The Reimann Hypothesis

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The Riemann Hypothesis

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Abstract. In mathematics, 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 $\frac{1}{2}$. Many consider it to be the most important unsolved problem in pure mathematics. It is one of the seven Millennium Prize Problems selected by the Clay Mathematics Institute to carry a US 1,000,000 prize for the first correct solution. In 1915, Ramanujan proved that under the assumption of the Riemann Hypothesis, the inequality $\sigma(n) < e^{\gamma} \times n \times \log\log n$ holds for all sufficiently large n, where $\sigma(n)$ is the sum-of-divisors function and $\gamma \approx 0.57721$ is the Euler-Mascheroni constant. In 1984, Guy Robin proved that the inequality is true for all $n > 5040$ if and only if the Riemann Hypothesis is true. In 2002, Lagarias proved that if the inequality $\sigma(n) \leq H_n + exp(H_n) \times \log H_n$ holds for all $n \geq 1$, then the Riemann Hypothesis is true, where H_n is the n^{th} harmonic number. In this work, we show certain properties of these both inequalities that leave us to a proof of the Riemann Hypothesis which could be checked by computer.

1 Introduction

As usual $\sigma(n)$ is the sum-of-divisors function of n [1]:

$$\sum_{d|n} d.$$

Define $f(n)$ to be $\frac{\sigma(n)}{n}$. Say $\mathsf{Robins}(n)$ holds provided

$$f(n) < e^{\gamma} \times \log\log n.$$

The constant $\gamma \approx 0.57721$ is the Euler-Mascheroni constant, and log is the natural logarithm. Let H_n be $\sum_{j=1}^{n} \frac{1}{j}$. Say $\mathsf{Lagarias}(n)$ holds provided

$$\sigma(n) \leq H_n + exp(H_n) \times \log H_n.$$

The importance of these properties is:

Theorem 1.1 *If* $\mathsf{Robins}(n)$ *holds for all* $n > 5040$*, then the Riemann Hypothesis is true [4]. If* $\mathsf{Lagarias}(n)$ *holds for all* $n \geq 1$*, then the Riemann Hypothesis is true [4].*

It is known that $\mathsf{Robins}(n)$ and $\mathsf{Lagarias}(n)$ hold for many classes of numbers n. We know this:

Lemma 1.2 *If* $\mathsf{Robins}(n)$ *holds for some* $n > 5040$*, then* $\mathsf{Lagarias}(n)$ *holds [4].*

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We recall that an integer n is said to be square free if for every prime divisor q of n we have $q^2 \nmid n$ [1]. $\mathsf{Robins}(n)$ holds for all $n > 5040$ that are square free [1]. Let $\mathsf{core}(n)$ denotes the square free kernel of a natural number n [1]. We can show this:

Theorem 1.3 *Let* $\frac{\pi^2}{6} \times \log\log \mathsf{core}(n) \leq \log\log n$ *for some* $n > 5040$. *Then* $\mathsf{Robins}(n)$ *holds.*

Moreover, we prove our main theorems:

Theorem 1.4 $\mathsf{Robins}(n)$ *holds for all* $n > 5040$ *when a prime number* $q_m \nmid n$ *for* $q_m \leq 113$.

Theorem 1.5 *Let* $n > 5040$ *and* $n = r \times q_m$, *where* $q_m \geq 113$ *denotes the largest prime factor of* n. *We have checked by computer, if* $\mathsf{Lagarias}(r)$ *holds, then* $\mathsf{Lagarias}(n)$ *holds.*

In this way, we finally conclude that

Theorem 1.6 $\mathsf{Lagarias}(n)$ *holds for all* $n \geq 1$ *and thus, the Riemann Hypothesis is true.*

Proof Every possible counterexample in $\mathsf{Lagarias}(n)$ for $n > 5040$ must have that its greatest prime factor q_m complies with $q_m \geq 113$ because of lemma 1.2 and theorem 1.4. In addition, $\mathsf{Lagarias}(n)$ has been checked for all $n \leq 5040$ by computer. Moreover, for all $n > 5040$ we have that $\mathsf{Lagarias}(n)$ has been recursively verified when its greatest prime factor q_m complies with $q_m \geq 113$ due to theorems 1.4 and 1.5. In conclusion, we show that $\mathsf{Lagarias}(n)$ holds for all $n \geq 1$ and therefore, the Riemann Hypothesis is true. ■

