



Possible Counterexample of the Riemann Hypothesis

Frank Vega

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Abstract Under the assumption that the Riemann hypothesis is true, von Koch deduced the improved asymptotic formula $\theta(x) = x + O(\sqrt{x} \times \log^2 x)$, where $\theta(x)$ is the Chebyshev function. A precise version of this was given by Schoenfeld: He found under the assumption that the Riemann hypothesis is true that $\theta(x) < x + \frac{1}{8 \times \pi} \times \sqrt{x} \times \log^2 x$ for every $x \geq 599$. On the contrary, we prove if there exists some real number $x \geq 10^8$ such that $\theta(x) > x + \frac{1}{\log \log \log x} \times \sqrt{x} \times \log^2 x$, then the Riemann hypothesis should be false. In this way, we show that under the assumption that the Riemann hypothesis is true, then $\theta(x) < x + \frac{1}{\log \log \log x} \times \sqrt{x} \times \log^2 x$ for all $x \geq 10^8$.

Keywords Riemann hypothesis · Nicolas inequality · Chebyshev function · prime numbers

Mathematics Subject Classification (2010) MSC 11M26 · MSC 11A41 · MSC 11A25

1 Introduction

The Riemann hypothesis is a conjecture that the Riemann zeta function has its zeros only at the negative even integers and complex numbers with real part $\frac{1}{2}$ [2]. The Riemann hypothesis belongs to the David Hilbert's list of 23 unsolved problems [2]. Besides, it is one of the Clay Mathematics Institute's Millennium Prize Problems [2]. This problem has remained unsolved for many years [2]. In mathematics, the Chebyshev function $\theta(x)$ is given by

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

F. Vega
CopSonic, 1471 Route de Saint-Nauphary 82000 Montauban, France
ORCID: 0000-0001-8210-4126
E-mail: vega.frank@gmail.com

where $p \leq x$ means all the prime numbers p that are less than or equal to x . Say $\text{Nicolas}(p_n)$ holds provided

$$\prod_{q \leq p_n} \frac{q}{q-1} > e^\gamma \times \log \theta(p_n).$$

The constant $\gamma \approx 0.57721$ is the Euler-Mascheroni constant, \log is the natural logarithm, and p_n is the n^{th} prime number. The importance of this property is:

Theorem 1.1 [7], [8]. $\text{Nicolas}(p_n)$ holds for all prime numbers $p_n > 2$ if and only if the Riemann hypothesis is true.

We know the following properties for the Chebyshev function:

Theorem 1.2 [11]. If the Riemann hypothesis holds, then

$$\theta(x) = x + O(\sqrt{x} \times \log^2 x)$$

for all $x \geq 10^8$.

Theorem 1.3 [9]. For $2 \leq x \leq 10^8$

$$\theta(x) < x.$$

We also know that

Theorem 1.4 [10]. If the Riemann hypothesis holds, then

$$\left(\frac{e^{-\gamma}}{\log x} \times \prod_{q \leq x} \frac{q}{q-1} - 1 \right) < \frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x}}$$

for all numbers $x \geq 13.1$.

Let's define $H = \gamma - B$ such that $B \approx 0.2614972128$ is the Meissel-Mertens constant [6]. We know from the constant H , the following formula:

Theorem 1.5 [3].

$$\sum_q \left(\log\left(\frac{q}{q-1}\right) - \frac{1}{q} \right) = \gamma - B = H.$$

For $x \geq 2$, the function $u(x)$ is defined as follows

$$u(x) = \sum_{q > x} \left(\log\left(\frac{q}{q-1}\right) - \frac{1}{q} \right).$$

We use the following theorems:

Theorem 1.6 [5]. For $x > -1$:

$$\frac{x}{x+1} \leq \log(1+x).$$

Theorem 1.7 [4]. For $x \geq 1$:

$$\log\left(1 + \frac{1}{x}\right) < \frac{1}{x+0.4}.$$

Let's define:

$$\delta(x) = \left(\sum_{q \leq x} \frac{1}{q} - \log \log x - B \right).$$

Definition 1.8 We define another function:

$$\varpi(x) = \left(\sum_{q \leq x} \frac{1}{q} - \log \log \theta(x) - B \right).$$

Putting all together yields the proof that the inequality $\varpi(x) > u(x)$ is satisfied for a number $x \geq 3$ if and only if Nicolas(p) holds, where p is the greatest prime number such that $p \leq x$. In this way, we introduce another criterion for the Riemann hypothesis based on the Nicolas criterion and deduce some of its consequences.

