New reflection formulas for Euler sums

Marc-Antoine Coppo, Bernard Candelpergher

HAL Id: hal-02921391

https://hal.univ-cotedazur.fr/hal-02921391v2

Preprint submitted on 12 Jan 2021 (v2), last revised 16 Apr 2021 (v7)

New reflection formulas for Euler sums

Marc-Antoine Coppo* , Bernard Candelpergher

Université Côte d'Azur, CNRS, LJAD (UMR 7351), Nice, France

Abstract. In this study, we apply the Ramanujan summation method to a certain class of Euler sums and provide new reflection formulas that extend the well-known relation of symmetry between reciprocal linear Euler sums.

Introduction

The study of Euler sums has a fairly long history dating back to the middle of the 18th century. In response to a letter from Goldbach dated from december 1742, Euler considered infinite sums of the form

$$\mathcal{S}_{p,q} = \sum_{n=1}^{\infty} \frac{H_n^{(p)}}{n^q} \, ,$$

where p and q are positive integers, and $H_n^{(p)} = \sum_{k=1}^{n} \frac{1}{k^p}$ are generalized harmonic numbers. For $p = 1$, the generalized harmonic numbers reduce to classical harmonic numbers $H_n = H_n^{(1)}$. The importance of harmonic numbers comes from the fact that they appear (sometimes quite unexpectedly) in different branches of number theory and combinatorics. In our times, the sums $\mathcal{S}_{p,q}$ are called the *linear Euler sums* (cf. [12]). Euler discovered that for all pairs (p, q) with $p = 1$, or $p = q$,

---

*Corresponding author.

Email address: coppo@unice.fr (M-A. Coppo).

or $p + q$ odd, these sums have expressions in terms of zeta values (i.e. the values of Riemann's zeta function $\zeta(s) = \sum_{n \geq 1} n^{-s}$ at positive integers), a remarkable result that will be also found and completed later by Nielsen[1].

Among the elegant formulas already known to Euler[2], the following two are particularly noteworthy:

– The reflection formula (cf. [10, 12])

$$\mathcal{S}_{p,q} + \mathcal{S}_{q,p} = \zeta(p)\zeta(q) + \zeta(p+q) \qquad (p, q \geq 2),$$

which allows to express $\mathcal{S}_{q,p}$ as a function of $\mathcal{S}_{p,q}$ and vice versa.

– Euler's formula (cf. [10, 12])

$$\mathcal{S}_{1,2} = 2\zeta(3) \quad \text{and} \quad 2\mathcal{S}_{1,p} = (p+2)\zeta(p+1) - \sum_{j=1}^{p-2} \zeta(p-j)\zeta(j+1) \qquad (p > 2),$$

that will be several times rediscovered throughout the 20th century (see [10, Remark 3.1] for historical details).

Ramanujan's method of summation of series appears in chapter VI of the second *Notebook*. Because of the ambiguities (observed by Hardy[3]) contained in the definition of the "constant of a series" that made its use very tricky, Ramanujan's method, based on the Euler-MacLaurin summation formula, had fallen into neglect. The method has known a revival of interest at the end of the 20th century when a clear and rigorous definition of the sum of a series (in the sense of Ramanujan summation) was given at the same time as the link with usual summation was completely clarified. The reader will find in [4] a masterful synthesis of main definitions, fundamental properties, and scope of application of Ramanujan summation.

Ramanujan's method is particulary appropriate to Euler sums and allows to treat both the convergence case and the divergence case. In the remainder of this article, we give a complete evaluation of the sums (in the sense of Ramanujan summation) corresponding respectively to $\mathcal{S}_{1,p}$ and $\mathcal{S}_{p,1}$ which allows to extend the classical reflection formula mentioned above (see propositions 1 and 2 and the theorem).

---

1. N. Nielsen, Handbuch der Theorie der Gammafunction, Teubner, Leipzig, 1906.

2. These formulas are given without proof in Euler's masterwork dated 1776 *Meditationes circa singulare serierum genus.*

3. G. H. Hardy, Divergent Series, Clarendon press, Oxford, 1949, Chapter XIII.

1   Ramanujan summation of Euler sums

Let us recall that the generalized harmonic numbers $H_n^{(p)}$ are defined by

$$H_n^{(p)} = \sum_{k=1}^{n} \frac{1}{k^p} \quad \text{for } n, p = 1, 2, 3, \ldots.$$

