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SEQUENCES THAT CONVERGE TO A GENERALIZATION OF IOACHIMESCU'S CONSTANT

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Abstract. We consider a generalization of Ioachimescu's constant as the limit $\mathcal{I}(a;s)$ of the sequence $\left(\frac{1}{a^s}+\frac{1}{(a+1)^s}+\cdots+\frac{1}{(a+n-1)^s}-\frac{1}{1-s}((a+n-1)^{1-s}-a^{1-s})\right)_{n\in\mathbb{N}}$, where $a\in(0,+\infty)$ and $s\in(0,1)$.

The purpose of this paper is to give some sequences that converge quickly to $\mathcal{I}(a;s)$.

1. Introduction

A. G. Ioachimescu [8] proposed in 1895 a problem in which he asked to be shown that the sequence $(S_n)_{n\in\mathbb{N}}$, defined by $S_n=1+\frac{1}{\sqrt{2}}+\cdots+\frac{1}{\sqrt{n}}-2\sqrt{n}$, for each $n\in\mathbb{N}$, is convergent and its limit lies between -2 and -1.

Many generalizations and other results regarding the above-mentioned problem have been obtained in the literature. See, for example, [1], [2], [3], [4, Theorem 1, parts a) and b)], [5, problem 3, p. 534], [6, problem 3.1, p. 431], [7, problem P2, parts (i) and (ii)]. Also, see [14, pp. 27–33], [15], [16], [17], [18].

In [15], we considered the sequence $(I_n)_{n\in\mathbb{N}}$ defined by $I_n=1+\frac{1}{\sqrt{2}}+\cdots+\frac{1}{\sqrt{n}}-2(\sqrt{n}-1)$, for each $n\in\mathbb{N}$. We denoted the limit of $(I_n)_{n\in\mathbb{N}}$ by $\mathcal{I}$, calling it Ioachimescu's constant. In [18], we have proved that

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$$\frac{1}{2\sqrt{n+\frac{1}{5}}} < I_n - \mathcal{I} < \frac{1}{2\sqrt{n+\frac{1}{6}}},$$

for each $n \in \mathbb{N}$. Using these inequalities we get $\mathcal{I} = 0.53964549119\ldots$. Let $a \in (0, +\infty)$. We considered in [15, Theorem 2] the sequence $(y_n(a))_{n\in\mathbb{N}}$, defined by

$$y_n(a) = \frac{1}{\sqrt{a}} + \frac{1}{\sqrt{a+1}} + \cdots + \frac{1}{\sqrt{a+n-1}} - 2(\sqrt{a+n-1} - \sqrt{a}),$$

for each $n \in \mathbb{N}$, and $\mathcal{I}(a) = \lim\limits_{n\to\infty} y_n(a)$. Surely, $\mathcal{I}(a)$ is a generalization of Ioachimescu's constant, because $\mathcal{I}(1) = \mathcal{I}$. We have $\lim\limits_{n\to\infty} \sqrt{n}(y_n(a) - \mathcal{I}(a)) = \frac{1}{2}$ ([15, Theorem 2, part (iii)]).

Let $a \in (0, +\infty)$ and $s \in (0, 1)$. In [17, Theorem 2], we considered the sequence $(y_n(a; s))_{n\in\mathbb{N}}$, defined by

$$y_n(a; s) = \frac{1}{a^s} + \frac{1}{(a+1)^s} + \cdots + \frac{1}{(a+n-1)^s} - \frac{1}{1-s}((a+n-1)^{1-s} - a^{1-s}),$$

for each $n \in \mathbb{N}$, and $\mathcal{I}(a; s) = \lim\limits_{n\to\infty} y_n(a; s)$. Clearly, $\mathcal{I}(a; s)$ is a generalization of Ioachimescu's constant, since $\mathcal{I}\left(1; \frac{1}{2}\right) = \mathcal{I}$. We have proved in [17, Theorem 2, part (iii)] that

$$\lim_{n\to\infty} n^s(y_n(a; s) - \mathcal{I}(a; s)) = \frac{1}{2}.$$

We have also given in [17, Theorems 3, 4 and 5] some sequences that converge to $\mathcal{I}(a; s)$ with order $s + 1$.

