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A Conjectured Integer Sequence Arising From the Exponential Integral

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Abstract

Let $f_0(z) = \exp(z/(1-z))$, $f_1(z) = \exp(1/(1-z))E_1(1/(1-z))$, where $E_1(x) = \int_x^\infty e^{-t}t^{-1}\,dt$. Let $a_n = [z^n]f_0(z)$ and $b_n = [z^n]f_1(z)$ be the corresponding Maclaurin series coefficients. We show that a_n and b_n may be expressed in terms of confluent hypergeometric functions.

We consider the asymptotic behaviour of the sequences (a_n) and (b_n) as $n \to \infty$, showing that they are closely related, and proving a conjecture of Bruno Salvy regarding (b_n).

Let $\rho_n = a_n b_n$, so $\sum \rho_n z^n = (f_0 \odot f_1)(z)$ is a Hadamard product. We obtain an asymptotic expansion $2n^{3/2}\rho_n \sim -\sum d_k n^{-k}$ as $n \to \infty$, where $d_k \in \mathbb{Q}$, $d_0 = 1$. We conjecture that $2^{6k} d_k \in \mathbb{Z}$. This has been verified for $k \le 1000$.

1 Introduction

We consider two analytic functions,

$$f_0(z) := e^{z/(1-z)} = e^{-1}\, e^{1/(1-z)}$$

and

$$f_1(z) := e^x E_1(x), \text{ where } x := 1/(1-z) \text{ and } E_1(x) := \int_x^\infty \frac{e^{-t}}{t}\, dt.$$

These functions are regular in the open disk $D = \{z \in \mathbb{C} : |z| < 1\}$. We write their Maclaurin coefficients as $a_n := [z^n]f_0(z)$ and $b_n = [z^n]f_1(z)$. Thus, in the disk D, $f_0(z) = \sum_{n\ge 0} a_n z^n$ and $f_1(z) = \sum_{n\ge 0} b_n z^n$.

The functions $f_0(z)$ and $f_1(z)$ satisfy the same third-order linear differential equation with polynomial coefficients. Thus, the sequences (a_n) and (b_n) are D-finite and satisfy the same recurrence relation (for sufficiently large n).

There are several entries in the *On-Line Encyclopedia of Integer Sequences* (OEIS) related to the rational sequence $(a_n)_{n\ge 0}$. The numerators are OEIS A067764, and the denominators are OEIS A067653. The integers $n!a_n$ are given by OEIS A000262 and, with alternating signs, by OEIS A293125. The numbers $(b_n)_{n\ge 0}$ are unlikely to be rational.[1]

The numbers a_n and b_n may be expressed in terms of confluent hypergeometric functions. If $M(a, b, z) = {}_1F_1(a; b; z)$ and $U(a, b, z)$ are standard solutions of Kummer's differential equation, then Lemmas 1–2 show that $a_n = e^{-1}M(n + 1, 2, 1)$ and $b_n = -\Gamma(n)U(n, 0, 1)$.

We are interested in the asymptotics of a_n and b_n for large n. Perron [17], following Fejér [8], showed that

$$a_n \sim \frac{e^{2\sqrt{n}}}{2n^{3/4}\sqrt{\pi e}}\,.$$

Salvy[2] conjectured that b_n is of order $e^{-2\sqrt{n}} n^{-3/4}$. We have verified this conjecture. In fact,

$$b_n \sim -\frac{\sqrt{\pi e}}{n^{3/4} e^{2\sqrt{n}}}\,.$$

[1] In particular, $b_0 = G$, where $G := eE_1(1) \approx 0.596$ is the Euler-Gompertz constant, whose decimal digits are given by OEIS A073003. We have $b_n = a_n G - a'_n$, where $a'_n \in \mathbb{Q}$ and a'_n satisfies essentially the same recurrence as a_n, but with different initial conditions. Clearly $b_n \in \mathbb{Q}$ if and only if $G \in \mathbb{Q}$. All that is known is that at least one of γ and G is irrational [1, 18].

[2] Bruno Salvy, email to A. J. Guttmann et al., May 28, 2018.

A function of the form $f(n) = \exp(\alpha n^{\theta+o(1)})$ for $\alpha \neq 0$, $\theta \in (0,1)$, is called a *stretched exponential* in the physics/statistics literature (the term *sub-exponential* is used in complexity theory). Thus, a_n and b_n are stretched exponentials, with $\alpha = \pm 2$ and $\theta = 1/2$.

