



**HAL**  
open science

## A hypergeometric proof that Iso is bijective

Alin Bostan, Sergey Yurkevich

► **To cite this version:**

Alin Bostan, Sergey Yurkevich. A hypergeometric proof that Iso is bijective. Proceedings of the American Mathematical Society, 2022, 150 (5), pp.2131-2136. 10.1090/proc/15836 . hal-03426008

**HAL Id: hal-03426008**

**<https://hal.science/hal-03426008v1>**

Submitted on 11 Nov 2021

**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.

# A hypergeometric proof that $\mathbf{Iso}$ is bijective

Alin Bostan<sup>\*</sup> and Sergey Yurkevich<sup>‡</sup>

November 11, 2021

## Abstract

We provide a short and elementary proof of the main technical result of the recent article “*On the uniqueness of Clifford torus with prescribed isoperimetric ratio*” [4] by Thomas Yu and Jingmin Chen. The key of the new proof is an explicit expression of the central function ( $\mathbf{Iso}$ , to be proved bijective) as a quotient of Gaussian hypergeometric functions.

In their recent paper [4], Thomas Yu and Jingmin Chen needed to prove, as a crucial intermediate result, that a certain real-valued function  $\mathbf{Iso}$  (related to isoperimetric ratios of Clifford tori) is strictly increasing. They reduced the proof of this fact to the positivity of a sequence of rational numbers  $(d_n)_{n \geq 0}$ , defined explicitly in terms of nested binomial sums. This positivity was subsequently proved by Stephen Melczer and Marc Mezzarobba [3], who used a computer-assisted approach relying on analytic combinatorics and rigorous numerics, combined with the fact (proved in [4]) that the sequence  $(d_n)_{n \geq 0}$  satisfies an explicit linear recurrence of order seven with polynomial coefficients in  $n$ .

In this note, we provide an alternative, short and conceptual, proof of the monotonicity of the function  $\mathbf{Iso}$ . Our approach is different in spirit from the ones in [4] and [3]. Our main result (Theorem 2 below) is that the function  $\mathbf{Iso}(z)$  can be expressed in terms of Gaussian hypergeometric functions  ${}_2F_1$  defined by

$${}_2F_1 \left[ \begin{matrix} a & b \\ c \end{matrix} ; z \right] = \sum_{n=0}^{\infty} \frac{(a)_n (b)_n}{(c)_n} \frac{z^n}{n!}, \quad (1)$$

where  $(a)_n$  denotes the rising factorial  $(a)_n = a(a+1) \cdots (a+n-1)$  for  $n \in \mathbb{N}$ .

In the notation of Yu and Chen, the function

$$\mathbf{Iso} : [0, \sqrt{2} - 1] \rightarrow [3/2 \cdot (2\pi^2)^{-1/4}, 1)$$

is given as

$$\mathbf{Iso}(z) = 6\sqrt{\pi} \cdot \frac{V(z)}{A^{3/2}(z)}, \quad (2)$$

---

<sup>\*</sup>Inria, Univ. Paris-Saclay, France, [alin.bostan@inria.fr](mailto:alin.bostan@inria.fr).

<sup>‡</sup>U. Wien, Austria and Inria, Univ. Paris-Saclay, France, [sergey.yurkevich@univie.ac.at](mailto:sergey.yurkevich@univie.ac.at).

where  $A(z) = \sum_{n \geq 0} a_n z^{2n}$  and  $V(z) = \sum_{n \geq 0} v_n z^{2n}$  are complex analytic functions in the disk  $\{z : |z| < \sqrt{2} - 1\}$ , given by the power series expansions

$$A(z) = \sqrt{2}\pi^2 \cdot \left( 4 + 52z^2 + 477z^4 + 3809z^6 + \frac{451625}{16}z^8 + \dots \right),$$

$$V(z) = \sqrt{2}\pi^2 \cdot \left( 2 + 48z^2 + \frac{1269}{2}z^4 + 6600z^6 + \frac{1928025}{32}z^8 + \dots \right).$$