When $p = 1$, they reduce to classical harmonic numbers denoted $H_n = H_n^{(1)}$. It is convenient to express them in the form

$$H_n = \psi(n+1) + \gamma\,,$$

where $\psi(z) = \partial \ln(\Gamma(z))$ is the digamma function and $\gamma = -\psi(1)$ is Euler's constant; in the same way (cf. [3, 7]), we have

$$H_n^{(p)} = \frac{(-1)^{p-1}}{(p-1)!} \partial^{p-1} \psi(n+1) + \zeta(p) \quad (p \geq 2)\,.$$

Definition 1. For any positive integer p, the function $s \mapsto \zeta^{\mathcal{R}}(p, s)$ is defined as the analytic continuation of the function defined in the half-plane $\mathrm{Re}(s) > 1$ by

$$\sum_{n=1}^{+\infty} H_n^{(p)}\, n^{-s} - \int_1^{+\infty} \psi_p(x)\, x^{-s}\, dx\,,$$

where $\psi_1(x) = \psi(x+1) + \gamma$, and

$$\psi_p(x) = \frac{(-1)^{p-1}}{(p-1)!} \partial^{p-1} \psi(x+1) + \zeta(p) \quad (p \geq 2)\,.$$

It follows from [4, Theorem 9] that this function can be analytically continued as an entire function in the whole $\mathbb{C}$.

Thus, the values $\zeta^{\mathcal{R}}(p, q)$ at integers $q \in \mathbb{Z}$ are well-defined and can be interpreted as the $\mathcal{R}$-sum (i.e. the sum in the sense of Ramanujan summation) of the (possibly divergent) series $\sum_{n \geq 1} H_n^{(p)} n^{-q}$.

The function $s \mapsto \zeta^{\mathcal{R}}(1, s)$ is closely linked to the harmonic zeta function ζ_H (cf. [6]) defined for $\mathrm{Re}(s) > 1$ by

$$\zeta_H(s) = \sum_{n=1}^{\infty} H_n\, n^{-s}\,,$$

through the relation

$$\zeta^{\mathcal{R}}(1, s) = \zeta_H(s) - \int_1^{\infty} x^{-s}\, (\psi(x+1) + \gamma)\, dx \qquad \text{for } \mathrm{Re}(s) > 1\,.$$

Since
$$\zeta_H(p) = \mathcal{S}_{1,p} \quad \text{for } p = 2, 3, \ldots,$$
it follows that
$$\zeta^{\mathcal{R}}(1, p) = \mathcal{S}_{1,p} - \int_1^\infty \frac{\psi(x+1) + \gamma}{x^p} \, dx \qquad (p \geq 2). \tag{1}$$

2 Evaluation of $\zeta^{\mathcal{R}}(1, p)$

Definition 2. For any positive integer p, let τ_p defined by the series representation
$$\tau_p = \sum_{k=1}^\infty (-1)^{k+p} \frac{\zeta(k+p)}{k}. \tag{2}$$

Remark 1. Series representations τ_p $(p = 1, 2, \ldots)$ have been extensively studied in [9] and also appear in [2] and [6].

To give an evaluation of the $\mathcal{R}$-sum $\zeta^{\mathcal{R}}(1, p)$, we first prove the following lemma:

Lemma 1. For $p > 2$, we have the relation
$$\int_1^\infty \frac{\psi(x+1) + \gamma}{x^p} \, dx = \sum_{j=1}^{p-2} \frac{(-1)^{p-j}}{j} \zeta(p-j) - (-1)^p \zeta'(p) - \tau_p \tag{3}$$
which, for $p = 2$, reduces to
$$\int_1^\infty \frac{\psi(x+1) + \gamma}{x^2} \, dx = -\zeta'(2) - \tau_2.$$

Proof. For $p \geq 2$, the convergent series $\sum_{n \geq 1} \frac{\ln(n+1)}{n^p}$ may be splitted into the two series
$$\sum_{n=1}^\infty \frac{\ln(n+1)}{n^p} = \sum_{n=1}^\infty \frac{\ln(n)}{n^p} + \sum_{n=1}^\infty \frac{1}{n^p} \ln\left(1 + \frac{1}{n}\right).$$
The well-known expansion of $\ln(1 + 1/n)$ in power series leads to the identity
$$\sum_{n=1}^\infty \frac{1}{n^p} \ln\left(1 + \frac{1}{n}\right) = \sum_{n=1}^\infty \frac{1}{n^p} \left[\sum_{k=1}^\infty \frac{(-1)^{k-1}}{k} \left(\frac{1}{n}\right)^k\right] = (-1)^{p-1} \tau_p,$$
then it follows that
$$\sum_{n=1}^\infty \frac{\ln(n+1)}{n^p} = -\zeta'(p) - (-1)^p \tau_p. \tag{4}$$

