A Very Brief Note on the Riemann Hypothesis

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August 14, 2022

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Abstract. Robin's criterion states that the Riemann Hypothesis is true if and only if the inequality $\sigma(n) < e^{\gamma} \cdot n \cdot \log \log n$ holds for all natural numbers $n > 5040$, where $\sigma(n)$ is the sum-of-divisors function of n and $\gamma \approx 0.57721$ is the Euler-Mascheroni constant. We also require the properties of superabundant numbers, that is to say left to right maxima of $n \mapsto \frac{\sigma(n)}{n}$. In this note, using Robin's inequality on superabundant numbers, we prove that the Riemann Hypothesis is true.

Keywords: Riemann Hypothesis · Robin's inequality · Sum-of-divisors function · Superabundant numbers · Prime numbers.

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 $\frac{1}{2}$. It is considered by many to be the most important unsolved problem in pure mathematics. It was proposed by Bernhard Riemann (1859). The Riemann Hypothesis belongs to the Hilbert's eighth problem on David Hilbert's list of twenty-three unsolved problems. This is one of the Clay Mathematics Institute's Millennium Prize Problems. As usual $\sigma(n)$ is the sum-of-divisors function of n

$$\sum_{d \mid n} d,$$

where $d \mid n$ means the integer d divides n. Define $f(n)$ as $\frac{\sigma(n)}{n}$. We say that $\mathsf{Robin}(n)$ holds provided that

$$f(n) < e^{\gamma} \cdot \log \log n,$$

where the constant $\gamma \approx 0.57721$ is the Euler-Mascheroni constant and log is the natural logarithm. The Ramanujan's Theorem stated that if the Riemann Hypothesis is true, then the previous inequality holds for large enough n. Next we have the Robin's Theorem:

Proposition 1. $\mathsf{Robin}(n)$ *holds for all natural numbers* $n > 5040$ *if and only if the Riemann Hypothesis is true [7, Theorem 1 pp. 188].*

It is known that $\mathsf{Robin}(n)$ holds for many classes of natural numbers n.

Proposition 2. $\mathsf{Robin}(n)$ *holds for all natural numbers* $n > 5040$ *such that* $p \leq e^{31.018189471}$*, where* p *is the largest prime divisor of* n *[8, Theorem 4.2 pp. 4].*

Superabundant numbers were defined by Leonidas Alaoglu and Paul Erdős (1944). In 1997, Ramanujan's old notes were published where he defined the generalized highly composite numbers, which include the superabundant and colossally abundant numbers. Let $q_1 = 2, q_2 = 3, \ldots, q_k$ denote the first k consecutive primes, then an integer of the form $\prod_{i=1}^{k} q_i^{a_i}$ with $a_1 \geq a_2 \geq \ldots \geq a_k \geq 1$ is called a Hardy-Ramanujan integer [4, pp. 367]. A natural number n is called superabundant precisely when, for all natural numbers $m < n$

$$f(m) < f(n).$$

Proposition 3. *If* n *is superabundant, then* n *is a Hardy-Ramanujan integer [2, Theorem 1 pp. 450].*

Proposition 4. *[2, Theorem 9 pp. 454]. For some constant* $c > 0$*, the number of superabundant numbers less than* x *exceeds*

$$\frac{c \cdot \log x \cdot \log\log x}{(\log\log\log x)^2}.$$

A number n is said to be colossally abundant if, for some $\epsilon > 0$,

$$\frac{\sigma(n)}{n^{1+\epsilon}} \geq \frac{\sigma(m)}{m^{1+\epsilon}} \ \ for \ \ (m > 1).$$

Proposition 5. *Every colossally abundant number is superabundant [2, pp. 455].*

Several analogues of the Riemann Hypothesis have already been proved. Many authors expect (or at least hope) that it is true. However, there are some implications in case of the Riemann Hypothesis might be false.

Proposition 6. *If the Riemann Hypothesis is false, then there are infinitely many colossally abundant numbers* $n > 5040$ *such that* $\mathsf{Robin}(n)$ *fails (i.e.* $\mathsf{Robin}(n)$ *does not hold) [7, Proposition pp. 204].*

Proposition 7. *The smallest counterexample of the Robin's inequality greater than* 5040 *must be a superabundant number [1, Theorem 3 pp. 1].*

Putting all together yields the proof of the Riemann Hypothesis.