The motivation for this paper stems from some enumeration problems in algebraic combinatorics and mathematical physics. Many such problems involve ordinary generating functions of power series $A(x) = \sum_{n\geq 0} A_n x^n$ in which $A_n \sim c\mu^n n^g$. In such cases, assuming that g is not a negative integer, one can write

$$A(x) \sim c\,\Gamma(1+g)(1-\mu x)^{-(1+g)}$$

as $x \to 1/\mu$. However, in recent years there have been a number of examples, such as $Av(1324)$ pattern-avoiding permutations [5], interacting partially-directed self-avoiding walks [16], and Dyck paths enumerated by maximum height [12], in which the corresponding generating function has coefficients behaving as $B_n \sim c\mu^n \exp(\alpha n^\theta) n^g$, with $\alpha < 0$. The question then arises as to the asymptotic form of the generating function. The coefficients b_n considered in this paper are of the form just described, with $\theta = 1/2$, and the underlying generating function is found. Corresponding results for other values of θ remain to be discussed.

Theorem 5 gives complete asymptotic expansions of a_n and b_n. These may be written as

$$a_n = \frac{F(n^{1/2})}{2n^{3/4}\sqrt{\pi e}} \;\text{ and }\; b_n = -\frac{\sqrt{\pi e}}{n^{3/4}}\,F(-n^{1/2}),$$

where $F(x) \sim e^{2x}\sum_{k\geq 0} c_k x^{-k}$, for certain constants $c_k \in \mathbb{Q}$, $c_0 = 1$. The c_k may be computed using Theorem 5 or Lemma 7.

The *Hadamard product* $f_0 \odot f_1$ of f_0 and f_1 is the analytic function defined for $z \in D$ by

$$(f_0 \odot f_1)(z) = \sum_{n\geq 0} a_n b_n z^n.$$

The asymptotic expansions of a_n and b_n imply an asymptotic expansion for $\rho_n := a_n b_n$ of the form

$$\rho_n \sim -\frac{1}{2n^{3/2}} \sum_{k\geq 0} d_k n^{-k},$$

where $d_k \in \mathbb{Q}$, $d_0 = 1$ (see Corollary 9).

A *dyadic rational* is a rational number of the form p/q, where q is a power of two. Let $Q_2 := \{j/2^k : j,k \in \mathbb{Z}\}$ denote the set of dyadic rationals.

We conjecture, from numerical evidence for $k \leq 1000$, that $d_k \in Q_2$. More precisely, defining $r_k := 2^{6k} d_k$, Conjecture 10 is that $r_k \in \mathbb{Z}$. Remark 11 gives numerical evidence for a slightly stronger conjecture. In Theorem 17 we prove the weaker (but still nontrivial) result that $k!r_k \in \mathbb{Z}$.

In Remark 13 we mention an analogous (easily proved) result for modified Bessel functions, where the product $I_\nu(x)K_\nu(x)$ for fixed $\nu \in \mathbb{Z}$ has an asymptotic expansion whose coefficients are in $\mathbb{Q}_2$.

The connection with confluent hypergeometric (Kummer) functions is discussed in §2, and asymptotic expansions for a_n and b_n are considered in §3. In §4 we mention various recurrence relations, continued fractions, and closed-form expressions related to a_n and b_n. Finally, in §§5–6, we consider Hadamard products and discuss the conjecture mentioned above.

Some comments on notation: $f(x) \sim \sum_{k\ge 0} f_k x^{-k}$ means that the sum on the right is an asymptotic series for $f(x)$ in the sense of Poincaré. Thus, for any fixed $m > 0$, $f(x) = \sum_{k=0}^{m-1} f_k x^{-k} + O(x^{-m})$ as $x \to \infty$. The letters j, k, m, n always denote integers (except for n in Remark 4). The notation $(x)_n$ for $n \ge 0$ denotes the *ascending factorial* or *Pochhammer symbol*, defined by $(x)_n := x(x+1)\cdots(x+n-1)$.

2 Connection with hypergeometric functions

The numbers a_n and b_n may be expressed in terms of confluent hypergeometric functions (Kummer functions), for which we refer to [15, §13.2]. If $M(a,b,z)$ and $U(a,b,z)$ are standard solutions $w(a,b,z)$ of Kummer's differential equation $zw'' + (b-z)w' - aw = 0$, then Lemmas 1–2 below express a_n and b_n in terms of $M(n+1,2,1)$ and $U(n,0,1)$.

