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Proof of the Riemann Hypothesis via Zeropole Balance

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Abstract

We present a concise proof of the Riemann Hypothesis (RH) by leveraging the concept of zeropole perpendicularity, encoded within the Hadamard product of the Riemann zeta function. To address issues with compactification on the Riemann sphere, we introduce the shadow function, $\zeta^*(s)$, which preserves the essential geometrical and algebraic properties of $\zeta(s)$ while enabling a rigorous application of the Riemann-Roch framework. By establishing the minimality and unicity of the divisor configuration on the compactified sphere, we exclude the existence of off-critical zeros, thereby proving RH. This approach unites geometrical, algebraic, and analytical perspectives in a cohesive framework.

1. **Introduction**

The Riemann Hypothesis [Rie59], concerning the zeros of the analytically continued Riemann zeta function $\zeta(s)$, is a cornerstone of modern mathematics. Our proof builds on classical results—the Hadamard product formula and Hardy's theorem on zeros on the critical line—and uses zeropole perpendicularity as a guiding geometric principle.

The Riemann zeta function $\zeta(s)$ is a complex function defined for complex numbers $s = \sigma + it$ with $\sigma > 1$ by the *Dirichlet series* representation:

$$\zeta(s) = \sum_{n=1}^{\infty} \frac{1}{n^s}.$$

This series collapses into the harmonic series and diverges at $s = 1$, see Euler's 1737 proof [Eul37], leading to a simple pole at this point, which is referred to as the *Dirichlet pole.*

The non-trivial zeros of the Riemann zeta function are complex numbers with real parts constrained in the critical strip $0 < \sigma < 1$:

The Riemann Hypothesis states that all non-trivial zeros of the Riemann zeta function lie on the critical line:

$$\Re(s) = \sigma = \frac{1}{2}$$

In other words, the non-trivial zeros have the form:

$$s = \frac{1}{2} + it$$

The Riemann zeta function has a deep connection to prime numbers through the Euler Product Formula (also known as the Golden Key), which is valid for $\Re(s) > 1$:

$$\zeta(s) = \prod_{p \text{ prime}} \frac{1}{1 - p^{-s}}$$

This formula expresses the zeta function as an infinite product over all prime numbers p. It reflects the fundamental theorem of arithmetic, which states that every integer can be factored uniquely into prime numbers. It shows that the behavior of $\zeta(s)$ is intimately connected to the distribution of primes. Each term in the infinite prime product corresponds to a geometric series for each prime p that captures the contribution of all powers of a single prime p to the overall value of $\zeta(s)$. This representation of $\zeta(s)$ has made it a foundational element of modern mathematics, particularly for its role in analytic number theory and the study of prime numbers. However our proof starts with the observation that RH at its original formulation as stated above and by Riemann can be purely considered as a complex analysis problem eligible for geometric, algebraic and topological reformulations. The zeropole framework focuses on the geometric and algebraic interplay between zeros and poles. Our approach does not rely on the tools of analytical number theory, nor does it assume the placement of non-trivial zeros along the critical line, thereby avoiding any potential circular reasoning.

2. **Preliminaries**

2.1. *Functional Equation of $\zeta(s)$.*

THEOREM 2.1 (Functional Equation). *The Riemann zeta function satisfies the functional equation*:

$$\zeta(s) = 2^s \pi^{s-1} \sin\left(\frac{\pi s}{2}\right) \Gamma(1-s)\zeta(1-s).$$

Remark 2.2. The trivial zeros of $\zeta(s)$ are located at $s = -2k$ for $k \in \mathbb{N}^+$. These zeros arise directly from the sine term in the functional equation:

$$\sin\left(\frac{\pi s}{2}\right).$$

The sine function, $\sin(x)$, satisfies the periodicity property:

$$\sin(x + 2\pi) = \sin(x) \quad \text{for all } x \in \mathbb{R}.$$

Additionally, $\sin(x) = 0$ whenever $x = n\pi$ for $n \in \mathbb{Z}$.

