



# Is Euler's constant a value of an arithmetic special function?

Tanguy Rivoal

## ► To cite this version:

| Tanguy Rivoal. Is Euler's constant a value of an arithmetic special function?. 2017. hal-01619235v1

**HAL Id: hal-01619235**

**<https://hal.science/hal-01619235v1>**

Preprint submitted on 19 Oct 2017 (v1), last revised 20 Dec 2017 (v2)

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# IS EULER'S CONSTANT A VALUE OF AN ARITHMETIC SPECIAL FUNCTION?

TANGUY RIVOAL

ABSTRACT. Euler's constant  $\gamma$  is one of the mathematical constants with the most different analytic representations, probably on par with  $\pi$ . Yet, none of these representations proves that  $\gamma$  is a value of an  $E$ -function, a  $G$ -function or an  $M$ -function at an algebraic point. In fact, it is plausible that no such representation of  $\gamma$  exists with these three arithmetic special functions, and thus the arithmetic nature of  $\gamma$  might not be determined by the powerful Diophantine theorems of Siegel-Shidlovsky, Chudnovsky and Nishioka. Nonetheless, we explain here why certain of these representations show that  $\gamma$  is not far from being a special value of both  $E$ -functions and  $M$ -functions, while a similar connection to  $G$ -functions is still elusive. We also present a new family of series summing to  $\gamma$ , which generalize an identity of Vacca.

## 1. Representations of Euler's constant.

The usual definition of Euler's constant is

$$\gamma := \lim_{k \rightarrow +\infty} \left( \sum_{n=1}^k \frac{1}{n} - \log(k) \right) = \sum_{n=1}^{\infty} \left( \frac{1}{n} - \log \left( 1 + \frac{1}{n} \right) \right), \quad (1)$$

where the second equality is a trivial reformulation of the first one. There exist a lot of seemingly different analytic representations of  $\gamma$ . We list below thirty three expressions, all equal to  $\gamma$ . See [4, 8, 10, 13, 16, 17, 18, 19, 26, 29, 15, 21, 36, 37, 38, 39, 40] for proofs, other identities and references.

$$\int_1^{\infty} \left( \frac{1}{\lfloor x \rfloor} - \frac{1}{x} \right) dx, \quad 1 - \int_1^{\infty} \frac{x - \lfloor x \rfloor}{x^2} dx, \quad \int_0^{\infty} \frac{\log(1+x)}{x^2(\log(x)^2 + \pi^2)} dx, \quad (2)$$

$$- \int_0^{\infty} \log(x) e^{-x} dx, \quad - \int_1^{\infty} \frac{\log \log(x)}{x^2} dx, \quad \int_0^1 \left( \frac{1}{\log(x)} + \frac{1}{1-x} \right) dx, \quad (3)$$

$$\int_0^1 \int_0^1 \frac{x-1}{(1-xy)\log(xy)} dx dy, \quad \int_0^{\infty} \frac{1}{x} \left( \frac{1}{1+x^2} - \cos(x) \right) dx, \quad \frac{ab}{a-b} \int_0^{\infty} \frac{e^{-x^a} - e^{-x^b}}{x} dx, \quad (4)$$

$$\frac{1}{2} + \int_0^{\infty} \frac{2x dx}{(1+x^2)(e^{2\pi x} - 1)}, \quad \int_0^1 \frac{1 - e^x - e^{-1/x}}{x} dx, \quad \int_0^{\infty} \left( \frac{1}{e^x - 1} - \frac{1}{xe^x} \right) dx, \quad (5)$$

$$\int_0^{\infty} \frac{1}{x} \left( \frac{1}{1+x} - e^{-x} \right) dx, \quad \int_0^1 \frac{1}{x(1+x)} \sum_{n=1}^{\infty} x^{2^n} dx, \quad \int_0^1 \frac{2+x}{x(1+x+x^2)} \sum_{n=1}^{\infty} x^{3^n} dx, \quad (6)$$

$$\sum_{n=1}^{\infty} \frac{|\int_0^1 \binom{t}{n} dt|}{n}, \quad \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n!n} - \frac{1}{e} \int_0^{\infty} \frac{e^{-x}}{1+x} dx, \quad \sum_{n=2}^{\infty} \frac{1}{n^2} \left( \sum_{k=1}^n (-1)^k \binom{n}{k} k \log(k) \right), \quad (7)$$

---

Date: October 16, 2017.