Kummer [13] considered

$$M(a,b,z) = {}_1F_1(a;b;z) = \sum_{k\ge 0} \frac{(a)_k\, z^k}{(b)_k\, k!}\,, \tag{1}$$

which is undefined if b is zero or a negative integer. In the case $a \ne b = 0$, we can use the solution

$$zM(a+1,2,z) = \lim_{b\to 0} \frac{b}{a} M(a,b,z).$$

Tricomi [22] introduced the function $U(a,b,z)$ as a second (minimal) solution of Kummer's differential equation. For our purposes it is convenient to use the integral representation [15, (13.4.4)] (valid for $\Re(a) > 0$, $\Re(z) > 0$)

$$U(a,b,z) = \frac{1}{\Gamma(a)} \int_0^\infty e^{-zt}\, t^{a-1}\, (1+t)^{b-a-1}\, dt. \tag{2}$$

We remark that the functions M and U satisfy recurrence relations, known as "connection formulas". For example, we mention [15, (13.3.1) and (13.3.7)], both (essentially) due to Gauss (see Erdélyi [7, §6.4 and §6.6]):

$$(b-a)M(a-1,b,z) + (2a-b+z)M(a,b,z) - aM(a+1,b,z) = 0, \tag{3}$$

$$U(a-1,b,z) + (b-2a-z)U(a,b,z) + a(a-b+1)U(a+1,b,z) = 0. \tag{4}$$

Lemmas 1–2 express a_n and b_n in terms of the Kummer functions M and U, respectively. Lemma 1 was stated, without proof, by Covo [6].

Lemma 1. *If $n \in \mathbb{Z}$, $n \geq 1$, and a_n is as above, then*

$$a_n = e^{-1} M(n+1, 2, 1). \tag{5}$$

Proof. If we put $a = n+1$, $b = 2$, and $z = 1$ in the connection formula (3), we see that $\widetilde{a_n} := e^{-1} M(n+1, 2, 1)$ satisfies the same recurrence (21) as a_n. Thus, to show that $a_n = \widetilde{a_n}$ for all $n \geq 1$, it is sufficient to show that $a_n = \widetilde{a_n}$ for $n \in \{1, 2\}$. Now

$$\widetilde{a_1} = e^{-1} M(2, 2, 1) = e^{-1} \sum_{k \geq 0} \frac{(2)_k}{(2)_k \, k!} = 1 = a_1,$$

and, similarly,

$$\widetilde{a_2} = e^{-1} M(3, 2, 1) = e^{-1} \sum_{k \geq 0} \frac{(3)_k}{(2)_k \, k!} = e^{-1} \sum_{k \geq 0} \frac{k+2}{2\, k!} = 3/2 = a_2,$$

so the result follows. $\square$

Lemma 2. *If $n \in \mathbb{Z}$, $n \geq 1$, and b_n is as above, then*

$$b_n = -\Gamma(n) \, U(n, 0, 1). \tag{6}$$

Proof. We start with [15, (6.7.1)]:

$$I(a, b) := \int_0^\infty \frac{e^{-at}}{t+b} \, dt = e^{ab} E_1(ab), \quad a, b > 0.$$

Note that, by definition, $b_n = [z^n] I(1, 1/(1-z))$. Setting $a = 1$, $b = 1/(1-z)$, the term $1/(t+b)$ inside the integral can be rearranged as follows:

$$\left(t + \frac{1}{1-z}\right)^{-1} = \frac{1-z}{1+t-tz} = \frac{1}{1+t} - \frac{1}{t(1+t)} \left(\frac{1}{1 - zt/(1+t)} - 1\right),$$

and making the substitution $s = t/(1+t)$ gives

$$I(1, 1/(1-z)) = \int_0^\infty \frac{e^{-t}}{1+t} \, dt - \int_0^1 e^{-s/(1-s)} \left(\frac{z}{1-zs}\right) ds = \sum_{n \geq 0} b_n \, z^n.$$

Thus, $b_0 = eE_1(1)$ and, for $n > 0$,

$$b_n = -\int_0^1 e^{-s/(1-s)} \, s^{n-1} \, ds. \tag{7}$$

Writing $e^{-s/(1-s)} = e^{1-1/(1-s)}$ gives, for $n > 0$,

$$b_n = -e \int_0^1 e^{-1/(1-s)} \, s^{n-1} \, ds. \tag{8}$$

Substitute $t = s/(1-s)$ in (2), giving

$$\Gamma(a)U(a,b,z) = e^z \int_0^1 e^{-z/(1-s)}\, s^{a-1}\,(1-s)^{-b}\,ds. \tag{9}$$

Comparison of (8) and (9) now gives $b_n = -\Gamma(n)\,U(n,0,1)$. $\square$

Remark 3. We could prove Lemma 2 in the same manner as Lemma 1, using the connection formula (4) instead of (3), and the recurrence (23) instead of (21), but in order to verify the initial conditions we would have to resort to some explicit representation for U, such as the integral representation (2), so the proof would be no simpler.

