(x) = \sum_{i=1}^{\infty}\frac{d(i)}{x^i}\quad\text{where }d(n)=\sum_{d|n}1,$$

$$\zeta(x)\zeta(x-1) = \sum_{i=1}^{\infty}\frac{S(i)}{x^i}\quad\text{where }S(n)=\sum_{d|n}d,$$

$$\zeta(2n) = \frac{2^{2n-1}|B_{2n}|}{(2n)!}\pi^{2n},\quad n\in\mathbb{N},$$

$$\frac{x}{\sin x} = \sum_{i=0}^{\infty}(-1)^{i-1}\frac{(4^i-2)B_{2i}x^{2i}}{(2i)!},$$

$$\left(\frac{1-\sqrt{1-4x}}{2x}\right)^n = \sum_{i=0}^{\infty}\frac{n(2i+n-1)!}{i!(n+i)!}x^i,$$

$$e^x\sin x = \sum_{i=1}^{\infty}\frac{2^{i/2}\sin\frac{i\pi}{4}}{i!}x^i,$$

$$\sqrt{\frac{1-\sqrt{1-x}}{x}} = \sum_{i=0}^{\infty}\frac{(4i)!}{16^i\sqrt{2}(2i)!(2i+1)!}x^i,$$

$$\left(\frac{\arcsin x}{x}\right)^2 = \sum_{i=0}^{\infty}\frac{4^i i!^2}{(i+1)(2i+1)!}x^{2i}.$$

$$\left(\frac{1}{x}\right)^{\overline{-n}} = \sum_{i=0}^{\infty}\begin{Bmatrix}i\\n\end{Bmatrix}x^i,$$

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

$$x\cot x = \sum_{i=0}^{\infty}\frac{(-4)^i B_{2i}x^{2i}}{(2i)!},$$

$$\zeta(x) = \sum_{i=1}^{\infty}\frac{1}{i^x},$$

$$\frac{\zeta(x-1)}{\zeta(x)} = \sum_{i=1}^{\infty}\frac{\phi(i)}{i^x},$$

### 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 $a\le b\le c$ 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

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

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

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

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

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:

$$a_{1,1}x_1 + a_{1,2}x_2 + \cdots + a_{1,n}x_n = b_1$$
$$a_{2,1}x_1 + a_{2,2}x_2 + \cdots + a_{2,n}x_n = b_2$$
$$\vdots\qquad\quad\vdots\qquad\qquad\quad\vdots$$
$$a_{n,1}x_1 + a_{n,2}x_2 + \cdots + a_{n,n}x_n = b_n$$

Let $A=(a_{i,j})$ and $B$ be the column matrix $(b_i)$. Then there is a unique solution iff $\det A\ne 0$. 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 $k_i\ge k_{i+1}+2$ for all $i$, $1\le i< m$ and $k_m\ge 2$.

### Fibonacci Numbers

$$1,1,2,3,5,8,13,21,34,55,89,\ldots$$

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:

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