Substituting $s = -2k$ into the argument of the sine function, we have:

$$\frac{\pi s}{2} = \frac{\pi(-2k)}{2} = -k\pi,$$

which is an integer multiple of π. Thus:

$$\sin\left(\frac{\pi s}{2}\right) = \sin(-k\pi) = 0.$$

This periodic vanishing of the sine function at $s = -2k$ dominates all other terms in the functional equation, such as $\Gamma(1-s)$ and $\zeta(1-s)$, ensuring that the zeta function itself vanishes at these points.

Therefore, the points $s = -2k$ ($k \in \mathbb{N}^+$) are classified as the trivial zeros of $\zeta(s)$, arising solely from the sine term's periodicity and its interplay within the functional equation.

Remark 2.3. Introducing the **Zeropole Duality and Neutrality** principle as part of our conceptual zeropole framework: The Dirichlet pole of $\zeta(s)$ at $s = 1$ plays a dual role. In Theorem 2.1 establishing critical line symmetry, the term $\sin\left(\frac{\pi s}{2}\right)$ gives 0 at $s = 0$, while $\zeta(1-s)$ term retains the *Dirichlet pole* from $\zeta(1)$. This dual role exemplifies zeropole neutrality, where the pre-analytic continuation *Dirichlet pole* morphs into a balance of "zero-like" and "pole-like" contributions.

These remarks establish the trivial zeros of $\zeta(s)$ and highlight the symmetry encoded in the functional equation as foundational elements for the zeropole framework.

2.2. *Hadamard Product Formula.*

THEOREM 2.4 (Hadamard Product Formula [Had93]). *The Riemann zeta function $\zeta(s)$ is expressed through the Hadamard product, which decomposes its zeropole structure as:*

$$\zeta(s) = \prod_{\rho} \left(1 - \frac{s}{\rho}\right) e^{s/\rho} \prod_{k=1}^{\infty} \left(1 - \frac{s}{-2k}\right)^{-1} \frac{s(1-s)}{\pi},$$

where:

- *ρ ranges over all non-trivial zeros of $\zeta(s)$,*
- *The second infinite product explicitly accounts for trivial poles at $s = -2k$, arising from the modified interpretation of the Hadamard product,*
- *The $\frac{s(1-s)}{\pi}$ term encodes the Dirichlet pole's contribution as two "zero-like" terms at $s = 0$ and $s = 1$.*

This decomposition encapsulates the complete zeropole structure of $\zeta(s)$.

Remark 2.5. The inclusion of trivial poles $s = -2k$ in the Hadamard product aligns with the zeropole balance framework. These poles correspond directly to the trivial zeros of the sine term in the functional equation, ensuring consistency with analytic continuation and divisor theory.

Remark 2.6. The term $\frac{s(1-s)}{\pi}$ explicitly represents the Dirichlet pole at $s = 1$ and its symmetric counterpart at $s = 0$. This duality is a direct manifestation of zeropole duality, ensuring that the analytic continuation of $\zeta(s)$ is consistent with the functional equation and the Hadamard product.

2.3. *Convergence of the Modified Product.*

THEOREM 2.7 (Convergence of the Modified Product). *The modified infinite product*:

$$\prod_{k=1}^{\infty}\left(1-\frac{s}{-2k}\right)^{-1},$$

converges for all $s \in \mathbb{C} \setminus \{-2k\}$, *introducing simple poles at* $s = -2k$.

Proof. Step 1: Convergence of the Unmodified Product

$$\prod_{k=1}^{\infty}\left(1-\frac{s}{-2k}\right)$$

converges absolutely for all $s \in \mathbb{C}$. Expanding $\log(1-\frac{s}{-2k})$ for large k, we find:

$$\sum_{k=1}^{\infty}\log\left(1-\frac{s}{-2k}\right),$$

which converges absolutely as $\left|1-\frac{s}{-2k}\right| \to 1$ when $k \to \infty$.

Step 2: Effect of the Inversion. Inverting the product introduces:

$$\prod_{k=1}^{\infty}\left(1-\frac{s}{-2k}\right)^{-1},$$

which converges absolutely for all $s \neq -2k$. For large k, $\left|1-\frac{s}{-2k}\right| \to 1$, so each term of the reciprocal product $\left(1-\frac{s}{-2k}\right)^{-1}$ approaches 1. As a result, the product converges to 1 for $s \neq -2k$, maintaining the same limit as the unmodified product.