The precise definitions of  $A$  and  $V$  are given in Section 4.3 of [4], notably in equations (4.2)–(4.3). Since the sequences  $(a_n)_{\geq 0}$  and  $(v_n)_{\geq 0}$  are expressed in terms of nested binomial sums,  $A(z)$  and  $V(z)$  satisfy linear differential equations with polynomial coefficients in  $z$ , that can be found and proved automatically using *creative telescoping* [2]. Yu and Chen, resp. Melczer and Mezzarobba, use this methodology to find a linear recurrence satisfied by the coefficients  $(d_n)_{n \geq 0}$  of

$$F(z) := \frac{1}{4\pi^4} \cdot \left( \frac{2V'(\sqrt{z})A(\sqrt{z}) - 3V(\sqrt{z})A'(\sqrt{z})}{\sqrt{z}} \right) = 72 + 1932z + 31248z^3 + \dots,$$

respectively a linear differential equation satisfied by the function  $F(z)$ .

Similarly, one can compute linear differential equations satisfied individually by

$$\bar{A}(z) := \frac{1}{\sqrt{2}\pi^2} \cdot A(\sqrt{z}) = 4 + 52z + 477z^2 + 3809z^3 + \frac{451625}{16}z^4 + \frac{3195333}{16}z^5 + \dots$$

and by

$$\bar{V}(z) := \frac{1}{\sqrt{2}\pi^2} \cdot V(\sqrt{z}) = 2 + 48z + \frac{1269}{2}z^2 + 6600z^3 + \frac{1928025}{32}z^4 + \frac{2026101}{4}z^5 + \dots.$$

Concretely,  $\bar{A}(z)$  and  $\bar{V}(z)$  satisfy second-order linear differential equations:

$$z(z-1)(z^2-6z+1)(z+1)^2 \bar{A}''(z) + (z+1)(5z^4-8z^3-32z^2+28z-1) \bar{A}'(z) \\ + (4z^4+11z^3-z^2-43z+13) \bar{A}(z) = 0$$

and respectively

$$z(z-1)(z+1)(z^2-6z+1)^2 \bar{V}''(z) \\ + (z^2-6z+1)(7z^4-22z^3-18z^2+26z-1) \bar{V}'(z) \\ + 3(3z^5-24z^4-2z^3+56z^2-25z+8) \bar{V}(z) = 0.$$

From these equations, we deduce the following closed-form expressions:

**Theorem 1.** *The following equalities hold for all  $z \in \mathbb{R}$  with  $0 \leq z \leq \sqrt{2} - 1$ :*

$$\bar{A}(z) = \frac{4(1-z^2)}{(z^2-6z+1)^2} \cdot {}_2F_1 \left[ \begin{matrix} -\frac{1}{2} & -\frac{1}{2} \\ 1 \end{matrix}; \frac{4z}{(1-z)^2} \right]$$

and

$$\bar{V}(z) = \frac{2(1-z)^3}{(z^2-6z+1)^3} \cdot {}_2F_1 \left[ \begin{matrix} -\frac{3}{2} & -\frac{3}{2} \\ 1 \end{matrix}; \frac{4z}{(1-z)^2} \right].$$

*Proof.* It is enough to check that the right-hand side expressions satisfy the same linear differential equations as  $\bar{A}$  and  $\bar{V}$ , with the same initial conditions.  $\square$

As a direct consequence of Theorem 1 and of definition (2) we get:

**Theorem 2.** *The function Iso admits the following closed-form expression:*

$$\text{Iso}^2(z) = \frac{9\sqrt{2}}{8\pi} \cdot \frac{{}_2F_1\left[-\frac{3}{2}, -\frac{3}{2}; \frac{4z^2}{(1-z^2)^2}\right]^2}{{}_2F_1\left[-\frac{1}{2}, -\frac{1}{2}; \frac{4z^2}{(1-z^2)^2}\right]^3} \cdot \left(\frac{1-z^2}{1+z^2}\right)^3.$$

Using the expression in Theorem 2, we can now prove the main result of [4].