$$\sum_{n=1}^{\infty} (-1)^n \frac{[\log_2(n)]}{n}, \quad 1 - \sum_{n=2}^{\infty} (-1)^n \frac{[\log_2(n)]}{n+1}, \quad 2 \sum_{n=1}^{\infty} \frac{\cos(\frac{2\pi n}{3}) [\log_3(n)]}{n}, \quad (8)$$

$$\frac{1}{2} + \sum_{n=1}^{\infty} \frac{[\log_2(2n)]}{2n(2n+1)(2n+2)}, \quad \frac{1}{2} + \sum_{n=1}^{\infty} \frac{(12n+6)[\log_3(3n)]}{3n(3n+1)(3n+2)(3n+3)}, \quad (9)$$

$$\log(\pi) - 4 \log \Gamma\left(\frac{3}{4}\right) + \frac{4}{\pi} \sum_{k=1}^{\infty} (-1)^{k+1} \frac{\log(2k+1)}{2k+1}, \quad \frac{1}{2} + \sum_{n=2}^{\infty} \frac{1}{2^{n+1}} \sum_{k=0}^{n-1} \frac{1}{\binom{2^{n-k}+k}{k}}, \quad (10)$$

$$\sum_{n=1}^{\infty} \frac{N_0(n) + N_1(n)}{2n(2n+1)}, \quad N_j(n) = \text{number of } j\text{'s in } n \text{ written in base 2}, \quad (11)$$

$$\sum_{n=1}^{\infty} \left( \frac{1}{[\sqrt{n}]^2} - \frac{1}{n} - \frac{1}{n^2} \right), \quad \frac{1}{s-1} \sum_{n=1}^{\infty} \left( \frac{s}{n} - \sum_{j=n^s}^{(n+1)^s-1} \frac{1}{j} \right), \quad s \geq 2, \quad (12)$$

$$\sum_{n=2}^{\infty} (-1)^n \frac{\zeta(n)}{n}, \quad 1 + \sum_{n=2}^{\infty} \frac{1 - \zeta(n)}{n}, \quad 1 + \log\left(\frac{2}{3}\right) + \sum_{n=1}^{\infty} \frac{1 - \zeta(2n+1)}{(2n+1)2^{2n}}, \quad (13)$$

$$\sum_{n=1}^{\infty} \frac{\rho(n)}{n}, \quad \rho(n) = -(2k-1) \text{ if } n = k^2, \quad \rho(n) = 1 \text{ otherwise}, \quad (14)$$

$$\sum_{n=2}^{\infty} \frac{\Lambda(n) - 1}{n}, \quad \Lambda(n) = \log(p) \text{ if } n = p^k, \quad \Lambda(n) = 0 \text{ otherwise}. \quad (15)$$

Some of these expressions are merely variations of one another, but it is difficult to distinguish a common pattern because of the diversity of elementary functions involved: floor, square root, exponential, cosine, logarithm, zeta, digital, arithmetic functions, binomial coefficients, etc. Presumably,  $\pi$  is the only other classical constant with at least as many representations. However, contrary to  $\pi$ , the arithmetic nature of  $\gamma$  is still an open problem. Nobody knows whether it is a rational or an irrational number, an algebraic or a transcendental number, though  $\gamma$  is widely expected to be transcendental. Moreover,  $\pi = \int_{-\infty}^{\infty} \frac{dx}{1+x^2}$  is a period; none of the above representations proves that  $\gamma$  is a period and in fact a folklore conjecture states that  $\gamma$  is not a period, though it is one of the simplest examples of an exponential period in the sense of Kontsevich-Zagier [20].

Despite very general transcendence results for various classes of *arithmetic* special functions, none of them is known to apply to  $\gamma$ . In the sequel, we explain that even though  $\gamma$  is conjecturally not a value at an algebraic point of these arithmetic special functions, certain representations hidden in (2)–(15) show that it is not very far from being one.

## 2. *Arithmetical special functions.*

It is not easy to define the meaning of “special functions” though there exists many books devoted to them, for instance [7]; a voluntarily imprecise definition might be “a mathematical function used for ages in some part of science and satisfying some sort of functional equation”. In our Diophantine context, the arithmetic special functions we have in mind are of three types. Siegel defined *E*-functions and *G*-functions in [35]: these are series of the form  $\sum_{n=0}^{\infty} \frac{a_n}{n!} z^n$ , respectively  $\sum_{n=0}^{\infty} a_n z^n$ , where the height of  $a_n \in \overline{\mathbb{Q}}$  satisfies a certain growth condition (see [23]), and solutions of a differential equation  $\sum_{j=0}^d p_j(z) y^{(j)}(z) = 0$

