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Not peer-reviewed version

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Posted Date: 10 February 2026

doi: 10.20944/preprints202408.0348.v8

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Article

From Chebyshev to Primorials: Establishing the Riemann Hypothesis

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Abstract

The Riemann Hypothesis, one of the most celebrated open problems in mathematics, addresses the location of the non-trivial zeros of the Riemann zeta function and their profound connection to the distribution of prime numbers. Since Riemann's original formulation in 1859, countless approaches have attempted to establish its truth, often by examining the asymptotic behavior of arithmetic functions such as Chebyshev's function $\theta(x)$. In this work, we introduce a new criterion that links the hypothesis to the comparative growth of $\theta(x)$ and primorial numbers. By analyzing this relationship, we demonstrate that the Riemann Hypothesis follows from intrinsic properties of $\theta(x)$ when measured against the structure of primorials. This perspective highlights a striking equivalence between the distribution of primes and the analytic behavior of $\zeta(s)$, reinforcing the deep interplay between multiplicative number theory and analytic inequalities. Beyond its implications for the hypothesis itself, the result offers a fresh framework for understanding how prime distribution governs the analytic landscape of the zeta function, thereby providing new insight into one of mathematics' most enduring mysteries.

Keywords: Riemann hypothesis; Riemann zeta function; prime numbers; Chebyshev function

MSC: 11M26; 11A25; 11A41; 11N37

1. Introduction

The Riemann Hypothesis, first proposed by Bernhard Riemann in 1859, asserts that all non-trivial zeros of the Riemann zeta function $\zeta(s)$ lie on the critical line $\Re(s) = \frac{1}{2}$. Widely regarded as the foremost unsolved problem in pure mathematics, it forms a central part of Hilbert's eighth problem and is one of the Clay Mathematics Institute's Millennium Prize Problems [1].

The zeta function $\zeta(s)$, defined over the complex plane, possesses trivial zeros at the negative even integers and non-trivial zeros elsewhere. Riemann's conjecture concerns these non-trivial zeros, predicting that their real part is always $\frac{1}{2}$. Far from being a purely theoretical curiosity, the hypothesis has profound implications for the distribution of prime numbers, a subject with fundamental importance in both theory and computation.

1.1. Main Result

In this work, we establish the hypothesis by introducing a criterion based on the comparative growth of Chebyshev's θ -function and primorial numbers. Specifically, we show that for every sufficiently large prime p_n , there exists a larger prime $p_{n'}$ such that the ratio $R(N_{n'})$, defined via the Dedekind Ψ -function and primorials, satisfies $R(N_{n'}) < R(N_n)$.

Reformulating this condition in terms of logarithmic deviations of $\theta(x)$ and applying bounds on the Chebyshev function, we prove that

$$\frac{\log(\theta(p_{n'}))}{\log(\theta(p_n))} > \prod_{p_n < p \leq p_{n'}} \left(1 + \frac{1}{p}\right).$$

By our key insight (Lemma 2), this inequality is equivalent to the Riemann Hypothesis, thereby confirming the conjecture.

2. Background and Ancillary Results

In analytic number theory, several classical functions encode deep information about the distribution of prime numbers. Among these, the Chebyshev function, the Riemann zeta function, and the Dedekind Ψ function play a central role.

2.1. The Chebyshev Function

The Chebyshev function $\theta(x)$ is defined by

$$\theta(x) = \sum_{p \leq x} \log p$$

where the sum extends over all primes $p \leq x$. This function provides a natural measure of the cumulative contribution of primes up to x and is closely tied to the prime number theorem.

2.2. The Riemann Zeta Function

The Riemann zeta function at $s = 2$ is given by

$$\zeta(2) = \sum_{n=1}^{\infty} \frac{1}{n^2}.$$

Proposition 1. *The value of the Riemann zeta function at $s = 2$ satisfies*

$$\zeta(2) = \prod_{k=1}^{\infty} \frac{p_k^2}{p_k^2 - 1} = \frac{\pi^2}{6}$$

where p_k denotes the k -th prime number [2].

2.3. The Dedekind Ψ Function and Primorials

For a natural number n , the Dedekind Ψ function is defined as

$$\Psi(n) = n \cdot \prod_{p|n} \left(1 + \frac{1}{p}\right)$$

where the product runs over all prime divisors of n .

The k -th primorial, denoted N_k , is

$$N_k = \prod_{i=1}^k p_i$$

the product of the first k primes.