**Theorem 3.** *Iso is a strictly increasing function and  $\lim_{z \rightarrow \sqrt{2}-1} \text{Iso}(z) = 1$ . In particular, Iso is a bijection.*

*Proof.* The value of  $\text{Iso}^2(z)$  at  $z = \sqrt{2} - 1$  is equal to

$$\text{Iso}^2(\sqrt{2} - 1) = \frac{9\sqrt{2}}{8\pi} \cdot \frac{{}_2F_1\left[-\frac{3}{2}, -\frac{3}{2}; 1\right]^2}{{}_2F_1\left[-\frac{1}{2}, -\frac{1}{2}; 1\right]^3} \cdot \frac{\sqrt{2}}{4}.$$

From Gauss's summation theorem [1, Th. 2.2.2] it follows that  ${}_2F_1\left[-\frac{3}{2}, -\frac{3}{2}; 1\right] = 32/(3\pi)$  and  ${}_2F_1\left[-\frac{1}{2}, -\frac{1}{2}; 1\right] = 4/\pi$ ; therefore,

$$\text{Iso}^2(\sqrt{2} - 1) = \frac{9\sqrt{2}}{8\pi} \cdot \frac{(32/(3\pi))^2}{(4/\pi)^3} \cdot \frac{\sqrt{2}}{4} = 1.$$

It remains to prove that Iso is strictly increasing. It is enough to show that

$$z \mapsto \frac{{}_2F_1\left[-\frac{3}{2}, -\frac{3}{2}; \frac{4z}{(1-z)^2}\right]^2}{{}_2F_1\left[-\frac{1}{2}, -\frac{1}{2}; \frac{4z}{(1-z)^2}\right]^3} \cdot \left(\frac{1-z}{1+z}\right)^3$$

is increasing on  $[0, 3-2\sqrt{2})$ . Equivalently, via the change of variables  $x = \frac{4z}{(1-z)^2}$ , it is enough to prove that the function

$$h: x \mapsto \frac{{}_2F_1\left[-\frac{3}{2}, -\frac{3}{2}; x\right]^2}{{}_2F_1\left[-\frac{1}{2}, -\frac{1}{2}; x\right]^3} \cdot (x+1)^{-\frac{3}{2}}$$

is increasing on  $[0, 1)$ . Clearly,  $h$  can be written as  $h = f^3 \cdot g^2$ , where

$$f(x) = \frac{\sqrt{x+1}}{{}_2F_1\left[-\frac{1}{2}, -\frac{1}{2}; x\right]} \quad \text{and} \quad g(x) = \frac{{}_2F_1\left[-\frac{3}{2}, -\frac{3}{2}; x\right]}{(x+1)^{\frac{3}{2}}}.$$

Hence, it is enough to prove that both  $f$  and  $g$  are increasing on  $[0, 1]$ . We will actually prove a more general fact in Proposition 1, which may be of independent interest. Using that  $w_{1/2} = 1/f$  and  $w_{3/2} = g$ , we deduce from Proposition 1 that both  $f$  and  $g$  are increasing. This concludes the proof of Theorem 3.  $\square$

**Proposition 1.** *Let  $a \geq 0$  and let  $w_a : [0, 1] \rightarrow \mathbb{R}$  be defined by*

$$w_a(x) = \frac{{}_2F_1\left[\begin{matrix} -a & -a \\ 1 \end{matrix}; x\right]}{(x+1)^a}.$$

*Then  $w_a$  is: decreasing if  $0 < a < 1$ ; increasing if  $a > 1$ ; constant if  $a \in \{0, 1\}$ .*

*Proof.* Clearly, if  $a \in \{0, 1\}$ , then  $w_a(x)$  is constant, equal to 1 on  $[0, 1]$ .

Consider now the case  $a > 0$  with  $a \neq 1$ . The derivative of  $w_a(x)$  satisfies the hypergeometric identity

$$\frac{w'_a(x) \cdot (x+1)^{a+1}}{a \cdot (a-1) \cdot (1-x)^{2a}} = {}_2F_1\left[\begin{matrix} a+1 & a \\ 2 \end{matrix}; x\right], \quad (3)$$

which is a direct consequence of Euler's transformation formula [1, Eq. (2.2.7), p. 68] and of Lemma 1 with  $a$  substituted by  $-a$ .