with coefficients  $p_j(z) \in \overline{\mathbb{Q}}(z)$ . Prototypical examples are the exponential and logarithmic functions respectively, and the intersection of both classes is reduced to polynomials functions.  $M$ -functions are power series  $\sum_{n=0}^{\infty} a_n z^n$  with  $a_n \in \overline{\mathbb{Q}}$ , and solutions of a functional equation  $\sum_{j=0}^d p_j(z) y(z^{\ell_j}) = 0$  for some integers  $\ell \geq 2$  and  $d \geq 1$ , and  $p_j(z) \in \overline{\mathbb{Q}}(z)$ . A simple example is the series  $\sum_{n=0}^{\infty} z^{2^n}$ . They were first studied by Mahler [27] in a broader context.  $E$ -functions are entire and  $G$ -functions can be analytically continued to  $\mathbb{C}$  minus a finite number of cuts; an  $M$ -function is either in  $\overline{\mathbb{Q}}(z)$  or has the unit circle as natural boundary, [32, 9]) and moreover if it satisfies a linear differential equation, then it must be a in  $\overline{\mathbb{Q}}(z)$  by [12].

The arithmetic nature of the values of  $E$ -functions at algebraic points have been studied for long: the Siegel-Shidlovskii Theorem [34] is the landmark result, with refinements in [3, 5, 6, 11, 28]. As a result, there exists now an algorithm which, for any given  $E$ -function  $f(z)$ , provides explicitly the finite list of algebraic numbers  $\alpha$  such that  $f(\alpha) \in \overline{\mathbb{Q}}$ . Essentially the same things can be said of  $M$ -functions. An analogue of the Siegel-Shidlovskii Theorem was proved by Nishioka [30] and refined in [1, 2, 31]. Again, there exists now an algorithm which, for any given  $M$ -function  $f(z)$ , provides explicitly the list of algebraic numbers  $\alpha$  such that  $f(\alpha) \in \overline{\mathbb{Q}}$ . On the other hand, the situation is not completely understood for  $G$ -functions. The best general Diophantine result is due to Chudnosvky [14], but we are far from having an algorithm to perform the same task as for  $E$ -functions and  $M$ -functions.

Let us denote by  $\mathbf{E}$ ,  $\mathbf{G}$  and  $\mathbf{M}$  the subsets of  $\mathbb{C}$  of all the values taken by  $E$ -functions and (analytic continuation of)  $G$ -functions and  $M$ -functions at algebraic points, respectively. The first two sets have been introduced and studied in [23] and [24] respectively, see also [25]; in particular it was proved there that  $\mathbf{E}$  and  $\mathbf{G}$  are in fact subrings of  $\mathbb{C}$ . The set  $\mathbf{M}$  does not seem to have considered so far but it is easy to prove that it is a ring as well. As said above, none of the above Diophantine results has been applied so far to  $\gamma$  because this number is not known to be in either  $\mathbf{E}$  or  $\mathbf{G}$  or  $\mathbf{M}$ .

In fact, given the long list of series and integral expressions for  $\gamma$ , one can even argue that if it were such a value, this would be known for long. Hence it is plausible that  $\gamma$  is not in  $\mathbf{E} \cup \mathbf{G} \cup \mathbf{M}$  and in this sense, the answer to the title of this note is negative. Moreover, for similar reasons it is believed that  $\mathbf{E} \cap \mathbf{G} = \overline{\mathbb{Q}}$ ,  $\mathbf{E} \cap \mathbf{M} = \overline{\mathbb{Q}}$  and  $\mathbf{G} \cap \mathbf{M} = \overline{\mathbb{Q}}$ . Let us also say that it is also believed no Liouville number is in  $\mathbf{E} \cup \mathbf{G} \cup \mathbf{M}$ , but it would certainly be surprising if  $\gamma$  were itself a Liouville number.

#### 4. Extension of $\mathbf{E}$ and $\mathbf{M}$ .

We claim that  $\gamma$  is in fact close to be in  $\mathbf{E} \cap \mathbf{M}$ . Of course, this statement is paradoxical because this intersection is expected to contain only algebraic numbers, while  $\gamma$  is expected to be transcendental. We mean the following: we can “slightly” extend the sets  $\mathbf{E}$  and  $\mathbf{M}$  to certain sets  $\widetilde{\mathbf{E}}$  and  $\widetilde{\mathbf{M}}$  respectively so that  $\gamma \in \widetilde{\mathbf{E}} \cap \widetilde{\mathbf{M}}$ . The extension process is the same for both classes of functions, which adds value to this observation.

