



CIRNO
09

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All-in at the River

Standard Code Library

Shanghai Jiao Tong University

Desprado2 fstqwq AntiLeaf

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1 数学

1.1 FWT

矩阵表示

or 形式 (子集卷积):

$$T_{ij} = [i|j = i] = [j \in i]$$

$$\begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}$$

and 形式 (超集卷积):

$$T_{ij} = [i \& j = i] = [i \in j]$$

$$\begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix}$$

xor 形式 (T 与自身互为逆矩阵):

$$T_{ij} = (-1)^{\text{parity}(i \& j)}$$

$$\begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$$

```

1 using ll = long long;
2
3 // or
4 void FWT(ll *a, int len, int inv) {
5     for (int h = 1; h < len; h <= 1) {
6         for (int i = 0; i < len; i += (h << 1)) {
7             for (int j = 0; j < h; ++j) {
8                 a[i + j + h] += a[i + j] * inv;
9             }
10        }
11    }
12 }
13 // and
14 void FWT(ll *a, int len, int inv) {
15     for (int h = 1; h < len; h <= 1) {
16         for (int i = 0; i < len; i += (h << 1)) {
17             for (int j = 0; j < h; ++j) {
18                 a[i + j] += a[i + j + h] * inv;
19             }
20        }
21    }
22 }
23 // xor
24 void FWT(ll *a, int len, int inv) {
25     for (int h = 1; h < len; h <= 1) {
26         for (int i = 0; i < len; i += (h << 1)) {
27             for (int j = 0; j < h; ++j) {
28                 ll x = a[i + j], y = a[i + j + h];
29                 a[i + j] = x + y, a[i + j + h] = x - y;
30                 if (inv == -1)
31                     a[i + j] /= 2, a[i + j + h] /= 2;
32             }
33        }
34    }
35 }

```

1.2 多项式

1.2.1 FFT

```

1 // 使用时一定要注意double的精度是否足够(极限大概是10 ^ 14)
2
3 const double pi = acos((double)-1.0);
4

```

```

5 // 手写复数类
6 // 支持加减乘三种运算
7 // += 运算符如果用的不多可以不重载
8 struct Complex {
9     double a, b; // 由于long double精度和double几乎相同, 通
    ↳ 常没有必要用Long double
10
11     Complex(double a = 0.0, double b = 0.0) : a(a), b(b) {}
12
13     Complex operator + (const Complex &x) const {
14         return Complex(a + x.a, b + x.b);
15     }
16
17     Complex operator - (const Complex &x) const {
18         return Complex(a - x.a, b - x.b);
19     }
20
21     Complex operator * (const Complex &x) const {
22         return Complex(a * x.a - b * x.b, a * x.b + b *
    ↳ x.a);
23     }
24
25     Complex operator * (double x) const {
26         return Complex(a * x, b * x);
27     }
28
29     Complex &operator += (const Complex &x) {
30         return *this = *this + x;
31     }
32
33     Complex conj() const { // 共轭, 一般只有MTT需要用
34         return Complex(a, -b);
35     }
36 } omega[maxn], omega_inv[maxn];
37 const Complex ima = Complex(0, 1);
38
39 int fft_n; // 要在主函数里初始化
40
41 // FFT初始化
42 void FFT_init(int n) {
43     fft_n = n;
44
45     for (int i = 0; i < n; i++) // 根据单位根的旋转性质可以
    ↳ 节省计算单位根逆元的时间
46         omega[i] = Complex(cos(2 * pi / n * i), sin(2 * pi
    ↳ / n * i));
47
48     omega_inv[0] = omega[0];
49     for (int i = 1; i < n; i++)
50         omega_inv[i] = omega[n - i];
51     // 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
52 }
53
54 // FFT主过程
55 void FFT(Complex *a, int n, int tp) {
56     for (int i = 1, j = 0, k; i < n - 1; i++) {
57         k = n;
58         do
59             j ^= (k >>= 1);
60         while (j < k);
61
62         if (i < j)
63             swap(a[i], a[j]);
64     }
65
66     for (int k = 2, m = fft_n / 2; k <= n; k *= 2, m /= 2)
67         for (int i = 0; i < n; i += k)
68             for (int j = 0; j < k / 2; j++) {

```

```

69 |         Complex u = a[i + j], v = (tp > 0 ? omega :
    |         ↪ omega_inv)[m * j] * a[i + j + k / 2];
70 |
71 |         a[i + j] = u + v;
72 |         a[i + j + k / 2] = u - v;
73 |     }
74 |
75 |     if (tp < 0)
76 |         for (int i = 0; i < n; i++) {
77 |             a[i].a /= n;
78 |             a[i].b /= n; // 一般情况下是不需要的, 只有MTT时
    |             ↪ 才需要
79 |         }
80 | }

```

钦定 (至少) k 个与恰好 k 个之间的转化

记号:

记 $f(n)$ 表示先钦定至少选 n 个, 再统计钦定情况如此的方案数之和, 其中会包含重复的方案数.

记 $g(n)$ 表示恰好选 n 个的方案数, 不会重复.

那么, 对于 $i \geq n$, $g(i)$ 在 $f(n)$ 中被重复计算了 $\binom{i}{n}$ 次, 故

$f(n) = \sum_{i=n}^m \binom{i}{n} g(i)$, 其中 m 为数目上限

通常, f 较易求, 再通过反演即可求 g

1.3 组合数行区间和

```

1  using ll = long long;
2
3  // 边界从 (s, x) 移动到 (s + 1, nx)
4  ll move(int x, int nx, int s, ll sum) {
5      assert(x >= -1);
6      ll res = (2 * sum + mod - C(s, x)) % mod;
7      while (x + 1 <= nx) {
8          x++;
9          res = (res + C(s + 1, x)) % mod;
10     }
11     while (x > nx) {
12         res = (res + mod - C(s + 1, x)) % mod;
13         x--;
14     }
15     return res;
16 };
17
18 void proc(int k) {
19     // 第 s 行的 左右边界
20     auto le = [&](int s) -> int {
21         // ...
22     };
23     auto ri = [&](int s) -> int {
24         // ...
25     };
26     // 这里应该暴力计算首行和当首行为 0 时也可以这样写
27     ll lsum = move(-1, le(0), -1, 0);
28     ll rsum = move(-1, ri(0), -1, 0);
29
30     for (int s = 0; s <= k; s++) {
31         if (le(s) < ri(s)) {
32             // ... 第 s 行对答案的贡献
33         }
34         lsum = move(le(s), le(s + 1), s, lsum);
35         rsum = move(ri(s), ri(s + 1), s, rsum);
36     }
37 }