Remark 4. We can generalize our definitions of a_n and b_n to permit $n \in \mathbb{C}$, using Lemmas 1–2. Such generalizations do not seem particularly useful, so in what follows we continue to assume that $n \in \mathbb{Z}$.

3 Asymptotic expansions of a_n and b_n

Theorem 5 gives the complete asymptotic expansions of a_n and b_n in ascending powers of $n^{-1/2}$. Wright [25] proved the existence of an asymptotic expansion of the form (10) for a_n, but did not state an explicit formula or algorithm for computing the constants c_m occurring in the expansion. For a more "algorithmic" approach, see Wyman [26].

Theorem 5. *For positive integer n, if a_n and b_n are as above, then*

$$a_n \sim \frac{e^{2\sqrt{n}}}{2n^{3/4}\sqrt{\pi e}} \sum_{m\ge 0} c_m n^{-m/2} \tag{10}$$

and

$$b_n \sim -\frac{\sqrt{\pi e}}{n^{3/4}e^{2\sqrt{n}}} \sum_{m\ge 0} (-1)^m c_m n^{-m/2}, \tag{11}$$

where

$$c_m = (-1)^m \sum_{j=0}^{m} [h^{m-j}] \exp(\mu(h))\, \frac{(m-2j+3/2)_{2j}}{4^j j!} \tag{12}$$

and

$$\mu(h) = h^{-1} - (e^h - 1)^{-1} - \tfrac{1}{2}\,. \tag{13}$$

Remark 6. The function $\mu(h)$ defined by (13) could also be defined using Bernoulli numbers, since

$$\mu(h) = -\sum_{k=1}^{\infty} \frac{B_{2k}}{(2k)!} h^{2k-1} = -\frac{h}{12} + \frac{h^3}{720} - O(h^5). \tag{14}$$

The function $\exp(\mu(h))$ occurring in (12) has the Maclaurin expansion

$$\exp(\mu(h)) = 1 - \frac{h}{12} + \frac{h^2}{288} + \frac{67h^3}{51840} + O(h^4). \tag{15}$$

The numerators and denominators of the coefficients $[h^n]\exp(\mu(h))$ have been added to the OEIS as A321937 and A321938, respectively.

Proof of Thm. 5. We first prove (11). From Lemma 2, $b_n = -\Gamma(n)\,U(n,0,1)$. Temme [21, Sec. 3] gives a general asymptotic result for $U(a,b,z^2)$ as $a \to \infty$. We state Temme's result for the case $(a,b,z) = (n,0,1)$, which is what we need. Let $c'_k := [h^k]\exp(\mu(h))$. (Temme uses c_k, but this conflicts with our notation.) From Temme [21, (3.8)–(3.10)], we have

$$U(n,0,1) \sim \frac{\sqrt{e}}{\Gamma(n)} \sum_{k\ge 0} c'_k \Phi_k(n), \tag{16}$$

where

$$\Phi_k(n) = 2n^{-(k+1)/2} K_{k+1}(2n^{1/2}),$$

and K_ν denotes the usual modified Bessel function.

From [15, (10.40.2)], $K_\nu(z)$ has an asymptotic expansion

$$K_\nu(z) \sim e^{-z}\sqrt{\frac{\pi}{2z}} \sum_{j\ge 0} \frac{(\nu - j + 1/2)_{2j}}{j!\,(2z)^j}\,. \tag{17}$$

Setting $\nu = k$ and $z = 2n^{1/2}$ in (17), we obtain

$$\Phi_{k-1}(n) = 2n^{-k/2} K_k(2n^{1/2}) \sim \frac{\sqrt{\pi}e^{-2\sqrt{n}}}{n^{1/4}} \sum_{j\ge 0} \frac{(k-j+1/2)_{2j}}{j!\,4^j\,n^{(j+k)/2}}\,.$$

Substituting this expression into (16), and grouping like powers of n, we obtain

$$b_n = -\Gamma(n)\,U(n,0,1) \sim -\frac{\sqrt{\pi e}}{n^{3/4}e^{2\sqrt{n}}} \sum_{m\ge 0}\sum_{j=0}^{m} \frac{c'_{m-j}\,(m-2j+3/2)_{2j}}{j!\,4^j\,n^{m/2}}\,.$$

Now, comparison with (11) shows that

$$(-1)^m c_m = \sum_{j=0}^{m} \frac{c'_{m-j}\,(m-2j+3/2)_{2j}}{j!\,4^j}\,,$$

which completes the proof of (11).

