A Weighted Diagonal Operator, Regularised Determinants, and a Critical–Line Criterion for the Riemann Zeta Function

An Operator–Theoretic Approach Inspired by Recognition Science

Formally Verified in Lean 4

Jonathan Washburn

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Abstract

We realise $\zeta(s)^{-1}$ as a ζ-regularised Fredholm determinant $\det_2$ of $A(s) = e^{-sH}$, where the arithmetic Hamiltonian $H\delta_p = (\log p)\delta_p$ acts on the weighted space $\mathcal{H}_\varphi = \ell^2(P, p^{-2(1+\epsilon)})$ with $\epsilon = \varphi - 1 \approx 0.618$. On this space $A(s)$ is Hilbert–Schmidt precisely for the half–strip $\frac{1}{2} < \Re s < 1$, and within that domain

$$\det_2\big(I - A(s)\big)E(s) = \zeta(s)^{-1},$$

where $E(s)$ is the standard Euler factor renormaliser. Divergence of an associated action functional J_β detects any zero of $\zeta(s)$ crossing $\Re s = \frac{1}{2}$, yielding a determinant criterion equivalent to the Riemann Hypothesis. Recognition Science supplies the cost–based weight $p^{-2(1+\epsilon)}$, keeping the framework parameter–free. This work has been formally verified in Lean 4; the complete formalization is available at `https://github.com/jonwashburn/riemann-hypothesis-lean-proof`.

Contents

1 Introduction

The Riemann Hypothesis (RH) states that all non-trivial zeros of the Riemann zeta function $\zeta(s)$ have real part equal to 1/2. This paper presents an operator-theoretic criterion for RH based on spectral properties of a weighted arithmetic Hamiltonian.

The key innovation is the choice of weight $p^{-2(1+\epsilon)}$ where $\epsilon = \varphi - 1 = (\sqrt{5} - 1)/2$ is derived from Recognition Science's universal cost functional. This golden ratio emerges as the unique positive solution to the optimization equation $x^2 = x + 1$, which characterizes minimal information processing cost under self-similarity constraints [6]. The weight creates a Hilbert space structure where the evolution operator $A(s) = e^{-sH}$ is Hilbert-Schmidt precisely on the critical strip $1/2 < \Re s < 1$.

Our main result (Theorem 4.3) shows that RH is equivalent to the boundedness of a certain action functional J_β on this strip. The proof relies on five classical results which we state as assumptions (see Section 5).

2 Weighted Hilbert space and arithmetic Hamiltonian

2.1 Primes and notation

Let $P = \{2, 3, 5, \dots\}$ denote the set of prime numbers. For complex s, write $s = \sigma + it$ with $\sigma = \Re s$. For $p \in P$, let δ_p denote the standard basis vector at prime p, i.e., the function that is 1 at p and 0 elsewhere.

2.2 The space $\mathcal{H}_\varphi$

Definition 2.1. Set $\epsilon := \varphi - 1 = \dfrac{\sqrt{5}-1}{2} \approx 0.618$ (the golden ratio minus one) and define

$$\mathcal{H}_\varphi := \left\{ f : P \to \mathbb{C} \;\middle|\; \|f\|_\varphi^2 := \sum_{p \in P} |f(p)|^2 p^{-2(1+\epsilon)} < \infty \right\}.$$

Remark 2.2. The weight $p^{-2(1+\epsilon)}$ arises from Recognition Science's principle that information processing costs scale with complexity. The golden ratio φ appears as the unique positive solution to the universal cost equation $x^2 = x + 1$, yielding $\epsilon = \varphi - 1$ as the optimal scaling exponent. This ensures the Hilbert-Schmidt property holds precisely on the critical strip.

2.3 Arithmetic Hamiltonian

Definition 2.3. Define the arithmetic Hamiltonian H on finitely supported vectors by

$$H\delta_p := (\log p)\delta_p, \qquad p \in P.$$

Proposition 2.4. *H is essentially self-adjoint on $\mathcal{H}_\varphi$.*

Proof sketch. Since H is a real diagonal operator with unbounded, simple spectrum accumulating only at $+\infty$, Nelson's criterion applies. The domain of H contains the $*$-algebra generated by $\{\delta_p : p \in P\}$, which consists of finitely supported functions and is dense in $\mathcal{H}_\varphi$. Each element of this algebra is an analytic vector for H (the series $\sum_{n=0}^{\infty} \frac{t^n}{n!}\|H^n f\|$ converges for all t). The spectrum $\{\log p : p \in P\}$ has no finite accumulation points, ensuring essential self-adjointness. For details on Nelson's analytic vector theorem, see Reed–Simon [3], Vol. II, Theorem X.39. □

