The Complexity of Number Theory

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Abstract

On the one hand, the Goldbach's conjecture has been described as the most difficult problem in the history of Mathematics. This conjecture states that every even integer greater than 2 can be written as the sum of two primes. This is known as the strong Goldbach's conjecture. The conjecture that all odd numbers greater than 7 are the sum of three odd primes is known today as the weak Goldbach conjecture. A major complexity class is NSPACE(S(n)) for some S(n). We show if the weak Goldbach's conjecture is true, then the problem PRIMES is not in NSPACE(S(n)) for all S(n) = o(log n). However, if PRIMES is not in NSPACE(S(n)) for all S(n) = o(log n), then the strong Goldbach's conjecture is true or this has an infinite number of counterexamples. Since Harald Helfgott proved that the weak Goldbach's conjecture is true, then the strong Goldbach's conjecture is true or this has an infinite number of counterexamples, where the case of infinite number of counterexamples statistically seems to be unlikely. On the other hand, we have the functional problem FACTORIZATION is not in NSPACE(S(n)) for all S(n) = o(log n), since this uses the decision problem PRIMES as subroutine. However, this implies that the Beal's conjecture is true. Since the Beal's conjecture is a generalization of Fermat's Last Theorem, then this is also a simple and short proof for that Theorem.

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1 Introduction

1.1 Goldbach's conjecture

Number theory is a branch of pure mathematics devoted primarily to the study of the integers and integer-valued functions [26]. Goldbach's conjecture is one of the most important and unsolved problems in number theory [13]. Nowadays, it is one of the open problems of Hilbert and Landau [13]. 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" [10]. 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 [29]. 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" [10]. This is known as the strong Goldbach conjecture.

Using Vinogradov's method [28], it has been showed that almost all even numbers can be written as the sum of two primes. In 1973, Chen showed that every sufficiently large even number can be written as the sum of some prime number and a semiprime [6]. 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 [10]. 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 [15], [16]. In this work, we prove the strong Goldbach's conjecture is true or this has an infinite number of counterexamples.

1.2 Beal's conjecture

Fermat's Last Theorem was first conjectured by Pierre de Fermat in 1637, famously in the margin of a copy of Arithmetica where he claimed he had a proof that was too large to fit in the margin [29]. This theorem states that no three positive integers a, b, and c can satisfy the equation $a^n + b^n = c^n$ for any integer value of n greater than two [29]. It is not known whether Fermat found a valid proof or not [29]. His proof of one case ($n = 4$) by infinite descent has survived [29]. After many intents, the proof of Fermat's Last Theorem for every integer $n > 2$ was finally accomplished, after 358 years, by Andrew Wiles in 1995 [30]. However, the Andrew's proof seems to be quite different to the simple and unknown proof that Fermat claimed.

On the other hand, there is a similar and unsolved conjecture called the Beal's conjecture [17]. This conjecture states if $A^x + B^y = C^z$, where A, B, C, x, y and z are positive integers and x, y and z are all greater than 2, then A, B and C must have a common prime factor [29]. Fermat's Last Theorem can be seen as a special case of the Beal's conjecture restricted to $x = y = z$. Billionaire banker Andrew Beal claims to have discovered this conjecture in 1993 while investigating generalizations of Fermat's Last Theorem [17]. This conjecture has occasionally been referred to as a generalized Fermat equation [4] and the Mauldin or Tijdeman-Zagier conjecture [11].

Beal offered a prize of US $1,000,000 to the first person who tries to resolve it [29]. For example, the solution $3^3 + 6^3 = 3^5$ has bases with a common factor of 3, and the solution $7^6 + 7^7 = 98^3$ has bases with a common factor of 7. There are some particular cases which have been proved for this conjecture [8], [22], [25], [5]. There are considerable advances on this topic [19], [9]. We contribute on this subject showing the Beal's conjecture is true.

2 Background Theory

In 1936, Turing developed his theoretical computational model [27]. The deterministic and nondeterministic Turing machines have become in two of the most important definitions related to this theoretical model for computation [27]. A deterministic Turing machine has only one next action for each step defined in its program or transition function [27]. A nondeterministic Turing machine could contain more than one action defined for each step of its program, where this one is no longer a function, but a relation [27].