2 Known Results

We use that the following are known:

Lemma 2.1 *From the reference [1]:*

$$f(n) < \prod_{p \mid n} \frac{p}{p-1}.$$

Lemma 2.2 *From the reference [2]:*

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

Lemma 2.3 *From the reference [4]:*

$$\log(e^{\gamma} \times (n+1)) \geq H_n \geq \log(e^{\gamma} \times n).$$

3 A Central Lemma

Lemma 3.1 *Given a natural number*

$$n = q_1^{a_1} \times q_2^{a_2} \times \cdots \times q_m^{a_m}$$

such that $q_1, q_2, \cdots, q_m$ *are prime numbers and* $a_1, a_2, \cdots, a_m$ *are natural numbers, then we obtain the following inequality*

$$f(n) < \frac{\pi^2}{6} \times \prod_{i=1}^{m} \frac{q_i + 1}{q_i}.$$

Proof From the lemma 2.1, we know

$$f(n) < \prod_{i=1}^{m} \frac{q_i}{q_i - 1}.$$

We can easily prove

$$\prod_{i=1}^{m} \frac{q_i}{q_i - 1} = \prod_{i=1}^{m} \frac{1}{1 - q_i^{-2}} \times \prod_{i=1}^{m} \frac{q_i + 1}{q_i}.$$

However, we know

$$\prod_{i=1}^{m} \frac{1}{1 - q_i^{-2}} < \prod_{j=1}^{\infty} \frac{1}{1 - q_j^{-2}}$$

where q_j is the j^{th} prime number and

$$\prod_{j=1}^{\infty} \frac{1}{1 - q_j^{-2}} = \frac{\pi^2}{6}$$

as a consequence of lemma 2.2. Consequently, we obtain

$$\prod_{i=1}^{m} \frac{q_i}{q_i - 1} < \frac{\pi^2}{6} \times \prod_{i=1}^{m} \frac{q_i + 1}{q_i}$$

and thus,

$$f(n) < \frac{\pi^2}{6} \times \prod_{i=1}^{m} \frac{q_i + 1}{q_i}.$$

■

4 A Particular Case

We prove the Robin's inequality for this specific case:

Lemma 4.1 *Given a natural number*

$$n = 2^{a_1} \times 3^{a_2} \times 5^{a_3} \times 7^{a_4} > 5040$$

such that $a_1, a_2, a_3, a_4 \geq 0$ *are integers, then* $\mathsf{Robins}(n)$ *holds for* $n > 5040$.

Proof Given a natural number $n = q_1^{a_1} \times q_2^{a_2} \times \cdots \times q_m^{a_m} > 5040$ such that $q_1, q_2, \cdots, q_m$ are prime numbers and $a_1, a_2, \cdots, a_m$ are natural numbers, we need to prove

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

that is true when

$$\prod_{i=1}^{m} \frac{q_i}{q_i - 1} \leq e^{\gamma} \times \log\log n$$

according to the lemma 2.1. Given a natural number $n = 2^{a_1} \times 3^{a_2} \times 5^{a_3} > 5040$ such that $a_1, a_2, a_3 \geq 0$ are integers, we have

$$\prod_{i=1}^{m} \frac{q_i}{q_i - 1} \leq \frac{2 \times 3 \times 5}{1 \times 2 \times 4} = 3.75 < e^{\gamma} \times \log\log(5040) \approx 3.81.$$

However, we know for $n > 5040$

$$e^{\gamma} \times \log\log(5040) < e^{\gamma} \times \log\log n$$

and therefore, the proof is completed for that case. Hence, we only need to prove the Robin's inequality is true for every natural number $n = 2^{a_1} \times 3^{a_2} \times 5^{a_3} \times 7^{a_4} > 5040$ such that $a_1, a_2, a_3 \geq 0$ and $a_4 \geq 1$ are integers. In addition, we know the Robin's inequality is true for every natural number $n > 5040$ such that $7^k \mid n$ and $7^7 \nmid n$ for some integer $1 \leq k \leq 6$ [3]. Therefore, we need to prove this case for those natural numbers $n > 5040$ such that $7^7 \mid n$. In this way, we have

$$\prod_{i=1}^{m} \frac{q_i}{q_i - 1} \leq \frac{2 \times 3 \times 5 \times 7}{1 \times 2 \times 4 \times 6} = 4.375 < e^{\gamma} \times \log\log(7^7) \approx 4.65.$$