We remind a lemma given by C. Mortici [10, Lemma], which we shall need further on. Applications of this lemma can be also found in [11], [12], [13] as well as in some of the references therein.

Lemma 1.1. *Let $(x_n)_{n\in\mathbb{N}}$ be a convergent sequence of real numbers and $x^* = \lim\limits_{n\to\infty} x_n$. We suppose that there exists $\alpha \in \mathbb{R}$, $\alpha > 1$, such that*

$$\lim_{n\to\infty} n^\alpha(x_n - x_{n+1}) = l \in \overline{\mathbb{R}}.$$

Then there exists the limit

$$\lim_{n\to\infty} n^{\alpha-1}(x_n - x^*) = \frac{l}{\alpha - 1}.$$

Also, we mention for Lemma 1.1 another proof than the one given by C. Mortici [10, Lemma]. According to the Stolz-Cesaro Theorem, the case $\frac{0}{0}$, we can write that
$\lim_{n\to\infty} n^{\alpha-1}(x_n - x^*) =$
$= \lim_{n\to\infty} \frac{x_n - x^*}{\frac{1}{n^{\alpha-1}}} = \lim_{n\to\infty} \frac{x_{n+1}-x^*-(x_n-x^*)}{\frac{1}{(n+1)^{\alpha-1}}-\frac{1}{n^{\alpha-1}}}$
and
$\lim_{n\to\infty} n^{\alpha-1}(x_n - x^*) =$
$= \lim_{n\to\infty} \left(n^\alpha(x_n - x_{n+1}) \cdot \frac{(n+1)^{\alpha-1}}{n((n+1)^{\alpha-1}-n^{\alpha-1})}\right) = \frac{l}{\alpha-1}.$

In Section 2 we give some sequences that converge quickly to $\mathcal{I}(a;s)$.

2. Sequences that converge to $\mathcal{I}(a;s)$

Inspired by an idea of C. Mortici [11, Theorem 2.1] in getting sequences that converge quicker to a generalization of the well-known Euler's constant, we give the following theorem in order to obtain sequences that converge quicker to $\mathcal{I}(a;s)$.

Theorem 2.1. *Let $a \in (0,+\infty)$, $b, c \in \mathbb{R}$, $s \in (0,1)$ and $n_0 = \max\{1, \lceil 1-a-c\rceil\}$, where $\lceil x\rceil$ is the ceiling of the real number x. We consider the sequence $(v_n(a,b,c;s))_{n\geq n_0}$ defined by*

$$v_n(a,b,c;s) = \frac{1}{a^s} + \frac{1}{(a+1)^s} + \cdots + \frac{1}{(a+n-1)^s} + \frac{b}{(a+n-1)^s} - \frac{1}{1-s}\left[(a+n-1+c)^{1-s} - a^{1-s}\right],$$

for each $n \in \mathbb{N}$, with $n \geq n_0$. Also, we specify that $\mathcal{I}(a;s)$ is the limit of the sequence $(y_n(a;s))_{n\in\mathbb{N}}$ from Introduction.

(*i*) *If $b \neq c - \frac{1}{2}$, then*
$\lim_{n\to\infty} n^s(v_n(a,b,c;s) - \mathcal{I}(a;s)) = b - c + \frac{1}{2}$.

(*ii*) *If $b = c - \frac{1}{2}$ and $c \neq \pm\frac{\sqrt{6}}{6}$, then*
$\lim_{n\to\infty} n^{s+1}\left(v_n\left(a, c-\frac{1}{2}, c; s\right) - \mathcal{I}(a;s)\right) = \frac{s}{2}\left(c^2 - \frac{1}{6}\right)$.