```

1.4 二项式反演

形式一:

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

形式二: (常用)

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

常见用法

2 数论

2.1 常见预处理与快速幂

```

1 // 预处理组合数
2 const int N = 2e5 + 7;
3 const ll mod = 998244353;
4
5 ll fac[N], ifac[N];
6 void init() {
7     fac[0] = 1;
8     for (int i = 1; i < N; ++i) fac[i] = i * fac[i-1] %
    ↪ mod;
9     ifac[N - 1] = fpow(fac[N - 1], mod - 2);
10    for (int i = N - 1; i; --i) ifac[i - 1] = i * ifac[i] %
    ↪ mod;
11 }
12
13 ll C(int n, int k) {
14     if (k < 0 || k > n) return 0;
15     return (fac[n] * ifac[k] % mod) * ifac[n - k] % mod;
16 }
17
18 // 线性求逆元 注意有效的 i < mod
19 ll inv[maxn];
20 void init() {
21     inv[0] = 0, inv[1] = 1;
22     for (int i = 2; i < N; ++i)
23         inv[i] = inv[mod % i] * (mod - mod / i) % mod;
24 }
25
26 // 快速幂
27 ll fpow(ll a, ll k = mod - 2, ll p = mod) {
28     ll res = 1; a %= p;
29     for (; k; k >>= 1, a = a * a % p) {
30         if (k & 1)
31             res = res * a % p;
32     }
33     return res;
34 }

```

2.2 因数分解与素性判定

2.2.1 朴素因数分解

```

1 // 素因数分解
2 int p[maxn], l[maxn], cnt2 = 0;
3 void Fact(int x) {
4     cnt2 = 0;
5     for (int i = 2; 1ll * i * i <= x; i++) {
6         if (x % i == 0) {
7             p[++cnt2] = i; l[cnt2] = 0;
8             while (x % i == 0) {
9                 x /= i; ++l[cnt2];
10            }
11        }
12    }
13    if (x != 1) { // 则此时x一定是素数 且为原本x的大于根
    ↪ 号x的唯一素因子
14        p[++cnt2] = x; l[cnt2] = 1;
15    }
16 }
17
18 // vector ver. 无次数
19 void Fact(ll x, vector<int>& fact) {
20     for (ll i = 2; 1ll * i * i <= x; ++i) {
21         if (x % i == 0) {
22             fact.push_back(i);
23             while (x % i == 0) x /= i;
24         }
25     }
26 }

```

```

25     }
26     if (x != 1) fact.push_back(x);
27 }

```

2.2.2 Miller-Rabin 与 Pollard-Rho

```

1 #include<bits/stdc++.h>
2 using namespace std;
3 typedef long long ll;
4
5 ll randint(ll l, ll r) {
6     static mt19937 eng(time(0));
7     uniform_int_distribution<ll> dis(l, r);
8     return dis(eng);
9 }
10
11 bool is_prime(ll x) {
12     int s = 0; ll t = x - 1;
13     if (x == 2) return true;
14     if (x < 2 || !(x & 1)) return false;
15     while (!(t & 1)) { //将x分解成(2^s)*t的样子
16         s++; t >>= 1;
17     }
18     ll lst[] = {2, 325, 9375, 28178, 450775, 9780504,
    ↪ 1795265022};
19     for (ll a : lst) { //随便选一个素数进行测试
20         if (a >= x) break;
21         ll b = Pow(a, t, x); //先算出a^t
22         for (int j = 1; j <= s; ++j) { //然后进行s次平方
23             ll k = mul(b, b, x); //求b的平方
24             if (k == 1 && b != 1 && b != x - 1) //用二次探
    ↪ 测判断
25                 return false;
26             b = k;
27         }
28         if (b != 1)
29             return false; //用费马小定律判断
30     }
31     return true; //如果进行多次测试都是对的 那么x就很有可
    ↪ 能是素数
32 }
33
34 ll gcd(ll a, ll b) { return b == 0 ? a : gcd(b, a % b); }
35
36 // @author: Pecco
37 ll Pollard_Rho(ll n) {
38     if (n == 4) return 2;
39     if (is_prime(n)) return n;
40     while (1) {
41         ll c = randint(1, n - 1); // 生成随机的c
42         auto f = [=](ll x) { return ((__int128)x * x + c) %
    ↪ n; }; // 1LL表示__int128防溢出
43         ll t = f(0), r = f(f(0));
44         while (t != r) {
45             ll d = __gcd(abs(t - r), n);
46             if (d > 1)
47                 return d;
48             t = f(t), r = f(f(r));
49         }
50     }
51 }
52
53 // 优化掉一个log
54 ll Pollard_Rho(ll n) {
55     if (n == 4) return 2;
56     if (is_prime(n)) return n;
57     while (1) {
58         ll c = randint(1, n - 1);
59         auto f = [=](ll x) { return ((__int128)x * x + c) %
    ↪ n; };
60     }

```

```

61     ll t = 0, r = 0, p = 1, q;
62     do {
63         for (int i = 0; i < 128; ++i) { // 令固定距
        ↪ 离C=128
64             t = f(t), r = f(f(r));
65             if (t == r || (q = (lll)p * abs(t - r) % n)
        ↪ == 0) // 如果发现环或者积即将为0退出
66                 break;
67             p = q;
68         }
69         ll d = gcd(p, n);
70         if (d > 1)
71             return d;
72     } while (t != r);
73 }
74 }
75
76 vector<ll> factors;
77
78 void getfactors(ll n) {
79     if (n == 1) return;
80     if (is_prime(n)) { factors.push_back(n); return; } //
    ↪ 如果是质因子
81     ll p = n;
82     while (p == n)
83         p = Pollard_Rho(n);
84     getfactors(n / p), getfactors(p); //递归处理
85 }

```

2.3 筛法

2.3.1 线性筛

```

1  const int maxn = 1000000 + 5;
2  bool isnt[maxn];
3  int prime[maxn];
4  int cnt = 0;
5
6  // 线性筛法 [1, n] 内素数
7  void Prime(int n) {
8      isnt[1] = true;
9      cnt = 0;
10     for (int i = 2; i <= n; i++) {
11         if (!isnt[i]) prime[++cnt] = i;
12         for (int j = 1; j <= cnt; j++) {
13             if (lll * i * prime[j] > n) break;
14             isnt[i * prime[j]] = 1;
15             if (i % prime[j] == 0) break;
16         }
17     }
18 }
19
20 // 线性筛求积性函数
21 int phi[maxn], mu[maxn], d[maxn], D[maxn], q[maxn];
22 void Sieve(int n) {
23     isnt[1] = true;
24     phi[1] = 1;
25     //mu[1] = 1;
26     cnt = 0;
27     for (int i = 2; i <= n; i++) {
28         if (!isnt[i]) {
29             prime[++cnt] = i;
30             phi[i] = i - 1;
31             //mu[i] = -1;
32             // d[i] = 2; q[i] = 1;
33             // D[i] = i + 1; q[i] = 1;
34         }
35         for (int j = 1; j <= cnt; j++) {
36             int x = i * prime[j];
37             if (x > n) break;
38             isnt[x] = 1;