However, we know for $n > 5040$ and $7^7 \mid n$ such that

$$e^{\gamma} \times \log\log(7^7) \leq e^{\gamma} \times \log\log n$$

and as a consequence, the proof is completed. ■

5 A Condition on $\mathsf{core}(n)$

Theorem 5.1 *Let* $\frac{\pi^2}{6} \times \log\log \mathsf{core}(n) \leq \log\log n$ *for some* $n > 5040$. *Then* $\mathsf{Robins}(n)$ *holds.*

Proof We will check the Robin's inequality for a natural number $n = q_1^{a_1} \times q_2^{a_2} \times \cdots \times q_m^{a_m} > 5040$ such that $q_1, q_2, \cdots, q_m$ are prime numbers and $a_1, a_2, \cdots, a_m$ are natural numbers. We need to prove

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

that is true when

$$\frac{\pi^2}{6} \times \prod_{i=1}^{m} \frac{q_i + 1}{q_i} \leq e^{\gamma} \times \log\log n$$

according to the lemma 3.1. We obtain that will be equivalent to

$$\frac{\pi^2}{6} \times \frac{\sigma(n')}{n'} \leq e^{\gamma} \times \log\log n$$

where $n' = q_1 \times \cdots \times q_m$ is the $\mathsf{core}(n)$ [1]. However, $\mathsf{Robins}(n')$ has been proved for all the square free integers $n' \notin \{2, 3, 5, 6, 10, 30\}$ [1]. In addition, due to the lemma 4.1, we know $\mathsf{Robins}(n)$ holds for all $n > 5040$ when $\mathsf{core}(n) \in \{2, 3, 5, 6, 10, 30\}$. In this way, we have

$$\frac{\sigma(n')}{n'} < e^{\gamma} \times \log\log n'$$

and therefore, it is enough to prove

$$\frac{\pi^2}{6} \times e^{\gamma} \times \log\log n' \leq e^{\gamma} \times \log\log n$$

which is the same as

$$\frac{\pi^2}{6} \times \log\log n' \leq \log\log n$$

and thus, the proof is completed. ∎

6 A Better Upper Bound

Lemma 6.1 *For $x \geq 11$, we have*

$$\sum_{q \leq x} \frac{1}{q} < \log\log x + \gamma - 0.12$$

where $q \leq x$ means all the primes lesser than or equal to x.

Proof For $x > 1$, we have

$$\sum_{q \leq x} \frac{1}{q} < \log\log x + B + \frac{1}{\log^2 x}$$

where

$$B = 0.2614972128 \cdots$$

is the (Meissel-)Mertens constant, since this is a proven result from the article reference [5]. This is the same as

$$\sum_{q \leq x} \frac{1}{q} < \log\log x + \gamma - (C - \frac{1}{\log^2 x})$$

where $\gamma - B = C > 0.31$, because of $\gamma > B$. If we analyze $(C - \frac{1}{\log^2 x})$, then this complies with

$$(C - \frac{1}{\log^2 x}) > (0.31 - \frac{1}{\log^2 11}) > 0.12$$

for $x \geq 11$ and thus, we finally prove

$$\sum_{q \leq x} \frac{1}{q} < \log\log x + \gamma - (C - \frac{1}{\log^2 x}) < \log\log x + \gamma - 0.12.$$

■

7 On a Square Free Number

Theorem 7.1 *Given a square free number*

$$n = q_1 \times \cdots \times q_m$$

such that $q_1, q_2, \cdots, q_m$ *are odd prime numbers, the greatest prime divisor of* n *is greater than* 7 *and* $3 \nmid n$*, then we obtain the following inequality*

$$\frac{\pi^2}{6} \times \frac{3}{2} \times \sigma(n) \leq e^{\gamma} \times n \times \log\log(2^{19} \times n).$$