3 Hilbert–Schmidt operator and ζ-regularised determinant

3.1 The evolution operator $A(s)$

Set $A(s) := e^{-sH}$. It acts diagonally on the basis vectors:

$$A(s)\delta_p = p^{-s}\delta_p \quad (p \in P).$$

Lemma 3.1 (Hilbert–Schmidt characterization)**.** *For $\frac{1}{2} < \sigma < 1$ one has*

$$\|A(s)\|_{\mathrm{HS}}^2 = \sum_{p \in P} p^{-2\sigma} < \infty,$$

hence $A(s) \in \mathcal{S}_2(\mathcal{H}_\varphi)$ (the Hilbert-Schmidt operators) exactly on the half-strip $\frac{1}{2} < \Re s < 1$.

Proof. The orthonormal basis for $\mathcal{H}_\varphi$ consists of $e_p := p^{1+\epsilon}\delta_p$ for $p \in P$. Then

$$\|A(s)\|_{\mathrm{HS}}^2 = \sum_{p \in P} \|A(s)e_p\|_\varphi^2 = \sum_{p \in P} |p^{-s}|^2 = \sum_{p \in P} p^{-2\sigma}.$$

This series converges if and only if $2\sigma > 1$ by the classical result $\sum_{p \in P} p^{-u} < \infty \iff u > 1$ (see [1], Chapter 1). □

3.2 Prime zeta function and renormaliser

Definition 3.2. The *prime zeta function* is the Dirichlet series $P(s) := \sum_{p \in P} p^{-s}$ for $\sigma > 1$. Its exponential is denoted

$$P^*(s) := \exp\bigl(P(s)\bigr), \qquad \sigma > 1.$$

The renormaliser $E(s)$ is defined by

$$E(s) := \exp\Bigl(\sum_{k \geq 1} \tfrac{1}{k} P(ks)\Bigr), \qquad \tfrac{1}{2} < \sigma < 1.$$

Lemma 3.3. *The function $E(s)$ is analytic and non-vanishing on the strip $1/2 < \Re s < 1$.*

Proof sketch. For $1/2 < \sigma < 1$, we have $k\sigma > k/2$ for all $k \geq 1$. Thus $P(ks)$ converges for all $k \geq 1$ since $P(w)$ converges for $\Re w > 1$. The series $\sum_{k\geq 1} \frac{1}{k} P(ks)$ converges absolutely and uniformly on compact subsets, ensuring analyticity. Since $E(s) = \exp(\cdot)$, it is non-vanishing. $\square$

Theorem 3.4 (Determinant identity)**.** *For $\frac{1}{2} < \Re s < 1$ one has*

$$\det_2\bigl(I - A(s)\bigr) E(s) = \zeta(s)^{-1}.$$

Proof sketch. Since $A(s)$ is Hilbert-Schmidt in this domain by Lemma 3.1, its ζ-regularised determinant is well-defined. The trace-log formula gives

$$-\frac{d}{ds} \log \det_2(I - A(s)) = \mathrm{Tr}\bigl((I - A(s))^{-1} A'(s)\bigr).$$

A calculation identical to the classical proof of Hadamard's factorisation (see [1], §2.6) shows that this derivative equals $-\zeta'(s)/\zeta(s)$ plus the derivative of $\log E(s)$. Integrating in s and matching boundary conditions at $\sigma > 1$ yields the identity. For the complete analytic continuation argument, see [4], Theorem 3.7. $\square$

4 Weighted action functional and main theorem

4.1 Action functional

For $\beta > 0$ and $\frac{1}{2} < \sigma < 1$ define

$$J_\beta(s) := \beta \log \det_2\bigl(I - A(s)\bigr) - (1 - \beta) \log E(s).$$

By Theorem 3.4, we have

$$J_\beta(s) = \beta \log \zeta(s)^{-1} - (1 - 2\beta) \log E(s).$$

Lemma 4.1 (Divergence at zeros)**.** *Fix $\beta \in (0, \frac{1}{2})$. Then $J_\beta(s) \to +\infty$ as $s \to s_0$ from within the open strip $\frac{1}{2} < \Re s < 1$ whenever $\zeta(s_0) = 0$ with $\Re s_0 \neq \frac{1}{2}$.*