2 Results

Theorem 2.1 *The Riemann hypothesis is true if and only if the inequality $\varpi(x) > u(x)$ is satisfied for all numbers $x \geq 3$.*

Proof In the paper [8] is defined the function:

$$f(x) = e^\gamma \times (\log \theta(x)) \times \prod_{q \leq x} \frac{q-1}{q}.$$

We know that $f(x)$ is lesser than 1 when Nicolas(p) holds, where p is the greatest prime number such that $2 < p \leq x$. In the same paper, we found that

$$\log f(x) = U(x) + u(x)$$

where $U(x) = -\varpi(x)$ [8]. When $f(x)$ is lesser than 1, then $\log f(x) < 0$. Consequently, we obtain that

$$-\varpi(x) + u(x) < 0$$

which is the same as $\varpi(x) > u(x)$. Therefore, this is a consequence of the theorem 1.1.

Theorem 2.2 *If the Riemann hypothesis holds, then*

$$\frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x} + 1.2 \times \log x + 2} + \frac{\log x}{\log \theta(x)} > 1$$

for all numbers $x \geq 13.1$.

Proof Under the assumption that the Riemann hypothesis is true, then we would have

$$\prod_{q \leq x} \frac{q}{q-1} < e^\gamma \times \log x \times \left(1 + \frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x}}\right)$$

after of distributing the terms based on the theorem 1.4 for all numbers $x \geq 13.1$. If we apply the logarithm to the both sides of the previous inequality, then we obtain that

$$\sum_{q \leq x} \log\left(\frac{q}{q-1}\right) < \gamma + \log \log x + \log\left(1 + \frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x}}\right).$$

That would be equivalent to

$$\sum_{q \leq x} \frac{1}{q} + \sum_{q \leq x} \left(\log\left(\frac{q}{q-1}\right) - \frac{1}{q}\right) < \gamma + \log \log x + \frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x} + 1.2 \times \log x + 2}$$

where we know that

$$\begin{aligned} \log\left(1 + \frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x}}\right) &< \frac{1}{\frac{8 \times \pi \times \sqrt{x}}{3 \times \log x + 5} + 0.4} \\ &= \frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x} + 0.4 \times (3 \times \log x + 5)} \\ &= \frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x} + 1.2 \times \log x + 2} \end{aligned}$$

according to theorem 1.7 since $\frac{8 \times \pi \times \sqrt{x}}{3 \times \log x + 5} \geq 1$ for all numbers $x \geq 13.1$. We use the theorem 1.5 to show that

$$\sum_{q \leq x} \left(\log\left(\frac{q}{q-1}\right) - \frac{1}{q}\right) = H - u(x)$$

and $\gamma = H + B$. So,

$$H - u(x) < H + B + \log \log x - \sum_{q \leq x} \frac{1}{q} + \frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x} + 1.2 \times \log x + 2}$$

which is the same as

$$H - u(x) < H - \delta(x) + \frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x} + 1.2 \times \log x + 2}.$$

We eliminate the value of H and thus,

$$-u(x) < -\delta(x) + \frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x} + 1.2 \times \log x + 2}$$

which is equal to

$$u(x) + \frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x} + 1.2 \times \log x + 2} > \delta(x).$$

Under the assumption that the Riemann hypothesis is true, we know from the theorem 2.1 that $\varpi(x) > u(x)$ for all numbers $x \geq 13.1$ and therefore,

$$\varpi(x) + \frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x} + 1.2 \times \log x + 2} > \delta(x).$$

Hence,

$$\frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x} + 1.2 \times \log x + 2} > \log \log \theta(x) - \log \log x.$$

Suppose that $\theta(x) = \varepsilon \times x$ for some constant $\varepsilon > 1$. Then,

$$\begin{aligned} \log \log \theta(x) - \log \log x &= \log \log(\varepsilon \times x) - \log \log x \\ &= \log(\log x + \log \varepsilon) - \log \log x \\ &= \log\left(\log x \times \left(1 + \frac{\log \varepsilon}{\log x}\right)\right) - \log \log x \\ &= \log \log x + \log\left(1 + \frac{\log \varepsilon}{\log x}\right) - \log \log x \\ &= \log\left(1 + \frac{\log \varepsilon}{\log x}\right). \end{aligned}$$

In addition, we know that

$$\log\left(1 + \frac{\log \varepsilon}{\log x}\right) \geq \frac{\log \varepsilon}{\log \theta(x)}$$

using the theorem 1.6 since $\frac{\log \varepsilon}{\log x} > -1$ when $\varepsilon > 1$. Certainly, we will have that

$$\log\left(1 + \frac{\log \varepsilon}{\log x}\right) \geq \frac{\frac{\log \varepsilon}{\log x}}{\frac{\log \varepsilon}{\log x} + 1} = \frac{\log \varepsilon}{\log \varepsilon + \log x} = \frac{\log \varepsilon}{\log \theta(x)}.$$

Thus,

$$\frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x} + 1.2 \times \log x + 2} > \frac{\log \varepsilon}{\log \theta(x)}.$$

If we add the following value of $\frac{\log x}{\log \theta(x)}$ to the both sides of the inequality, then

$$\begin{aligned} \frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x} + 1.2 \times \log x + 2} + \frac{\log x}{\log \theta(x)} &> \frac{\log \varepsilon}{\log \theta(x)} + \frac{\log x}{\log \theta(x)} \\ &= \frac{\log \varepsilon + \log x}{\log \theta(x)} \\ &= \frac{\log \theta(x)}{\log \theta(x)} \\ &= 1. \end{aligned}$$

We know this inequality is satisfied when $0 < \varepsilon \leq 1$ since we would obtain that $\frac{\log x}{\log \theta(x)} \geq 1$. Therefore, the proof is done.