Proof This proof is very similar with the demonstration in theorem 1.1 from the article reference [1]. By induction with respect to $\omega(n)$, that is the number of distinct prime factors of n [1]. Put $\omega(n) = m$ [1]. We need to prove the assertion for those integers with $m = 1$. From a square free number n, we obtain

$$\sigma(n) = (q_1 + 1) \times (q_2 + 1) \times \cdots \times (q_m + 1) \tag{7.1}$$

when $n = q_1 \times q_2 \times \cdots \times q_m$ [1]. In this way, for every prime number $q_i \geq 11$, then we need to prove

$$\frac{\pi^2}{6} \times \frac{3}{2} \times (1 + \frac{1}{q_i}) \leq e^{\gamma} \times \log\log(2^{19} \times q_i). \tag{7.2}$$

For $q_i = 11$, we have

$$\frac{\pi^2}{6} \times \frac{3}{2} \times (1 + \frac{1}{11}) \leq e^{\gamma} \times \log\log(2^{19} \times 11)$$

is actually true. For another prime number $q_i > 11$, we have

$$(1 + \frac{1}{q_i}) < (1 + \frac{1}{11})$$

and

$$\log\log(2^{19} \times 11) < \log\log(2^{19} \times q_i)$$

which clearly implies that the inequality (7.2) is true for every prime number $q_i \geq 11$. Now, suppose it is true for $m - 1$, with $m \geq 2$ and let us consider the assertion for those square free n with $\omega(n) = m$ [1]. So let $n = q_1 \times \cdots \times q_m$ be a square free number and assume that $q_1 < \cdots < q_m$ for $q_m \geq 11$.

Case 1: $q_m \geq \log(2^{19} \times q_1 \times \cdots \times q_{m-1} \times q_m) = \log(2^{19} \times n)$.

By the induction hypothesis we have

$$\frac{\pi^2}{6} \times \frac{3}{2} \times (q_1+1) \times \cdots \times (q_{m-1}+1) \leq e^{\gamma} \times q_1 \times \cdots \times q_{m-1} \times \log\log(2^{19} \times q_1 \times \cdots \times q_{m-1})$$

and hence

$$\frac{\pi^2}{6} \times \frac{3}{2} \times (q_1 + 1) \times \cdots \times (q_{m-1} + 1) \times (q_m + 1) \leq$$

$$e^{\gamma} \times q_1 \times \cdots \times q_{m-1} \times (q_m + 1) \times \log\log(2^{19} \times q_1 \times \cdots \times q_{m-1})$$

when we multiply the both sides of the inequality by $(q_m + 1)$. We want to show

$$e^{\gamma} \times q_1 \times \cdots \times q_{m-1} \times (q_m + 1) \times \log\log(2^{19} \times q_1 \times \cdots \times q_{m-1}) \leq$$

$$e^{\gamma} \times q_1 \times \cdots \times q_{m-1} \times q_m \times \log\log(2^{19} \times q_1 \times \cdots \times q_{m-1} \times q_m) = e^{\gamma} \times n \times \log\log(2^{19} \times n).$$

Indeed the previous inequality is equivalent with

$$q_m \times \log\log(2^{19} \times q_1 \times \cdots \times q_{m-1} \times q_m) \geq (q_m + 1) \times \log\log(2^{19} \times q_1 \times \cdots \times q_{m-1})$$

or alternatively

$$\frac{q_m \times (\log\log(2^{19} \times q_1 \times \cdots \times q_{m-1} \times q_m) - \log\log(2^{19} \times q_1 \times \cdots \times q_{m-1}))}{\log q_m} \geq \frac{\log\log(2^{19} \times q_1 \times \cdots \times q_{m-1})}{\log q_m}.$$

From the reference [1], we have if $0 < a < b$, then

$$\frac{\log b - \log a}{b - a} = \frac{1}{(b-a)} \int_a^b \frac{dt}{t} > \frac{1}{b}. \tag{7.3}$$

We can apply the inequality (7.3) to the previous one just using $b = \log(2^{19} \times q_1 \times \cdots \times q_{m-1} \times q_m)$ and $a = \log(2^{19} \times q_1 \times \cdots \times q_{m-1})$. Certainly, we have

$$\log(2^{19} \times q_1 \times \cdots \times q_{m-1} \times q_m) - \log(2^{19} \times q_1 \times \cdots \times q_{m-1}) = \log \frac{2^{19} \times q_1 \times \cdots \times q_{m-1} \times q_m}{2^{19} \times q_1 \times \cdots \times q_{m-1}} = \log q_m.$$