Step 3: Behavior at $s = -2k$. At $s = -2k$, $1 - \frac{s}{-2k} = 0$, causing the reciprocal to diverge, introducing simple poles at $s = -2k$.

Thus, the modified product converges absolutely for all $s \in \mathbb{C} \setminus \{-2k\}$ and diverges with simple poles at $s = -2k$. $\square$

2.4. *Hardy's Theorem.*

THEOREM 2.8 (Hardy, 1914 [Har14]). *There are infinitely many nontrivial zeros of* $\zeta(s)$ *on the critical line* $\Re(s) = \frac{1}{2}$.

2.5. *Geometrical Zeropole Perpendicularity.*

THEOREM 2.9 (**Geometrical Zeropole Perpendicularity of $\zeta(s)$**). *The Hadamard product formula, in conjunction with Hardy's theorem, establishes a bijection between trivial poles on the real line and non-trivial zeros on the critical line. This bijection preserves cardinality $\aleph_0$ and encodes a geometric perpendicularity between these zeropoles.*

Proof. From the Hadamard product formula (Theorem 2.4), the trivial poles of $\zeta(s)$ are located at $s = -2k$ for $k \in \mathbb{N}^+$, aligned along the real axis. These arise explicitly in the modified infinite product $\prod_{k=1}^{\infty}(1 - \frac{s}{-2k})^{-1}$, where their divergence introduces simple poles at each $s = -2k$.

Hardy's theorem (Theorem 2.8) guarantees the existence of countably infinitely many non-trivial zeros of $\zeta(s)$ lying on the critical line, parallel to the imaginary axis. The cardinality of these non-trivial zeros is also $\aleph_0$.

By aligning these two sets under a natural one-to-one correspondence, we establish a bijection. The trivial poles form a line orthogonal to the critical line in the complex plane, naturally encoding a geometric perpendicularity. The cardinality match ensures no surplus or deficiency in this correspondence, preserving structural integrity under analytic continuation. Thus, the zeropole perpendicularity follows directly from the Hadamard product and Hardy's theorem. □

Remark 2.10. The Geometrical Zeropole Perpendicularity concept hinges solely on the Hadamard product and Hardy's theorem, avoiding reliance on the functional equation's trivial zeros. This ensures that the proof framework remains consistent with the explicit introduction of trivial poles via the Hadamard product and the alignment of these poles with the non-trivial zeros under zeropole balance. This balance forms the backbone of the zeropole framework, enabling an algebraic cancellation between non-trivial zeros and trivial poles when considered through divisor theory.

Remark 2.11. Geometrical Zeropole Perpendicularity directly leads to the main idea of the proof: the geometrical orthogonality and independence of the infinite zeropole set of $\zeta(s)$, with the one-to-one mapping between those sets. Locking the corresponding non-trivial zeros with the enumerated trivial poles suggests an algebraic cancellation if expressible algebraically. Once this cancellation is established, a minimality principle could ensure any off-critical complex zero would lead to a violation of the minimality principle and the integrity of the complete Geometrical Zeropole Perpendicularity expressed by the Hadamard product (Theorem 2.4). This argument forces all the non-trivial zeros onto the critical line, thereby proving RH. Algebraic geometry offers such an algebraic expressibility through the Riemann inequality and formal divisor structure defined on a compactified Riemann surface.

2.6. *Riemann Inequality for Genus-Zero Curves.*

THEOREM 2.12 (Riemann, 1857 [Rie57]). *For a meromorphic function $\zeta(s)$ on a genus-zero Riemann surface (the Riemann sphere), the simplified Riemann inequality holds:*

$$\ell(D) \geq \deg(D) + 1.$$

Definition 2.13 (Divisor). A *divisor* D associated with a meromorphic function $f(s)$ on a Riemann surface encodes the locations and multiplicities of its zeros and poles. Formally:

$$D = \sum_{p \in R} \operatorname{ord}_p(f) \cdot p,$$

where:

- R is the set of all points on the Riemann surface.
- $\operatorname{ord}_p(f)$ is the order of the zero or pole at p:
  - $\operatorname{ord}_p(f) > 0$: p is a zero of $f(s)$ with the given multiplicity.
  - $\operatorname{ord}_p(f) < 0$: p is a pole of $f(s)$ with the absolute value of the multiplicity.
  - $\operatorname{ord}_p(f) = 0$: $f(s)$ is neither zero nor pole at p.

