# 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  $k \leq 1000$ .

#### 1 Introduction

We consider two analytic functions,

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

and

$$f_1(z) := e^x E_1(x)$$
, where  $x := 1/(1-z)$  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,  $f_0(z) = \sum_{n>0} a_n z^n$  and  $f_1(z) = \sum_{n>0} b_n z^n$ .

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 OEIS related to the rational sequence  $(a_n)_{n\geq 0}$ . The numerators are OEIS <u>A067764</u>, and the denominators are OEIS <u>A067653</u>. The integers  $n!a_n$  are given by OEIS <u>A000262</u> and, with alternating signs, by OEIS <u>A293125</u>. The numbers  $(b_n)_{n\geq 0}$  are unlikely to be rational.<sup>1</sup>

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

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

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

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

<sup>&</sup>lt;sup>1</sup>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 <u>A073003</u>. We have  $b_n = a_nG - a'_n$ , 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  $\gamma$  and G is irrational [1, 18].

<sup>&</sup>lt;sup>2</sup>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  $\theta$  remain to be discussed.

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

$$a_n = \frac{F(n^{1/2})}{2n^{3/4}\sqrt{\pi e}}$$
 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

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

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

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

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:  $f(x) \sim \sum_{k \geq 0} f_k x^{-k}$  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  $n \geq 0$  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

$$M(a,b,z) = {}_{1}F_{1}(a;b;z) = \sum_{k>0} \frac{(a)_{k} z^{k}}{(b)_{k} k!},$$
(1)

which is undefined if b is zero or a negative integer. In the case  $a \neq b = 0$ , 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  $\Re(a) > 0$ ,  $\Re(z) > 0$ )

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

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

$$U(a-1,b,z) + (b-2a-z)U(a,b,z) + a(a-b+1)U(a+1,b,z) = 0.$$
 (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

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

*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  $n \ge 1$ , it is sufficient to show that  $a_n = \widetilde{a_n}$  for  $n \in \{1,2\}$ . Now

$$\widetilde{a}_1 = e^{-1}M(2,2,1) = e^{-1} \sum_{k>0} \frac{(2)_k}{(2)_k \, k!} = 1 = a_1,$$

and, similarly,

$$\widetilde{a}_2 = e^{-1}M(3,2,1) = e^{-1}\sum_{k>0} \frac{(3)_k}{(2)_k \, k!} = e^{-1}\sum_{k>0} \frac{k+2}{2 \, k!} = 3/2 = a_2,$$

so the result follows.

**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)]:

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

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

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

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

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

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

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

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

and

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

where

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

and

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

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

$$\mu(h) = -\sum_{k=1}^{\infty} \frac{B_{2k}}{(2k)!} h^{2k-1} = -\frac{h}{12} + \frac{h^3}{720} - O(h^5).$$
 (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 <u>A321937</u> and <u>A321938</u>, 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  $K_{\nu}$  denotes the usual modified Bessel function.

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

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

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

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

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

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

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  $I_{\nu}$  replaces  $K_{\nu}$ . From [15, (10.40.1)],  $I_{\nu}(z)$  has an asymptotic expansion

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

which replaces (17).

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  $m \ge 1$ ,

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

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

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

The numerators and denominators have been added to the OEIS as <u>A321939</u> and <u>A321940</u>, 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  $\{1, 2, ..., n\}$  into ordered subsets, see Wallner [24, §5.3].

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

$$(1-z)^2 f_0'(z) - f_0(z) = 0, (20)$$

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

$$na_n - (2n-1)a_{n-1} + (n-2)a_{n-2} = 0 \text{ for } n \ge 2.$$
 (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  $n \ge 0$  provided that we define  $a_n = 0$  for n < 0. A closed-form expression, valid for  $n \ge 1$  (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

$$(1-z)^2 f_1'(z) - f_1(z) = z - 1, (22)$$

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

$$nb_n - (2n-1)b_{n-1} + (n-2)b_{n-2} = \begin{cases} 1, & \text{if } n = 2; \\ 0, & \text{if } n \ge 3. \end{cases}$$
 (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  $a_nG - a'_n$ , where  $a_n$  is as above, and  $a'_n$  satisfies essentially the same recurrence with different initial conditions. In fact,

$$na'_n - (2n-1)a'_{n-1} + (n-2)a'_{n-2} = \begin{cases} -1, & \text{if } n=2; \\ 0, & \text{if } n \ge 3. \end{cases}$$

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

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

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

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

We have contributed the sequence  $(n!a'_n)_{n\geq 1}$  to the OEIS as <u>A321942</u>.

## 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  $\rho_n$  in decreasing powers of n. This is given in Corollary 9.

Corollary 9. We have

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

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

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

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

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

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 <u>A321941</u>. If Conjecture 10 holds, then the denominators are all 1, i.e., the denominators are given by <u>A000012</u>.

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

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

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  $(\rho_n)$  is D-finite.<sup>3</sup> In fact,  $\rho_n$  satisfies the 4-term recurrence

$$n^{2}(n-1)(2n-3)\rho_{n} = (n-1)(2n-1)(3n^{2}-5n+1)\rho_{n-1} - (n-2)(2n-3)(3n^{2}-5n+1)\rho_{n-2} + (n-2)(n-3)^{2}(2n-1)\rho_{n-3}$$
(24)

for  $n \geq 3$ , 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  $\sigma_n$  satisfies the slightly simpler recurrence

$$n(n-1)(2n-3)\sigma_n = (2n-1)(3n^2 - 5n + 1)\sigma_{n-1} - (2n-3)(3n^2 - 5n + 1)\sigma_{n-2} + (n-2)(n-3)(2n-1)\sigma_{n-3}$$
 (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  $\sigma_n$ :

$$\sigma_n \sim -\frac{1}{2n^{1/2}} \sum_{k>0} d_k n^{-k}.$$
 (26)

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

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

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

where

$$B(h) = -6 + 13h - 7h^2 + h^3 = -(2 - h)(3 - 5h + h^2),$$

$$C(h) = +6 - 19h + 17h^2 - 3h^3 = (2 - 3h)(3 - 5h + h^2), \text{ and}$$

$$D(h) = -2 + 11h - 17h^2 + 6h^3 = -(1 - 2h)(1 - 3h)(2 - h).$$

<sup>&</sup>lt;sup>3</sup> See Flajolet and Sedgewick [9, Appendix B.4], and Stanley [19, Theorem 2.10], for relevant background on D-finite sequences.