Let Σ be a finite alphabet with at least two elements, and let Σ^* be the set of finite strings over Σ [3]. A Turing machine M has an associated input alphabet Σ [3]. For each string w in Σ^* there is a computation associated with M on input w [3]. We say that M accepts w if this computation terminates in the accepting state, that is $M(w) =$ "*yes*" [3]. Note that M fails to accept w either if this computation ends in the rejecting state, that is $M(w) =$ "*no*", or if the computation fails to terminate, or the computation ends in the halting state with some output, that is $M(w) = y$ (when M outputs the string y on the input w) [3].

Another relevant advance in the last century has been the definition of a complexity class. A language over an alphabet is any set of strings made up of symbols from that alphabet [7]. A complexity class is a set of problems, which are represented as a language, grouped by measures such as the running time, memory, etc [7]. The language accepted by a Turing machine M, denoted $L(M)$, has an associated alphabet Σ and is defined by:

$$L(M) = \{w \in \Sigma^* : M(w) = \text{“}yes\text{”}\}.$$

Moreover, $L(M)$ is decided by M, when $w \notin L(M)$ if and only if $M(w) =$ "*no*" [7]. We denote by $t_M(w)$ the number of steps in the computation of M on input w [3]. For $n \in \mathbb{N}$ we denote by $T_M(n)$ the worst case run time of M; that is:

$$T_M(n) = max\{t_M(w) : w \in \Sigma^n\}$$

where Σ^n is the set of all strings over Σ of length n [3]. We say that M runs in polynomial time if there is a constant k such that for all n, $T_M(n) \leq n^k + k$ [3]. In other words, this means the language $L(M)$ can be decided by the Turing machine M in polynomial time. Therefore, P is the complexity class of languages that can be decided by deterministic Turing machines in polynomial time [7].

A logarithmic space Turing machine has a read-only input tape, a write-only output tape, and read/write work tapes [27]. The work tapes may contain at most $O(\log n)$ symbols [27]. In computational complexity theory, NL is the complexity class containing the decision problems that can be decided by a nondeterministic logarithmic space Turing machine [21].

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 $2 \times n^2 \neq o(n^2)$ [7].

In theoretical computer science and formal language theory, a regular language is a formal language that can be expressed using a regular expression [2]. The complexity class that contains all the regular languages is REG. 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 [18].

3 Results

3.1 Goldbach's conjecture

▶ **Definition 1.** *We define the weak Goldbach's language L_{WG} as follows:*

$$L_{WG} = \{1^{2\times n+1}0^p0^q0^r : n \in \mathbb{N} \wedge n \geq 4 \wedge p, q \text{ and } r \text{ are odd primes } \wedge 2\times n+1 = p+q+r\}.$$

We define the strong Goldbach's language L_G as follows:

$$L_G = \{1^{2\times n}0^p0^q : n \in \mathbb{N} \wedge n \geq 3 \wedge p \text{ and } q \text{ are odd primes } \wedge 2 \times n = p + q\}.$$

▶ **Theorem 2.** *If the weak Goldbach's conjecture is true, then the weak Goldbach's language L_{WG} is non-regular. Moreover, if the strong Goldbach's conjecture is true, then the strong Goldbach's language L_G is non-regular.*

Proof. If the weak Goldbach's conjecture is true, then the weak Goldbach's language L_{WG} is equal to the another language L' defined as follows:

$$L' = \{1^{2\times n+1}0^{2\times n+1} : n \in \mathbb{N} \wedge n \geq 4\}.$$

We can easily prove that L' is non-regular using the Pumping lemma for regular languages [23]. Moreover, if the strong Goldbach's conjecture is true, then the strong Goldbach's language L_G is equal to the another language L'' defined as follows:

$$L'' = \{1^{2\times n}0^{2\times n} : n \in \mathbb{N} \wedge n \geq 3\}.$$

We can easily prove that L'' is non-regular using the Pumping lemma for regular languages as well [23]. ◀

▶ **Definition 3.** *We define the weak verification Goldbach's language L_{WVG} as follows:*

$$L_{WVG} = \{(2 \times n + 1, p, q, r) : \text{ such that } 1^{2 \times n+1}0^p0^q0^r \in L_{WG}\}.$$

We define the strong verification Goldbach's language L_{VG} as follows:

$$L_{VG} = \{(2 \times n, p, q) : \text{ such that } 1^{2 \times n}0^p0^q \in L_G\}.$$

▶ **Theorem 4.** $L_{WVG} \in P$.