2 Main Results

Lemma 1. *If the Riemann Hypothesis is false, then there are infinitely many superabundant numbers* n *such that* $\mathsf{Robin}(n)$ *fails.*

Proof. This is a direct consequence of Propositions 1, 5 and 6. □

For every prime number q_k, we define the sequence $Y_k = \frac{e^{\frac{0.2}{\log^2(q_k)}}}{(1-\frac{0.01}{\log^3(q_k)})}$. As the prime number q_k increases, the sequence Y_k is strictly decreasing. In mathematics, the Chebyshev function $\theta(x)$ is given by

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

with the sum extending over all prime numbers q that are less than or equal to x. We know that

Lemma 2. *[3, Lemma 2.7 pp. 19]. For $x \geq 7232121212$:*

$$\theta(x) \geq (1 - \frac{0.01}{\log^3(x)}) \cdot x.$$

Lemma 3. *[3, Lemma 2.7 pp. 19]. For $x \geq 2278382$:*

$$\prod_{q \leq x} \frac{q}{q-1} \leq e^{\gamma} \cdot (\log x + \frac{0.2}{\log^2(x)}).$$

We will prove another important inequality:

Lemma 4. *Let $q_1, q_2, \ldots, q_k$ denote the first k consecutive primes such that $q_1 < q_2 < \ldots < q_k$ and $q_k > 7232121212$. Then*

$$\prod_{i=1}^{k} \frac{q_i}{q_i - 1} \leq e^{\gamma} \cdot \log\left(Y_k \cdot \theta(q_k)\right).$$

Proof. From the Lemma 2, we know that

$$\theta(q_k) \geq (1 - \frac{0.01}{\log^3(q_k)}) \cdot q_k.$$

In this way, we can show that

$$\begin{aligned} \log\left(Y_k \cdot \theta(q_k)\right) &\geq \log\left(Y_k \cdot (1 - \frac{0.01}{\log^3(q_k)}) \cdot q_k\right) \\ &= \log q_k + \log\left(Y_k \cdot (1 - \frac{0.01}{\log^3(q_k)})\right). \end{aligned}$$

We know that

$$\begin{aligned} \log\left(Y_k \cdot (1 - \frac{0.01}{\log^3(q_k)})\right) &= \log\left(\frac{e^{\frac{0.2}{\log^2(q_k)}}}{(1 - \frac{0.01}{\log^3(q_k)})} \cdot (1 - \frac{0.01}{\log^3(q_k)})\right) \\ &= \log\left(e^{\frac{0.2}{\log^2(q_k)}}\right) \\ &= \frac{0.2}{\log^2(q_k)}. \end{aligned}$$

Consequently, we obtain that

$$\log q_k + \log \left(Y_k \cdot (1 - \frac{0.01}{\log^3(q_k)}) \right) \geq (\log q_k + \frac{0.2}{\log^2(q_k)}).$$

Due to the Lemma 3, we prove that

$$\prod_{i=1}^{k} \frac{q_i}{q_i - 1} \leq e^{\gamma} \cdot (\log q_k + \frac{0.2}{\log^2(q_k)}) \leq e^{\gamma} \cdot \log (Y_k \cdot \theta(q_k))$$

when $q_k > 7232121212$. □

We use the following Lemmas:

Lemma 5. *[5, Lemma 1 pp. 2]. Let $\prod_{i=1}^{k} q_i^{a_i}$ be the representation of n as a product of prime numbers $q_1 < \ldots < q_k$ with natural numbers $a_1, \ldots, a_k$ as exponents. Then,*

$$f(n) = \left(\prod_{i=1}^{k} \frac{q_i}{q_i - 1} \right) \cdot \left(\prod_{i=1}^{k} (1 - \frac{1}{q_i^{a_i+1}}) \right).$$

Lemma 6. *[6, Lemma 3.3 pp. 8]. Let $x \geq 11$. For $y > x$ we have*

$$\frac{\log \log y}{\log \log x} < \sqrt{\frac{y}{x}}.$$

Theorem 1. *Let $\prod_{i=1}^{k} q_i^{a_i}$ be the representation of a superabundant number $n > 5040$ as the product of the first k consecutive primes $q_1 < \ldots < q_k$ with the natural numbers $a_1 \geq a_2 \geq \ldots \geq a_k \geq 1$ as exponents. Suppose that $\mathsf{Robin}(n)$ fails. Then, $n < \alpha^2 \cdot (N_k)^{Y_k}$, where $N_k = \prod_{i=1}^{k} q_i$ is the primorial number of order k and $\alpha = \prod_{i=1}^{k} \left(1 - \frac{1}{q_i^{a_i+1}} \right)$.*

Proof. When $\mathsf{Robin}(n)$ fails, then $q_k > e^{31.018189471}$ by Proposition 2. From the Lemma 5, we note that

$$f(n) = \left(\prod_{i=1}^{k} \frac{q_i}{q_i - 1} \right) \cdot \prod_{i=1}^{k} \left(1 - \frac{1}{q_i^{a_i+1}} \right).$$