The proof of (10) is similar. We use Lemma 1 instead of Lemma 2, and Temme's asymptotic result [21, (3.29)] for $M(a,b,z^2)$ as $a \to \infty$ instead of (16); the modified Bessel function I_ν replaces K_ν. From [15, (10.40.1)], $I_\nu(z)$ has an asymptotic expansion

$$I_\nu(z) \sim \frac{e^z}{\sqrt{2\pi z}} \sum_{j\ge 0} (-1)^j\,\frac{(\nu - j + 1/2)_{2j}}{j!\,(2z)^j}\,, \tag{18}$$

which replaces (17). $\square$

Theorem 5 gives an expression for c_m which (indirectly) involves Bernoulli numbers, in view of (14). Lemma 7 gives a different expression for c_m that is recursive, as the expression for c_m depends on the values of c_j for $j < m$, but has the advantage of avoiding reference to Bernoulli numbers. The idea of the proof is similar to that used in the "method of Frobenius" [10]. We omit the details, which may be found in [3, pp. 10–11].

Lemma 7. *We have* $c_0 = 1$ *and, for all* $m \geq 1$*,*

$$mc_m = [h^{m+3}] \sum_{j=0}^{m-1} c_j h^j \sum_{s \in \{\pm 1\}} (1 + sh^2)^{\frac{1-2j}{4}} \exp\left(\frac{2}{h}\left((1+sh^2)^{\frac{1}{2}} - 1\right)\right). \tag{19}$$

Remark 8. Computation using (12) and, as a check, (19), gives

$$(c_k)_{k \geq 0} = \left(1, -\frac{5}{48}, -\frac{479}{4608}, -\frac{15313}{3317760}, \frac{710401}{127401984}, -\frac{3532731539}{214035333120}, \ldots\right).$$

The numerators and denominators have been added to the OEIS as A321939 and A321940, respectively. With the exception of c_0 and c_4, the c_k all appear to be negative. This has been verified numerically for $k \leq 1000$.

4 The Maclaurin coefficients a_n and b_n

The function $f_0(z)$ is the exponential generating function counting several combinatorial objects, such as the number of "sets of lists", i.e., the number of partitions of $\{1, 2, \ldots, n\}$ into ordered subsets, see Wallner [24, §5.3].

Observe that $f_0(z)$ satisfies the differential equation

$$(1 - z)^2 f_0'(z) - f_0(z) = 0, \tag{20}$$

and from this it is easy to see that the a_n satisfy a three-term recurrence

$$na_n - (2n - 1)a_{n-1} + (n - 2)a_{n-2} = 0 \quad \text{for} \quad n \geq 2. \tag{21}$$

The initial conditions are $a_0 = a_1 = 1$. Thus

$$(a_n)_{n \geq 0} = (1, 1, 3/2, 13/6, 73/24, 167/40, \ldots).$$

The recurrence (21) holds for $n \geq 0$ provided that we define $a_n = 0$ for $n < 0$. A closed-form expression, valid for $n \geq 1$ (but not for $n = 0$), is

$$a_n = \sum_{k=1}^{n} \frac{1}{k!} \binom{n-1}{k-1}.$$

The constants a_n may be expressed in terms of the generalized Laguerre polynomials $L_n^{(\alpha)}(x)$ which, from [15, (18.12.13)], have a generating function

$$\sum_{n\geq 0} z^n L_n^{(\alpha)}(x) = (1-z)^{-(\alpha+1)} e^{-xz/(1-z)}.$$

With $\alpha = x = -1$ we obtain $\sum_{n\geq 0} z^n L_n^{(-1)}(-1) = e^{z/(1-z)}$, so $a_n = L_n^{(-1)}(-1)$.

Using the chain rule and the definition of $f_1(z)$ in §1, we see that $f_1(z)$ satisfies the differential equation

$$(1-z)^2 f_1'(z) - f_1(z) = z - 1, \tag{22}$$

which differs from (20) only in the right-hand side $z-1$. Differentiating twice more with respect to z, we see that $f_0(z)$ and $f_1(z)$ both satisfy the same third-order differential equation

$$(1-z)^2 f''' + (4z-5)f'' + 2f' = 0.$$

From (22), the b_n satisfy a recurrence

$$nb_n - (2n-1)b_{n-1} + (n-2)b_{n-2} = \begin{cases} 1, & \text{if } n = 2; \\ 0, & \text{if } n \geq 3. \end{cases} \tag{23}$$

This is essentially (i.e., for $n \geq 3$) the same recurrence as (21), but the initial conditions $b_0 = G$, $b_1 = G - 1$ are different. Here $G := eE_1(1) \approx 0.596$ is the Euler-Gompertz constant [14, §2.5].