4

On the other side, for $p > 2$, the finite Taylor expansion of the logarithm allows to write

$$\ln(x+1) = \sum_{j=1}^{p-2} \frac{(-1)^{j-1}}{j} x^j + (-1)^p x^{p-1} \int_1^\infty \frac{1}{t^{p-1}(t+x)} dt \,,$$

and thus, for any positive integer n, we have

$$\frac{\ln(n+1)}{n^p} = \sum_{j=1}^{p-2} \frac{(-1)^{j-1}}{j} \frac{1}{n^{p-j}} + (-1)^p \int_1^\infty \frac{1}{t^{p-1}n(t+n)} dt \,.$$

By summing this identity, we get

$$\sum_{n=1}^\infty \frac{\ln(n+1)}{n^p} = \sum_{j=1}^{p-2} \frac{(-1)^{j-1}}{j} \zeta(p-j) + (-1)^p \int_1^\infty \frac{\psi(x+1)+\gamma}{x^p} dx \,.$$

Hence, formula (3) follows from (4) by substitution. For $p = 2$, it reduces to

$$\int_1^\infty \frac{\psi(x+1)+\gamma}{x^2} dx = \sum_{n=1}^\infty \frac{\ln(n+1)}{n^2} = -\zeta'(2) - \tau_2 \,. \tag{5}$$

$\square$

Proposition 1. For any positive integer $p > 2$, we have

$$\zeta^{\mathcal{R}}(1,p) = \mathcal{S}_{1,p} - \sum_{j=1}^{p-2} \frac{(-1)^{p-j}}{j} \zeta(p-j) + (-1)^p \zeta'(p) + \tau_p \,, \tag{6}$$

where τ_p is defined by formula (2), and for $p = 2$,

$$\zeta^{\mathcal{R}}(1,2) = 2\zeta(3) + \zeta'(2) + \tau_2 \,.$$

Corollary 1. For $p > 1$, we have the formula

$$\zeta^{\mathcal{R}}(1,2p) = (p+1)\zeta(2p+1) - \sum_{j=1}^{p-1} \zeta(2p-j)\zeta(j+1) - \sum_{j=1}^{2p-2} \frac{(-1)^j}{j} \zeta(2p-j) + \zeta'(2p) + \tau_{2p} \,. \tag{7}$$

Proof. By formula (1), we have the relation

$$\zeta^{\mathcal{R}}(1,p) = \mathcal{S}_{1,p} - \int_1^\infty \frac{\psi(x+1)+\gamma}{x^p} dx \,,$$

5

and, by (3), we have

$$(-1)^p \int_1^\infty \frac{\psi(x+1) + \gamma}{x^p} \, dx = -\zeta'(p) - (-1)^p \tau_p + \sum_{j=1}^{p-2} \frac{(-1)^j}{j} \zeta(p-j) \,.$$

Then formula (6) follows immediately by substitution, and (7) results from the expression of $S_{1,2p}$ given by Euler's formula:

$$\mathcal{S}_{1,2p} = (p+1)\zeta(2p+1) - \sum_{j=1}^{p-1} \zeta(2p-j)\zeta(j+1) \quad (p > 1) \,. \tag{8}$$

□

Example 1.

$$\zeta^{\mathcal{R}}(1,2) = 2\zeta(3) + \zeta'(2) + \tau_2 \,,$$

$$\zeta^{\mathcal{R}}(1,4) = 3\zeta(5) - \zeta(3)\zeta(2) + \zeta(3) - \frac{1}{2}\zeta(2) + \zeta'(4) + \tau_4 \,,$$

$$\zeta^{\mathcal{R}}(1,6) = 4\zeta(7) - \zeta(3)\zeta(4) - \zeta(2)\zeta(5) + \zeta(5) - \frac{1}{2}\zeta(4) + \frac{1}{3}\zeta(3) - \frac{1}{4}\zeta(2)$$

$$+ \zeta'(6) + \tau_6 \,.$$

Remark 2. We point out an analogy between our formula (7) and the "dual" formula given in [8, Eq. (8)]

$$\zeta^{\mathcal{R}}(1,-2p) = \frac{1-2p}{2}\zeta(1-2p) + \zeta'(-2p) + \nu_{2p}$$

where ν_p is defined for $p \geq -1$ by the series representation

$$\nu_p = \sum_{n=2}^\infty (-1)^n \frac{\zeta(n)}{n+p} \quad (\text{note that } \nu_{-1} = \tau_1) \,.$$

3   Evaluation of $\zeta^{\mathcal{R}}(p,1)$

We now give an evaluation of the "reciprocal" sum $\zeta^{\mathcal{R}}(p,1)$ (note that, as a divergent series, $S_{p,1}$ is not defined).