```

```

39         if (i % prime[j] == 0) {
40             phi[x] = phi[i] * prime[j];
41             // mu[x] = 0;
42             // d[x] = d[i] / (q[i] + 1) * (q[i] + 2),
        ↪ q[x] = q[i] + 1;
43             // D[x] = D[i] / (prime[j] ^ (q[i] + 1) -
        ↪ 1) * (prime[j] ^ (q[i] + 2) - 1), q[x] = q[i] + 1;
44             break;
45         } else {
46             phi[x] = phi[i] * (prime[j] - 1); // mu[x]
        ↪ = -mu[i]
47             // d[x] = 2 * d[i], q[x] = 1;
48             // D[x] = (prime[j] + 1) * D[i], q[x] = 1;
49         }
50     }
51 }
52 }

```

2.3.2 Min25 筛

```

1  using ll = long long;
2  using i128 = __int128;
3  //using i128 = int64_t;
4
5  const ll mod = 998244353;
6
7  namespace min25 {
8      const int N = 1e6 + 10;
9      ll po[40][N];
10     inline ll fpow(ll e, ll k) {
11         return po[e][k];
12     }
13     void precalc() {
14         for (int e = 0; e < 40; ++e) {
15             po[e][0] = 1;
16             for (int i = 1; i < N; i++)
17                 po[e][i] = e * po[e][i - 1] % mod;
18         }
19     }
20     ll n;
21     int B;
22     int _id[N * 2];
23     inline int id(ll x) {
24         return x <= B ? x : n / x + B;
25     }
26     inline int Id(ll x) {
27         return _id[id(x)];
28     }
29     // f(p) = p - 1 = fh(p) - fg(p);
30     inline ll fg(ll x) {
31         // assert(x <= sqrt(n));
32         return 1;
33     }
34     inline ll fh(ll x) {
35         // assert(x <= sqrt(n));
36         return x;
37     }
38     // \sum_{i=2}^n fg(i)
39     inline ll sg(ll x) {
40         return (x - 1) % mod;
41     }
42     // \sum_{i=2}^n fh(i)
43     inline ll sh(ll x) {
44         return ((i128) x * (x + 1) / 2 + mod - 1) % mod;
45     }
46     // f(p^e)
47     inline ll f(ll p, ll e) {
48         //return (pe - pe / p) % mod;
49         return (p + (mod - 2) * fpow(e, p)) % mod;
50     }

```

```

51 bitset<N> np;
52 ll p[N>>2], pn;
53 ll pg[N>>2], ph[N>>2];
54 void sieve(ll sz) {
55     for(int i = 2; i <= sz; i++) {
56         if(!np[i]) {
57             p[++pn] = i;
58             pg[pn] = (pg[pn - 1] + fg(i)) % mod;
59             ph[pn] = (ph[pn - 1] + fh(i)) % mod;
60         }
61         for(int j = 1; j <= pn && i * p[j] <= sz; j++)
62             np[i * p[j]] = 1;
63         if(i % p[j] == 0) {
64             break;
65         }
66     }
67 }
68 ll m;
69 ll g[N * 2], h[N * 2];
70 ll w[N * 2];
71
72 void compress() {
73     for (int i = 1; i <= m; i++) {
74         g[i] = (h[i] + mod - g[i] + mod - g[i]) % mod;
75     }
76     for (int i = 1; i <= pn; i++) {
77         pg[i] = (ph[i] + mod - pg[i] + mod - pg[i]) %
78         mod;
79     }
80 }
81
82 ll dfs_F(int k, ll n) {
83     if (n < p[k] || n <= 1) return 0;
84     ll res = g[Id(n)] + mod - pg[k - 1], pw2;
85     for (int i = k; i <= pn && (pw2 = (ll) p[i] * p[i])
86     <= n; ++i) {
87         ll pw = p[i];
88         for (int c = 1; pw2 <= n; ++c, pw = pw2, pw2 *=
89         p[i])
90             res = (res + ((ll) f(p[i], c) * dfs_F(i +
91             1, n / pw) + f(p[i], c + 1))) % mod;
92     }
93     return res;
94 }
95
96 void init(ll _n) {
97     n = _n;
98     B = sqrt(n) + 100;
99     pn = 0;
100     sieve(B);
101     m = 0;
102     for(ll i = 1, j; i <= n; i = j + 1) {
103         j = n / (n / i);
104         ll t = n / i;
105         _id[id(t)] = ++m;
106         w[m] = t;
107         g[m] = sg(t);
108         h[m] = sh(t);
109         //printf("id: %lld, w: %lld, g: %lld, h:
110         %lld\n", m, t, g[m], h[m]);
111     }
112     for (int j = 1; j <= pn; j++) {
113         ll z = (ll) p[j] * p[j];
114         for(int i = 1; i <= m && z <= w[i]; i++) {
115             int k = Id(w[i] / p[j]);
116             g[i] = (g[i] + (ll) (mod - fg(p[j])) *
117             (g[k] - pg[j - 1] + mod)) % mod;

```

```

113         h[i] = (h[i] + (ll) (mod - fh(p[j])) *
114         (h[k] - ph[j - 1] + mod)) % mod;
115     }
116     compress();
117
118     /* 递推 min25
119     for(int j = pn; j > 0; j--) {
120         ll z = (ll) p[j] * p[j];
121         for(int i = 1; i <= m && z <= w[i]; i++) {
122             ll pe = p[j];
123             for(int e = 1; pe * p[j] <= w[i]; e++, pe
124             *= p[j]) {
125                 g[i] = (g[i] + (ll) f(p[j], e) *
126                 (g[Id(w[i] / pe)] - pg[j] + mod) + f(p[j], e + 1)) %
127                 mod;
128             }
129         }
130     } */
131     ll get(ll x) { // x == n / i
132         if(x < 1) return 0;
133         return (dfs_F(1, x) + 1) % mod;
134     }
135     ll get(ll l, ll r) {
136         return get(r) - get(l - 1);
137     }
138 }
139 void Solve() {
140     long long n;
141     scanf("%lld", &n);
142     min25::init(n);
143     long long res = min25::get(n);
144     printf("%lld\n", res);
145 }
146 int main() {
147     min25::precalc();
148     int T;
149     scanf("%d", &T);
150     while(T--) {
151         Solve();
152     }
153 }