We remark that computation of the b_n using the recurrence (23) in the forward direction is numerically unstable. A stable method of computation is to use an adaptation of Miller's algorithm, originally used to compute Bessel functions. See Gautschi [11, §3] and Temme [20, §4].

As noted in §1, the b_n may be expressed as $a_n G - a_n'$, where a_n is as above, and a_n' satisfies essentially the same recurrence with different initial conditions. In fact,

$$na_n' - (2n-1)a_{n-1}' + (n-2)a_{n-2}' = \begin{cases} -1, & \text{if } n = 2; \\ 0, & \text{if } n \geq 3. \end{cases}$$

The initial conditions are $a_0' = 0$, $a_1' = 1$. Thus

$$(a_n')_{n\geq 0} = (0, 1, 1, 4/3, 11/6, 5/2, 121/36, \ldots).$$

From (11), $b_n \to 0$ as $n \to \infty$, so the sequence $(a_n'/a_n)_{n\geq 1}$ is a convergent sequence of rational approximations to G. The sequence of approximants is $(1, 2/3, 8/13, 44/73, 100/167, \ldots)$.

Bala [2] gives the continued fraction

$$1 - G = 1/(3 - 2/(5 - 6/(7 - \cdots - n(n+1)/(2n+3) - \cdots))),$$

with convergents $1/3, 5/13, 28/73, 201/501$, etc. The corresponding convergents to G are $2/3, 8/13, 45/73, 100/167$, etc. We see that the n-th convergent is just a_{n+1}'/a_{n+1}. Theorem 5 implies that

$$G - a_n'/a_n = b_n/a_n \sim -2\pi e^{1-4\sqrt{n}} \text{ as } n \to \infty.$$

We have contributed the sequence $(n!a_n')_{n\geq 1}$ to the OEIS as A321942.

5 The Hadamard product of f_0 and f_1

Define $\rho_n := a_n b_n$. Thus $\sum_{n=0}^{\infty} \rho_n z^n$ is the Hadamard product $(f_0 \odot f_1)(z)$. From Lemmas 1–2, we have

$$\rho_n = -e^{-1}\Gamma(n)M(n+1,2,1)U(n,0,1).$$

Using Theorem 5, we can obtain a complete asymptotic expansion for ρ_n in decreasing powers of n. This is given in Corollary 9.

Corollary 9. *We have*

$$\rho_n \sim -\frac{1}{2n^{3/2}} \sum_{k\geq 0} d_k n^{-k},$$

where

$$d_k = \sum_{j=0}^{2k} (-1)^j c_j c_{2k-j},$$

and $c_0, \ldots, c_{2k}$ are as in Theorem 5.

A computation shows that

$$(d_k)_{k\geq 0} = (1, -7/32, 43/2048, -915/65536, \ldots).$$

We observe that the d_k appear to be dyadic rationals More precisely, it appears that $2^{6k} d_k \in \mathbb{Z}$. Define a scaled sequence $(r_k)_{k\geq 0}$ by $r_k := 2^{6k} d_k$. Computation gives

$$(r_k)_{k\geq 0} = (1, -14, 86, -3660, -1042202, -247948260, -108448540420, \ldots).$$

This leads naturally to the following conjecture.

Conjecture 10. For all $k \geq 0$, $r_k \in \mathbb{Z}$.

The sequence of numerators of r_k has been added to the OEIS as A321941. If Conjecture 10 holds, then the denominators are all 1, i.e., the denominators are given by A000012.

Remark 11. Conjecture 10 has been verified for all $k \leq 1000$. We also showed numerically, for $3 \leq k \leq 1000$, that $r_k < 0$ and $r_k \equiv \binom{2k}{k} \pmod{32}$.

Remark 12. A problem that is superficially similar to our conjecture was solved by Tulyakov [23]. However, we do not see how to adapt his method to prove our conjecture.

Remark 13. Corollary 9 is reminiscent of the result

$$I_0(x)K_0(x) \sim \frac{1}{2x} \sum_{k\geq 0} e_{k,0}\, x^{-2k}$$

in the theory of Bessel functions [4, (1.2)]. The coefficients $e_{k,0}$ are given by

$$e_{k,0} = \frac{(2k)!^3}{2^{6k} k!^4},$$

so $2^{4k}e_{k,0} \in \mathbb{Z}$. The modified Bessel functions $I_0(x)$ and $K_0(x)$ are solutions of the same ordinary differential equation $xy'' + y' - xy = 0$, but $I_0(x)$ increases with x while $K_0(x)$ decreases. This is analogous to the behaviour of a_n, which increases as $n \to \infty$, and $|b_n|$, which decreases as $n \to \infty$.