Since  $a > 0$ , the right-hand side of (3) has only positive Taylor coefficients, therefore it is positive on  $[0, 1]$ . It follows that  $w'_a(x) \geq 0$  on  $[0, 1]$  if  $a - 1 > 0$ , and  $w'_a(x) \leq 0$  on  $[0, 1]$  if  $a - 1 < 0$ . Equivalently,  $w_a$  is increasing on  $[0, 1]$  if  $a > 1$ , and decreasing on  $[0, 1]$  if  $a < 1$ .  $\square$

**Lemma 1.** *The following identity holds:*

$$(a+1)(1-x) \cdot {}_2F_1\left[\begin{matrix} a+1 & a+2 \\ 2 \end{matrix}; x\right] = a(x+1) \cdot {}_2F_1\left[\begin{matrix} a+1 & a+1 \\ 2 \end{matrix}; x\right] + {}_2F_1\left[\begin{matrix} a & a \\ 1 \end{matrix}; x\right].$$

*Proof.* We will use two of the classical Gauss' contiguous relations [1, §2.5]:

$${}_2F_1\left[\begin{matrix} a+1 & b+1 \\ c+1 \end{matrix}; x\right] = \frac{c}{bx} \cdot \left( {}_2F_1\left[\begin{matrix} a+1 & b \\ c \end{matrix}; x\right] - {}_2F_1\left[\begin{matrix} a & b \\ c \end{matrix}; x\right] \right) \quad (4)$$

and

$$a \cdot \left( {}_2F_1\left[\begin{matrix} a+1 & b \\ c \end{matrix}; x\right] - {}_2F_1\left[\begin{matrix} a & b \\ c \end{matrix}; x\right] \right) = \frac{(c-b) \cdot {}_2F_1\left[\begin{matrix} a & b-1 \\ c \end{matrix}; x\right] + (b-c+ax) \cdot {}_2F_1\left[\begin{matrix} a & b \\ c \end{matrix}; x\right]}{1-x}. \quad (5)$$

Applying (4) twice, once with  $(b, c) = (a, 1)$  and once with  $(b, c) = (a+1, 1)$ , the proof of the lemma is reduced to that of the identity

$$(x-1) \cdot {}_2F_1\left[\begin{matrix} a+1 & a+1 \\ 1 \end{matrix}; x\right] + 2 \cdot {}_2F_1\left[\begin{matrix} a & a+1 \\ 1 \end{matrix}; x\right] = {}_2F_1\left[\begin{matrix} a & a \\ 1 \end{matrix}; x\right],$$

which follows from (5) with  $(b, c) = (a+1, 1)$ .  $\square$

**Remark 1.** A natural question is whether the function  $\text{Iso}$  enjoys higher monotonicity properties. It can be easily seen that both  $\text{Iso}$  and its reciprocal  $1/\text{Iso}$  are neither convex nor concave. However we will prove that  $z \mapsto \text{Iso}(\sqrt{z})$  is concave and  $z \mapsto 1/\text{Iso}(\sqrt{z})$  is convex, on their domain of definition  $[0, 3 - 2\sqrt{2})$ .

First recall that  $1/\text{Iso}(\sqrt{z}) = \frac{2^{5/4} \cdot \sqrt{\pi}}{3} \cdot w_{1/2}(r(z))^{3/2} \cdot w_{3/2}(r(z))^{-1}$ , where we set  $r(z) = 4z/(1-z)^2$ . Since  $w_{1/2} = 1/f$  and  $w_{3/2}^{-1} = 1/g$  are positive and decreasing, while  $r$  is nonnegative and increasing, proving that  $w_{1/2} \circ r$  and  $w_{3/2}^{-1} \circ r$  are both convex is enough to establish convexity of  $z \mapsto 1/\text{Iso}(\sqrt{z})$ .