```

2.4 扩展欧几里得

```

1 using i128 = __int128;
2
3 // ax + by = c
4 // 有解当且仅当 gcd(a, b) | c
5 // 要求 a, b 不全为 0
6 // 无合法性检查
7 void exgcd(i128 a, i128 b, i128 &x, i128 &y, i128 c = 1) {
8     if (b == 0) {
9         x = c / a;
10        y = 0;
11    } else {
12        exgcd(b, a % b, x, y, c);
13        i128 tmp = x;
14        x = y;
15        y = tmp - (a / b) * y;
16    }
17 }

```

2.5 中国剩余定理

2.5.1 两个数的 crt

```
1 // mul 表示慢速乘
2 ll crt(ll a1, ll p, ll a2, ll q) {
3     ll ip = fpow(p, q-2, q);
4     ll iq = fpow(q, p-2, p);
5     ll n = p * q;
6     return (mul(mul(a1, q, n), iq, n) + mul(mul(a2, p, n),
7     ↪ ip, n)) % n;
8 }
```

2.5.2 exCRT

```
1 using ll = long long;
2
3 ll gcd(ll a, ll b) {
4     return b == 0 ? a : gcd(b, a % b);
5 }
6
7 // x === a1 (mod b1), x === a2 (mod b2)
8 // 合法性检查返回 -1 则为无解
9 pair<ll, ll> exCRT(ll a1, ll b1, ll a2, ll b2) {
10     ll g = gcd(b1, b2);
11     ll lcm = (b1 / g) * b2;
12
13     if ((a1 - a2) % g) return {-1, -1};
14
15     i128 x, y;
16     exgcd(b1, b2, x, y, a1 - a2);
17     ll res = (a1 - b1 * x) % lcm;
18     if (res < 0) res += lcm;
19     return {res, lcm};
20 }
```

2.6 卢卡斯定理

2.6.1 模素数卢卡斯

```
1 // 卢卡斯定理, 要求 p 为素数
2 ll lucas(ll n, ll m, ll p) {
3     if (!m) return 1;
4     return C(n % p, m % p, p) * lucas(n / p, m / p, p) % p;
5 }
```

2.6.2 扩展卢卡斯

```
1 // 扩展卢卡斯定理
2
3 // 扩欧求逆元
4 ll INV(ll a, ll p) {
5     ll x, y;
6     exgcd(a, p, x, y);
7     return (x % p + p) % p;
8 }
9
10 // 递归求解(n! / px) mod pk
11 ll F(ll n, ll p, ll pk) {
12     if (n == 0) return 1;
13     ll rou = 1; // 循环节
14     ll rem = 1; // 余项
15     for (ll i = 1; i <= pk; ++i) {
16         if (i % p)
17             rou = rou * i % pk;
18     }
19     rou = fpow(rou, n / pk, pk);
20     for (ll i = pk * (n / pk); i <= n; ++i) {
21         if (i % p)
22             rem = rem * (i % pk) % pk; // 小心i炸int
23     }
```

```
23     }
24     return F(n / p, p, pk) * rou % pk * rem % pk;
25 }
26
27 // 素数p在n!中的次数
28 ll G(ll n, ll p) {
29     if (n < p) return 0;
30     return G(n / p, p) + (n / p);
31 }
32
33 ll C_pk(ll n, ll m, ll p, ll pk) {
34     ll fz = F(n, p, pk), fm1 = INV(F(m, p, pk), pk),
35         fm2 = INV(F(n - m, p, pk), pk);
36     ll mi = fpow(p, G(n, p) - G(m, p) - G(n - m, p), pk);
37     return fz * fm1 % pk * fm2 % pk * mi % pk;
38 }
39
40 ll exlucas(ll n, ll m, ll P) {
41     Fact(P); // 素因子分解见素因子分解.cpp
42     for (int i = 1; i <= cnt2; ++i) {
43         ll pk = 1;
44         for (int j = 0; j < l[i]; ++j) {
45             pk *= p[i];
46         }
47         bi[i] = pk, ai[i] = C_pk(n, m, p[i], pk);
48     }
49     return exCRT(cnt2) % P;
50 }
```

2.7 原根与离散对数

2.7.1 原根

```
1 // 得到 p 的原根
2 ll generator(ll p) {
3     static ll rec, ans;
4     if (p == rec)
5         return ans;
6     rec = p;
7     vector<ll> fact;
8     ll phi = p - 1, n = phi;
9     for (ll i = 2; 1ll * i * i <= n; ++i) {
10         if (n % i == 0) {
11             fact.push_back(i);
12             while (n % i == 0)
13                 n /= i;
14         }
15     }
16     if (n > 1)
17         fact.push_back(n);
18     for (ll res = 2; res <= p; ++res) {
19         bool ok = 1;
20         for (ll factor : fact) {
21             if (fpow(res, phi / factor, p) == 1) {
22                 ok = false;
23                 break;
24             }
25         }
26         if (ok)
27             return ans = res;
28     }
29     return ans = -1;
30 }
```

2.7.2 BSGS

```
1 // a ^ k == b mod p
2 ll BSGS(ll a, ll b, ll p) { // p <= 1e9
3     static ll rec;
4     static map<ll, ll> mp;
```



```

5
6    ll sq = (ll)ceil(sqrt(p));
7    if (rec != p) {
8        rec = p;
9        mp.clear();
10       ll le = 1, bs = fpow(a, sq, p);
11       for (ll i = 1; i <= sq; ++i) {
12           le = le * bs % p;
13           if (le < 0)
14               le += p;
15           mp[le] = i * sq;
16       }
17   }
18
19   ll ri = (b % p);
20   if (ri < 0)
21       ri += p;
22   for (ll j = 0; j <= sq; ++j) {
23       if (mp.count(ri)) {
24           return mp[ri] - j;
25       }
26       ri = ri * a % p;
27       if (ri < 0)
28           ri += p;
29   }
30   return -1;
31 }
32
33 // x ^ a == b mod p
34 ll calc(ll a, ll b, ll p) {
35     ll g = generator(p); // 求原根-见原根.cpp
36     ll ga = fpow(g, a, p);
37     ll c = BSGS(ga, b, p);
38     ll res = fpow(g, c, p);
39     return res;
40 }