Definition 3. Let σ_p defined by $\sigma_2 = 1$ and, for $p > 2$,

$$\sigma_p = \frac{1 + (-1)^p}{p} + \sum_{j=1}^{p-2} (-1)^j \zeta(p-j) \left[\frac{(j-1)!(p-1-j)!}{(p-1)!} - \frac{1}{j} \right] \,. \tag{9}$$

Example 2. The first values of σ_p are

$$\sigma_2 = 1\,,$$

$$\sigma_3 = \frac{1}{2}\zeta(2)\,,$$

$$\sigma_4 = \frac{2}{3}\zeta(3) - \frac{1}{3}\zeta(2) + \frac{1}{2}\,,$$

$$\sigma_5 = \frac{3}{4}\zeta(4) - \frac{5}{12}\zeta(3) + \frac{1}{4}\zeta(2)\,,$$

$$\sigma_6 = \frac{4}{5}\zeta(5) - \frac{9}{20}\zeta(4) + \frac{9}{10}\zeta(3) - \frac{1}{5}\zeta(2) + \frac{1}{3}\,.$$

Remark 3. We can deduce from [5, Eq. (27)] another interesting expression of σ_p. Let us define the infinite sum $Z(i,j)$ by

$$Z(i,j) = \sum_{n=1}^{\infty} \frac{1}{n^i\,(n+1)^j} \quad \text{for } i,j \geq 1\,.$$

Partial fraction decomposition of $\frac{1}{n^i\,(n+1)^j}$ shows that $Z(i,j)$ have an expression as $\mathbb{Z}$-linear combinations of zeta values and integers. Explicitly,

$$Z(1,j) = j - \sum_{r=0}^{j-2} \zeta(j-r) \qquad (j \geq 2)\,,$$

$$Z(i,1) = (-1)^{i-1} + \sum_{r=0}^{i-2} (-1)^r \zeta(i-r) \qquad (i \geq 2)\,,$$

$$Z(i,j) = (-1)^i \sum_{r=0}^{j-2} \binom{i+r-1}{i-1}\zeta(j-r) + \sum_{r=0}^{i-2} (-1)^r \binom{j+r-1}{j-1}\zeta(i-r)$$

$$+ (-1)^{i-1}\binom{i+j-1}{j-1} \qquad (i,j \geq 2)\,.$$

Then, formula [5, Eq. (27)] may be translated into the identity

$$\sigma_p = \sum_{i+j=p} \frac{1}{j} Z(i,j)\,.$$

Proposition 2. For any positive integer $p \geq 2$, we have

$$\zeta^{\mathcal{R}}(p,1) = \gamma\zeta(p) + \zeta(p+1) - \mathcal{S}_{1,p} - \sigma_p - \zeta'(p) - (-1)^p \tau_p\,, \tag{10}$$

where τ_p and σ_p are respectively defined by formulas (2) and (9).

Corollary 2. For $p > 1$, we have the formula

$$\zeta^{\mathcal{R}}(2p,1) = \gamma\zeta(2p) - p\,\zeta(2p+1) + \sum_{j=1}^{p-1} \zeta(2p-j)\zeta(j+1) - \sigma_{2p} - \zeta'(2p) - \tau_{2p}\,. \tag{11}$$

7

Proof. By summing (in the sense of Ramanujan summation) the following equations :

$$\frac{H_n^{(p)}}{n} - \frac{1}{n}\zeta(p) = -\frac{1}{n}\sum_{m=n+1}^{+\infty}\frac{1}{m^p} = \frac{1}{n}\frac{(-1)^{p-1}}{(p-1)!}\partial^{p-1}\psi(n+1)\,,$$

we get

$$\sum_{n\geq 1}^{\mathcal{R}}\left(\frac{H_n^{(p)}}{n} - \frac{\zeta(p)}{n}\right) = -\sum_{n\geq 1}^{\mathcal{R}}\frac{1}{n}\sum_{m=n+1}^{+\infty}\frac{1}{m^p}$$

$$= \sum_{n\geq 1}^{\mathcal{R}}\frac{1}{n}\frac{(-1)^{p-1}}{(p-1)!}\partial^{p-1}\psi(n+1)$$

$$= -\sum_{n=1}^{+\infty}\frac{1}{n}\sum_{m=n+1}^{+\infty}\frac{1}{m^p} + \frac{(-1)^p}{(p-1)!}\int_1^{+\infty}\partial^{p-1}\psi(x+1)\frac{1}{x}\,dx\,,$$

