



## The Complexity of Mathematics

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June 11, 2020

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Frank Vega 

Joysonic, Uzun Mirkova 5, Belgrade, 11000, Serbia  
vega.frank@gmail.com

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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  $1/2$ . 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. We prove the Riemann hypothesis using the Complexity Theory. Number theory is a branch of pure mathematics devoted primarily to the study of the integers and integer-valued functions. The Goldbach's conjecture is one of the most important and unsolved problems in number theory. Nowadays, it is one of the open problems of Hilbert and Landau. We demonstrate the Goldbach's conjecture is true or this has an infinite number of counterexamples using the Complexity Theory as well. An important complexity class is  $\text{NSPACE}(S(n))$  for some  $S(n)$ . These mathematical proofs are based on if some unary language belongs to  $\text{NSPACE}(S(\log n))$ , then the binary version of that language belongs to  $\text{NSPACE}(S(n))$  and vice versa.

**2012 ACM Subject Classification** Theory of computation  $\rightarrow$  Complexity classes; Theory of computation  $\rightarrow$  Regular languages; Theory of computation  $\rightarrow$  Problems, reductions and completeness

**Keywords and phrases** complexity classes, regular languages, reduction, complement, primes, number theory

## 1 Introduction

### 1.1 The Riemann hypothesis

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 [15]. It is of great interest in number theory because it implies results about the distribution of prime numbers [15]. It was proposed by Bernhard Riemann (1859), after whom it is named [15]. In 1915, Ramanujan proved that under the assumption of the Riemann hypothesis, the inequality:

$$\sum_{d|n} d < e^\gamma \times n \times \log \log n$$

holds for all sufficiently large  $n$ , where  $\gamma \approx 0.57721$  is the Euler's constant and  $d|n$  means that the natural number  $d$  divides  $n$  [11]. The largest known value that violates the inequality is  $n = 5040$ . In 1984, Guy Robin proved that the inequality is true for all  $n > 5040$  if and only if the Riemann hypothesis is true [11]. Using this inequality, we prove the Riemann hypothesis is true.

### 1.2 The Goldbach's conjecture

The Goldbach's original conjecture, written on 7 June 1742 in a letter to Leonhard Euler, states: "... at least it seems that every number that is greater than 2 is the sum of three primes" [5]. This is known as the ternary Goldbach conjecture. We call a prime as a natural number that is greater than 1 and has exactly two divisors, 1 and the number itself [17]. However, the mathematician Christian Goldbach considered 1 as a prime number. Euler

replied in a letter dated 30 June 1742 the following statement: “Every even integer greater than 2 can be written as the sum of two primes” [5]. This is known as the strong Goldbach conjecture.

Using Vinogradov’s method, Van der Corput and Estermann showed that almost all even numbers can be written as the sum of two primes (in the sense that the fraction of even numbers which can be so written tends towards 1) [16], [6]. In 1973, Chen showed that every sufficiently large even number can be written as the sum of some prime number and a semi-prime [3]. The strong Goldbach conjecture implies the conjecture that all odd numbers greater than 7 are the sum of three odd primes, which is known today as the weak Goldbach conjecture [5]. In 2012 and 2013, Peruvian mathematician Harald Helfgott published a pair of papers claiming to improve major and minor arc estimates sufficiently to unconditionally prove the weak Goldbach conjecture [9], [10]. In this work, we prove the strong Goldbach’s conjecture is true or this has an infinite number of counterexamples.