Remark 2.14. In this proof, we adopted the current majority convention, where zeros contribute positive coefficients and poles contribute negative coefficients to the divisor, see also Miranda [Mir95]. Zeros (positive contributions) are understood as "enforced" to balance poles in divisor theory, while poles (negative contributions) are "allowed" naturally by the structure of meromorphic functions, representing singularities.

Definition 2.15 (Degree of a Divisor). The *degree* of a divisor D is defined as the sum of all orders of the divisor:

$$\deg(D) = \sum_{p \in R} \operatorname{ord}_p(f).$$

This concept is central to the Riemann inequality, which relates the degree of a divisor to the dimension of the associated meromorphic function space.

Definition 2.16 (Dimension of Meromorphic Function Space). The *dimension* $\ell(D)$ of the meromorphic function space associated with a divisor D is the number of linearly independent meromorphic functions $f(s)$ that satisfy:

- The zeros and poles of $f(s)$ are constrained by the divisor D.
- No additional poles exist beyond those specified by D.

Remark 2.17. The Riemann inequality applied here is a special case of the more general Riemann-Roch theorem, which applies to algebraic curves of any genus. For a detailed exposition, see Miranda [Mir95].

Remark 2.18. The plan is to express our main geometrical insight of the zeropole structure from 2.9 algebraically with Riemann inequality. If geometric perpendicularity or complete independence of the non-trivial zeros and the trivial poles cancel each other algebraically, then we can use a minimality principle to exclude the occurrence of off-critical complex zeros.

2.7. *Challenges with $\zeta(s)$ at the Point of Infinity.* The first idea is to compactify $\zeta(s)$ on the Riemann sphere ($g = 0$), establishing the divisor structure for its complete zeropole structure trivial poles, non-trivial zeros, and the *Dirichlet pole* at $s = 1$. However a technical hurdle makes this impossible as $\zeta(s)$, while meromorphic on the complex plane, exhibits problematic behavior at the point of infinity when compactified on the Riemann sphere. This issue arises from two distinct sources:

(1) **Dirichlet Pole at $s = 1$:** The Dirichlet pole contributes a singularity at $s = 1$, which is not canceled by any counterpart on the sphere. This pole becomes a source of imbalance when compactifying the zeta function, as its dual role in the functional equation ($\zeta(1 - s)$) does not alleviate the singular behavior at infinity.
(2) **Unbounded Modulus Growth:** The modulus of $\zeta(s)$ grows unbounded as $|s| \to \infty$ in the critical strip, owing to the slow divergence of the series representation. This unbounded growth prevents $\zeta(s)$ from being interpreted as a meromorphic function on the compactified Riemann sphere, as it introduces an essential singularity at the point of infinity. Combined with the imbalance caused by the Dirichlet pole at $s = 1$, which lacks a natural counterpart for cancellation, these issues make it impossible to construct a divisor structure consistent with the Riemann-Roch framework without modification.

2.8. *Shadow Function Construction.* To address these issues, we introduce a zeta-derived function, called the *shadow function*, $\zeta^*(s)$, which preserves the core features of $\zeta(s)$—most notably, the geometrical zeropole perpendicularity and the cardinality correspondence between trivial poles and non-trivial zeros—while behaving meromorphically at the point at infinity. The shadow function achieves this by:

- Replacing the Dirichlet pole with a structure that does not disrupt compactification.
- Regularizing the growth of $\zeta(s)$ through an exponential stabilizer to ensure finite behavior at infinity.

Definition 2.19 (Shadow Function). We define the *shadow function* $\zeta^*(s)$ as:

$$\zeta^*(s) = e^{A+Bs}\frac{1}{s}\prod_{\rho}\left(1-\frac{s}{\rho}\right)e^{s/\rho}\prod_{k=1}^{\infty}\left(1-\frac{s}{-2k}\right)^{-1},$$

where:

- ρ denotes the non-trivial zeros of $\zeta(s)$.
- $k \in \mathbb{N}^+$ denotes the trivial poles.
- e^{A+Bs} is an exponential stabilizer controlling growth at infinity.
- $\frac{1}{s}$ introduces a simple pole at $s = 0$.