where the symbol $\sum_{n\geq 1}^{\mathcal{R}}$ denotes the $\mathcal{R}$-sum of the series (see [4] for a precise definition). Since

$$\sum_{n\geq 1}^{+\infty}\frac{1}{n}\sum_{m=n+1}^{+\infty}\frac{1}{m^p} = \sum_{n=1}^{+\infty}\frac{H_n}{n^p} - \zeta(p+1)\,,$$

this can be rewritten

$$\sum_{n\geq 1}^{\mathcal{R}}\left(\frac{H_n^{(p)}}{n} - \frac{\zeta(p)}{n}\right) = \zeta(p+1) - \sum_{n=1}^{+\infty}\frac{H_n}{n^p} + \frac{(-1)^p}{(p-1)!}\int_1^{+\infty}\partial^{p-1}\psi(x+1)\frac{1}{x}\,dx\,.$$

Thus we have

$$\sum_{n\geq 1}^{\mathcal{R}}\frac{H_n^{(p)}}{n} = \gamma\zeta(p) + \zeta(p+1) - \sum_{n=1}^{+\infty}\frac{H_n}{n^p} + \frac{(-1)^p}{(p-1)!}\int_1^{+\infty}\partial^{p-1}\psi(x+1)\frac{1}{x}\,dx\,,$$

i.e.

$$\zeta^{\mathcal{R}}(p,1) = \gamma\zeta(p) + \zeta(p+1) - S_{1,p} + \frac{(-1)^p}{(p-1)!}\int_1^{+\infty}\frac{\partial^{p-1}\psi(x+1)}{x}\,dx\,. \qquad (12)$$

We evaluate the integral in the right member of (12) by integrating $p-1$ times by parts. When $p=2$, this is just

$$\int_1^{+\infty}\frac{\partial\psi(x+1)}{x}\,dx = \int_1^{\infty}\frac{\psi(x+1) + \gamma}{x^2}\,dx - 1\,,$$

which, by (5), is $-\zeta'(2) - \tau_2 - 1$. Hence, by (12), we have

$$\zeta^{\mathcal{R}}(2,1) = \gamma\zeta(2) + \zeta(3) - \mathcal{S}_{1,2} - \sigma_2 - \zeta'(2) - \tau_2\,.$$

We now assume that $p > 2$. From

$$\partial^{p-k}\psi(2) = (-1)^{p-k}(p-k)! + (-1)^{p-k+1}(p-k)!\zeta(p-k+1) \qquad (p-k \geq 1)$$

(cf. [7, Proposition 9.6.41]) results the relation

$$\frac{(-1)^p}{(p-1)!}\int_1^{+\infty}\frac{\partial^{p-1}\psi(x+1)}{x}\,dx = (-1)^p\int_1^{\infty}\frac{\psi(x+1)+\gamma}{x^p}\,dx$$

$$+ \frac{1}{(p-1)!}\sum_{k=0}^{p-3}(-1)^k k!(p-k-2)!\,\zeta(p-k-1) - \frac{1}{(p-1)!}\sum_{k=0}^{p-2}(-1)^k k!(p-k-2)!\,.$$

In this expression, the last term is much more simplified by means of the formula

$$\frac{1}{(p-1)!}\sum_{k=0}^{p-2}(-1)^k k!(p-k-2)! = \frac{1}{p-1}\sum_{k=0}^{p-2}\frac{(-1)^k}{\binom{p-2}{k}} = \frac{1+(-1)^p}{p}$$

(cf. [11, Eq. (14)]). After reindexation, we have

$$\frac{1}{(p-1)!}\sum_{k=0}^{p-3}(-1)^k k!(p-k-2)!\,\zeta(p-k-1) = -\sum_{j=1}^{p-2}(-1)^j\frac{(j-1)!(p-j-1)!}{(p-1)!}\,\zeta(p-j)\,.$$

Moreover, by (3), we have

$$(-1)^p\int_1^{\infty}\frac{\psi(x+1)+\gamma}{x^p}\,dx = \sum_{j=1}^{p-2}\frac{(-1)^j}{j}\,\zeta(p-j) - \zeta'(p) - (-1)^p\tau_p\,.$$

Thanks to these simplifications, formula (12) can now be rewritten

$$\zeta^{\mathcal{R}}(p,1) = \gamma\zeta(p) + \zeta(p+1) - \mathcal{S}_{1,p} - \zeta'(p) - (-1)^p\tau_p - \sigma_p\,,$$

with

$$\sigma_p = \frac{1+(-1)^p}{p} + \sum_{j=1}^{p-2}(-1)^j\frac{(j-1)!(p-j-1)!}{(p-1)!}\,\zeta(p-j) - \sum_{j=1}^{p-2}\frac{(-1)^j}{j}\,\zeta(p-j)\,.$$