```

```

3    ll phi = x, num = x;
4    for (int p : primes) {
5        if (p > x / p) break;
6        if (x % p == 0)
7            phi = (phi / p) * (p - 1), x /= p;
8        while (x % p == 0)
9            x /= p;
10    }
11    if (x > 1)
12        phi = phi / x * (x - 1);
13    return phi;
14 }

```

2.8 杂项

2.8.1 大数整除小数取模

计算 $\frac{a}{b} \bmod p$

当 a 的本值太大无法表示时 可以计算 a 对 b * p 取模的结果 再除 b 模 p

$$\frac{a}{b} \bmod p = \frac{a \bmod b * p}{b} \bmod p$$

2.8.2 立方根复杂度求 mobius 函数

```

1 int getmu(int x) {
2     int pr, cur = 0;
3     for (int i = 1; i <= cnt; ++i) {
4         cur = 0;
5         while (x % prime[i] == 0) {
6             ++cur; x /= prime[i];
7         }
8         if (cur > 1) return 0;
9     }
10    if (x == 1) return 1;
11    int sq = sqrt(x) + 0.5;
12    if (1ll * sq * sq == x) return 0;
13    return 1;
14 }

```

2.8.3 直接求 euler 函数

```

1 // primes 为预处理的素数表
2 ll getPhi(ll x) {

```

3 图论

3.1 最小生成树

3.1.1 Boruvka算法

思想：每次选择连接每个连通块的最小边，把连通块缩起来。

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

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

应用：最小异或生成树

3.1.2 动态最小生成树

动态最小生成树的离线算法比较容易，而在线算法通常极为复杂。

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

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

- Reduction: 待修改边标为+INF，跑MST后把非树边删掉，减少无用边
- 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

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

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

```

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

```

```

37
38 for(int i = q; i; i--)
39     e[0][a[i].id].w = a[i].u;
40
41 CDQ(1, q, 0, m, 0); // 这是调用方法
42
43
44 // 分治主过程  $O(n\log^2 n)$ 
45 // 需要调用Reduction和Contraction
46 void CDQ(int l, int r, int d, int m, long long ans) { //
47     // CDQ分治
48     if (1 == r) { // 区间长度已减小到1,输出答案,退出
49         e[d][id[d][a[l].id]].w = a[l].v;
50         printf("%lld\n", ans + Kruskal(m, e[d]));
51         e[d][id[d][a[l].id]].w = a[l].u;
52         return;
53     }
54     int tmp = top;
55
56     Reduction(l, r, d, m);
57     ans += Contraction(l, r, d, m); // R-C
58
59     int mid = (l + r) / 2;
60
61     copy(e[d] + 1, e[d] + m + 1, e[d + 1] + 1);
62     for (int i = 1; i <= m; i++)
63         id[d + 1][e[d][i].id] = i; // 准备好下一层要用的数
64     // 组
65
66     CDQ(l, mid, d + 1, m, ans);
67
68     for (int i = 1; i <= mid; i++)
69         e[d][id[d][a[i].id]].w = a[i].v; // 进行左边的修改
70
71     copy(e[d] + 1, e[d] + m + 1, e[d + 1] + 1);
72     for (int i = 1; i <= m; i++)
73         id[d + 1][e[d][i].id] = i; // 重新准备下一层要用的
74     // 数组
75
76     CDQ(mid + 1, r, d + 1, m, ans);
77
78     for (int i = top; i > tmp; i--)
79         cut(stk[i]); // 撤销所有操作
80     top = tmp;
81 }
82
83 // Reduction(减少无用边):待修改边标为+INF,跑MST后把非树边删
84 // 掉,减少无用边
85 // 需要调用Kruskal
86 void Reduction(int l, int r, int d, int &m) {
87     for (int i = 1; i <= r; i++)
88         e[d][id[d][a[i].id]].w = INF; // 待修改的边标为INF
89
90     Kruskal(m, e[d]);
91
92     copy(e[d] + 1, e[d] + m + 1, t + 1);
93
94     int cnt = 0;
95     for (int i = 1; i <= m; i++)
96         if (t[i].w == INF || t[i].vis) { // 非树边扔掉
97             id[d][t[i].id] = ++cnt; // 给边重新编号
98             e[d][cnt] = t[i];
99         }
100
101     for (int i = r; i >= l; i--)
102         e[d][id[d][a[i].id]].w = a[i].u; // 把待修改的边改
103     // 回去

```

```

102     m=cnt;
103 }
104
105 // 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
107 // 返回缩掉的边的总权值
108 // 需要调用Kruskal
109 long long Contraction(int l, int r, int d, int &m) {
110     long long ans = 0;
111
112     for (int i = l; i <= r; i++)
113         e[d][id[d][a[i].id]].w = -INF; // 待修改边标为-INF
114
115     Kruskal(m, e[d]);
116     copy(e[d] + 1, e[d] + m + 1, t + 1);
117
118     int cnt = 0;
119     for (int i = 1; i <= m; i++) {
120
121         if (t[i].w != -INF && t[i].vis) { // 必须边
122             ans += t[i].w;
123             mergeset(t[i].u, t[i].v);
124         }
125         else { // 不确定边
126             id[d][t[i].id] = ++cnt;
127             e[d][cnt] = t[i];
128         }
129     }
130
131     for (int i = r; i >= l; i--) {
132         e[d][id[d][a[i].id]].w = a[i].u; // 把待修改的边改
    ↳ 回去
133         e[d][id[d][a[i].id]].vis = false;
134     }
135
136     m = cnt;
137
138     return ans;
139 }
140
141 // Kruskal算法 O(mLogn)
142 // 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
144 long long Kruskal(int m, edge *e) {
145     int tmp = top;
146     long long ans = 0;
147
148     sort(e + 1, e + m + 1); // 比较函数在结构体中定义过了
149
150     for (int i = 1; i <= m; i++) {
151         if (findroot(e[i].u) != findroot(e[i].v)) {
152             e[i].vis = true;
153             ans += e[i].w;
154             mergeset(e[i].u, e[i].v);
155         }
156         else
157             e[i].vis = false;
158     }
159
160     for(int i = top; i > tmp; i--)
161         cut(stk[i]); // 撤销所有操作
162     top = tmp;
163
164     return ans;
165 }
166
167 // 以下是并查集相关函数