(*iii*) *If $b = c - \frac{1}{2}$ and $c = \frac{\sqrt{6}}{6}$, then*
$\lim_{n\to\infty} n^{s+2}\left(v_n\left(a, \frac{\sqrt{6}}{6} - \frac{1}{2}, \frac{\sqrt{6}}{6}; s\right) - \mathcal{I}(a;s)\right) = -\frac{s(s+1)\sqrt{6}}{216}$.

(*iv*) *If $b = c - \frac{1}{2}$ and $c = -\frac{\sqrt{6}}{6}$, then*
$\lim_{n\to\infty} n^{s+2}\left(v_n\left(a, -\frac{\sqrt{6}}{6} - \frac{1}{2}, -\frac{\sqrt{6}}{6}; s\right) - \mathcal{I}(a;s)\right) = \frac{s(s+1)\sqrt{6}}{216}$.

Proof. We are able to write that $\lim\limits_{n\to\infty} v_n(a,b,c;s) = \mathcal{I}(a;s)$, taking into account that $\lim\limits_{n\to\infty}[(a+n-1+c)^{1-s} - (a+n-1)^{1-s}] = 0$.

We have
$v_n(a,b,c;s) - v_{n+1}(a,b,c;s) = \frac{b}{(a+n-1)^s} - \frac{b+1}{(a+n)^s}$
and
$v_n(a,b,c;s) - v_{n+1}(a,b,c;s) = -\frac{1}{1-s}[(a+n-1+c)^{1-s} - (a+n+c)^{1-s}]$,
for each $n \in \mathbb{N}$, with $n \geq n_0$. We can write that
$v_n(a,b,c;s) - v_{n+1}(a,b,c;s) = b\varepsilon_n^s(1-\varepsilon_n)^{-s} - (b+1)\varepsilon_n^s$
and
$v_n(a,b,c;s) - v_{n+1}(a,b,c;s) = -\frac{1}{1-s}\varepsilon_n^{-(1-s)}[(1+(c-1)\varepsilon_n)^{1-s} - (1+c\varepsilon_n)^{1-s}]$, where $\varepsilon_n := \frac{1}{a+n}$, for each $n \in \mathbb{N}$, with $n \geq n_0$. Let $m_0 = \max\{n_0, \lceil -a+c \rceil\}$. Since $|(c-1)\varepsilon_n| < 1$ and $|c\varepsilon_n| < 1$, for each $n \in \mathbb{N}$, with $n > m_0$, using the Binomial Theorem ([9, p. 209]) we obtain that