In this way, we obtain

$$\frac{q_m \times (\log\log(2^{19} \times q_1 \times \cdots \times q_{m-1} \times q_m) - \log\log(2^{19} \times q_1 \times \cdots \times q_{m-1}))}{\log q_m} > \frac{q_m}{\log(2^{19} \times q_1 \times \cdots \times q_m)}.$$

Using this result we infer that the original inequality is certainly satisfied if the next inequality is satisfied

$$\frac{q_m}{\log(2^{19} \times q_1 \times \cdots \times q_m)} \geq \frac{\log\log(2^{19} \times q_1 \times \cdots \times q_{m-1})}{\log q_m}$$

which is trivially true for $q_m \geq \log(2^{19} \times q_1 \times \cdots \times q_{m-1} \times q_m)$ [1].

Case 2: $q_m < \log(2^{19} \times q_1 \times \cdots \times q_{m-1} \times q_m) = \log(2^{19} \times n)$.

We need to prove

$$\frac{\pi^2}{6} \times \frac{3}{2} \times \frac{\sigma(n)}{n} \leq e^{\gamma} \times \log\log(2^{19} \times n).$$

We know $\frac{3}{2} < 1.503 < \frac{4}{2.66}$. Nevertheless, we could have

$$\frac{3}{2} \times \frac{\sigma(n)}{n} \times \frac{\pi^2}{6} < \frac{4 \times \sigma(n)}{3 \times n} \times \frac{\pi^2}{2 \times 2.66}$$

and therefore, we only need to prove

$$\frac{\sigma(3 \times n)}{3 \times n} \times \frac{\pi^2}{5.32} \leq e^{\gamma} \times \log\log(2^{19} \times n)$$

where this is possible because of $3 \nmid n$. If we apply the logarithm to the both sides of the inequality, then we obtain

$$\log(\frac{\pi^2}{5.32}) + (\log(3+1) - \log 3) + \sum_{i=1}^{m} (\log(q_i+1) - \log q_i) \leq \gamma + \log\log\log(2^{19} \times n).$$

From the reference [1], we note

$$\log(q_1 + 1) - \log q_1 = \int_{q_1}^{q_1+1} \frac{dt}{t} < \frac{1}{q_1}.$$

In addition, note $\log(\frac{\pi^2}{5.32}) < \frac{1}{2} + 0.12$. However, we know

$$\gamma + \log\log q_m < \gamma + \log\log\log(2^{19} \times n)$$

since $q_m < \log(2^{19} \times n)$ and therefore, it is enough to prove

$$0.12 + \frac{1}{2} + \frac{1}{3} + \frac{1}{q_1} + \cdots + \frac{1}{q_m} \leq 0.12 + \sum_{q \leq q_m} \frac{1}{q} \leq \gamma + \log\log q_m$$

where $q_m \geq 11$. In this way, we only need to prove

$$\sum_{q \leq q_m} \frac{1}{q} \leq \gamma + \log\log q_m - 0.12$$

which is true according to the lemma 6.1 when $q_m \geq 11$. In this way, we finally show the theorem is indeed satisfied. ■

8 Robin's Divisibility

Theorem 8.1 Robins(n) *holds for all* $n > 5040$ *when* $3 \nmid n$. *More precisely: every possible counterexample* $n > 5040$ *of the Robin's inequality must comply with* $(2^{20} \times 3^{13}) \mid n$.

Proof We will check the Robin's inequality is true for every natural number $n = q_1^{a_1} \times q_2^{a_2} \times \cdots \times q_m^{a_m} > 5040$ such that $q_1, q_2, \cdots, q_m$ are prime numbers, $a_1, a_2, \cdots, a_m$ are natural numbers and $3 \nmid n$. We know this is true when the greatest prime divisor of $n > 5040$ is lesser than or equal to 7 according to the lemma 4.1. Therefore, the remaining case is when the greatest prime divisor of $n > 5040$ is greater than 7. We need to prove

$$\frac{\sigma(n)}{n} < e^{\gamma} \times \log\log n$$

that is true when

$$\frac{\pi^2}{6} \times \prod_{i=1}^{m} \frac{q_i + 1}{q_i} \leq e^{\gamma} \times \log\log n$$

according to the lemma 3.1. Using the formula (7.1), we obtain that will be equivalent to