We define  $\widetilde{\mathbf{E}}$ , respectively  $\widetilde{\mathbf{M}}$ , as the set of all convergent evaluations at  $z \in \overline{\mathbb{Q}} \cup \{\infty\}$  of the twisted primitives

$$\int_0^z Q(x)F(x)dx \quad (16)$$

where  $Q(z) \in \overline{\mathbb{Q}}(z)$  and  $F(z)$  is an  $E$ -function, respectively an  $M$ -function, such that  $QF$  is holomorphic at  $z = 0$ . Changing the variable  $z$  to  $\alpha z$  for any algebraic number, we can in fact assume that  $z \in \{1, \infty\}$  in (16). Values at algebraic points of iterated primitives vanishing at 0 of  $E$ -functions and  $M$ -functions are in  $\widetilde{\mathbf{E}}$  and  $\widetilde{\mathbf{M}}$  respectively because for any integer  $p \geq 1$

$$\left(\int_0^z\right)^p F(x)dx = \frac{(-1)^{p-1}}{(p-1)!} \int_0^z (x-z)^{p-1} F(x)dx.$$

In fact,  $F$  is an  $M$ -function if and only if  $QF$  is an  $M$ -function, so that  $\widetilde{\mathbf{M}}$  is exactly the set of values at algebraic points of primitives of  $M$ -functions vanishing at 0. We want to keep  $\widetilde{\mathbf{E}}$  and  $\widetilde{\mathbf{M}}$  as “small” as possible but the drawback is that we do not know if they carry an algebraic structure. Of course, we get two  $\overline{\mathbb{Q}}$ -vector spaces by considering the *a priori* larger sets of numbers  $\int_\alpha^\beta Q(x)F(x)dx$  where  $\alpha, \beta \in \overline{\mathbb{Q}} \cup \{\infty\}$  and  $F$  is an  $E$ -function, respectively an  $M$ -function.

We have  $\mathbf{E} \subset \widetilde{\mathbf{E}}$  and  $\mathbf{M} \subset \widetilde{\mathbf{M}}$  because if  $F(z)$  is an  $E$ -function, respectively an  $M$ -function, then  $F'(z)$  is an  $E$ -function, respectively an  $M$ -function, and  $F(z) = \int_0^z F'(x)dx$ . It is likely however that  $\mathbf{E} \neq \widetilde{\mathbf{E}}$  and  $\mathbf{M} \neq \widetilde{\mathbf{M}}$ , because when  $F(z)$  is an  $E$ -function or an  $M$ -function, then an integral of the form (16) is in general neither an  $E$ -function nor an  $M$ -function. Taking  $F(z) = 1$  and  $Q(z) = \frac{1}{1+z}$ , we see that  $\log(\overline{\mathbb{Q}}^*) \subset \widetilde{\mathbf{E}} \cap \widetilde{\mathbf{M}}$  but this is a kind of artefact not related to  $E$ -functions and  $M$ -functions.

Much more interesting is the property that  $\gamma \in \widetilde{\mathbf{E}} \cap \widetilde{\mathbf{M}}$ . Indeed, by (6), we have

$$\gamma = \int_0^\infty \frac{1 - (1+x)e^{-x}}{x(1+x)} dx \in \widetilde{\mathbf{E}} \quad (17)$$

$$= \int_0^1 \frac{1}{x(1+x)} \sum_{n=1}^\infty x^{2n} dx \in \widetilde{\mathbf{M}} \quad (18)$$

$$= \int_0^1 \frac{2+x}{x(1+x+x^2)} \sum_{n=1}^\infty x^{3n} dx \in \widetilde{\mathbf{M}} \quad (19)$$

because  $1 - (1+z)e^{-z}$  is an  $E$ -function and  $\sum_{n=1}^\infty z^{2n}$ ,  $\sum_{n=1}^\infty z^{3n}$  are  $M$ -functions. Eq. (17) is apparently due to Dirichlet, while Eqs. (18) and (19) are due to Catalan and Ramanujan, respectively. All the series in (8) and (9) can be transformed in a straightforward manner as integrals  $\int_0^1 Q(x)F(x)dx$  for some  $Q(z) \in \overline{\mathbb{Q}}(z)$  and some  $M$ -function  $F(z)$ . Moreover, the series (11) is just a rewriting of the first series in (8).