This completes the demonstration of the expected formula (10). Formula (11) is immediately deduced from Euler's formula (8). $\qquad\square$

Example 3.

$$\zeta^{\mathcal{R}}(2,1) = \gamma\zeta(2) - \zeta(3) - 1 - \zeta'(2) - \tau_2$$

$$\zeta^{\mathcal{R}}(3,1) = \gamma\zeta(3) - \frac{1}{4}\zeta(4) - \frac{1}{2}\zeta(2) - \zeta'(3) + \tau_3\,,$$

$$\zeta^{\mathcal{R}}(4,1) = \gamma\zeta(4) - 2\zeta(5) + \zeta(3)\zeta(2) - \frac{2}{3}\zeta(3) + \frac{1}{3}\zeta(2) - \frac{1}{2} - \zeta'(4) - \tau_4\,,$$

$$\zeta^{\mathcal{R}}(5,1) = \gamma\zeta(5) - \frac{3}{4}\zeta(6) - \frac{3}{4}\zeta(4) + \frac{1}{2}(\zeta(3))^2 + \frac{5}{12}\zeta(3) - \frac{1}{4}\zeta(2) - \zeta'(5) + \tau_5\,.$$

4   Values of $\zeta^{\mathcal{R}}(p,p)$

The following formula (cf. [4, Eq. (3.23)]) allows to extend formula (10) to the case $p = 1$. We have

$$\zeta^{\mathcal{R}}(1,1) = \frac{1}{2}\gamma^2 - \frac{1}{2}\zeta(2) + \gamma_1 + \tau_1\,,\tag{13}$$

where γ_1 is the first Stieltjes constant and $\tau_1 = 1.25774688\ldots$ is defined by (2).

A new proof of this formula is given below.

Proof. The relation

$$\zeta^{\mathcal{R}}(1,1) = \frac{1}{2}\gamma^2 + \frac{1}{2}\zeta(2) - \frac{1}{2} + \frac{1}{2}\int_0^1 \psi^2(x+1)\,dx$$

(cf. [4, Eq. (2.6) p. 40]) is a direct consequence of [4, Theorem 3]. Since $\psi(x+1) = \psi(x) + 1/x$, this relation can be rewritten

$$\int_0^1 \left(\psi^2(x) + 2\frac{\psi(x)}{x} + \frac{1}{x^2}\right)dx = 2\zeta^{\mathcal{R}}(1,1) - \gamma^2 - \zeta(2) + 1\,.$$

Moreover, from [7, p. 145], we have

$$\int_0^1 \left(\psi^2(x) - \frac{2\gamma}{x} - \frac{1}{x^2}\right)dx = 2\gamma_1 - 2\zeta(2) + 1\,.$$

Subtracting these two expressions, we obtain the following

$$2\int_0^1 \left((\psi(x) + \gamma)\frac{1}{x} + \frac{1}{x^2}\right)dx = \zeta^{\mathcal{R}}(1,1) - \gamma^2 - \zeta(2) + 1 - (2\gamma_1 - 2\zeta(2) + 1)\,.$$

Since

$$(\psi(x) + \gamma)\frac{1}{x} + \frac{1}{x^2} = \frac{\psi(x+1) + \gamma}{x}\,,$$

we deduce the relation

$$2\int_0^1 \frac{\psi(x+1) + \gamma}{x}\,dx = 2\zeta^{\mathcal{R}}(1,1) + \zeta(2) - \gamma^2 - 2\gamma_1\,.$$

An integration of the expansion of ψ in power series

$$\psi(x+1) + \gamma = \sum_{n=2}^{\infty}(-1)^n\zeta(n)x^{n-1} \qquad (|x| < 1)$$

shows that the integral in the left member of the previous relation is nothing else than the series τ_1, i.e.

$$\int_0^1 \frac{\psi(x+1) + \gamma}{x}\,dx = \sum_{n=1}^{\infty}(-1)^{n+1}\frac{\zeta(n+1)}{n} = \tau_1.$$

Hence we obtain formula (13) after division by 2. □

Remark 4. The $\mathcal{R}$-sum $\zeta^{\mathcal{R}}(1,1)$ coincides with the constant

$$\kappa_1 = \sum_{n=1}^{\infty} \frac{|G_n|}{n^2} = \frac{1}{2} + \frac{1}{48} + \frac{1}{216} + \frac{19}{11520} + \frac{3}{4000} + \frac{863}{2177280} + \cdots = 0.5290529\ldots$$

studied in detail in [1] (cf. [1, Appendix A]). This series expansion involves the Gregory coefficients G_n also known as Bernoulli numbers of the second kind.