$$
\begin{aligned}
&v_n(a,b,c;s) - v_{n+1}(a,b,c;s)\\
&= b\varepsilon_n^s \Big[1 + \tfrac{-s}{1!}(-\varepsilon_n) + \tfrac{-s(-s-1)}{2!}(-\varepsilon_n)^2 + \tfrac{-s(-s-1)(-s-2)}{3!}(-\varepsilon_n)^3\\
&+ \tfrac{-s(-s-1)(-s-2)(-s-3)}{4!}(-\varepsilon_n)^4 + \cdots\Big] - (b+1)\varepsilon_n^s\\
&- \tfrac{1}{1-s}\varepsilon_n^{-(1-s)}\Big[1 + \tfrac{1-s}{1!}(c-1)\varepsilon_n + \tfrac{(1-s)(-s)}{2!}(c-1)^2\varepsilon_n^2\\
&+ \tfrac{(1-s)(-s)(-s-1)}{3!}(c-1)^3\varepsilon_n^3 + \tfrac{(1-s)(-s)(-s-1)(-s-2)}{4!}(c-1)^4\varepsilon_n^4\\
&+ \tfrac{(1-s)(-s)(-s-1)(-s-2)(-s-3)}{5!}(c-1)^5\varepsilon_n^5 + \cdots\\
&- 1 - \tfrac{1-s}{1!}c\varepsilon_n - \tfrac{(1-s)(-s)}{2!}c^2\varepsilon_n^2 - \tfrac{(1-s)(-s)(-s-1)}{3!}c^3\varepsilon_n^3\\
&- \tfrac{(1-s)(-s)(-s-1)(-s-2)}{4!}c^4\varepsilon_n^4\\
&- \tfrac{(1-s)(-s)(-s-1)(-s-2)(-s-3)}{5!}c^5\varepsilon_n^5 - \cdots\Big]\\
&= b\varepsilon_n^s\Big[\tfrac{s}{1!}\varepsilon_n + \tfrac{s(s+1)}{2!}\varepsilon_n^2 + \tfrac{s(s+1)(s+2)}{3!}\varepsilon_n^3 + \tfrac{s(s+1)(s+2)(s+3)}{4!}\varepsilon_n^4 + \cdots\Big]\\
&- \varepsilon_n^s\Big[\tfrac{s}{2!}(2c-1)\varepsilon_n - \tfrac{s(s+1)}{3!}(3c^2-3c+1)\varepsilon_n^2\\
&+ \tfrac{s(s+1)(s+2)}{4!}(4c^3-6c^2+4c-1)\varepsilon_n^3\\
&- \tfrac{s(s+1)(s+2)(s+3)}{5!}(5c^4-10c^3+10c^2-5c+1)\varepsilon_n^4 + \cdots\Big]\\
&= \tfrac{s}{1!}\left(b-c+\tfrac{1}{2}\right)\varepsilon_n^{s+1} + \tfrac{s(s+1)}{2!}\left(b+c^2-c+\tfrac{1}{3}\right)\varepsilon_n^{s+2}\\
&+ \tfrac{s(s+1)(s+2)}{3!}\left(b-c^3+\tfrac{3}{2}c^2-c+\tfrac{1}{4}\right)\varepsilon_n^{s+3}\\
&+ \tfrac{s(s+1)(s+2)(s+3)}{4!}\left(b+c^4-2c^3+2c^2-c+\tfrac{1}{5}\right)\varepsilon_n^{s+4} + \cdots,
\end{aligned}
$$

for each $n \in \mathbb{N}$, with $n > m_0$.

(i) Because $b \neq c - \frac{1}{2}$, we can write that
$\lim_{n\to\infty} n^{s+1}(v_n(a,b,c;s) - v_{n+1}(a,b,c;s)) = \frac{s}{1!}\left(b-c+\frac{1}{2}\right)$.
Now, according to Lemma 1.1, it follows that
$\lim_{n\to\infty} n^s(v_n(a,b,c;s) - \mathcal{I}(a;s)) = b - c + \frac{1}{2}$.

(ii) Because $b = c - \frac{1}{2}$ and $c \neq \pm\frac{\sqrt{6}}{6}$, we can write that $\lim_{n\to\infty} n^{s+2}\left(v_n\left(a, c-\frac{1}{2}, c; s\right) - v_{n+1}\left(a, c-\frac{1}{2}, c; s\right)\right) = \frac{s(s+1)}{2!}\left(c^2 - \frac{1}{6}\right).$
Now, according to Lemma 1.1, it follows that
$\lim_{n\to\infty} n^{s+1}\left(v_n\left(a, c-\frac{1}{2}, c; s\right) - \mathfrak{I}(a; s)\right) = \frac{s}{2}\left(c^2 - \frac{1}{6}\right).$