However, we know that

$$\prod_{i=1}^{k} \frac{q_i}{q_i - 1} \leq e^{\gamma} \cdot \log (Y_k \cdot \theta(q_k))$$

by Lemma 4, when $q_k > e^{31.018189471} > 7232121212$. If we multiply both sides by the value of $\alpha = \prod_{i=1}^{k} \left(1 - \frac{1}{q_i^{a_i+1}} \right)$, then we obtain that

$$f(n) \leq e^{\gamma} \cdot \log (Y_k \cdot \theta(q_k)) \cdot \alpha.$$

Since $\mathsf{Robin}(n)$ fails

$$e^{\gamma} \cdot \log \log n \leq e^{\gamma} \cdot \log (Y_k \cdot \theta(q_k)) \cdot \alpha$$

because of

$$e^{\gamma} \cdot \log \log n \leq f(n).$$

That's the same as

$$\log \log n \leq \log (Y_k \cdot \theta(q_k)) \cdot \alpha$$

which is equivalent to

$$\frac{\log \log n}{\log (Y_k \cdot \theta(q_k))} \leq \alpha.$$

We know that

$$\log (Y_k \cdot \theta(q_k)) = \log \log (N_k)^{Y_k}.$$

We assume that $(N_k)^{Y_k} > n > 5040 > 11$ since $0 < \alpha < 1$. Consequently,

$$\sqrt{\frac{n}{(N_k)^{Y_k}}} < \frac{\log \log n}{\log \log (N_k)^{Y_k}}$$

by Lemma 6. In this way, we obtain that

$$n < \alpha^2 \cdot (N_k)^{Y_k}$$

and therefore, the proof is done. □

Corollary 1. *Let $\prod_{i=1}^{k} q_i^{a_i}$ be the representation of a superabundant number n as the product of the first k consecutive primes $q_1 < \ldots < q_k$ with the natural numbers $a_1 \geq a_2 \geq \ldots \geq a_k \geq 1$ as exponents. If $n > 5040$ is the smallest number such that $\mathsf{Robin}(n)$ fails, then $n < \alpha^2 \cdot (N_k)^{1.000208229291}$, where $N_k = \prod_{i=1}^{k} q_i$ is the primorial number of order k and $\alpha = \prod_{i=1}^{k} \left(1 - \frac{1}{q_i^{a_i+1}}\right)$.*

Proof. The number n is indeed superabundant according to the Proposition 7. For $q_k > e^{31.018189471}$, we know that $Y_k < 1.000208229291$ after of evaluating in the value of q_k due to Y_k is strictly decreasing. □

In number theory, the *p-adic* order of an integer n is the exponent of the highest power of the prime number p that divides n. It is denoted $\nu_p(n)$. Equivalently, $\nu_p(n)$ is the exponent to which p appears in the prime factorization of n. We also use the following Lemmas:

Lemma 7. *[6, Theorem 4.4 pp. 12]. Let n be a superabundant number such that p is the largest prime factor of n and $2 \leq q \leq p$, then*

$$\left\lfloor \frac{\log p}{\log q} \right\rfloor \leq \nu_q(n).$$

Lemma 8. *[2, Theorem 7 pp. 454]. Let n be a superabundant number such that p is the largest prime factor of n, then*

$$p \sim \log n, \quad (n \to \infty).$$

Lemma 9. *[6, Proposition 4.12. pp. 14]. For large enough superabundant number n*

$$\log n < 2^{\nu_2(n)}.$$

Theorem 2. *The Riemann Hypothesis is true.*

Proof. There are infinitely many superabundant numbers by Proposition 4. For every prime q, $\nu_q(n)$ goes to infinity as long as n goes to infinity when n is superabundant by Lemmas 7 and 8. Since Y_k is strictly decreasing and $0 < \alpha^2 < 1$, then we deduce that the following inequality $n \geq \alpha^2 \cdot (N_k)^{Y_k}$ is always satisfied for a sufficiently large superabundant number n. Let n_k be a superabundant number such that q_k is the largest prime factor of n, then

$$\lim_{k\to\infty} \frac{n_k}{N_k} = \infty,$$

where N_k is the primorial number of order k. Certainly, for large enough superabundant number n_k, we can see that $\frac{n_k}{N_k} > 2^{\nu_2(n_k)} > \log n_k$ by Lemma 9. Hence, it is enough to show that

$$\lim_{k\to\infty} \log n_k = \infty$$

as a consequence of Proposition 4. Moreover, we would have

$$\lim_{k\to\infty} \frac{(N_k)^{Y_k}}{N_k} = 1,$$

since we only need to check that

$$\lim_{k\to\infty} Y_k = 1.$$

Accordingly, $\mathsf{Robin}(n)$ holds for all large enough superabundant numbers n. This contradicts the fact that there are infinite superabundant numbers n, such that $\mathsf{Robin}(n)$ fails when the Riemann Hypothesis is false according to Lemma 1. By reductio ad absurdum, we prove that the Riemann Hypothesis is true. □

3 Conclusions

Practical uses of the Riemann Hypothesis include many propositions that are known to be true under the Riemann Hypothesis and some that can be shown to be equivalent to the Riemann Hypothesis. Indeed, the Riemann Hypothesis is closely related to various mathematical topics such as the distribution of primes, the growth of arithmetic functions, the Lindelöf Hypothesis, the Large Prime Gap Conjecture, etc. Certainly, a proof of the Riemann Hypothesis could spur considerable advances in many mathematical areas, such as number theory and pure mathematics in general.

Acknowledgments

The author wishes to thank his mother, maternal brother, maternal aunt, and friends Liuva, Yary, Sonia, and Arelis for their support. The author thanks the reviewers for their valuable suggestions and comments that were helpful in significantly improving the quality of the manuscript.

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