Proof. This result is based on the breakthrough approach that 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]. Certainly, we can check in polynomial time whether p, q and r are odd primes and the other verifications can be easily done in polynomial time as well. ◀

▶ **Definition 5.** *We define the weak Goldbach's language with separator L_{WSG} as follows:*

$$L_{WSG} = \{0^{2 \times n+1}\#0^p\#0^q\#0^r : \text{ such that } 1^{2 \times n+1}0^p0^q0^r \in L_{WG}\}$$

and we define the strong Goldbach's language with separator L_{SG} as follows:

$$L_{SG} = \{0^{2 \times n}\#0^p\#0^q : \text{ such that } 1^{2 \times n}0^p0^q \in L_G\}$$

where # is the blank symbol.

▶ **Lemma 6.** *The weak Goldbach's language with separator L_{WSG} is the unary representation of the weak verification Goldbach's language L_{WVG}. The strong Goldbach's language with separator L_{SG} is the unary representation of the strong verification Goldbach's language L_{VG}.*

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

▶ **Theorem 7.** *If $L_{WVG} \in NSPACE(S(n))$ for some $S(n) = o(\log n)$, then $L_{WG} \in REG$.*

Proof. In case of $L_{WVG} \in NSPACE(S(n))$ for some $S(n) = o(\log n)$, then there is a nondeterministic Turing machine which decides L_{WSG} that uses space that is smaller than $c \times \log \log n$ for all $c > 0$, because of L_{WSG} is the unary version of L_{WVG} due to Lemma 6 [12]. Certainly, the standard space translation between the unary and binary languages actually works for nondeterministic machines with small space [12]. This means that if some language belongs to $NSPACE(S(n))$, then the unary version of that language belongs to $NSPACE(S(\log n))$ [12]. In this way, we obtain that $L_{WSG} \in REG$ because of $REG = NSPACE(o(\log \log n))$ [18]. In addition, we can reduce in a nondeterministic constant space the language L_{WG} to L_{WSG} just nondeterministically inserting the blank symbol # within two arbitrary positions between the 0's on the input. Moreover, this nondeterminism reduction inserts the blank symbol # between the 1's and 0's and converts the 1's to 0's from the original input of L_{WG} just generating the final output to L_{WSG}. Consequently, we prove $L_{WG} \in REG$ under the assumption that $L_{WVG} \in NSPACE(S(n))$ for some $S(n) = o(\log n)$, since REG is also the complexity class of languages decided by nondeterministic Turing machines in constant space [24]. ◀

▶ **Theorem 8.** *$L_{WVG} \notin NSPACE(S(n))$ for all $S(n) = o(\log n)$.*

Proof. If the weak Goldbach's conjecture is true, then $L_{WG} \notin REG$ as a consequence of Theorem 2. However, if $L_{WVG} \in NSPACE(S(n))$ for some $S(n) = o(\log n)$, then $L_{WG} \in REG$ due to Theorem 7. In this way, the weak Goldbach's conjecture cannot be true under the assumption that $L_{WVG} \in NSPACE(S(n))$ for some $S(n) = o(\log n)$. Since the weak Goldbach's conjecture is true, then we obtain that $L_{WVG} \notin NSPACE(S(n))$ for all $S(n) = o(\log n)$ [15], [16]. ◀