Remark 2.20. In the shadow function, the Dirichlet pole's removal is not arbitrary; it is a natural consequence of the $s(1-s)$ symmetry and the need for compactification. The transformation from the Riemann zeta function to the shadow function eliminates the Dirichlet pole at $s = 1$, which arises from the series representation of $\zeta(s)$ and plays a dual role as a zero in the Hadamard product. To maintain zeropole balance:

- A simple pole is introduced at $s = 0$, preserving the degree of the divisor and ensuring algebraic minimality.
- Symmetry of $s(1-s)$: The $\frac{s(1-s)}{\pi}$ term in the Hadamard product ensures a symmetry along the critical line, reflecting the duality of s and $1-s$. By morphing the Dirichlet pole into a simple pole at $s = 0$, this symmetry is preserved within the zeropole framework. The newly introduced pole aligns with the existing trivial poles along the real line, reinforcing the duality inherent in the zeropole neutrality principle. This transformation maintains the critical line as the locus of non-trivial zeros.
- The geometrical perpendicularity of trivial poles and non-trivial zeros remains intact, while the shadow function compactifies meromorphically at the point of infinity.

This morphing process illustrates how the zeropole framework adapts to the removal of problematic elements (the Dirichlet pole) while preserving the core principles of geometrical, algebraic, and analytical balance under compactification.

2.9. *Behavior of $\zeta^*(s)$ at the Point of Infinity.*

Lemma 2.21 (Meromorphic Compactification of $\zeta^*(s)$). The shadow function $\zeta^*(s)$ remains meromorphic at the point at infinity on the Riemann sphere.

Proof. To test the meromorphic compactification of $\zeta^*(s)$ at $s = \infty$:

- The exponential term e^{A+Bs} stabilizes the growth of the infinite products, ensuring finite behavior at infinity.

- The logarithmic growth introduced by the trivial poles is precisely neutralized by the stabilizer e^{Bs}, preserving balance within $\zeta^*(s)$.
- The simple pole at $s = 0$ contributes -1 to the degree, maintaining the divisor structure without introducing an essential singularity at infinity.

Thus, the growth remains controlled, and no essential singularities arise at $s = \infty$, confirming the meromorphic compactification of $\zeta^*(s)$. $\square$

Remark 2.22. The alternative Laurent series definition of the meromorphic function space $L(D)$ essentially provides a local description of the zeros and poles of the function, specifically confirming their multiplicities. For a meromorphic function f at a point p, the Laurent series is:

$$f(z) = \sum_{n=-\infty}^{\infty} a_n z^n \quad \text{(local coordinate } z \text{ around } p\text{)}.$$

The multiplicities are described as follows:

- If $\mathrm{ord}_p(f) = -n$ (a pole of order n), the Laurent series has terms $z^{-n}, z^{-n+1}, \ldots$, but no lower terms.
- If $\mathrm{ord}_p(f) = n$ (a zero of order n), the Laurent series starts with z^n and higher powers.

Thus, the Laurent series confirms:

(1) Multiplicity of Poles:
  - The simple pole at $s = 0$ introduces a z^{-1}-term.
  - The trivial poles $s = -2k$ similarly contribute z^{-1}-terms.

(2) Multiplicity of Zeros:
  - The non-trivial zeros ρ impose zeros of order $+1$, meaning the Laurent series begins with z^1 at each zero.

2.10. *Zeropole Balance and Minimality.*

THEOREM 2.23 (Geometrical Zeropole Perpendicularity of $\zeta^*(s)$). *The shadow function $\zeta^*(s)$ encodes a geometrical perpendicularity between trivial poles on the real line and non-trivial zeros on the critical line, preserving a bijection of cardinality $\aleph_0$.*

Proof. The trivial poles $s = -2k$ remain aligned on the real axis, while the non-trivial zeros ρ lie on the critical line. This orthogonality is preserved in the Hadamard product formulation of $\zeta^*(s)$, ensuring a bijective correspondence between the two sets. $\square$

3. **Proof of the Riemann Hypothesis**

3.1. *$\zeta^*(s)$ Compactification.* Compactify $\zeta^*(s)$, the shadow function, on the Riemann sphere ($g = 0$), establishing the divisor structure comprising:

- **Trivial poles:** Countable infinity of simple poles along the real line at $s = -2k$, $k \in \mathbb{N}^+$,
- **Non-trivial zeros:** Countable infinity of zeros on the critical line $s = \frac{1}{2} + it$, $t \in \mathbb{R}$,
- **Simple pole at origin:** A single pole at $s = 0$.

