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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. 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. Note that, the von Koch asymptotic formula uses the Big O notation, where $f(x) = O(g(x))$ means that there exists a positive real number M and a real number y, such that $|f(x)| \leq M \times g(x)$ for all $x \geq y$. However, no matter how big we get the real number $y \geq 10^8$, the another positive real number M could always prevail over the value of $\frac{1}{\log\log\log x}$ for sufficiently large numbers $x \geq y$.

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

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

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

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

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

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

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 $x \geq 1$:*

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

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 $\mathsf{Nicolas}(p)$ 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 $\mathsf{Nicolas}(p)$ 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

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

That would be equivalent to

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

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

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

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,

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

In addition, we know that

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

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

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

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 $x \geq 10^8$ due to 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

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

and so,

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

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

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

If the Riemann hypothesis holds, then

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

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

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

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

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

The Riemann hypothesis is false when there exists some number $y \geq 10^8$ such that for all $x \geq y$ the inequality $\upsilon(x) \leq 0$ 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 $\upsilon(x)$ is monotonically decreasing for every number $x \geq 10^8$. The derivative of $\upsilon(x)$ is negative for all $x \geq 10^8$. Indeed, a function $\upsilon(x)$ of a real variable x is monotonically decreasing in some interval if the derivative of $\upsilon(x)$ is lesser than zero and the function $\upsilon(x)$ is continuous over that interval [1]. It is enough to find a value of $y \geq 10^8$ such that $\upsilon(y) \leq 0$ since for all $x \geq y$ we would have that $\upsilon(x) \leq \upsilon(y) \leq 0$, because of $\upsilon(x)$ is monotonically decreasing. We found the value $y = 10^8$ complies with $\upsilon(y) \leq 0$. In this way, we obtain that $\upsilon(x) \leq 0$ for every number $x \geq 10^8$. Hence, the proof is complete.

Appendix

We found the derivative of $\upsilon(x)$ in the web site `https://www.wolframalpha.com/input`. Besides, we determine the sign of the function $\upsilon(x)$ 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 $F(X) = \upsilon(x)$. We also checked that is still negative for $X = 100000!$, where $(\ldots)!$ means the factorial function.

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