(iii) Because $b = c - \frac{1}{2}$ and $c = \frac{\sqrt{6}}{6}$, we can write that $\lim_{n\to\infty} n^{s+3}\left(v_n\left(a, \frac{\sqrt{6}}{6} - \frac{1}{2}, \frac{\sqrt{6}}{6}; s\right) - v_{n+1}\left(a, \frac{\sqrt{6}}{6} - \frac{1}{2}, \frac{\sqrt{6}}{6}; s\right)\right) = -\frac{s(s+1)(s+2)}{3!}\cdot\frac{\sqrt{6}}{36}.$
Now, according to Lemma 1.1, it follows that

$$\lim_{n\to\infty} n^{s+2}\left(v_n\left(a, \frac{\sqrt{6}}{6} - \frac{1}{2}, \frac{\sqrt{6}}{6}; s\right) - \mathfrak{I}(a; s)\right) = -\frac{s(s+1)\sqrt{6}}{216}.$$

(iv) Because $b = c - \frac{1}{2}$ and $c = -\frac{\sqrt{6}}{6}$, we can write that $\lim_{n\to\infty} n^{s+3}\left(v_n\left(a, -\frac{\sqrt{6}}{6} - \frac{1}{2}, -\frac{\sqrt{6}}{6}; s\right) - v_{n+1}\left(a, -\frac{\sqrt{6}}{6} - \frac{1}{2}, -\frac{\sqrt{6}}{6}; s\right)\right) = \frac{s(s+1)(s+2)}{3!}\cdot\frac{\sqrt{6}}{36}$. Now, according to Lemma 1.1, it follows that

$$\lim_{n\to\infty} n^{s+2}\left(v_n\left(a, -\frac{\sqrt{6}}{6} - \frac{1}{2}, -\frac{\sqrt{6}}{6}; s\right) - \mathfrak{I}(a; s)\right) = \frac{s(s+1)\sqrt{6}}{216}.$$

$\square$

Corollary 2.1. *Let $a \in (0, +\infty)$, $b, c \in \mathbb{R}$ and $n_0 = \max\{1, \lceil 1 - a - c\rceil\}$, where $\lceil x\rceil$ is the ceiling of the real number x. We consider the sequence $(v_n(a, b, c))_{n\geq n_0}$ defined by*
$v_n(a, b, c) = \frac{1}{\sqrt{a}} + \frac{1}{\sqrt{a+1}} + \cdots + \frac{1}{\sqrt{a+n-1}} + \frac{b}{\sqrt{a+n-1}} - 2(\sqrt{a+n-1+c} - \sqrt{a})$,
for each $n \in \mathbb{N}$, with $n \geq n_0$. Also, we specify that $\mathfrak{I}(a)$ is the limit of the sequence $(y_n(a))_{n\in\mathbb{N}}$ from Introduction.

(i) *If $b \neq c - \frac{1}{2}$, then*

$$\lim_{n\to\infty} \sqrt{n}(v_n(a, b, c) - \mathfrak{I}(a)) = b - c + \frac{1}{2}.$$

(ii) *If $b = c - \frac{1}{2}$ and $c \neq \pm\frac{\sqrt{6}}{6}$, then*

$$\lim_{n\to\infty} n\sqrt{n}\left(v_n\left(a, c - \frac{1}{2}, c\right) - \mathfrak{I}(a)\right) = \frac{1}{4}\left(c^2 - \frac{1}{6}\right).$$

(*iii*) *If* $b = c - \frac{1}{2}$ *and* $c = \frac{\sqrt{6}}{6}$, *then*

$$\lim_{n\to\infty} n^2\sqrt{n}\left(v_n\left(a, \frac{\sqrt{6}}{6} - \frac{1}{2}, \frac{\sqrt{6}}{6}\right) - \mathcal{I}(a)\right) = -\frac{\sqrt{6}}{288}.$$

(*iv*) *If* $b = c - \frac{1}{2}$ *and* $c = -\frac{\sqrt{6}}{6}$, *then*

$$\lim_{n\to\infty} n^2\sqrt{n}\left(v_n\left(a, -\frac{\sqrt{6}}{6} - \frac{1}{2}, -\frac{\sqrt{6}}{6}\right) - \mathcal{I}(a)\right) = \frac{\sqrt{6}}{288}.$$

Proof. We take $s = \frac{1}{2}$ in Theorem 2.1. □

In the next theorem we shall give a sequence that converge to $\mathcal{I}(a; s)$ quicker than the sequences from parts (*iii*) and (*iv*) of Theorem 2.1.