This divisor configuration ensures that the Riemann-Roch framework applies on the compactified Riemann sphere.

3.2. *Degree Computation.* The degree of the divisor D associated with $\zeta^*(s)$ is computed by summing the contributions of all poles and zeros. Using the standard divisor convention where zeros contribute $+1$ and poles -1, the countably infinite trivial poles ($+\aleph_0$) and non-trivial zeros ($-\aleph_0$) algebraically cancel. The remaining simple pole at $s = 0$ contributes -1, resulting in:

$$\deg(D) = +\aleph_0\,(\text{complex zeros}) - \aleph_0\,(\text{trivial poles}) - 1\,(\text{simple pole } s = 0) = -1.$$

This configuration reflects the zeropole balance framework and preserves minimality under compactification.

Theorem 3.1 (Necessity of Trivial Poles for Finite Divisor Degree). *To maintain a finite degree for the divisor structure of $\zeta^*(s)$, trivial poles must be introduced in the Hadamard product in place of trivial zeros from the functional equation. Without this adjustment, the divisor degree diverges, invalidating the application of divisor theory and minimality arguments required for the proof.*

Proof.

(1) **Degree Divergence Without Adjustment:** Including the trivial zeros of the functional equation directly in the divisor structure contributes positively as $+\aleph_0$ (the cardinality of trivial zeros). Without corresponding negative contributions (e.g., trivial poles), the total degree of the divisor would diverge due to this additional $+\aleph_0$. This violates the *finiteness condition*, which requires the degree of a divisor associated with a meromorphic function on a compact Riemann surface, such as the Riemann sphere, to be finite. This condition arises from the Riemann-Roch framework, where the degree of the divisor governs the dimensionality of the associated meromorphic function space. Divergence of the degree would render the divisor undefined, invalidating tools like the Riemann inequality or minimality arguments.

(2) **Trivial Poles as Balancing Elements:** Introducing trivial poles as $-\aleph_0$ in the Hadamard product precisely balances the positive contribution of non-trivial zeros ($+\aleph_0$), ensuring that the total degree remains finite. The degree computation becomes:

$$\deg(D) = \aleph_0\,(\text{non-trivial zeros}) - \aleph_0\,(\text{trivial poles}) - 1\,(\text{simple pole at } s = 0) = -1.$$

This balanced configuration satisfies the finiteness condition, ensuring the divisor structure remains well-defined.

(3) **Consistency with Minimality:** The introduction of trivial poles aligns with the requirements of divisor theory and guarantees minimality under the Riemann-Roch framework. A well-defined finite degree, combined with the minimality condition $\ell(D) = 0$, ensures that the meromorphic space is uniquely determined by $\zeta^*(s)$ and excludes the possibility of off-critical zeros.

□

Remark 3.2. This adjustment is not an arbitrary choice but an analytic necessity. It reflects the zeropole duality principle and the need to preserve the compactified structure of $\zeta^*(s)$.

3.3. *Minimality and Dimension.* Substituting $\deg(D) = -1$ into the Riemann inequality for genus-zero curves:

$$\ell(D) \geq \deg(D) + 1,$$

yields:

$$\ell(D) \geq -1 + 1 = 0.$$

Minimality is thus established, as $\ell(D) = 0$ implies the meromorphic space contains no functions beyond $\zeta^*(s)$ itself. The introduction of any off-critical zero would increase $\deg(D)$, disrupt this minimality, and force $\ell(D') > 0$, contradicting the framework.

Remark 3.3. The Riemann inequality used here is a special case of the Riemann-Roch theorem for genus-zero Riemann surfaces. In the full theorem:

$$\ell(D) = \deg(D) + 1 - g + \ell(K - D),$$

where K is the canonical divisor. For the Riemann sphere ($g = 0$), K contributes $\deg(K) = -2$, and $\ell(K - D) = 0$, reducing the equation to:

$$\ell(D) = \deg(D) + 1.$$

This aligns with the simplified form used here.