## 2 Theory and Methods

We use  $o$ -notation to denote an upper bound that is not asymptotically tight. We formally define  $o(g(n))$  as the set

$$o(g(n)) = \{f(n) : \text{for any positive constant } c > 0, \text{ there exists a constant}$$

$$n_0 > 0 \text{ such that } 0 \leq f(n) < c \times g(n) \text{ for all } n \geq n_0\}.$$

For example,  $2 \times n = o(n^2)$ , but  $2 \times n^2 \neq o(n^2)$  [4]. In theoretical computer science and formal language theory, a regular language is a formal language that can be expressed using a regular expression [2]. On the one hand, the complexity class  $DSPACE(f(n))$  is the set of decision problems that can be solved by a deterministic Turing machine  $M$ , using space  $f(n)$ , where  $n$  is the length of the input [13]. On the other hand, the complexity class  $NSPACE(f(n))$  is the set of decision problems that can be solved by a nondeterministic Turing machine  $M$ , using space  $f(n)$ , where  $n$  is the length of the input [13].

## 3 Results

### 3.1 The Complexity of PRIMES

The checking whether a number is prime can be decided in polynomial time by a deterministic Turing machine [1]. This problem is known as *PRIMES* [1].

► **Theorem 1.** *PRIMES*  $\notin$   $NSPACE(S(n))$  for all  $S(n) = o(\log n)$ .

**Proof.** If we assume that *PRIMES*  $\in$   $NSPACE(o(\log n))$ , then the unary version should be regular. Certainly, the standard space translation between the unary and binary languages actually works for nondeterministic machines with small space [7]. This means that if some language belongs to  $NSPACE(S(n))$ , then the unary version of that language belongs to  $NSPACE(S(\log n))$  [7]. In this way, when *PRIMES*  $\in$   $NSPACE(o(\log n))$ , then the unary version should be in  $NSPACE(o(\log \log n))$  and we know that  $REG = NSPACE(o(\log \log n))$  [13], [7]. Since we know that the unary version of *PRIMES* is non-regular [12], then we obtain that *PRIMES*  $\notin$   $NSPACE(S(n))$  for all  $S(n) = o(\log n)$ . ◀

### 3.2 The Riemann hypothesis

► **Definition 2.** We define the Robin's language  $L_R$  as follows:

$$L_R = \{0^n \# 0^{m_1} \# 0^{m_2} : n \in \mathbb{N} \wedge n > 5040 \wedge m_1 = (\sigma(n) - n) \\ \wedge m_2 = \lceil e^\gamma \times n \times \log \log n \rceil \wedge m_1 + n < m_2\}$$

where  $\#$  is the blank symbol,  $\lceil \dots \rceil$  is the ceiling function,  $\gamma$  is the Euler's constant and  $\sigma(n) = \sum_{d|n} d$  [11]. We define the language  $coL_R$  as

$$coL_R = \{0^n \# 0^{m_1} \# 0^{m_2} : n \in \mathbb{N} \wedge n > 5040 \wedge m_1 = (\sigma(n) - n) \\ \wedge m_2 = \lceil e^\gamma \times n \times \log \log n \rceil \wedge m_1 + n \geq m_2\}$$

where  $coL_R$  is the complement language of  $L_R$ .

► **Definition 3.** We define the verification Robin's language  $L_{VR}$  as follows:

$$L_{VR} = \{(n, m_1, m_2) : \text{such that } 0^n \# 0^{m_1} \# 0^{m_2} \in L_R\}.$$

Besides, we define the language  $coL_{VR}$  as

$$coL_{VR} = \{(n, m_1, m_2) : \text{such that } 0^n \# 0^{m_1} \# 0^{m_2} \in coL_R\}$$

where  $coL_{VR}$  is the complement language of  $L_{VR}$ .

► **Lemma 4.**  $coL_R$  is the unary representation of  $coL_{VR}$ .

**Proof.** This is trivially true from the definition of these languages. ◀

► **Theorem 5.**  $L_{VR} \notin NSPACE(S(n))$  for all  $S(n) = o(\log n)$ .