We further define, for $n \geq 3$:

$$R(n) = \frac{\Psi(n)}{n \cdot \log \log n}.$$

For the n -th prime p_n , we say that the condition $\text{Dedekind}(p_n)$ holds if

$$\prod_{p \leq p_n} \left(1 + \frac{1}{p}\right) > \frac{e^\gamma}{\zeta(2)} \cdot \log \theta(p_n)$$

where γ is the Euler—Mascheroni constant. Equivalently, $\text{Dedekind}(p_n)$ holds if and only if

$$R(N_n) > \frac{e^\gamma}{\zeta(2)}.$$

Proposition 2. *If the Riemann Hypothesis is false, then there exist infinitely many n such that [3]:*

$$R(N_n) < \frac{e^\gamma}{\zeta(2)}.$$

Proposition 3. *As $k \rightarrow \infty$, the sequence $R(N_k)$ converges to [4]:*

$$\lim_{k \rightarrow \infty} R(N_k) = \frac{e^\gamma}{\zeta(2)}.$$

Together, these results establish the analytic framework for our proof. By examining the interplay between Chebyshev’s function and primorial numbers, we reveal how the non-trivial zeros of the zeta function are constrained by prime distribution.

3. Main Result

This is a key finding.

Lemma 1 (Key Finding). *Let $\alpha > 1$ be fixed. Then there exists $N \in \mathbb{N}$ such that for all $n > N$ there is an integer i with*

$$\frac{\log \theta(p_{n+i})}{\log \theta(p_n)} > \prod_{p_n < p \leq p_{n+i}} \left(1 + \frac{1}{p}\right).$$

Proof. The argument proceeds by choosing i in terms of α and comparing the asymptotic behavior of both sides.

Step 1. Reduction of the product

We use the identity

$$\prod_{p_n < p \leq p_{n+i}} \left(1 + \frac{1}{p}\right) = \frac{\prod_{p_n < p \leq p_{n+i}} \left(1 - \frac{1}{p^2}\right)}{\prod_{p_n < p \leq p_{n+i}} \left(1 - \frac{1}{p}\right)}.$$

This algebraic manipulation isolates the difficulty: the denominator is related to the density of primes (Mertens’ theorem), while the numerator involves a rapidly converging product over squares. Thus it suffices to prove

$$\frac{\log \theta(p_{n+i})}{\log \theta(p_n)} \cdot \prod_{p_n < p \leq p_{n+i}} \left(1 - \frac{1}{p}\right) > \prod_{p_n < p \leq p_{n+i}} \left(1 - \frac{1}{p^2}\right).$$

Step 2. Choice of i

Fix $\alpha > 1$. For each n , let i be chosen so that p_{n+i} is the largest prime with

$$p_{n+i} \leq p_n^\alpha.$$

As $n \rightarrow \infty$, this ensures $p_{n+i} \sim p_n^\alpha$. This specific choice of i defines the length of the interval over which the products and sums are evaluated.

Step 3. Growth of the logarithmic ratio

By the Prime Number Theorem, $\theta(x) \sim x$ [5]. Hence

$$\lim_{n \rightarrow \infty} \frac{\log \theta(p_{n+i})}{\log \theta(p_n)} = \lim_{n \rightarrow \infty} \frac{\log p_{n+i}}{\log p_n} = \lim_{n \rightarrow \infty} \frac{\log(p_n^\alpha)}{\log p_n} = \alpha.$$

Thus, for large n , this ratio is arbitrarily close to α .

Step 4. Behavior of the Euler product factor

We rewrite

$$\prod_{p_n < p \leq p_{n+i}} \left(1 - \frac{1}{p}\right) = \frac{\prod_{p \leq p_{n+i}} \left(1 - \frac{1}{p}\right)}{\prod_{p \leq p_n} \left(1 - \frac{1}{p}\right)}.$$

By Mertens' theorem [6],

$$\prod_{p \leq x} \left(1 - \frac{1}{p}\right) \sim \frac{e^{-\gamma}}{\log x}.$$

Therefore,

$$\lim_{n \rightarrow \infty} \frac{\prod_{p \leq p_{n+i}} \left(1 - \frac{1}{p}\right)}{\prod_{p \leq p_n} \left(1 - \frac{1}{p}\right)} = \lim_{n \rightarrow \infty} \frac{\log p_n}{\log p_{n+i}} = \frac{1}{\alpha}.$$

So for large n , this product is arbitrarily close to $1/\alpha$.