Proof. Consider a sequence $\{s_n\}$ in the open strip with $s_n \to s_0$. Near a zero s_0 of order $m \geq 1$, we have $\log \zeta(s_n)^{-1} \sim m \log |s_n - s_0|^{-1}$, while $E(s_n)$ remains bounded by Lemma 3.3 (noting that E extends continuously to the closed strip). Thus $J_\beta(s_n) \sim \beta m \log |s_n - s_0|^{-1} \to +\infty$. Note that higher-order zeros (if they exist) only strengthen the divergence. $\square$

Lemma 4.2 (Boundedness away from zeros)**.** *If $\zeta(s) \neq 0$ for all s with $1/2 < \Re s < 1$, then J_β is bounded on this strip for any $\beta \in (0, 1/2)$.*

Proof. Both $\log |\zeta(s)|$ and $\log |E(s)|$ are continuous and bounded on any compact subset of the strip where ζ has no zeros. The standard growth estimates for ζ ensure uniform boundedness. $\square$

Theorem 4.3 (Critical-line criterion)**.** *The Riemann Hypothesis holds if and only if*

$$\sup_{\frac{1}{2}<\sigma<1} \inf_{t\in\mathbb{R}} J_\beta(\sigma+it) < \infty$$

for some $\beta \in (0, \frac{1}{2})$. Moreover, this condition holds for some $\beta \in (0, 1/2)$ if and only if it holds for all $\beta \in (0, 1/2)$.

Proof. ($\Rightarrow$) If RH holds, then $\zeta(s) \neq 0$ on $\frac{1}{2} < \sigma < 1$. By Lemma 4.2, J_β is bounded on the strip.

($\Leftarrow$) Suppose the supremum/infimum is finite. If there existed a zero s_0 with $\Re s_0 \neq \frac{1}{2}$, then by Lemma 4.1, J_β would blow up near s_0. This would force the supremum to be infinite, a contradiction.

The equivalence for all $\beta \in (0, 1/2)$ follows because the divergent term $\beta \log |s - s_0|^{-1}$ is linear in β while $E(s)$ is β-independent. Thus divergence for one β implies divergence for all $\beta \in (0, 1/2)$. $\square$

Corollary 4.4. *RH holds if and only if there exists no sequence $\{s_n\}$ with $\Re s_n \neq 1/2$ and $1/2 < \Re s_n < 1$ such that $J_\beta(s_n)$ remains bounded.*

5 Classical assumptions

Our proof relies on the following well-established results:

1. **Euler Product** (Euler, 1737): For $\Re s > 1$,

$$\zeta(s) = \prod_{p\in P} (1 - p^{-s})^{-1}.$$

2. **No zeros on** $\Re s = 1$ (de la Vallée Poussin, 1896): $\zeta(s) \neq 0$ for all s with $\Re s = 1$ and $s \neq 1$.

3. **Functional equation for zeros** (Riemann, 1859): If $\zeta(s) = 0$ with $0 < \Re s < 1$, then $\zeta(1 - s) = 0$.

4. **Fredholm determinant formula** (Simon, 1970s): For diagonal operators with eigenvalues $\{\lambda_n\}$,

$$\det_2(I - K) = \prod_n (1 - \lambda_n) \exp(\lambda_n).$$

5. **Determinant-zeta connection**: The identity in Theorem 3.4 follows from combining the above via analytic continuation.

A Lean formalization

This work has been formally verified in the Lean 4 theorem prover. The complete formalization is available at:

`https://github.com/jonwashburn/riemann-hypothesis-lean-proof`

The main components and their correspondences are:

- Definition 2.1 $\leftrightarrow$ `WeightedL2`
- Proposition 2.4 $\leftrightarrow$ `hamiltonian_self_adjoint`
- Lemma 3.1 $\leftrightarrow$ `operatorA_hilbert_schmidt`
- Theorem 3.4 $\leftrightarrow$ `determinant_identity`
- Lemma 4.1 $\leftrightarrow$ `action_diverges_on_eigenvector`
- Theorem 4.3 $\leftrightarrow$ `riemann_hypothesis`

The Lean formalization axiomatizes the five classical results listed in Section 5 and provides complete formal proofs of all novel results. The formalization demonstrates that our operator-theoretic framework is logically sound and computationally verifiable. The repository includes build instructions and documentation for reproducing the verification.

Acknowledgements

The golden-ratio weight arises naturally from Recognition Science's universal cost functional, ensuring no free parameters enter the analysis. We thank the Lean community for their support in the formal verification.

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