From (3) and the chain rule it follows that

$$\frac{d}{dz} w_a(r(z)) = {}_2F_1 \left[ \begin{matrix} a+1 & a \\ 2 & \end{matrix}; \frac{4z}{(1-z)^2} \right] \cdot \frac{(1-6z+z^2)^{2a}}{(1-z)^{4a}} \cdot \frac{(1-z)^{2a-1}}{(1+z)^{2a+1}}. \quad (6)$$

We can justify convexity of both  $w_{1/2}(r(z))$  and  $w_{3/2}(r(z))^{-1}$  if we can prove that the right-hand side of (6) is decreasing on  $[0, 3 - 2\sqrt{2})$ . Moreover, it is easy to see that  $(1-z)^{2a-1}/(1+z)^{2a+1}$  is decreasing on this interval for  $a > 3/2 - \sqrt{2}$ . Therefore, after changing variables  $x = 4z/(1-z)^2$ , it remains to show that

$${}_2F_1 \left[ \begin{matrix} a+1 & a \\ 2 & \end{matrix}; \frac{4z}{(1-z)^2} \right] \cdot \frac{(1-6z+z^2)^{2a}}{(1-z)^{4a}} = {}_2F_1 \left[ \begin{matrix} a+1 & a \\ 2 & \end{matrix}; x \right] \cdot (1-x)^{2a}$$

is decreasing for all  $x \in [0, 1)$ . The derivative of the right-hand side is given by

$$-\left( \frac{a(3-a)}{2} \cdot {}_2F_1 \left[ \begin{matrix} a & a+1 \\ 3 & \end{matrix}; x \right] + \frac{a(a+1)x}{6} \cdot {}_2F_1 \left[ \begin{matrix} a+1 & a+2 \\ 4 & \end{matrix}; x \right] \right) \cdot (1-x)^{2a-1},$$

hence is indeed negative for all  $x \in [0, 1)$  if  $0 < a < 3$ . From this and (6) it follows that  $1/\text{Iso}(\sqrt{z})$  is the product of two positive, decreasing and convex functions and therefore inherits these properties. Finally, this also shows that  $\text{Iso}(\sqrt{z})$  is both increasing and concave on  $[0, 3 - 2\sqrt{2})$ .

**Remark 2.** Bruno Salvy (private communication) found an alternative short proof of Proposition 1. The main idea is inspired by the Sturm–Liouville theory and the proof is based on the observation that  $w_a(x)$  satisfies the linear differential equation (written in adjoint form):

$$\frac{d}{dx} \left( x \left( \frac{1+x}{1-x} \right)^{2a} \cdot \frac{d}{dx} w_a(x) \right) = \frac{a(a-1)x}{(1+x)^2} \left( \frac{1+x}{1-x} \right)^{4a} \cdot w_a(x).$$

The right-hand side is positive on  $(0, 1)$  when  $a > 1$  and negative if  $0 < a < 1$ . The same holds for its integral over  $[0, t]$  for any  $t < 1$ . Looking at the left-hand side, this implies that  $w'_a > 0$  whenever  $a > 1$  and  $w'_a < 0$  when  $0 < a < 1$ .

We note that the same idea allows for a different proof of Remark 1.

**Acknowledgements.** We thank Mourad Ismail for his challenging question which led to Remark 1 and Bruno Salvy for his alternative proof of Proposition 1. Moreover, we are grateful to both for their interest in this work. The first author was supported in part by [DeRerumNatura](#) ANR-19-CE40-0018. The second author was supported by the [Austrian Science Fund](#) (FWF): P-31338.

## References

- [1] George E. Andrews, Richard Askey, and Ranjan Roy. *Special functions*, volume 71 of *Encyclopedia of Mathematics and its Applications*. Cambridge University Press, Cambridge, 1999.
- [2] Frédéric Chyzak. An extension of Zeilberger’s fast algorithm to general holonomic functions. *Discrete Math.*, 217(1-3):115–134, 2000.
- [3] Stephen Melczer and Marc Mezzarobba. Sequence Positivity Through Numeric Analytic Continuation: Uniqueness of the Canham Model for Biomembranes, 2020. Technical Report [arXiv:2011.08155](#) [math.CO].
- [4] Thomas Yu and Jingmin Chen. On the Uniqueness of Clifford Torus with Prescribed Isoperimetric Ratio, 2020. Technical Report [arXiv:2003.13116](#) [math.DG]. To appear in *Proceedings of the AMS*.