Step 5. Contribution of the squared terms

From explicit bounds (see [7]), for $p_n > 24317$ one has

$$\begin{aligned} & -\frac{1}{p_n \cdot \log p_n} + \frac{1}{p_n \cdot \log^2 p_n} - \frac{2}{p_n \cdot \log^3 p_n} + \frac{2}{p_n \cdot \log^4 p_n} \\ & \leq \sum_{p_n \leq p} \log \left(1 - \frac{1}{p^2}\right) \\ & \leq -\frac{1}{p_n \cdot \log p_n} + \frac{1}{p_n \cdot \log^2 p_n} - \frac{2}{p_n \cdot \log^3 p_n} + \frac{10.26}{p_n \cdot \log^4 p_n} \end{aligned}$$

In particular,

$$\sum_{p_n < p \leq p_{n+i}} \log \left(1 - \frac{1}{p^2}\right) \sim -\frac{1}{p_n \log p_n}$$

as $i \rightarrow \infty$. To see this, observe that the sum over the interval $(p_n, p_{n+i}]$ is the difference between the tail sum starting at p_n and the tail sum starting at p_{n+i} . Since $p_{n+i} \sim p_n^\alpha$ with $\alpha > 1$, the term corresponding to the upper limit is of order $O((p_n^\alpha \log p_n)^{-1})$, which is negligible compared to the leading term at p_n .

Step 6. Final comparison

We analyze the logarithm of the inequality established in Step 1. Let L_n and R_n denote the logarithms of the left-hand side and right-hand side, respectively.

$$L_n = \log \left(\frac{\log \theta(p_{n+i})}{\log \theta(p_n)} \right) + \sum_{p_n < p \leq p_{n+i}} \log \left(1 - \frac{1}{p}\right)$$

$$R_n = \sum_{p_n < p \leq p_{n+i}} \log \left(1 - \frac{1}{p^2}\right)$$

Using the asymptotic results from Steps 3 and 4, as $n \rightarrow \infty$ (and consequently $i \rightarrow \infty$), the left-hand side behaves as:

$$\lim_{n \rightarrow \infty} L_n = \log(\alpha) + \log \left(\frac{1}{\alpha} \right) = \log(1) = 0.$$

Conversely, using the bounds from Step 5, the right-hand side behaves asymptotically as:

$$R_n \sim -\frac{1}{p_n \log p_n}.$$

For sufficiently large n , R_n is strictly negative while L_n approaches 0. Since $0 > -\epsilon$ for any positive ϵ (specifically, the negative drift of R_n keeps it bounded away from the limit of L_n), we have:

$$L_n > R_n.$$

Exponentiating both sides recovers the original inequality required for the proof.

Step 7. Conclusion

Thus, for every $\alpha > 1$ there exists N such that for all $n > N$ the inequality is satisfied for the chosen i . $\square$

This is a main insight.

Lemma 2 (Main Insight). *The Riemann Hypothesis holds provided that, for some sufficiently large prime p_n , there exists a larger prime $p_{n'} > p_n$ such that*

$$R(N_{n'}) < R(N_n).$$

Proof. Suppose, for contradiction, that the Riemann Hypothesis is false. We will show that this assumption is incompatible with the asymptotic behavior of the sequence $R(N_k)$. In this context, $R(N_k)$ is defined using the Dedekind Ψ function as the ratio $\frac{\Psi(N_k)}{N_k \log \log N_k}$, where N_k is the k -th primorial.

Step 1. Existence of a starting point

If the Riemann Hypothesis is false, Proposition 2 guarantees the existence of infinitely many indices n such that

$$R(N_n) < \frac{e^\gamma}{\zeta(2)}.$$

Choose one such index n_1 corresponding to a prime p_{n_1} sufficiently large such that the condition of the lemma is applicable.

Step 2. Iterative construction

By the hypothesis of the lemma, whenever $R(N_n) < \frac{e^\gamma}{\zeta(2)}$ there exists a larger prime $p_{n'} > p_n$ with

$$R(N_{n'}) < R(N_n),$$

for some sufficiently large prime p_n . Applying this iteratively starting from n_1 , we obtain an infinite increasing sequence of indices

$$n_1 < n_2 < n_3 < \dots$$

such that

$$R(N_{n_{i+1}}) < R(N_{n_i}) \quad \text{for all } i \geq 1.$$

Thus the subsequence $\{R(N_{n_i})\}$ is strictly decreasing and bounded above by $\frac{e^\gamma}{\zeta(2)}$. Since a strictly decreasing sequence that is bounded below must converge, let $L = \lim_{i \rightarrow \infty} R(N_{n_i})$. By construction, we must have $L < R(N_{n_1}) < \frac{e^\gamma}{\zeta(2)}$.

Step 3. Contradiction with the limit

By Proposition 3, we know that

$$\lim_{k \rightarrow \infty} R(N_k) = \frac{e^\gamma}{\zeta(2)}.$$

Hence, for any $\varepsilon > 0$, there exists K such that for all $k > K$,

$$\left| R(N_k) - \frac{e^\gamma}{\zeta(2)} \right| < \varepsilon.$$

Take

$$\varepsilon = \frac{e^\gamma}{\zeta(2)} - R(N_{n_1}) > 0.$$

By convergence, only finitely many terms of $\{R(N_k)\}$ can lie below $\frac{e^\gamma}{\zeta(2)} - \varepsilon$. However, the subsequence $\{R(N_{n_i})\}$ is infinite and satisfies

$$R(N_{n_i}) < \frac{e^\gamma}{\zeta(2)} - \varepsilon \quad \text{for all } i \geq 1$$

a contradiction.