```

```

169 int findroot(int x) { // 因为需要撤销,不写路径压缩
170     while (p[x] != x)
171         x = p[x];
172
173     return x;
174 }
175
176 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
177     x = findroot(x); // 但是按秩合并要再开一个栈记录合并之
    ↳ 前的秩
178     y = findroot(y);
179
180     if (x == y)
181         return;
182
183     if (size[x] > size[y])
184         swap(x, y);
185
186     p[x] = y;
187     size[y] += size[x];
188     stk[++top] = x;
189 }
190
191 void cut(int x) { // 并查集撤销
192     int y = x;
193
194     do
195         size[y = p[y]] -= size[x];
196     while (p[y] != y);
197
198     p[x] = x;
199 }

```

3.2 费用流

3.2.1 SPFA费用流

```

1  constexpr int maxn = 20005, maxm = 200005;
2
3  struct edge {
4      int to, prev, cap, w;
5  } e[maxm * 2];
6
7  int last[maxn], cnte, d[maxn], p[maxn]; // 记得把last初始化
    ↳ 成-1, 不然会死循环
8  bool inq[maxn];
9
10 void spfa(int s) {
11
12     memset(d, -63, sizeof(d));
13     memset(p, -1, sizeof(p));
14
15     queue<int> q;
16
17     q.push(s);
18     d[s] = 0;
19
20     while (!q.empty()) {
21         int x = q.front();
22         q.pop();
23         inq[x] = false;
24
25         for (int i = last[x]; ~i; i = e[i].prev)
26             if (e[i].cap) {
27                 int y = e[i].to;
28
29                 if (d[x] + e[i].w > d[y]) {
30                     p[y] = i;
31                     d[y] = d[x] + e[i].w;

```

```

32         if (!inq[y]) {
33             q.push(y);
34             inq[y] = true;
35         }
36     }
37 }
38 }
39 }
40
41 int mcmf(int s, int t) {
42     int ans = 0;
43
44     while (spfa(s), d[t] > 0) {
45         int flow = 0x3f3f3f3f;
46         for (int x = t; x != s; x = e[p[x] ^ 1].to)
47             flow = min(flow, e[p[x]].cap);
48
49         ans += flow * d[t];
50
51         for (int x = t; x != s; x = e[p[x] ^ 1].to) {
52             e[p[x]].cap -= flow;
53             e[p[x] ^ 1].cap += flow;
54         }
55     }
56
57     return ans;
58 }
59
60 void add(int x, int y, int c, int w) {
61     e[cnte].to = y;
62     e[cnte].cap = c;
63     e[cnte].w = w;
64
65     e[cnte].prev = last[x];
66     last[x] = cnte++;
67 }
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 }

```

3.2.2 Dijkstra费用流

有的地方也叫原始-对偶费用流。

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

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

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

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

```

1 struct edge {
2     int to, cap, prev, w;
3 } e[maxe * 2];
4
5 int last[maxn], cnte;
6
7 long long d[maxn], h[maxn];
8 int p[maxn];
9
10 bool vis[maxn];
11 int s, t;
12
13 void Adde(int x, int y, int z, int w) {
14     e[cnte].to = y;
15     e[cnte].cap = z;
16     e[cnte].w = w;

```

```

17     e[cnte].prev = last[x];
18     last[x] = cnte++;
19 }
20
21 void addedge(int x, int y, int z, int w) {
22     Adde(x, y, z, w);
23     Adde(y, x, 0, -w);
24 }
25
26 void dijkstra() {
27     memset(d, 63, sizeof(d));
28     memset(vis, 0, sizeof(vis));
29
30     priority_queue<pair<long long, int>> heap;
31
32     d[s] = 0;
33     heap.push(make_pair(0ll, s));
34
35     while (!heap.empty()) {
36         int x = heap.top().second;
37         heap.pop();
38
39         if (vis[x])
40             continue;
41
42         vis[x] = true;
43         for (int i = last[x]; ~i; i = e[i].prev)
44             if (e[i].cap > 0 && d[e[i].to] > d[x] + e[i].w
45                 ↪ + h[x] - h[e[i].to]) {
46                 d[e[i].to] = d[x] + e[i].w + h[x] -
47                 ↪ h[e[i].to];
48                 p[e[i].to] = i;
49                 heap.push(make_pair(-d[e[i].to], e[i].to));
50             }
51     }
52
53     pair<long long, long long> mcmf() {
54         /*
55         spfa();
56         for (int i = 1; i <= t; i++)
57             h[i] = d[i];
58         // 如果初始有负权就像这样跑一遍SPFA预处理
59         */
60
61         long long flow = 0, cost = 0;
62
63         while (dijkstra(), d[t] < 0x3f3f3f3f) {
64             for (int i = 1; i <= t; i++)
65                 h[i] += d[i];
66
67             int a = 0x3f3f3f3f;
68
69             for (int x = t; x != s; x = e[p[x] ^ 1].to)
70                 a = min(a, e[p[x]].cap);
71
72             flow += a;
73             cost += (long long)a * h[t];
74
75             for (int x = t; x != s; x = e[p[x] ^ 1].to) {
76                 e[p[x]].cap -= a;
77                 e[p[x] ^ 1].cap += a;
78             }
79         }
80
81         return make_pair(flow, cost);
82     }
83 }

```

```
84 // 记得初始化
85 memset(last, -1, sizeof(last));
```


4 字符串

4.1 后缀自动机

```

1 // 在字符集比较小的时候可以直接开go数组，否则需要用map或者
  ↳ 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, len[maxn], fa[maxn], go[maxn][26], sam_cnt;
6 int c[maxn], q[maxn]; // 用来桶排序
7
8 // 在主函数开头加上这句初始化
9 last = sam_cnt = 1;
10
11 // 以下是按val进行桶排序的代码
12 for (int i = 1; i <= sam_cnt; i++)
13     c[len[i] + 1]++;
14 for (int i = 1; i <= n; i++)
15     c[i] += c[i - 1]; // 这里n是串长
16 for (int i = 1; i <= sam_cnt; i++)
17     q[++c[len[i]]] = i;
18
19 //加入一个字符 均摊O(1)
20 void extend(int c) {
21     int p = last, np = ++sam_cnt;
22     len[np] = len[p] + 1;
23
24     while (p && !go[p][c]) {

```

```

25         go[p][c] = np;
26         p = fa[p];
27     }
28
29     if (!p)
30         fa[np] = 1;
31     else {
32         int q = go[p][c];
33
34         if (len[q] == len[p] + 1)
35             fa[np] = q;
36         else {
37             int nq = ++sam_cnt;
38             len[nq] = len[p] + 1;
39             memcpy(go[nq], go[q], sizeof(go[q]));
40
41             fa[nq] = fa[q];
42             fa[np] = fa[q] = nq;
43
44             while (p && go[p][c] == q){
45                 go[p][c] = nq;
46                 p = fa[p];
47             }
48         }
49     }
50
51     last = np;
52 }

```

Theoretical Computer Science Cheat Sheet

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

Theoretical Computer Science Cheat Sheet

Identities Cont.