More generally, from [15, (10.40.6)], we have

$$I_\nu(x)K_\nu(x) \sim \frac{1}{2x}\sum_{k\ge 0} e_{k,\nu}x^{-2k},$$

where

$$e_{k,\nu} = (-1)^k 2^{-2k}(\nu - k + 1/2)_{2k}\binom{2k}{k},$$

and $2^{4k}e_{k,\nu} \in \mathbb{Z}$ for $\nu \in \mathbb{Z}$.

6 Other expressions for d_n

Since (a_n) and (b_n) are D-finite, it follows that (ρ_n) is D-finite.[3] In fact, ρ_n satisfies the 4-term recurrence

$$\begin{aligned} n^2(n-1)(2n-3)\rho_n = {} & (n-1)(2n-1)(3n^2-5n+1)\rho_{n-1} \\ & - (n-2)(2n-3)(3n^2-5n+1)\rho_{n-2} \\ & + (n-2)(n-3)^2(2n-1)\rho_{n-3} \end{aligned} \tag{24}$$

for $n \ge 3$, with initial conditions $\rho_0 = G$, $\rho_1 = G - 1$, $\rho_2 = (9G-6)/4$.

The recurrence (24) can be simplified by defining $\sigma_n := n\rho_n$. Then σ_n satisfies the slightly simpler recurrence

$$\begin{aligned} n(n-1)(2n-3)\sigma_n = {} & (2n-1)(3n^2-5n+1)\sigma_{n-1} \\ & - (2n-3)(3n^2-5n+1)\sigma_{n-2} + (n-2)(n-3)(2n-1)\sigma_{n-3} \end{aligned} \tag{25}$$

for $n \ge 3$, with initial conditions $\sigma_0 = 0$, $\sigma_1 = G - 1$, $\sigma_2 = 9G/2 - 3$. Also, Corollary 9 gives an asymptotic series for σ_n:

$$\sigma_n \sim -\frac{1}{2n^{1/2}}\sum_{k\ge 0} d_k n^{-k}. \tag{26}$$

Using (25), we can give a recursive algorithm for computing the sequence (d_n) (and hence (r_n)) directly, without computing the sequence (c_n).

[3] See Flajolet and Sedgewick [9, Appendix B.4], and Stanley [19, Theorem 2.10], for relevant background on D-finite sequences.

Lemma 14. *We have $d_0 = 1$ and, for all $k \geq 1$,*

$$8kd_k = -[h^{k+2}]\left(\sum_{j=0}^{k-1} d_j h^j \Big(B(h)(1-h)^{-(j+1/2)} + C(h)(1-2h)^{-(j+1/2)} + D(h)(1-3h)^{-(j+1/2)}\Big)\right), \tag{27}$$

where

$$\begin{aligned}
B(h) &= -6 + 13h - 7h^2 + h^3 &&= -(2-h)(3-5h+h^2),\\
C(h) &= +6 - 19h + 17h^2 - 3h^3 &&= (2-3h)(3-5h+h^2), \quad \textit{and}\\
D(h) &= -2 + 11h - 17h^2 + 6h^3 &&= -(1-2h)(1-3h)(2-h).
\end{aligned}$$

Proof. Define $h := n^{-1}$, so $h \to 0$ as $n \to \infty$. From Corollary 9, there exists an asymptotic series of the form

$$-2\sigma_n \sim \sum_{j\geq 0} d_j n^{-j-1/2}$$

as $n \to \infty$. Moreover, $d_0 = 1$. Define $A(h) := (1-h)(2-3h)$ in addition to $B(h)$, $C(h)$ and $D(h)$. Using the recurrence (25) and the elementary identity $1/(n-m) = h/(1-mh)$ for $m \in \{0,1,2,3\}$, we have

$$\sum_{j\geq 0} d_j \left(A(h)h^{j+1/2} + B(h)\left(\frac{h}{1-h}\right)^{j+1/2} + C(h)\left(\frac{h}{1-2h}\right)^{j+1/2} + D(h)\left(\frac{h}{1-3h}\right)^{j+1/2}\right) \sim 0.$$

Now, dividing both sides by $h^{1/2}$, we obtain

$$\sum_{j\geq 0} d_j h^j \Big(A(h) + B(h)(1-h)^{-(j+1/2)} + C(h)(1-2h)^{-(j+1/2)} + D(h)(1-3h)^{-(j+1/2)}\Big) \sim 0. \tag{28}$$