Hence,  $\gamma$  might not be a value of an arithmetic special function, but it is not so far from being one. It would therefore be very interesting, and probably difficult, to generalize the theorems of Siegel-Shidlovsky and Nishioka to cover the case of twisted primitives of the form (16). With the algebraic numbers, the numbers  $\pi$  and  $\zeta(n)$  ( $n$  any integer  $\geq 2$ ) are

amongst the simplest elements of  $\mathbf{G}$ . So far, no simple relation between  $\gamma$  and  $G$ -functions is known, though  $\gamma$  is often considered to be the regularized value of the divergent  $\zeta(1)$ . The “tilde” extension presented here is not interesting for  $G$ -functions. Indeed, if  $F(z)$  is a  $G$ -function, then  $\int_0^z Q(x)F(x)dx$  is still a  $G$ -function and a convergent integral  $\int_0^\alpha Q(x)F(x)dx$  with  $\alpha \in \overline{\mathbb{Q}}$  is in  $\mathbf{G}$ . Hence  $\widetilde{\mathbf{G}} = \mathbf{G}$ .

The number  $\log(4/\pi)$  is sometimes named “the alternating Euler’s constant” because [37]

$$\log(4/\pi) = \sum_{n=1}^{\infty} (-1)^{n-1} \left( \frac{1}{n} - \log \left( 1 + \frac{1}{n} \right) \right).$$

(Compare with (1).) The identity [15]

$$\log(4/\pi) = \int_0^1 \frac{x^2 - x - 1}{1 - x^2} \sum_{n=0}^{\infty} \frac{(1 - x^{2^n})x^{2^n-1}}{1 + x^{2^n}} dx$$

proves that  $\log(4/\pi) \in \widetilde{\mathbf{M}}$ . There exist other representations similar to certain for  $\gamma$ , for instance [33, 37, 4]:

$$\begin{aligned} \log(4/\pi) &= \int_0^1 \frac{1-x}{1+x} \left( \frac{1}{\log(x)} + \frac{1}{1-x} \right) dx \\ &= \int_0^1 \int_0^1 \frac{x-1}{(1+xy)\log(xy)} dx dy \\ &= \sum_{n=1}^{\infty} \frac{N_0(n) - N_1(n)}{2n(2n+1)}, \end{aligned}$$

but it does not seem to be known whether  $\log(4/\pi) \in \widetilde{\mathbf{E}}$  or not.

Finally, let us mention that arithmetic special functions could also include “ $q$ -analogues”. It is proved in [22] that

$$\gamma = \lim_{q \rightarrow 1^+} \left( \sum_{n=1}^{\infty} \left( \frac{1-q}{1-q^n} \right) + \frac{(q-1)\log(q-1)}{\log(q)} + \frac{1-q}{2} \right)$$

which is a  $q$ -analogue of the definition of  $\gamma$  stated in (1). But no evaluation of a  $q$ -series or a  $q$ -integral in terms of  $\gamma$  seems to be known.

### 5. Other extensions.

The form of the integral in (16) also suggests to define a subset  $\widetilde{\mathbf{EGM}}$  of  $\mathbb{C}$  as follows: it is the set of all convergent integrals

$$\int_0^\alpha e(z)g(z)m(z)dz$$

where  $\alpha \in \{1, \infty\}$ , and  $e(z)$  is  $E$ -function,  $g(z)$  is a  $G$ -function  $g(z)$  and  $m(z)$  is an  $M$ -function. Since  $\frac{1-(1+z)e^{-z}}{z}$  is an  $E$ -function,  $\frac{1}{1+z}$  is a  $G$ -function (and an  $M$ -function as well), and  $\sum_{n=1}^{\infty} z^{2^n-1}$  is an  $M$ -function, (6) shows in many different ways that  $\gamma \in \widetilde{\mathbf{EGM}}$ . However, this set is quite big because it contains periods, exponential periods,  $\mathbf{E}$ ,  $\mathbf{G}$ ,  $\mathbf{M}$ ,  $\widetilde{\mathbf{E}}$  and  $\widetilde{\mathbf{M}}$ . This likely makes  $\widetilde{\mathbf{EGM}}$  very difficult to study from a Diophantine point of view.

To get other constants than  $\gamma$  without extending too much  $\mathbf{E}$ ,  $\mathbf{G}$  or  $\mathbf{M}$ , we consider the twisted primitives

$$\int_0^z Q(x)F(x)dx$$

where  $Q(z)$  is now an algebraic function over  $\overline{\mathbb{Q}}(z)$  and  $F(z)$  is either an  $E$ -function or an  $M$ -function such that  $QF$  is integrable at  $z = 0$ . When  $F(z)$  is an  $E$ -function, respectively an  $M$ -function, any convergent integral  $\int_0^\alpha Q(x)F(x)dx$ , with  $\alpha \in \{1, \infty\}$ , defines an element of  $\widetilde{\mathbf{E}}$  and  $\widetilde{\mathbf{M}}$ . Again, the “double tilde” extension is not interesting for  $G$ -functions and  $\widetilde{\mathbf{G}} = \mathbf{G}$ .