**Proof.** The language  $L_{VR}$  cannot be computed in  $NSPACE(S(n))$  for some  $S(n) = o(\log n)$ , because of this would imply that the problem  $PRIMES$  belongs to  $NSPACE(S(n))$  for some  $S(n) = o(\log n)$  as well. Certainly if this could be true, then we can find  $m_2 = \lceil e^\gamma \times p \times \log \log p \rceil$  and check whether the triple  $(p, 1, m_2)$  is an element of  $L_{VR}$  and thus, we could decide whether  $p$  is a prime greater than 10. Indeed, a number  $p$  is prime if and only if the sum of its divisors is  $p + 1$  [8]. This could be nondeterministically done on input  $p$  just choosing arbitrarily another number  $m_2$ , but instead of putting in the work tapes, then this will put with  $p$  and 1 in the output tape just using constant space. We are able to do this, because of  $m_2$  should be polynomially bounded by the input  $p$ . After that, we use the space composition reduction just using the previous output of  $p$ , 1 and some integer  $m_2$  into a new nondeterministic Turing machine that would decide whether the instance belongs to  $L_{VR}$  in  $NSPACE(S(n))$  for some  $S(n) = o(\log n)$  using  $(p, 1, m_2)$  as input [14]. Since  $NSPACE(S(n))$  for some  $S(n) = o(\log n)$  is closed under  $NSPACE$ -reductions with constant space, then the whole computation could be done in  $NSPACE(S(n))$  for some  $S(n) = o(\log n)$ . Certainly, an  $NSPACE$ -reduction with constant space could be done in  $DSPACE(o(\log \log n))$  [13]. This is possible, because the Robin's inequality is always true on  $p$  for every prime number  $p$  greater than 10. Moreover, the set of prime numbers lesser than 10 can be decided in constant space. However, this would be a contradiction according to Theorem 1, since the language  $PRIMES \notin NSPACE(S(n))$  for all  $S(n) = o(\log n)$ . Consequently, we obtain that  $L_{VR} \notin NSPACE(S(n))$  for all  $S(n) = o(\log n)$ . ◀

► **Theorem 6.**  $coL_{VR} \notin NSPACE(S(n))$  for all  $S(n) = o(\log n)$ .

**Proof.** The reason is because of  $NSPACE(S(n))$  is closed under complement for  $S(n) \geq \log n$  [13]. In this way, this is a direct consequence of Theorem 5. ◀

► **Theorem 7.** *The Riemann hypothesis is true.*

**Proof.** We may have only three options:  $coL_R$  is equal to the empty set or  $coL_R \in REG$  and  $coL_R$  is not empty or  $coL_R$  is non-regular and  $coL_R$  is infinite, since every finite set is regular [14]. Let's assume the possibility of  $coL_R \in REG$  and  $coL_R$  is not empty. Nevertheless, this implies that the exponentially more succinct version of  $coL_R$ , that is  $coL_{VR}$ , should be in  $NSPACE(S(n))$  for some  $S(n) = o(\log n)$ , because of  $REG = NSPACE(o(\log \log n))$  and the same algorithm that decides  $coL_R$  within  $NSPACE(o(\log \log n))$  could be easily transformed into a slightly modified algorithm that decides  $coL_{VR}$  within  $NSPACE(S(n))$  for some  $S(n) = o(\log n)$  [13], [7]. Actually,  $coL_R$  is the unary version of  $coL_{VR}$  due to Lemma 4. As we mentioned before, the standard space translation between the unary and binary languages actually works for nondeterministic machines with small space [7]. This means that if some unary language belongs to  $NSPACE(S(\log n))$ , then the binary version of that language belongs to  $NSPACE(S(n))$  [7]. In this way, we obtain that  $coL_R \notin REG$ , since it is not possible that  $coL_R \in NSPACE(o(\log \log n))$  under the result of  $coL_{VR} \notin NSPACE(S(n))$  for all  $S(n) = o(\log n)$  as a consequence of Theorem 6. Consequently, we obtain a contradiction just assuming that  $coL_R \in REG$  and  $coL_R$  is not empty. Therefore,  $coL_R$  is infinite or  $coL_R$  is equal to the empty set. Hence, we obtain that the Riemann hypothesis is true when  $coL_R$  is equal to the empty set or the Robin's inequality has an infinite number of counterexamples when  $coL_R$  is infinite. However, the asymptotic growth rate of the sigma function can be expressed by [11]:

$$\limsup_{n \rightarrow \infty} \frac{\sigma(n)}{n \times \log \log n} = e^\gamma$$

where  $\lim \sup$  is the limit superior and  $\sigma(n) = \sum_{d|n} d$ . In this way, if the Robin's inequality has an infinite number of counterexamples, then the previous limit superior should be false. Since this is a previous checked result, then we have the Riemann hypothesis is true as the remaining only option. ◀

### 3.3 The Goldbach's conjecture

► **Definition 8.** *We define the Goldbach's language  $L_G$  as follows:*

$$L_G = \{0^{2 \times n} \# 0^p \# 0^q : n \in \mathbb{N} \wedge n > 2 \wedge p \text{ and } q \text{ are odd primes} \wedge 2 \times n = p + q\}$$

where  $\#$  is the blank symbol. We define the language  $coL_G$  as

$$coL_G = \{0^{2 \times n} \# 0^i \# 0^j : n \in \mathbb{N} \wedge n > 2 \wedge 2 \times n = i + j$$

$$\wedge \text{there are not odd primes } p \text{ and } q \text{ such that } 2 \times n = p + q\}$$

where  $coL_G$  is the complement language of  $L_G$ .

► **Definition 9.** *We define the verification Goldbach's language  $L_{VG}$  as follows:*

$$L_{VG} = \{(2 \times n, p, q) : \text{such that } 0^{2 \times n} \# 0^p \# 0^q \in L_G\}.$$

Besides, we define the language  $coL_{VG}$  as

$$coL_{VG} = \{(2 \times n, i, j) : \text{such that } 0^{2 \times n} \# 0^i \# 0^j \in coL_G\}$$

where  $coL_{VG}$  is the complement language of  $L_{VG}$ .

► **Lemma 10.**  $coL_G$  is the unary representation of  $coL_{VG}$ .

**Proof.** This is trivially true from the definition of these languages. ◀

► **Theorem 11.**  $L_{VG} \notin NSPACE(S(n))$  for all  $S(n) = o(\log n)$ .

**Proof.** The language  $L_{VG}$  cannot be computed in  $NSPACE(S(n))$  for some  $S(n) = o(\log n)$ , because of this would imply that the problem  $PRIMES$  belongs to  $NSPACE(S(n))$  for some  $S(n) = o(\log n)$  as well. Certainly, if this could be true, then we can take any number  $p$  and check whether  $p$  is an odd prime. This could be nondeterministically done on input  $p$  just deterministically generating the numbers  $p + 3$  and  $3$  and nondeterministically choosing an arbitrary number  $q$ , but instead of putting in the work tapes, then we will put them to the output tape just using constant space. After that, we use the space composition reduction just using the previous output of  $(p + 3, 3, q)$  as input into a new nondeterministic Turing machine that would decide whether the instance belongs to  $L_{VG}$  in  $NSPACE(S(n))$  for some  $S(n) = o(\log n)$ . Indeed, the nondeterministic computation will accept this input if and only if the nondeterministic generated number  $q$  is equal to  $p$  and  $p$  is an odd prime. In this reduction, we assume the initial string  $p$  has a binary representation with the least significant bit in the first position within the input tape from left to right. In this way, it will be possible to deterministically generate  $p + 3$  using constant space. Since  $NSPACE(S(n))$  for some  $S(n) = o(\log n)$  is closed under  $NSPACE$ -reductions with constant space, then the whole computation could be done in  $NSPACE(S(n))$  for some  $S(n) = o(\log n)$ . Certainly, an  $NSPACE$ -reduction with constant space could be done in  $DSPACE(o(\log \log n))$  [13]. This is possible, because the strong Goldbach's conjecture is always true on  $p + 3$  for every odd prime number  $p$ . Moreover, the even prime number  $2$  can be decided in constant space. Nevertheless, this would be a contradiction according to Theorem 1, since the language  $PRIMES \notin NSPACE(S(n))$  for all  $S(n) = o(\log n)$ . Consequently, we obtain that  $L_{VG} \notin NSPACE(S(n))$  for all  $S(n) = o(\log n)$ . ◀

► **Theorem 12.**  $coL_{VG} \notin NSPACE(S(n))$  for all  $S(n) = o(\log n)$ .