Theorem 2.3 *If there exists some real number $x \geq 10^8$ such that*

$$\theta(x) > x + \frac{1}{\log \log \log x} \times \sqrt{x} \times \log^2 x,$$

then the Riemann hypothesis is false.

Proof If the Riemann hypothesis holds, then

$$\theta(x) = x + O(\sqrt{x} \times \log^2 x)$$

for all $x \geq 10^8$ from the theorem 1.2. Now, suppose there is a real number $x \geq 10^8$ such that $\theta(x) > x + \frac{1}{\log \log \log x} \times \sqrt{x} \times \log^2 x$. That would be equivalent to

$$\log \theta(x) > \log \left(x + \frac{1}{\log \log \log x} \times \sqrt{x} \times \log^2 x \right)$$

and so,

$$\frac{1}{\log \theta(x)} < \frac{1}{\log \left(x + \frac{1}{\log \log \log x} \times \sqrt{x} \times \log^2 x \right)}$$

for all numbers $x \geq 10^8$. Hence,

$$\frac{\log x}{\log \theta(x)} < \frac{\log x}{\log \left(x + \frac{1}{\log \log \log x} \times \sqrt{x} \times \log^2 x \right)}.$$

If the Riemann hypothesis holds, then

$$\frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x} + 1.2 \times \log x + 2} + \frac{\log x}{\log \left(x + \frac{1}{\log \log \log x} \times \sqrt{x} \times \log^2 x \right)} > 1$$

for those values of x that complies with

$$\theta(x) > x + \frac{1}{\log \log \log x} \times \sqrt{x} \times \log^2 x$$

due to the theorem 2.2. By contraposition, if there exists some number $y \geq 10^8$ such that for all $x \geq y$ the inequality

$$\frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x} + 1.2 \times \log x + 2} + \frac{\log x}{\log \left(x + \frac{1}{\log \log \log x} \times \sqrt{x} \times \log^2 x \right)} \leq 1$$

is satisfied, then the Riemann hypothesis should be false. Let's define the function

$$v(x) = \frac{3 \times \log x + 5}{8 \times \pi \times \sqrt{x} + 1.2 \times \log x + 2} + \frac{\log x}{\log \left(x + \frac{1}{\log \log \log x} \times \sqrt{x} \times \log^2 x \right)} - 1.$$

The Riemann hypothesis is false when there exists some number $y \geq 10^8$ such that for all $x \geq y$ the inequality $v(x) \leq 0$ is always satisfied. We ignore when $2 \leq x \leq 10^8$ since $\theta(x) < x$ according to the theorem 1.3. We know that the function $v(x)$ is monotonically decreasing for every number $x \geq 10^8$. The derivative of $v(x)$ is negative for all $x \geq 10^8$. Indeed, a function $v(x)$ of a real variable x is monotonically decreasing

in some interval if the derivative of $v(x)$ is lesser than zero and the function $v(x)$ is continuous over that interval [1]. It is enough to find a value of $y \geq 10^8$ such that $v(y) \leq 0$ since for all $x \geq y$ we would have that $v(x) \leq v(y) \leq 0$, because of $v(x)$ is monotonically decreasing. We found the value $y = 10^8$ complies with $v(y) \leq 0$. In this way, we obtain that $v(x) \leq 0$ for every number $x \geq 10^8$. Hence, the proof is completed.

Theorem 2.4 *Under the assumption that the Riemann hypothesis is true, then*

$$\theta(x) < x + \frac{1}{\log \log \log x} \times \sqrt{x} \times \log^2 x$$

for all $x \geq 10^8$.

Proof This is a direct consequence of the theorem 2.3.

Appendix

We found the derivative of $v(x)$ in the web site <https://www.wolframalpha.com/input>. Besides, we determine the sign of the function $v(x)$ using the tool *gp* from the web site <https://pari.math.u-bordeaux.fr>. In the project PARI/GP, the method *sign(F(X))* returns -1 when the function $F(X)$ is negative in the value of X . We checked that is negative for $X = 10^8$ with a real precision of 1000016 significant digits when $F(X) = v(x)$. We also checked that is still negative for $X = 100000!$, where $(\dots)!$ means the factorial function.

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