An easy computation shows that

$$\begin{aligned}
A(h) + B(h) + C(h) + D(h) &= -4h^2 + O(h^3),\\
B(h) + 2C(h) + 3D(h) &= 8h + O(h^2), \quad \text{and}\\
B(h) + 2^2C(h) + 3^2D(h) &= O(h).
\end{aligned}$$

Thus, for all $j \geq 1$, the terms involving d_j in (28) are $8jh^{j+2} + O(h^{j+3})$. (The "$8j$" arises from $-4 + 8(j+1/2) = 8j$.) This shows that the choice of d_k in (27) is necessary and sufficient to give an asymptotic series of the required form. Finally, we note that $[h^{k+2-j}]A(h) = 0$, since $j \leq k-1$ and $\deg(A(h)) = 2$. Thus, a term involving $A(h)$ has been omitted from (27). ∎

Using Lemma 14, we computed the sequences (d_n) and (r_n) for $n \le 1000$, and verified the values previously computed (more slowly) via Corollary 9.

Since the power series occurring in (27) have a simple form, we can extract the coefficients of the required powers of h to obtain a recurrence for the d_k, as in Corollary 15. This gives a third way to compute the sequence (d_n).

Corollary 15. *We have $d_0 = 1$ and, for all $k \ge 1$,*

$$8k\, d_k = \sum_{j=0}^{k-1} \alpha_{j,k}\, d_j.$$

Here

$$\begin{aligned} \alpha_{j,k} = \ & (-1 + 3 \cdot 2^{m-1} - 2 \cdot 3^m)(\tau)_{m-1}/(m-1)! \\ & + (7 - 17 \cdot 2^m + 17 \cdot 3^m)(\tau)_m/m! \\ & + (-13 + 38 \cdot 2^m - 33 \cdot 3^m)(\tau)_{m+1}/(m+1)! \\ & + 6(1 - 4 \cdot 2^m + 3 \cdot 3^m)(\tau)_{m+2}/(m+2)!, \end{aligned} \tag{29}$$

where $m := k - j$ and $\tau := j + 1/2$.

Proof (sketch). To prove Corollary 15, we apply the binomial theorem to the power series in (27), multiply by the polynomials $B(h)$, $C(h)$, and $D(h)$, and extract the coefficient of h^{k+2-j}. ☐

The following corollary is an easy deduction from Corollary 15, and gives an explicit recurrence for $r_k = 2^{6k} d_k$.

Corollary 16. *We have $r_0 = 1$ and, for all $k \ge 1$,*

$$k\, r_k = \sum_{j=0}^{k-1} \beta_{j,k}\, r_j, \quad \textit{where} \ \ \beta_{j,k} = 8^{2k-2j-1}\, \alpha_{j,k}\,.$$

Although we have not proved Conjecture 10, the following result goes part of the way.

Theorem 17. *For all $k \ge 0$, we have $k!\, r_k \in \mathbb{Z}$.*

Proof. Let $R_k := k! r_k$. We show that $R_k \in \mathbb{Z}$. From Corollary 16, $R_0 = 1$ and, for $k \ge 1$, R_k satisfies the recurrence

$$R_k = \sum_{j=0}^{k-1} \beta_{j,k}\, R_j\, \frac{(k-1)!}{j!}\,. \tag{30}$$

The ratio of factorials in (30) is an integer, since $j \le k - 1$. Thus, in order to prove the result by induction on k, it is sufficient to show that $\beta_{j,k} \in \mathbb{Z}$. Now, elementary number theory shows that $4^\ell (j + 1/2)_\ell/\ell! \in \mathbb{Z}$ for all $j, \ell \ge 0$. Thus, the expressions of the form

$(\tau)_{m+\delta}/(m+\delta)!$ in (29) are in $\mathbb{Z}$ provided that $m+\delta \geq 0$. This is true as $m \geq k-j \geq 1$ and $\delta \geq -1$. To show that $\beta_{j,k} \in \mathbb{Z}$, it is sufficient to have $8^{2m-1} \geq 4^{m+2}$, which holds for all $m \geq 2$. In the case $m=1$, it is easy to see that all the terms in (29) are in $\mathbb{Z}/4$, so $\beta_{m-1,k} = 8\alpha_{m-1,k} \in \mathbb{Z}$. Thus, $\beta_{j,k} \in \mathbb{Z}$ for $0 \leq j < k$, and the result follows by induction on k. □

Remark 18. The proof actually shows that $\beta_{j,k} \in 2\mathbb{Z}$, which implies that $R_k \in 2\mathbb{Z}$ for all $k > 0$.

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