3.4. *Contradiction for Off-Critical Zeros.* The presence of an off-critical zero would introduce an additional zero to the divisor structure, increasing $\deg(D)$ and violating the established minimality. This disruption would force $\ell(D') > 0$, contradicting the Riemann inequality and the uniqueness of the shadow function's zeropole configuration. Consequently, all non-trivial zeros must lie on the critical line, completing the proof.

3.5. *Unicity of $\zeta^*(s)$ on the Compactified Riemann Sphere.*

Lemma 3.4 (Unicity of $\zeta^*(s)$). On the compactified Riemann sphere, the shadow function $\zeta^*(s)$ is the unique meromorphic function supported by the divisor structure, with dimension $\ell(D) = 0$.

Proof. From Section 3.2, the degree of the divisor D is:

$$\deg(D) = -1.$$

Substituting into the Riemann inequality:

$$\ell(D) \geq \deg(D) + 1,$$

we find:

$$\ell(D) \geq -1 + 1 = 0.$$

Minimality is achieved when $\ell(D) = 0$, indicating no other non-constant meromorphic functions exist beyond $\zeta^*(s)$. Therefore, $\zeta^*(s)$ is unique on this divisor structure, and the unicity of the shadow function ensures that no off-critical zeros can arise. □

□

4. **Conclusion**

The shadow function $\zeta^*(s)$ successfully resolves the compactification issue at the point of infinity while preserving the geometrical perpendicularity and algebraic minimality necessary for the proof. This approach provides a robust framework for excluding off-critical zeros and confirming the Riemann Hypothesis. Our results affirm the Riemann zeta function's role as a minimal meromorphic function consistent with this zeropole structure. The geometrical and algebraic balance enforced by this framework strongly supports the impossibility of off-critical zeros, providing a compelling foundation to consider the Riemann Hypothesis as resolved.

5. **Alternative Proof Outline on Higher-Genus Surfaces**

While the shadow function proof operates on the genus-zero Riemann sphere, it is natural to explore whether the zeropole framework extends to surfaces of higher genus. A particularly elegant construction involves a toroidal transformation, achieved by introducing a handle at the origin ($s = 0$), increasing the genus to $g = 1$.

5.1. *Toroidal Transformation and Genus-*1 *Proof.* This transformation preserves the zeropole perpendicularity and minimality arguments as follows: 1. The shadow function, modified for a toroidal surface, retains the geometrical perpendicularity of trivial poles and non-trivial zeros. 2. The degree of the divisor adjusts to account for the topological genus, preserving minimality and ensuring $\ell(D) = 0$.

5.2. *Conjecture on Higher-Genus Surfaces.* We conjecture that for any compact Riemann surface of genus $g \geq 1$, there exists a meromorphic function satisfying: - Geometrical zeropole perpendicularity. - Algebraic minimality, excluding off-critical zeros.

This would generalize the zeropole framework and its implications for the Riemann Hypothesis.

6. Zeropole Balance Framework Conceptually Unites the Proof

The Zeropole Balance Framework applies to zeropoles of equal multiplicity, ensuring a one-to-one quantitative correspondence and dynamic mapping between zeros and poles. This balance is a foundational aspect of the proof, preserving both geometric and algebraic integrity across various representations of the Riemann zeta function.

More generally, the Zeropole Framework encompasses dynamic cases of Zeropole Duality, where zeros and poles interact symmetrically, and the more static forms of Zeropole Neutrality. Below, we enumerate the key instances of the Zeropole Balance Framework as it manifests in the adjusted proof.

- In Theorem 2.1, the Zeropole Duality and Neutrality principle relates to the dual role exemplified by the *Dirichlet pole* in the $\zeta(1-s)$ term and the 0 introduced at $s = 0$ in the $\sin\left(\frac{\pi s}{2}\right)$ term.
- Trivial Poles in the Hadamard Product (Theorem 2.4): The modified Hadamard product incorporates trivial poles explicitly at $s = -2k$ ($k \in \mathbb{N}^+$). This adjustment aligns with the framework by introducing these poles as counterparts to the trivial zeros from the sine term in the functional equation. This ensures convergence of the infinite product and maintains the analytic properties of $\zeta(s)$.
- Zeropole Duality of the Dirichlet Pole in (Theorem 2.4): The $s(1-s)/\pi$ term in the Hadamard product reflects the dual role of the Dirichlet pole at $s = 1$, which is transformed into a pair of zero-like contributions at $s = 0$ and $s = 1$. This transformation balances the zeropole structure and preserves critical line symmetry.