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

Trees

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

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

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

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

Recurrences

Master method:

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

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

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

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

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

If $\exists \epsilon > 0$ such that $f(n) = \Omega(n^{\log_b a + \epsilon})$, and $\exists c < 1$ such that $af(n/b) \leq cf(n)$ for large n , then

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

Substitution (example): Consider the following recurrence

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

Note that T_i is always a power of two.

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

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

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

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

Substituting we find

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

which is simply $u_i = i/2$. So we find that T_i has the closed form $T_i = 2^{i2^{i-1}}$. Summing factors (example): Consider the following recurrence

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

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

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

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

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

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

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

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

Let $m = \log_2 n$. Summing the left side we get $T(n) - 3^m T(1) = T(n) - 3^m = T(n) - n^k$ where $k = \log_2 3 \approx 1.58496$.

Summing the right side we get

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

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

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

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

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

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

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

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

Note that

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

Subtracting we find

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

$$= T_i.$$

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

Generating functions:

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

Example:

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

Multiply and sum:

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

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

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

Simplify:

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

Solve for $G(x)$:

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

Expand this using partial fractions:

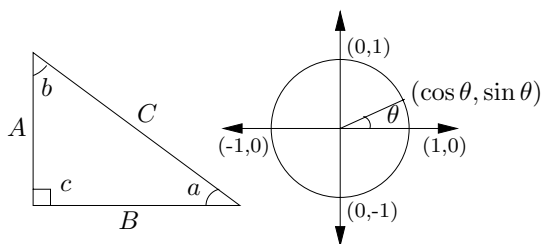
$$\begin{aligned}
 G(x) &= x \left(\frac{2}{1-2x} - \frac{1}{1-x} \right) \\
 &= x \left(2 \sum_{i \geq 0} 2^i x^i - \sum_{i \geq 0} x^i \right) \\
 &= \sum_{i \geq 0} (2^{i+1} - 1) x^{i+1}.
 \end{aligned}$$

So $g_i = 2^i - 1$.

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

Theoretical Computer Science Cheat Sheet

Trigonometry



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

Definitions:

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

Area, radius of inscribed circle:

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

Identities:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Euler's equation:

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

Matrices

Multiplication:

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

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

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

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

2×2 and 3×3 determinant:

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

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

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

Permanents:

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

Hyperbolic Functions

Definitions:

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

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

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

Identities:

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

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

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

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

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

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

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

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

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

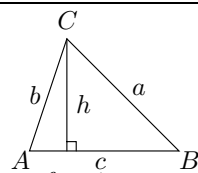
$$2 \sinh^2 \frac{x}{2} = \cosh x - 1, \quad 2 \cosh^2 \frac{x}{2} = \cosh x + 1.$$

θ	$\sin \theta$	$\cos \theta$	$\tan \theta$
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	∞

... in mathematics
you don't under-
stand things, you
just get used to
them.

– J. von Neumann

More Trig.



Law of cosines:

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

Area:

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

Heron's formula:

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

More identities:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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Theoretical Computer Science Cheat Sheet

Number Theory

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

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

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

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

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

Euler's function: $\phi(x)$ is the number of positive integers less than x relatively prime to x . If $\prod_{i=1}^n p_i^{e_i}$ is the prime factorization of x then

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

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

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

Fermat's theorem:

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

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

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

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

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

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

Wilson's theorem: n is a prime iff

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

Möbius inversion:

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

If

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

then

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

Prime numbers:

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

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

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

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

Graph Theory

Definitions:

Loop An edge connecting a vertex to itself.

Directed Each edge has a direction.

Simple Graph with no loops or multi-edges.

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

Trail A walk with distinct edges.

Path A trail with distinct vertices.

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

Component A maximal connected subgraph.

Tree A connected acyclic graph.

Free tree A tree with no root.

DAG Directed acyclic graph.

Eulerian Graph with a trail visiting each edge exactly once.

Hamiltonian Graph with a cycle visiting each vertex exactly once.

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

Cut-set A minimal cut.

Cut edge A size 1 cut.

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

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

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

k-Factor A k -regular spanning subgraph.

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

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

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

Vertex cover A set of vertices which cover all edges.

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

Plane graph An embedding of a planar graph.

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

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

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

Any planar graph has a vertex with degree ≤ 5 .

Notation:

$E(G)$ Edge set

$V(G)$ Vertex set

$c(G)$ Number of components

$G[S]$ Induced subgraph

$\deg(v)$ Degree of v

$\Delta(G)$ Maximum degree

$\delta(G)$ Minimum degree

$\chi(G)$ Chromatic number

$\chi_E(G)$ Edge chromatic number

G^c Complement graph

K_n Complete graph

K_{n_1, n_2} Complete bipartite graph

$r(k, \ell)$ Ramsey number

Geometry

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

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

Cartesian Projective

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

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

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

Distance formula, L_p and L_∞ metric:

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

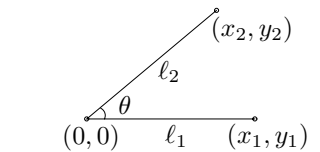
$$[|x_1 - x_0|^p + |y_1 - y_0|^p]^{1/p},$$

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

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

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

Angle formed by three points:



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

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

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

Area of circle, volume of sphere:

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

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

– Issac Newton

Theoretical Computer Science Cheat Sheet

π

Wallis' identity:

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

Brouncker's continued fraction expansion:

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

Gregory's series:

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

Newton's series:

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

Sharp's series:

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

Euler's series:

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

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

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

Partial Fractions

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

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

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

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

where

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

For a repeated factor:

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

where

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

The reasonable man adapts himself to the world; the unreasonable persists in trying to adapt the world to himself. Therefore all progress depends on the unreasonable.
– George Bernard Shaw

Calculus

Derivatives:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Integrals:

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

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

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

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

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

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

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

Theoretical Computer Science Cheat Sheet

Calculus Cont.

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

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Calculus Cont.