*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

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

An easy computation shows that

$$A(h) + B(h) + C(h) + D(h) = -4h^{2} + O(h^{3}),$$
  

$$B(h) + 2C(h) + 3D(h) = 8h + O(h^{2}), \text{ and}$$
  

$$B(h) + 2^{2}C(h) + 3^{2}D(h) = O(h).$$

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).  $\square$ 

Using Lemma 14, we computed the sequences  $(d_n)$  and  $(r_n)$  for  $n \leq 1000$ , 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

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

$$k r_k = \sum_{j=0}^{k-1} \beta_{j,k} r_j$$
, 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  $k \geq 0$ , 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  $k \geq 1$ ,  $R_k$  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  $j \leq k-1$ . 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  $j, \ell \geq 0$ .

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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#### References

- [1] A. I. Aptekarev, On linear forms containing the Euler constant, preprint, 2009, http://arxiv.org/abs/0902.1768v2.
- [2] P. Bala, Continued fraction for 1-G, entry in OEIS <u>A073003</u>, Oct. 11, 2012.
- [3] R. P. Brent, A. J. Guttmann, and M. L. Glasser, A conjectured integer sequence arising from the exponential integral, preprint, 2018, http://arxiv.org/abs/1812.0316v2.
- [4] R. P. Brent and F. Johannson, A bound for the error term in the Brent-McMillan algorithm, *Math. Comp.* **84** (2015), 2351–2359.
- [5] A. R. Conway, A. J. Guttmann, and P. Zinn-Justin, 1324-avoiding permutations revisited, *Adv. in Appl. Math.* **96** (2018), 312–333.
- [6] S. Covo, comment in OEIS <u>A000262</u>, Jan. 20, 2010.

- [7] A. Erdélyi (editor), *Higher Transcendental Functions*, Vol. 1, California Institute of Technology Bateman Manuscript Project, McGraw-Hill, 1953.
- [8] L. Fejér, Sur une méthode de M. Darboux, C. R. Acad. Sci. Paris 147 (1908), 1040–1042.
- [9] P. Flajolet and R. Sedgewick, *Analytic Combinatorics*, Cambridge Univ. Press, 2009.
- [10] G. Frobenius, Ueber die integration der linearen Differentialgleichungen durch Reihen, J. reine angew. Math. 76 (1873), 214–235.
- [11] W. Gautschi, Computational aspects of three-term recurrence relations, SIAM Review 9 (1967), 24–82.
- [12] A. J. Guttmann, Analysis of series expansions for non-algebraic singularities, J. Phys. A: Math. Theor. 48 (2015), 045209 (33pp).
- [13] E. E. Kummer, De integralibus quibusdam definitis et seriebus infinitis, J. reine angew. Math. 17 (1837), 228-242.
- [14] J. C. Lagarias, Euler's constant: Euler's work and modern developments, Bull. Amer. Math. Soc. **50** (2013), 527–628.
- [15] National Institute of Standards and Technology, NIST Digital Library of Mathematical Functions, http://dlmf.nist.gov/, version 1.0.19, 22 June 2018.
- [16] A. Owczarek, T. Prellberg, and R. Brak, New scaling form for the collapsed polymer phase, *Phys. Rev. Lett.* **71** (1993), 951–953.
- [17] O. Perron, Uber das infinitäre Verhalten der Koeffizienten einer gewissen Potenzreihe, Archiv d. Math. u. Phys. (3), 22 (1914), 329–340.
- [18] T. Rivoal, On the arithmetical nature of the values of the Gamma function, Euler's constant, and Gompertz's constant, *Michigan Math. J.* **61** (2012), 239–254.
- [19] R. P. Stanley, Differentiably finite power series, *Europ. J. Combinatorics* 1 (1980), 175–188.

- [20] N. M. Temme, Numerical evaluation of functions arising from transformations of formal series, *J. Math. Anal. Appl.* **51** (1975), 678–694.
- [21] N. M. Temme, Remarks on Slater's asymptotic expansions of Kummer functions for large values of the a-parameter, Adv. Dyn. Syst. Appl. 8 (2013), 365–377.
- [22] F. G. Tricomi, Funzioni ipergeometriche confluenti, *Edizioni Cremonese*, Rome, 1954.
- [23] D. N. Tulyakov, A system of recurrence relations for rational approximations of the Euler constant, *Mat. Zametki* **85** (2009), 782–787 (in Russian). English translation in *Math. Notes* **85** (2009), 746–750.
- [24] M. Wallner, A bijection of plane increasing trees with relaxed binary trees of right height at most one, *Theoret. Comput. Sci.* **755** (2019), 1–12.
- [25] E. M. Wright, The coefficients of a certain power series, *J. Lond. Math. Soc.* 7 (1932), 256–262.
- [26] M. Wyman, The asymptotic behaviour of the Laurent coefficients, Canad. J. Math. 11 (1959), 534–555.

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