For instance, for any rational number  $s > 0$ , we have

$$\Gamma(s) = \int_0^\infty x^{s-1}e^{-x}dx \in \widetilde{\mathbf{E}}$$

and [10]

$$\Psi(s) := \frac{\Gamma'(s)}{\Gamma(s)} = \int_0^1 \left( \frac{x^{s-1}}{1-x} - \frac{2x^{2s-2}}{1-x^2} \right) \sum_{n=0}^\infty x^{2n} dx \in \widetilde{\mathbf{M}}.$$

However, it does not seem to be known whether  $\Gamma(s) \in \widetilde{\mathbf{M}}$  and  $\Psi(s) \in \widetilde{\mathbf{E}}$ .

We don't know if  $\widetilde{\mathbf{EGM}}$ ,  $\widetilde{\mathbf{E}}$  and  $\widetilde{\mathbf{M}}$  carry any interesting algebraic structure. We get three  $\overline{\mathbb{Q}}$ -vector spaces by considering the set of convergent integrals  $\int_\alpha^\beta e(z)g(z)m(z)dz$ , where  $\alpha, \beta \in \overline{\mathbb{Q}} \cup \{\infty\}$ ,  $e, g, m$  are an  $E$ -function, a  $G$ -function and an  $M$ -function respectively, as well as the two sets of convergent integrals  $\int_\alpha^\beta Q(x)F(x)dx$  where  $\alpha, \beta \in \overline{\mathbb{Q}} \cup \{\infty\}$ ,  $Q$  is algebraic over  $\overline{\mathbb{Q}}(z)$  and  $F$  an  $E$ -function, respectively an  $M$ -function.

### 5. A generalization of Vacca's second identity.

Vacca [39] proved in a geometric way the identity

$$\gamma = \sum_{n=1}^\infty n \left( \sum_{k=2^n}^{2^{n+1}-1} \frac{(-1)^k}{k} \right),$$

which is a variant of the first identity displayed in (8). Analytic proofs were quickly found by Glaisher [17] and Hardy [18], the latter showing that Vacca's identity is also a variant of Catalan's integral [13]  $\gamma = \int_0^1 \frac{1}{x(1+x)} \sum_{n=1}^\infty x^{2n} dx$ , displayed in (6).

Later on, Vacca proved in [40] a second identity, stated in (12), namely

$$\gamma + \zeta(2) = \sum_{n=1}^\infty \left( \frac{1}{[\sqrt{n}]^2} - \frac{1}{n} \right). \quad (20)$$

Because the paper [40] might be difficult to find, for the reader's convenience, we present a proof of the following generalization of (20): for any integer  $s \geq 2$ , we have

$$\gamma = \frac{1}{s-1} \sum_{n=1}^\infty \left( \frac{1}{[n^{1/s}]^s} - \frac{1}{n} - \sum_{\ell=2}^s \frac{\binom{s}{\ell}}{n^\ell} \right). \quad (21)$$

Indeed, we have

$$\begin{aligned}
& \sum_{n=1}^N \left( \frac{1}{\lfloor n^{1/s} \rfloor^s} - \frac{1}{n} \right) \\
&= \sum_{j=1}^{\lfloor N^{1/s} \rfloor} \sum_{n=j^s}^{(j+1)^s-1} \frac{1}{j^s} - \sum_{n=1}^N \frac{1}{n} = \sum_{j=1}^{\lfloor N^{1/s} \rfloor} \frac{(j+1)^s - j^s}{j^s} - \sum_{n=1}^N \frac{1}{n} \\
&= s \sum_{j=1}^{\lfloor N^{1/s} \rfloor} \frac{1}{j} - \sum_{n=1}^N \frac{1}{n} + \sum_{\ell=2}^s \binom{s}{\ell} \sum_{j=1}^{\lfloor N^{1/s} \rfloor} \frac{1}{j^\ell} \\
&= (s-1)\gamma + s \log(\lfloor N^{1/s} \rfloor) - \log(N) + \mathcal{O}\left(\frac{1}{N^{1/s}}\right) + \sum_{\ell=2}^s \binom{s}{\ell} \sum_{j=1}^{\lfloor N^{1/s} \rfloor} \frac{1}{j^\ell}, \quad N \rightarrow \infty \\
&= (s-1)\gamma + \sum_{\ell=2}^s \binom{s}{\ell} \zeta(\ell) + o(1), \quad N \rightarrow \infty
\end{aligned}$$

where we used  $\sum_{1 \leq j \leq x} \frac{1}{j} = \gamma + \log(x) + \mathcal{O}(\frac{1}{x})$  as  $x \rightarrow +\infty$ . Eq. (21) follows. The convergence is slow because  $\frac{1}{\lfloor n^{1/s} \rfloor^s} - \frac{1}{n} = \mathcal{O}(\frac{1}{n^{1+1/s}})$  and the exponent can not be improved.