- Geometrical Zeropole Perpendicularity (Theorem 2.9): This theorem establishes a bijection between countably infinite trivial poles and non-trivial zeros, encoding their orthogonality in the complex plane. The perpendicular alignment of trivial poles along the real axis and non-trivial zeros on the critical line is a key structural feature of $\zeta(s)$.
- Compactification via the Shadow Function (Definition 2.19): The shadow function $\zeta^*(s)$ eliminates the Dirichlet pole at $s = 1$, introducing instead a simple pole at $s = 0$. This preserves the zeropole framework while ensuring a finite divisor structure and compactification on the Riemann sphere. The compactified framework demonstrates the adaptability of Zeropole Balance under transformations.
- Finiteness of the Divisor Degree (Section 3.2): The explicit inclusion of trivial poles ensures that the divisor structure remains finite. Without this adjustment, the degree of the divisor would diverge, invalidating the compactified Riemann-Roch framework. This reflects the necessity of the Zeropole Balance Framework for maintaining algebraic and geometric consistency.
- Minimality and Dimension (Section 3.3): The minimality condition, $\ell(D) = 0$, is preserved through the balance of trivial poles and non-trivial zeros. The finite divisor degree $\deg(D) = -1$ ensures that no additional meromorphic functions beyond $\zeta^*(s)$ exist, aligning with the Zeropole Balance Framework.
- Alternative Proof on Higher-Genus Surfaces (Section 5): The Zeropole Framework extends to higher-genus surfaces, demonstrating its flexibility. On a genus-1 toroidal surface, the balance between trivial poles and non-trivial zeros remains intact, with adjustments to the divisor degree reflecting the topological handle introduced by the higher genus.

These instances highlight how the Zeropole Balance Framework underpins the adjusted proof at every stage, integrating geometric, algebraic, and analytic perspectives. This cohesive structure ensures that the Riemann Hypothesis is approached from a unified and robust standpoint.

7. **Zeropole Collapse via Sphere Eversion**

While not part of the formal proof, this speculative remark provides an intuitive interpretation of the zeropole framework. It connects the framework to broader geometrical and topological concepts, offering potential insights beyond the immediate analytical results.

On the Riemann sphere, the critical line ($s = \frac{1}{2} + it$) and the real line ($s = -2k, k \in \mathbb{N}^+$) manifest as intersecting great circles. The critical line maps to a perpendicular circle passing through the poles at $\pm i$, while the real line maps to the equatorial circle. These geometric representations provide an intuitive visualization of the zeropole framework, with their intersection encoding the perpendicularity and symmetry inherent to $\zeta(s)$.

The zeropole balance framework suggests a conceptual unification through sphere eversion—a topological transformation rigorously formalized by Stephen Smale in 1957 [Sma57] and later visualized by Bernard Morin in the 1960s [Mor78]. Sphere eversion, the most extreme yet topologically permissible deformation of a sphere, involves turning the sphere inside-out through "rubber-sheet stretching" without tearing or creasing. This transformation mirrors the zeropole framework by emphasizing the interplay between symmetry and minimality.

Applied to the zeropole framework, this transformation offers a compelling visualization of balancing zeropole dynamics reaching a final equilibrium. The perpendicular zeropole circles—representing the countable infinities of trivial poles and non-trivial zeros—can collapse into the point at infinity on the Riemann sphere, achieving ultimate minimality and algebraic cancellation of the zeropole structure. This collapse also reflects the geometric symmetry encoded in the critical line of $\zeta(s)$.

Such a process underscores the fundamental unity inherent in the zeta function's complete zeropole structure, seamlessly integrating geometrical, analytical, algebraic, and topological perspectives. Beyond its mathematical rigor, this idea highlights the centrality of zeropole balance as a guiding principle in understanding the deeper structures of $\zeta(s)$

8. **Acknowledgements**

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