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

Finite Calculus

Difference, shift operators:

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

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

Fundamental Theorem:

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

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

Differences:

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

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

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

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

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

Sums:

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

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

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

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

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

Falling Factorial Powers:

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

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

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

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

Rising Factorial Powers:

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

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

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

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

Conversion:

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

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

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

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

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

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

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

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

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Series

Taylor's series:

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

Expansions:

$$\begin{aligned} \frac{1}{1-x} &= 1 + x + x^2 + x^3 + x^4 + \dots = \sum_{i=0}^{\infty} x^i, \\ \frac{1}{1-cx} &= 1 + cx + c^2x^2 + c^3x^3 + \dots = \sum_{i=0}^{\infty} c^i x^i, \\ \frac{1}{1-x^n} &= 1 + x^n + x^{2n} + x^{3n} + \dots = \sum_{i=0}^{\infty} x^{ni}, \\ \frac{x}{(1-x)^2} &= x + 2x^2 + 3x^3 + 4x^4 + \dots = \sum_{i=0}^{\infty} ix^i, \\ x^k \frac{d^n}{dx^n} \left(\frac{1}{1-x} \right) &= x + 2^n x^2 + 3^n x^3 + 4^n x^4 + \dots = \sum_{i=0}^{\infty} i^n x^i, \\ e^x &= 1 + x + \frac{1}{2}x^2 + \frac{1}{6}x^3 + \dots = \sum_{i=0}^{\infty} \frac{x^i}{i!}, \\ \ln(1+x) &= x - \frac{1}{2}x^2 + \frac{1}{3}x^3 - \frac{1}{4}x^4 - \dots = \sum_{i=1}^{\infty} (-1)^{i+1} \frac{x^i}{i}, \\ \ln \frac{1}{1-x} &= x + \frac{1}{2}x^2 + \frac{1}{3}x^3 + \frac{1}{4}x^4 + \dots = \sum_{i=1}^{\infty} \frac{x^i}{i}, \\ \sin x &= x - \frac{1}{3!}x^3 + \frac{1}{5!}x^5 - \frac{1}{7!}x^7 + \dots = \sum_{i=0}^{\infty} (-1)^i \frac{x^{2i+1}}{(2i+1)!}, \\ \cos x &= 1 - \frac{1}{2!}x^2 + \frac{1}{4!}x^4 - \frac{1}{6!}x^6 + \dots = \sum_{i=0}^{\infty} (-1)^i \frac{x^{2i}}{(2i)!}, \\ \tan^{-1} x &= x - \frac{1}{3}x^3 + \frac{1}{5}x^5 - \frac{1}{7}x^7 + \dots = \sum_{i=0}^{\infty} (-1)^i \frac{x^{2i+1}}{(2i+1)}, \\ (1+x)^n &= 1 + nx + \frac{n(n-1)}{2}x^2 + \dots = \sum_{i=0}^{\infty} \binom{n}{i} x^i, \\ \frac{1}{(1-x)^{n+1}} &= 1 + (n+1)x + \binom{n+2}{2}x^2 + \dots = \sum_{i=0}^{\infty} \binom{i+n}{i} x^i, \\ \frac{x}{e^x - 1} &= 1 - \frac{1}{2}x + \frac{1}{12}x^2 - \frac{1}{720}x^4 + \dots = \sum_{i=0}^{\infty} \frac{B_i x^i}{i!}, \\ \frac{1}{2x}(1 - \sqrt{1-4x}) &= 1 + x + 2x^2 + 5x^3 + \dots = \sum_{i=0}^{\infty} \frac{1}{i+1} \binom{2i}{i} x^i, \\ \frac{1}{\sqrt{1-4x}} &= 1 + x + 2x^2 + 6x^3 + \dots = \sum_{i=0}^{\infty} \binom{2i}{i} x^i, \\ \frac{1}{\sqrt{1-4x}} \left(\frac{1 - \sqrt{1-4x}}{2x} \right)^n &= 1 + (2+n)x + \binom{4+n}{2}x^2 + \dots = \sum_{i=0}^{\infty} \binom{2i+n}{i} x^i, \\ \frac{1}{1-x} \ln \frac{1}{1-x} &= x + \frac{3}{2}x^2 + \frac{11}{6}x^3 + \frac{25}{12}x^4 + \dots = \sum_{i=1}^{\infty} H_i x^i, \\ \frac{1}{2} \left(\ln \frac{1}{1-x} \right)^2 &= \frac{1}{2}x^2 + \frac{3}{4}x^3 + \frac{11}{24}x^4 + \dots = \sum_{i=2}^{\infty} \frac{H_{i-1} x^i}{i}, \\ \frac{x}{1-x-x^2} &= x + x^2 + 2x^3 + 3x^4 + \dots = \sum_{i=0}^{\infty} F_i x^i, \\ \frac{F_n x}{1 - (F_{n-1} + F_{n+1})x - (-1)^n x^2} &= F_n x + F_{2n} x^2 + F_{3n} x^3 + \dots = \sum_{i=0}^{\infty} F_{ni} x^i. \end{aligned}$$

Ordinary power series:

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

Exponential power series:

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

Dirichlet power series:

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

Binomial theorem:

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

Difference of like powers:

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

For ordinary power series:

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

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

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

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

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

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

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

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

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

Summation: If $b_i = \sum_{j=0}^i a_j$ then

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

Convolution:

$$A(x)B(x) = \sum_{i=0}^{\infty} \left(\sum_{j=0}^i a_j b_{i-j} \right) x^i.$$

God made the natural numbers;
all the rest is the work of man.
– Leopold Kronecker

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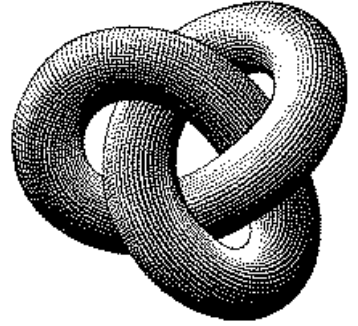
Series

Expansions:

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

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

Escher's Knot



Stieltjes Integration

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

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

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

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

If the integrals involved exist

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

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

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

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

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

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

Cramer's Rule

If we have equations:

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

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

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

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

Let $A = (a_{i,j})$ and B be the column matrix (b_i) . Then there is a unique solution iff $\det A \neq 0$. Let A_i be A with column i replaced by B . Then

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

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

00	47	18	76	29	93	85	34	61	52
86	11	57	28	70	39	94	45	02	63
95	80	22	67	38	71	49	56	13	04
59	96	81	33	07	48	72	60	24	15
73	69	90	82	44	17	58	01	35	26
68	74	09	91	83	55	27	12	46	30
37	08	75	19	92	84	66	23	50	41
14	25	36	40	51	62	03	77	88	99
21	32	43	54	65	06	10	89	97	78
42	53	64	05	16	20	31	98	79	87

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

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

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

Fibonacci Numbers

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

Definitions:

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

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

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

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

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

Additive rule:

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

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

Calculation by matrices:

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