**Proof.** The reason is because of  $NSPACE(S(n))$  is closed under complement for  $S(n) \geq \log n$  [13]. In this way, this is a direct consequence of Theorem 11. ◀

► **Theorem 13.** *The strong Goldbach's conjecture is true or this has an infinite number of counterexamples.*

**Proof.** We may have only three options:  $coL_G$  is equal to the empty set or  $coL_G \in REG$  and  $coL_G$  is not empty or  $coL_G$  is non-regular and  $coL_G$  is infinite, since every finite set is regular [14]. Let's assume the possibility of  $coL_G \in REG$  and  $coL_G$  is not empty. However, this implies that the exponentially more succinct version of  $coL_G$ , that is  $coL_{VG}$ , should be in  $NSPACE(S(n))$  for some  $S(n) = o(\log n)$ , because we would have  $REG = NSPACE(o(\log \log n))$  and the same algorithm that decides  $coL_G$  within the complexity  $NSPACE(o(\log \log n))$  could be easily transformed into a slightly modified algorithm that decides  $coL_{VG}$  within  $NSPACE(S(n))$  for some  $S(n) = o(\log n)$  [13], [7]. Actually,  $coL_G$  is the unary version of  $coL_{VG}$  due to Lemma 10. As we mentioned before, the standard space translation between the unary and binary languages actually works for nondeterministic machines with small space [7]. This means that if some unary language belongs to  $NSPACE(S(\log n))$ , then the binary version of that language belongs to  $NSPACE(S(n))$  [7]. Consequently, we obtain that  $coL_G \notin REG$ , since it is not possible that  $coL_G \in NSPACE(o(\log \log n))$  under the result of  $coL_{VG} \notin NSPACE(S(n))$  for all  $S(n) = o(\log n)$  as result of Theorem 12. In

this way, we obtain a contradiction just assuming that  $coL_G \in REG$  and  $coL_G$  is not empty. Therefore,  $coL_G$  is infinite or  $coL_G$  is equal to the empty set. Hence, we have the strong Goldbach's conjecture is true when  $coL_G$  is equal to the empty set or this has an infinite number of counterexamples when  $coL_G$  is infinite. ◀

## 4 Conclusions

### 4.1 The Riemann hypothesis

The practical uses of the Riemann hypothesis include many propositions known true under the Riemann hypothesis, and some that can be shown equivalent to the Riemann hypothesis [15]. Certainly, the Riemann hypothesis is close related to various mathematical topics such as the distribution of prime numbers, the growth of arithmetic functions, the Lindelöf hypothesis, the large prime gap conjecture, etc [15]. In this way, the veracity of the Riemann hypothesis could spur considerable advances in many mathematical areas, such as the number theory and pure mathematics [15]. In general, this work provides a new technique which could be useful for solving another outstanding problems in mathematics.

### 4.2 The Goldbach's conjecture

Statistical considerations that focus on the probabilistic distribution of prime numbers present informal evidence in pos of the strong conjecture for sufficiently large integers: The greater the integer, the more ways there are available for that number to be represented as the sum of two other numbers, and the more "likely" it becomes that at least one of these representations consists entirely of primes. In this way, the statement that the strong Goldbach's conjecture has an infinite number of counterexamples is certainly "unlikely". To sum up, this work represents a big step forward in showing the strong Goldbach's conjecture should be really true.

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