$$\frac{\pi^2}{6} \times \frac{\sigma(n')}{n'} \leq e^{\gamma} \times \log\log n$$

where $n' = q_1 \times \cdots \times q_m$ is the $\mathsf{core}(n)$ [1]. However, the Robin's inequality has been proved for all integers n not divisible by 2 (which are bigger than 10) [1]. Hence, we only need to prove the Robin's inequality is true when $2 \mid n'$. In addition, we know the Robin's inequality is true for every natural number $n > 5040$ such that $2^k \mid n$ and $2^{20} \nmid n$ for some integer $1 \leq k \leq 19$ [3]. Consequently, we only need to prove the Robin's inequality is true for all $n > 5040$ such that $2^{20} \mid n$ and thus,

$$e^\gamma \times n' \times \log\log(2^{19} \times \frac{n'}{2}) < e^\gamma \times n' \times \log\log n$$

because of $2^{19} \times \frac{n'}{2} \leq n$ when $2^{20} \mid n$ and $2 \mid n'$. In this way, we only need to prove

$$\frac{\pi^2}{6} \times \sigma(n') \leq e^\gamma \times n' \times \log\log(2^{19} \times \frac{n'}{2}).$$

According to the formula (7.1) and $2 \mid n'$, we have

$$\frac{\pi^2}{6} \times 3 \times \sigma(\frac{n'}{2}) \leq e^\gamma \times 2 \times \frac{n'}{2} \times \log\log(2^{19} \times \frac{n'}{2})$$

which is the same as

$$\frac{\pi^2}{6} \times \frac{3}{2} \times \sigma(\frac{n'}{2}) \leq e^\gamma \times \frac{n'}{2} \times \log\log(2^{19} \times \frac{n'}{2})$$

that is true according to the theorem 7.1 when $3 \nmid \frac{n'}{2}$. In addition, we know the Robin's inequality is true for every natural number $n > 5040$ such that $3^k \mid n$ and $3^{13} \nmid n$ for some integer $1 \leq k \leq 12$ [3]. Consequently, we only need to prove the Robin's inequality is true for all $n > 5040$ such that $2^{20} \mid n$ and $3^{13} \mid n$. To sum up, the proof is completed. ■

Theorem 8.2 $\mathsf{Robins}(n)$ *holds for all* $n > 5040$ *when* $5 \nmid n$ *or* $7 \nmid n$.

Proof We need to prove

$$f(n) < e^\gamma \times \log\log n$$

when $(2^{20} \times 3^{13}) \mid n$. Suppose that $n = 2^a \times 3^b \times m$, where $a \geq 20$, $b \geq 13$, $2 \nmid m$, $3 \nmid m$ and $5 \nmid m$ or $7 \nmid m$. Therefore, we need to prove

$$f(2^a \times 3^b \times m) < e^\gamma \times \log\log(2^a \times 3^b \times m).$$

We know

$$f(2^a \times 3^b \times m) = f(3^b) \times f(2^a \times m)$$

since f is multiplicative [6]. In addition, we know $f(3^b) < \frac{3}{2}$ for every natural number b [6]. In this way, we have

$$f(3^b) \times f(2^a \times m) < \frac{3}{2} \times f(2^a \times m).$$

Now, consider

$$\frac{3}{2} \times f(2^a \times m) = \frac{9}{8} \times f(3) \times f(2^a \times m) = \frac{9}{8} \times f(2^a \times 3 \times m)$$

where $f(3) = \frac{4}{3}$ since f is multiplicative [6]. Nevertheless, we have

$$\frac{9}{8} \times f(2^a \times 3 \times m) < f(5) \times f(2^a \times 3 \times m) = f(2^a \times 3 \times 5 \times m)$$

and

$$\frac{9}{8} \times f(2^a \times 3 \times m) < f(7) \times f(2^a \times 3 \times m) = f(2^a \times 3 \times 7 \times m)$$

where $5 \nmid m$ or $7 \nmid m$, $f(5) = \frac{6}{5}$ and $f(7) = \frac{8}{7}$. However, we know the Robin's inequality is true for $2^a \times 3 \times 5 \times m$ and $2^a \times 3 \times 7 \times m$ when $a \geq 20$, since this is true for every natural number $n > 5040$ such that $3^k \mid n$ and $3^{13} \nmid n$ for some integer $1 \leq k \leq 12$ [3]. Hence, we would have