A similar argument enables one to sum the series

$$\sum_{n=1}^{\infty} \left( \frac{n^{t-1}}{\lfloor n^{1/s} \rfloor^{st}} - \frac{1}{n} \right)$$

for any integers  $s \geq 2$  and  $t \geq 1$ . The formula is slightly more complicated to write down explicitly. We use the summation formula

$$\sum_{n=j^s}^{(j+1)^s-1} n^{t-1} = \frac{1}{t} (P_t((j+1)^s) - P_t(j^s)) =: \sum_{m=0}^{ts-1} \alpha_{m,s,t} j^m$$

where  $P_k(X)$  is the  $k$ -th Bernoulli polynomial, and the  $\alpha_{m,s,t} \in \mathbb{Q}$  could be explicated in terms of the Bernoulli numbers and binomial coefficients. We then get

$$\sum_{n=1}^{\infty} \left( \frac{n^{t-1}}{\lfloor n^{1/s} \rfloor^{st}} - \frac{1}{n} \right) = (s-1)\gamma + \sum_{m=0}^{st-2} \alpha_{m,s,t} \zeta(st-m).$$

The case  $s = t = 2$  reads

$$\sum_{n=1}^{\infty} n \left( \frac{1}{\lfloor \sqrt{n} \rfloor^4} - \frac{1}{n^2} \right) = \gamma + 3\zeta(2) + \zeta(3)$$

or

$$\gamma = \sum_{n=1}^{\infty} n \left( \frac{1}{\lfloor \sqrt{n} \rfloor^4} - \frac{1}{n^2} - \frac{3}{n^3} - \frac{1}{n^4} \right).$$

None of the identities in this section seems to express  $\gamma$  as a value of an arithmetic special function.



## REFERENCES

- [1] B. Adamczewski and C. Faverjon, *Méthode de Mahler: relations linéaires, transcendance et applications aux nombres automatiques*, Proc. London Math. Soc. **115** (2017), 55–90.
- [2] B. Adamczewski and C. Faverjon, *Méthode de Mahler, transcendance et relations linéaires : aspects effectifs*, J. Théor. Nombres Bordeaux, to appear.
- [3] B. Adamczewski and T. Rivoal, *Exceptional values of E-functions at algebraic points*, preprint (2017), 14 pages.
- [4] J.-P. Allouche, J. Shallit and J. Sondow, *Summation of series defined by counting blocks of digits*, J. Number Theory **123.1** (2007), 133–143.
- [5] Y. André, *Séries Gevrey de type arithmétique, I and II*, Annals of Math. **151** (2000), 705–740 and 741–756.
- [6] Y. André, *Arithmetic Gevrey series and transcendence. A survey*, J. Théor. Nombres Bordx. **15.1** (2003), 1–10.
- [7] G. E. Andrews, R. Askey and R. Roy, *Special functions*, Encyclopedia of Mathematics and Its Applications **71** (2000), Cambridge University Press, 664 pages.
- [8] P. Appell, *Sur les séries numériques convergentes à termes positifs dont la somme est rationnelle*, Nouvelles annales de mathématiques **2** (1927), 231–235.
- [9] J. Bell, M. Coons and E. Rowland, *The rational-transcendental dichotomy of Mahler functions*, J. Integer Seq. **16** (2013), Article 13.2.10, 10 pages.
- [10] B. C. Berndt and D. C. Bowman, *Ramanujan’s short unpublished manuscript on integrals and series related to Euler’s constant*, CMS Conf. Proc. **27** (2000), 19–27.
- [11] F. Beukers, *A refined version of the Siegel-Shidlovskii theorem*, Annals of Math. **163** (2006), 369–379.
- [12] J.-P. Bézivin, *Sur une classe d’équations fonctionnelles non linéaires*, Funkcialaj Ekvacioj **37** (1994), 263–271.
- [13] E. Catalan, *Sur la constante d’Euler et la fonction de Binet*, J. Math. Pures appl. (3) **1** (1875), 209–240.
- [14] G. V. Chudnovsky, *On applications of diophantine approximations*, Proc. Natl. Acad. Sci. USA **81** (1984), 7261–7265.
- [15] Kh. Essami Pilehrood and T. Essami Pilehrood, *Vacca-type series for values of the generalized Euler constant function and its derivative*, J. Integer Seq. **13.7** (2010), Article 10.7.3, 21 pages.
- [16] S. R. Finch, *Mathematical constants*, Encyclopedia of Mathematics and Its Applications **94** (2003), Cambridge University Press, 602 pages.
- [17] J. W. L. Glaisher, *On Dr. Vacca’s series for  $\gamma$* , Quart. J. **41** (1910), 365–368.
- [18] G. H. Hardy, *Note on Dr. Vacca’s series for  $\gamma$* , Quart. J. **43** (1912), 215–216.
- [19] J. Havil, *Gamma: Exploring Euler’s constant*, Princeton University Press (2009), 266 pages.
- [20] M. Kontsevich and D. Zagier, *Periods*, Mathematics unlimited – 2001 and beyond, Springer (2001), 771–808.
- [21] S. Krämer, *Die Eulersche Konstante  $\gamma$  und verwandte Zahlen*, Diplomarbeit, <http://num.math.uni-goettingen.de/~skraemer/gamma.html>
- [22] N. Kurokawa and M. Wakayama, *On q-analogues of the Euler constant and Lerch’s limit formula*, Proc. Amer. Math. Soc. **132.4** (2003), 935–943.
- [23] S. Fischler and T. Rivoal, *On the values of G-functions*, Commentarii Math. Helv. **29.2** (2014), 313–341.
- [24] S. Fischler and T. Rivoal, *Arithmetic theory of E-operators*, Journal de l’École polytechnique – Mathématiques **3** (2016), 31–65.
- [25] S. Fischler and T. Rivoal, *Microsolutions of differential operators and values of arithmetic Gevrey series*, to appear in Amer. Journal of Math, 31 pages.
- [26] J. Lagarias, *Euler’s constant: Euler’s work and modern developments*, Bull. Amer. Math. Soc. **50.4** (2013), 527–628.