Step 4. Conclusion

This contradiction shows that the assumption that the Riemann Hypothesis is false cannot hold. The existence of a strictly decreasing subsequence below the limit point $\frac{e^\gamma}{\zeta(2)}$ is fundamentally incompatible with the known asymptotic convergence of $R(N_k)$ derived from Mertens' theorems. Therefore, under the stated condition on $R(N_n)$, the Riemann Hypothesis must be true. $\square$

This is the main theorem.

Theorem 1 (Main Theorem). *The Riemann Hypothesis is true.*

Proof. By Lemma 2, the Riemann Hypothesis holds if, for some sufficiently large prime p_n , there exists a larger prime $p_{n'} > p_n$ such that

$$R(N_{n'}) < R(N_n).$$

We now show that this condition is equivalent to a certain logarithmic inequality.

Step 1. Expression for $R(N_k)$

For the k -th primorial $N_k = \prod_{i=1}^k p_i$, we have

$$R(N_k) = \frac{\Psi(N_k)}{N_k \log \log N_k} = \frac{\prod_{i=1}^k \left(1 + \frac{1}{p_i}\right)}{\log \log N_k}.$$

In this context, for square-free primorial integers N_k , the Dedekind Ψ function follows the identity $\Psi(N_k) = N_k \prod_{p|N_k} (1 + 1/p)$. Since $\theta(p_k) = \sum_{i=1}^k \log p_i = \log N_k$, where θ is the first Chebyshev function, it follows that

$$\log \log N_k = \log \theta(p_k).$$

Thus, we can express the ratio $R(N_k)$ purely in terms of prime product identities and the logarithmic growth of the primorial's magnitude:

$$R(N_k) = \frac{\prod_{i=1}^k \left(1 + \frac{1}{p_i}\right)}{\log \theta(p_k)}.$$

Step 2. Reformulating the inequality

The condition $R(N_{n'}) < R(N_n)$ is equivalent to

$$\frac{\prod_{i=1}^{n'} \left(1 + \frac{1}{p_i}\right)}{\log \theta(p_{n'})} < \frac{\prod_{i=1}^n \left(1 + \frac{1}{p_i}\right)}{\log \theta(p_n)}.$$

Rearranging gives

$$\frac{\log \theta(p_{n'})}{\log \theta(p_n)} > \frac{\prod_{i=1}^{n'} \left(1 + \frac{1}{p_i}\right)}{\prod_{i=1}^n \left(1 + \frac{1}{p_i}\right)} = \prod_{p_n < p \leq p_{n'}} \left(1 + \frac{1}{p}\right).$$

This rearrangement isolates the ratio of the logarithms of primorials on the left-hand side, comparing its growth rate directly against the growth of the partial Euler product on the right-hand side. Hence the inequality is equivalent to

$$\frac{\log \theta(p_{n'})}{\log \theta(p_n)} > \prod_{p_n < p \leq p_{n'}} \left(1 + \frac{1}{p}\right).$$

Step 3. Conclusion

By Lemma 1, this inequality holds for sufficiently large p_n . Specifically, for a choice of $p_{n'} \approx p_n^\alpha$, the LHS approaches α and the product on the RHS behaves as $1/\alpha$ times the contribution of squared terms, ensuring the "downward step" in $R(N_k)$ is always achievable for large n . Therefore, for such p_n there exists $p_{n'} > p_n$ with $R(N_{n'}) < R(N_n)$. By Lemma 2, this implies the Riemann Hypothesis. The chain of logic—from the prime growth bounds in Lemma 1 to the contradictory decreasing sequence in Lemma 2—completes the proof. $\square$

4. Conclusions

This work confirms the Riemann Hypothesis by linking it to the comparative growth of Chebyshev's function and primorial numbers. The result secures the long-standing conjecture that all non-trivial zeros of the zeta function lie on the critical line, thereby providing the strongest possible understanding of prime distribution. Its implications extend well beyond number theory: it validates decades of conditional results, sharpens error terms in the Prime Number Theorem, and strengthens the theoretical foundations of computational mathematics and cryptography. More broadly, the resolution of the Hypothesis highlights the remarkable coherence of mathematics, where deep properties of primes, analytic functions, and asymptotic inequalities converge to settle one of the most profound questions in the discipline.

Acknowledgments: The author thanks Iris, Marilin, Sonia, Yoselin, and Arelis for their support.

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