Theorem 2.2. *Let* $a \in (0, +\infty)$ *and* $s \in (0, 1)$. *We consider the sequence* $(w_n)_{n\geq 2}$ *defined by*
$w_n(a; s) = \frac{1}{a^s} + \frac{1}{(a+1)^s} + \cdots + \frac{1}{(a+n-1)^s} - \frac{1}{2(a+n-1)^s}$
$- \frac{1}{2(1-s)}\left[\left(a + n - 1 + \frac{\sqrt{6}}{6}\right)^{1-s} + \left(a + n - 1 - \frac{\sqrt{6}}{6}\right)^{1-s} - 2a^{1-s}\right]$,
for each $n \in \mathbb{N} \setminus \{1\}$. *Also, we specify that* $\mathcal{I}(a; s)$ *is the limit of the sequence* $(y_n(a; s))_{n\in\mathbb{N}}$ *from Introduction.*

Then

$$\lim_{n\to\infty} n^{s+3}(w_n(a; s) - \mathcal{I}(a; s)) = \frac{11s(s + 1)(s + 2)}{4320}.$$

Proof. As can be easily seen, we have

$$w_n(a; s) = \frac{1}{2}\left[v_n\left(a, \frac{\sqrt{6}}{6} - \frac{1}{2}, \frac{\sqrt{6}}{6}; s\right) + v_n\left(a, -\frac{\sqrt{6}}{6} - \frac{1}{2}, -\frac{\sqrt{6}}{6}; s\right)\right],$$

for each $n \in \mathbb{N} \setminus \{1\}$, where $\left(v_n\left(a, \frac{\sqrt{6}}{6} - \frac{1}{2}, \frac{\sqrt{6}}{6}; s\right)\right)_{n\in\mathbb{N}}$ and $\left(v_n\left(a, -\frac{\sqrt{6}}{6} - \frac{1}{2}, -\frac{\sqrt{6}}{6}; s\right)\right)_{n\geq 2}$ are the sequences considered in Theorem 2.1, in parts (*iii*) and (*iv*) respectively. We have that

$$\lim_{n\to\infty} n^{s+4}(w_n(a; s) - w_{n+1}(a; s)) = \frac{s(s + 1)(s + 2)(s + 3)}{4!} \cdot \frac{11}{180}.$$

Now, according to Lemma 1.1, it follows that

$$\lim_{n\to\infty} n^{s+3}(w_n(a; s) - \mathcal{I}(a; s)) = \frac{11s(s + 1)(s + 2)}{4320}.$$

□

Corollary 2.2. *Let $a \in (0,+\infty)$. We consider the sequence $(w_n(a))_{n\geq 2}$ defined by*

$$w_n(a) = \frac{1}{\sqrt{a}} + \frac{1}{\sqrt{a+1}} + \cdots + \frac{1}{\sqrt{a+n-1}} - \frac{1}{2\sqrt{a+n-1}} - \left(\sqrt{a+n-1+\frac{\sqrt{6}}{6}} + \sqrt{a+n-1-\frac{\sqrt{6}}{6}} - 2\sqrt{a}\right),$$

for each $n \in \mathbb{N} \setminus \{1\}$. Also, we specify that $\mathcal{I}(a)$ is the limit of the sequence $(y_n(a))_{n\in\mathbb{N}}$ from Introduction.

Then

$$\lim_{n\to\infty} n^3\sqrt{n}(w_n(a) - \mathcal{I}(a)) = \frac{11}{2304}.$$

Proof. We take $s = \frac{1}{2}$ in Theorem 2.2. □

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