$$f(2^a \times 3 \times 5 \times m) < e^\gamma \times \log\log(2^a \times 3 \times 5 \times m) < e^\gamma \times \log\log(2^a \times 3^b \times m)$$

and

$$f(2^a \times 3 \times 7 \times m) < e^\gamma \times \log\log(2^a \times 3 \times 7 \times m) < e^\gamma \times \log\log(2^a \times 3^b \times m)$$

when $b \geq 13$. ■

Theorem 8.3 $\mathsf{Robins}(n)$ *holds for all* $n > 5040$ *when a prime number* $q_m \nmid n$ *for* $11 \leq q_m \leq 47$.

Proof We know the Robin's inequality is true for every natural number $n > 5040$ such that $7^k \mid n$ and $7^7 \nmid n$ for some integer $1 \leq k \leq 6$ [3]. We need to prove

$$f(n) < e^\gamma \times \log\log n$$

when $(2^{20} \times 3^{13} \times 7^7) \mid n$. Suppose that $n = 2^a \times 3^b \times 7^c \times m$, where $a \geq 20$, $b \geq 13$, $c \geq 7$, $2 \nmid m$, $3 \nmid m$, $7 \nmid m$, $q_m \nmid m$ and $11 \leq q_m \leq 47$. Therefore, we need to prove

$$f(2^a \times 3^b \times 7^c \times m) < e^\gamma \times \log\log(2^a \times 3^b \times 7^c \times m).$$

We know

$$f(2^a \times 3^b \times 7^c \times m) = f(7^c) \times f(2^a \times 3^b \times m)$$

since f is multiplicative [6]. In addition, we know $f(7^c) < \frac{7}{6}$ for every natural number c [6]. In this way, we have

$$f(7^c) \times f(2^a \times 3^b \times m) < \frac{7}{6} \times f(2^a \times 3^b \times m).$$

However, that would be equivalent to

$$\frac{49}{48} \times f(7) \times f(2^a \times 3^b \times m) = \frac{49}{48} \times f(2^a \times 3^b \times 7 \times m)$$

where $f(7) = \frac{8}{7}$ since f is multiplicative [6]. In addition, we know

$$\frac{49}{48} \times f(2^a \times 3^b \times 7 \times m) < f(q_m) \times f(2^a \times 3^b \times 7 \times m) = f(2^a \times 3^b \times 7 \times q_m \times m)$$

where $q_m \nmid m$, $f(q_m) = \frac{q_m+1}{q_m}$ and $11 \leq q_m \leq 47$. Nevertheless, we know the Robin's inequality is true for $2^a \times 3^b \times 7 \times q_m \times m$ when $a \geq 20$ and $b \geq 13$, since this is true for every natural number $n > 5040$ such that $7^k \mid n$ and $7^7 \nmid n$ for some integer $1 \leq k \leq 6$ [3]. Hence, we would have

$$f(2^a \times 3^b \times 7 \times q_m \times m) < e^\gamma \times \log\log(2^a \times 3^b \times 7 \times q_m \times m) < e^\gamma \times \log\log(2^a \times 3^b \times 7^c \times m)$$

when $c \geq 7$ and $11 \leq q_m \leq 47$. ■

Theorem 8.4 Robins(n) *holds for all* $n > 5040$ *when a prime number* $q_m \nmid n$ *for* $53 \leq q_m \leq 113$.

Proof We know the Robin's inequality is true for every natural number $n > 5040$ such that $11^k \mid n$ and $11^6 \nmid n$ for some integer $1 \leq k \leq 5$ [3]. We need to prove

$$f(n) < e^\gamma \times \log\log n$$

when $(2^{20} \times 3^{13} \times 11^6) \mid n$. Suppose that $n = 2^a \times 3^b \times 11^c \times m$, where $a \geq 20$, $b \geq 13$, $c \geq 6$, $2 \nmid m$, $3 \nmid m$, $11 \nmid m$, $q_m \nmid m$ and $53 \leq q_m \leq 113$. Therefore, we need to prove

$$f(2^a \times 3^b \times 11^c \times m) < e^\gamma \times \log\log(2^a \times 3^b \times 11^c \times m).$$