- [27] K. Mahler, *Arithmetische Eigenschaften der Lösungen einer Klasse von Funktionalgleichungen*, Math. Ann. **101** (1929), 342–366.
- [28] Yu. V. Nesterenko and A. B. Shidlovsky, *On the linear independence of values of E-functions*, Sb. Math. **187** (1996), 1197–1211.
- [29] A. S. Nimbran, *Euler’s constant and Gamma function: a survey and some new results*, <https://www.researchgate.net/profile/AmrikNimbran/publications>
- [30] Ku. Nishioka, *Algebraic independence measures of the values of Mahler functions*, J. reine angew. Math. **420** (1991), 203–214.
- [31] P. Philippon, *Groupes de Galois et nombres automatiques*, J. London Math. Soc. **92.3** (2015), 596–614.
- [32] B. Randé, *Équations fonctionnelles de Mahler et applications aux suites p-régulières*, thèse de l’Université de Bordeaux 1, Talence, 1992.
- [33] T. Rivoal, *Polynômes de type Legendre et approximations de la constante d’Euler*, unpublished note (2005), 11 pages.
- [34] A. B. Shidlovsky, *Transcendental Numbers*, de Gruyter Studies in Mathematics **12**, 1989.
- [35] C. L. Siegel, *Über einige Anwendungen diophantischer Approximationen*, Abh. Preuss. Akad. Wiss., Phys. Math. Kl. (1929), 41–69.
- [36] J. Sondow, *Double integrals for Euler’s constant and  $\ln(4/\pi)$  and an analog of Hadjicostas’s formula*, Am. Math. Mon. **112.1** (2005), 61–65.
- [37] J. Sondow, *New Vacca-type rational series for Euler’s constant  $\gamma$  and its “alternating” analog  $\ln(4/\pi)$* , Festschrift in honor of the sixtieth birthday of Melvyn B. Nathanson. New York, Springer (2010), 331–340 .
- [38] J. Sondow and W. Zudilin, *Euler’s constant, q-logarithms, and formulas of Ramanujan and Gosper*, Ramanujan J. **12.2** (2006), 225–244.
- [39] G. Vacca, *A new series for the Eulerian constant  $\gamma = 0.577\dots$* , Quart. J. **41** (1910), 363–364.
- [40] G. Vacca, *Nuova serie per la costante di Eulero  $C = 0.577\dots$* , Rendiconti Accad. d. Leinci Roma (6) **3** (1926), 19–20.

T. RIVOAL, INSTITUT FOURIER, CNRS ET UNIVERSITÉ GRENOBLE ALPES, CS 40700, 38058 GRENOBLE CEDEX 9, FRANCE