Remark 5. For $p \geq 2$, the $\mathcal{R}$-sums $\zeta^{\mathcal{R}}(p,p)$ may be evaluated using the relation

$$\zeta^{\mathcal{R}}(p,p) = \mathcal{S}_{p,p} - \int_1^{\infty} \frac{\psi_p(x)}{x^p}\, dx\,,$$

with

$$\psi_p(x) = \frac{(-1)^{p-1}}{(p-1)!} \partial^{p-1} \psi(x+1) + \zeta(p)\,,$$

and the expression

$$\mathcal{S}_{p,p} = \frac{1}{2}\zeta(p)^2 + \frac{1}{2}\zeta(2p)$$

which results directly from the reflection formula. By means of $p - 1$ successive integrations by parts, we can deduce an expression of $\zeta^{\mathcal{R}}(p,p)$ in terms of zeta values $\zeta(2p), \zeta(2p-2), \cdots, \zeta(2)$, as well as $\zeta'(2p-1)$, τ_{2p-1} and a rational constant. For the first values, we thus obtain

$$\zeta^{\mathcal{R}}(2,2) = \frac{7}{4}\zeta(4) + \zeta(2) + 2\zeta'(3) - 2\tau_3 - 1\,,$$

$$\zeta^{\mathcal{R}}(3,3) = \frac{1}{2}\zeta(3)^2 + \frac{1}{2}\zeta(6) + \frac{5}{2}\zeta(3) - 6\zeta(4) - \frac{3}{2}\zeta(2) - 6\zeta'(5) + 6\tau_5 + 1\,.$$

The general formula is given by

$$\zeta^{\mathcal{R}}(p,p) = \frac{1}{2}\zeta(p)^2 + \frac{1}{2}\zeta(2p) - \frac{\zeta(p)}{p-1}$$
$$+ (-1)^p \binom{2p-2}{p-1}\left[\sum_{j=1}^{2p-3}\frac{(-1)^{j+1}}{j}\zeta(2p-1-j) + \zeta'(2p-1) - \tau_{2p-1}\right]$$
$$+ \frac{1}{((p-1)!)^2}\sum_{k=2}^{p-1}(-1)^k(p-k)!(p+k-3)!\,\zeta(p+1-k)$$
$$- \frac{1}{((p-1)!)^2}\sum_{k=2}^{p}(-1)^k(p-k)!(p+k-3)! \qquad (p \geq 3)\,.$$

5 Reflection formulas

5.1 The even case

Theorem (first part)**.** *For any integer $p \geq 2$, we have*

$$\zeta^{\mathcal{R}}(1, 2p) + \zeta^{\mathcal{R}}(2p, 1) = \gamma\zeta(2p) + \zeta(2p+1) - \sum_{j=1}^{2p-2} (-1)^j A_j\, \zeta(2p-j) - \frac{1}{p} \quad (14)$$

with

$$A_j = \frac{(j-1)!(2p-1-j)!}{(2p-1)!}\,.$$

Proof. By adding identities (7) and (11), we get

$$\zeta^{\mathcal{R}}(2p, 1) + \zeta^{\mathcal{R}}(1, 2p) = \gamma\zeta(2p) + \zeta(2p+1) - \sum_{j=1}^{2p-2} \frac{(-1)^j}{j}\, \zeta(2p-j) - \sigma_{2p}\,.$$

Formula (14) follows immediately by replacing σ_{2p} by its expression given by (9). $\qquad\square$

Example 4. We have the following relations:

$$\zeta^{\mathcal{R}}(1, 2) + \zeta^{\mathcal{R}}(2, 1) = \gamma\zeta(2) + \zeta(3) - 1\,,$$

$$\zeta^{\mathcal{R}}(1, 4) + \zeta^{\mathcal{R}}(4, 1) = \gamma\zeta(4) + \zeta(5) + \frac{1}{3}\zeta(3) - \frac{1}{6}\zeta(2) - \frac{1}{2}\,,$$

$$\zeta^{\mathcal{R}}(1, 6) + \zeta^{\mathcal{R}}(6, 1) = \gamma\zeta(6) + \zeta(7) + \frac{1}{5}\zeta(5) - \frac{1}{20}\zeta(4) + \frac{1}{30}\zeta(3) - \frac{1}{20}\zeta(2) - \frac{1}{3}\,.$$

