REMARKS ON A PAPER BY CHAO-PING CHEN
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(Communicated by Carmen C. Chicone)

Abstract. In a recent paper, Chao-Ping Chen and Feng Qi (2005) established sharp upper and lower bounds for the sequence $P_n := \frac{1.3\ldots(2n-1)}{2.4\ldots2n}$. We show that their result follows easily from a theorem of G. N. Watson published in 1959. We also show that the main result of Chen and Qi’s paper is a special case of a more general inequality which admits a very short proof.

1. Introduction and results

Let

$$P_n := \frac{1.3\ldots(2n-1)}{2.4\ldots2n}.$$           (1.1)

This sequence appears in Wallis’s well-known product formula of approximation of $\pi$ and in various other topics of analysis and number theory. In the recent paper [2], Chao-Ping Chen and Feng Qi proved the following inequality:

$$\frac{1}{\sqrt{\pi(n + \frac{1}{4})}} \leq P_n < \frac{1}{\sqrt{\pi(n + \frac{1}{4})}}, \quad n = 1, 2, \ldots.$$           (1.1)

The constants $\frac{4}{\pi} - 1$ and $\frac{1}{4}$ are the best possible. Inequality (1.1) improves some earlier results dealing with estimates of the sequence $P_n$.

Here we observe that (1.1) follows easily from a known result due to G. N. Watson [15]. Indeed, it is shown in [15] that the function

$$\theta(x) = \left( \frac{\Gamma(x + 1)}{\Gamma(x + \frac{1}{2})} \right)^2 - x$$

is strictly decreasing on $(-1/2, \infty)$. Applying this result, together with the observation that $\theta(1) = 4/\pi - 1$, $\lim_{x \to \infty} \theta(x) = 1/4$ and $P_n = \frac{\Gamma(n + \frac{1}{2})}{\sqrt{\pi} \Gamma(n + 1)}$, we obtain the double inequality (1.1).

The purpose of this note is to show that (1.1) is a special case of a more general inequality, which in fact, admits a very short proof. Let $0 < \alpha < 1$ and

$$d_n(\alpha) := \frac{(1 - \alpha)^n}{n!}.$$
As usual, \((a)_k\) denotes the Pochhammer symbol, defined by
\[(a)_0 = 1, \text{ and } (a)_k = a(a+1) \ldots (a+k-1) = \frac{\Gamma(k+a)}{\Gamma(a)}, \text{ for } k = 1, 2, \ldots .\]

Clearly, \(d_n(1/2) = P_n\). It is also well known and easy to see that
\[
1 \frac{1}{\Gamma(1-\alpha)(n+1)^\alpha} < d_n(\alpha) < \frac{1}{\Gamma(1-\alpha)n^\alpha}.
\]

Here we show that this inequality can be improved as follows.

**Theorem 1.1.** For all natural numbers \(n\), we have
\[
1 \frac{1}{\Gamma(1-\alpha)(n+c_2)^\alpha} \leq d_n(\alpha) < \frac{1}{\Gamma(1-\alpha)(n+c_1)^\alpha},
\]
where the constants
\[c_1 = c_1(\alpha) = \frac{1-\alpha}{2} \quad \text{and} \quad c_2 = c_2(\alpha) = \frac{1}{[\Gamma(2-\alpha)]^{1/\alpha}} - 1\]
are the best possible.

It is clear that for \(\alpha = 1/2\), inequality (1.3) coincides with (1.1).

Inequalities such as (1.2) and (1.3) are of particular importance in certain problems on positive trigonometric sums and positive sums of Gegenbauer polynomials, having \(d_k(\alpha)\) as a sequence of coefficients. See the recent papers [9] and [10]. We also refer to the paper [11] for some interesting estimates of ratios of gamma functions. Some other proofs of (1.1) and related results can be found in the recent articles [3], [4], [5], [6] and [7]. Compare also the papers [12], [13] and [14] for different proofs of (1.1) and various inequalities for the sequence \(P_n\).

2. **Proof of (1.3)**

For the proof of (1.3) we define
\[
Q_n(\alpha) := \left\{ \frac{\Gamma(n+1)}{\Gamma(n+1-\alpha)} \right\}^{1/\alpha} - n.
\]

Using the asymptotic formula
\[
x^{b-a} \frac{\Gamma(x+a)}{\Gamma(x+b)} = 1 + \frac{(a-b)(a+b-1)}{2x} + O\left(\frac{1}{x^2}\right), \quad x \to \infty
\]
(see [1], p. 615, for the complete form of this formula), we easily verify that
\[
\lim_{n \to \infty} Q_n(\alpha) = \frac{1-\alpha}{2} = c_1.
\]

Obviously \(c_2 = Q(1,\alpha)\).

The required inequality (1.3) follows from the fact that the sequence \(Q_n(\alpha)\) is strictly decreasing. This, in turn, is an immediate consequence of a result of N. Elezović, C. Giordano and J. Pečarić, [8] who showed that the function
\[
x \mapsto \left( \frac{\Gamma(x+t)}{\Gamma(x+s)} \right)^{1/(t-s)} - x
\]
is convex and decreasing on \((-r, \infty)\) if \(|t-s| < 1\), where \(s, t\) are given positive numbers and \(r = \min(s, t)\).

This completes the proof of (1.3). \(\square\)
References


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