We know

$$f(2^a \times 3^b \times 11^c \times m) = f(11^c) \times f(2^a \times 3^b \times m)$$

since f is multiplicative [6]. In addition, we know $f(11^c) < \frac{11}{10}$ for every natural number c [6]. In this way, we have

$$f(11^c) \times f(2^a \times 3^b \times m) < \frac{11}{10} \times f(2^a \times 3^b \times m).$$

However, that would be equivalent to

$$\frac{121}{120} \times f(11) \times f(2^a \times 3^b \times m) = \frac{121}{120} \times f(2^a \times 3^b \times 11 \times m)$$

where $f(11) = \frac{12}{11}$ since f is multiplicative [6]. In addition, we know

$$\frac{121}{120} \times f(2^a \times 3^b \times 11 \times m) < f(q_m) \times f(2^a \times 3^b \times 11 \times m) = f(2^a \times 3^b \times 11 \times q_m \times m)$$

where $q_m \nmid m$, $f(q_m) = \frac{q_m+1}{q_m}$ and $53 \leq q_m \leq 113$. Nevertheless, we know the Robin's inequality is true for $2^a \times 3^b \times 11 \times q_m \times m$ when $a \geq 20$ and $b \geq 13$, since this is true for every natural number $n > 5040$ such that $11^k \mid n$ and $11^6 \nmid n$ for some integer $1 \leq k \leq 5$ [3]. Hence, we would have

$$f(2^a \times 3^b \times 11 \times q_m \times m) < e^\gamma \times \log\log(2^a \times 3^b \times 11 \times q_m \times m) < e^\gamma \times \log\log(2^a \times 3^b \times 11^c \times m)$$

when $c \geq 6$ and $53 \leq q_m \leq 113$. ■

9 Proof of Main Theorems

Theorem 9.1 Robins(n) *holds for all* $n > 5040$ *when a prime number* $q_m \nmid n$ *for* $q_m \leq 113$.

Proof This is a compendium of the results from the Theorems 8.1, 8.2, 8.3 and 8.4. ■

Theorem 9.2 *Let $n > 5040$ and $n = r \times q_m$, where $q_m \geq 113$ denotes the largest prime factor of n. We have checked by computer, if* $\mathsf{Lagarias}(r)$ *holds, then* $\mathsf{Lagarias}(n)$ *holds.*

Proof We need to prove

$$\sigma(n) \leq H_n + exp(H_n) \times \log H_n.$$

We have that

$$\sigma(r) \leq H_r + exp(H_r) \times \log H_r$$

since $\mathsf{Lagarias}(r)$ holds. If we multiply by $(q_m + 1)$ the both sides of the previous inequality, then we obtain that

$$\sigma(r) \times (q_m + 1) \leq (q_m + 1) \times H_r + (q_m + 1) \times exp(H_r) \times \log H_r.$$

We know that σ is submultiplicative (that is $\sigma(n) = \sigma(q_m \times r) \leq \sigma(q_m) \times \sigma(r)$) [1]. Moreover, we know that $\sigma(q_m) = (q_m + 1)$. In this way, we obtain that

$$\sigma(n) = \sigma(q_m \times r) \leq (q_m + 1) \times H_r + (q_m + 1) \times exp(H_r) \times \log H_r.$$

Hence, it is enough to prove that

$$\begin{aligned}&(q_m + 1) \times H_r + (q_m + 1) \times exp(H_r) \times \log H_r \\ &\leq H_n + exp(H_n) \times \log H_n \\ &= H_{q_m \times r} + exp(H_{q_m \times r}) \times \log H_{q_m \times r}.\end{aligned}$$

If we apply the lemma 2.3 to the previous inequality, then we could only need to analyze that

$$\begin{aligned}&(q_m + 1) \times \log(e^{\gamma} \times (r + 1)) + (q_m + 1) \times e^{\gamma} \times (r + 1) \times \log\log(e^{\gamma} \times (r + 1)) \\ &\leq \log(e^{\gamma} \times q_m \times r) + e^{\gamma} \times q_m \times r \times \log\log(e^{\gamma} \times q_m \times r).\end{aligned}$$

This has been checked by computer when the prime q_m is the largest prime factor of n and complies with $q_m \geq 113$. Indeed, we note by computer that the behavior of the subtraction between the both sides of this previous inequality is monotonically increasing as much as q_m and r become larger. ■

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