5.2 The odd case

Theorem (second part)**.** *For any integer $p \geq 2$, we have*

$$\zeta^{\mathcal{R}}(1, 2p-1) + \zeta^{\mathcal{R}}(2p-1, 1)$$

$$= \gamma\zeta(2p-1) + \zeta(2p) - \sum_{j=1}^{2p-3} (-1)^j C_j\, \zeta(2p-1-j)$$

$$- 2\zeta'(2p-1) + 2\tau_{2p-1} \quad (15)$$

with

$$C_j = \frac{(j-1)!(2p-2-j)!}{(2p-2)!} - \frac{2}{j}\,.$$

12

Proof. By adding identities (6) and (10), we get

$$\zeta^{\mathcal{R}}(p,1) + \zeta^{\mathcal{R}}(1,p) = \gamma\zeta(p) + \zeta(p+1) - \sigma_p - (-1)^p \sum_{j=1}^{p-2} \frac{(-1)^j}{j}\zeta(p-j)$$
$$+ (1-(-1)^p)\tau_p + ((-1)^p - 1)\zeta'(p).$$

Hence we have the following relation

$$\zeta^{\mathcal{R}}(2p-1,1) + \zeta^{\mathcal{R}}(1,2p-1) = \zeta(2p) + \gamma\zeta(2p-1) - \sigma_{2p-1} + \sum_{j=1}^{2p-3} \frac{(-1)^j}{j}\zeta(2p-1-j)$$
$$- 2\zeta'(2p-1) + 2\tau_{2p-1}$$

Formula (15) follows by replacing σ_{2p-1} by its expression given by (9). Note that, in the odd case, the constant term of σ_{2p-1} is null. $\qquad\square$

Example 5. We have the following relations:

$$\zeta^{\mathcal{R}}(1,3) + \zeta^{\mathcal{R}}(3,1) = \gamma\zeta(3) + \zeta(4) - \frac{3}{2}\zeta(2) - 2\zeta'(3) + 2\tau_3,$$

$$\zeta^{\mathcal{R}}(1,5) + \zeta^{\mathcal{R}}(5,1) = \gamma\zeta(5) + \zeta(6) - \frac{7}{4}\zeta(4) + \frac{11}{12}\zeta(3) - \frac{7}{12}\zeta(2) - 2\zeta'(5) + 2\tau_5,$$

$$\zeta^{\mathcal{R}}(1,7) + \zeta^{\mathcal{R}}(7,1) = \gamma\zeta(7) + \zeta(8) - \frac{11}{6}\zeta(6) + \frac{29}{30}\zeta(5) - \frac{17}{30}\zeta(4) + \frac{2}{5}\zeta(3) - \frac{11}{30}\zeta(2)$$
$$- 2\zeta'(7) + 2\tau_7.$$

References

[1] I. Blagouchine, M-A. Coppo, A note on some constants related to the zeta-function and their relationship with the Gregory coeffficients, *Ramanujan J.* **47** (2018), 457-473.

[2] K. N. Boyadzhiev, A special constant and series with zeta values and harmonic numbers, *Gazeta Matematica*, Seria A, **115** (2018), 1–16.

[3] K. N. Boyadzhiev, New series identities with Cauchy, Stirling, and harmonic numbers, and Laguerre polynomials, 2020, arXiv:1911.00186v2.

[4] B. Candelpergher, *Ramanujan Summation of Divergent Series*, Lecture Notes in Math. 2185, Springer, 2017.

[5] B. Candelpergher, M-A. Coppo, A new class of identities involving Cauchy numbers, harmonic numbers and zeta values, *Ramanujan J.* **27** (2012), 305–328.

[6] B. Candelpergher, M-A. Coppo, Laurent expansion of harmonic zeta functions, *J. Math. Anal. App.* **491** (2020), Article 124309.

[7] H. Cohen, *Number Theory, Volume II: Analytic and Modern Tools*, Graduate Texts in Math., vol. 240, Springer, 2007.

[8] M-A. Coppo, A note on some alternating series involving zeta and multiple zeta values, *J. Math. Anal. App.* **475** (2019), 1831–1841.

[9] A. Dil, K. N. Boyadzhiev, and I. A. Aliev, On values of the Riemann zeta function at positive integers, *Lithuanian Math. J.* **60** (2020), 9–24.

[10] R. Sitaramachandrarao, A formula of S. Ramanujan, *J. Number Theory* **25** (1987), 1–19.

[11] B. Sury, T. Wang, and F. Z. Zhao, Identities involving reciprocals of binomial coefficients, *J. Integer Sequences* **7** (2004), Article 04.2.8 .

[12] W. Wang, Y. Lyu, Euler sums and Stirling sums, *J. Number Theory* **185** (2018), 160–193.