▶ **Theorem 9.** *$PRIMES \notin NSPACE(S(n))$ for all $S(n) = o(\log n)$.*

Proof. From the Theorem 8, we obtain that $L_{WVG} \notin NSPACE(S(n))$ for all $S(n) = o(\log n)$. However, the checking of whether the four numbers on the input are odds and proving the equality of the sum can be done in $NSPACE(\log \log n)$. Certainly, the verification of the odd property could be done in constant space. In addition, the verification of the equality of the sum $2 \times n + 1 = p + q + r$ can be done in $NSPACE(\log \log n)$, since we need a constant space to save the remainder of the sum from each step and a binary string of length bounded by $\log \log n$ which represents the position of the bits that we are currently summing. For example, if we want to check whether the binary numbers 1, 10000001, 100000001 and 110000011 comply with the sum $110000011 = 1 + 10000001 + 100000001$, then we start for the rightmost one until the leftmost ones using the binary digit 1 as a remainder only in the first step and saving the position of the bits we are summing using at most the binary number 1001, because of 9 is the greatest bit position. The ultimate remaining verification that we need to analyze in L_{WVG} is whether p, q and r are primes. Since $\log \log n = o(\log n)$ and $L_{WVG} \notin NSPACE(S(n))$ for all $S(n) = o(\log n)$, then we have as unique remaining possibility that $PRIMES \notin NSPACE(S(n))$ for all $S(n) = o(\log n)$. ◀

▶ **Theorem 10.** *The strong Goldbach's conjecture is true or this has an infinite number of counterexamples.*

Proof. If the strong Goldbach's conjecture is false, then $L_G \in REG$ or L_G is non-regular and its complement is infinite, since every finite set is regular and REG is also closed under complement [21]. However, this implies that the exponentially more succinct version of L_G, that is L_{VG}, 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 L_G in $NSPACE(o(\log \log n))$ could be easily transformed into a slightly modified algorithm that decides L_{VG} in $NSPACE(S(n))$ for some $S(n) = o(\log n)$ [18]. Actually, L_G could be reduced to L_{SG} in a nondeterministic constant space following the steps of Theorem 7 and L_{SG} is the unary version of L_{VG} due to Lemma 6. As we mentioned before, the standard space translation between the unary and binary languages actually works for nondeterministic machines with small space [12]. This means that if some unary language belongs to $NSPACE(S(\log n))$, then the binary version of that language belongs to $NSPACE(S(n))$ [12]. It is not possible that $L_{VG} \in NSPACE(S(n))$ for some $S(n) = o(\log n)$, because of $PRIMES \notin NSPACE(S(n))$ for all $S(n) = o(\log n)$. Certainly, the verification of whether p and q are primes need to be done in order to accept the elements of this language. Consequently, we obtain that $L_G \notin REG$, since it is not possible that $L_G \in NSPACE(o(\log \log n))$ under the result of $L_{VG} \notin NSPACE(S(n))$ for all $S(n) = o(\log n)$. In this way, we obtain a contradiction just assuming that the strong Goldbach's conjecture is false and $L_G \in REG$. In contraposition, we have the strong Goldbach's conjecture is true or this has an infinite number of counterexamples. ◀

3.2 Beal's conjecture

▶ **Definition 11.** *For a specific choice of exponents (x, y, z) where $x, y, z \in \mathbb{N}$ and $x, y, z \geq 3$, we define the Beal's language L_B as follows:*

$$L_B = \{1^r 0^p 0^q : p, q, r \in \mathbb{N} \wedge p \leq q \wedge r = p + q\}$$

such that when $p = 1$ then r has not a z-root or there are no positive integers p and q such that $r = p + q$, p has a x-root and q has a y-root otherwise when $p > 1$ then r has a z-root, p has a x-root and q has a y-root.

▶ **Theorem 12.** *If the Beal's conjecture is true, then the Beal's language L_B is non-regular.*

Proof. If the Beal's conjecture is true, then the Beal's language L_B is equal to the another language L' defined as follows:

$$L' = \{1^n 0^n : n \in \mathbb{N} \wedge n \geq 2\}.$$

We can easily prove that L' is non-regular using the Pumping lemma for regular languages [23]. ◀

▶ **Definition 13.** *We define the verification Beal's language L_{VB} as follows:*

$$L_{VB} = \{(r, p, q) : \text{ such that } 1^r 0^p 0^q \in L_B\}.$$

▶ **Definition 14.** *We define the Beal's language with separator L_{SB} as follows:*

$$L_{SB} = \{0^r \# 0^p \# 0^q : \text{ such that } 1^r 0^p 0^q \in L_B\}$$

where # is the blank symbol.

▶ **Lemma 15.** *The Beal's language with separator L_{SB} is the unary representation of the verification Beal's language L_{VB}.*

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

The problem $FACTORIZATION$ is the functional problem that obtains the unique prime factorization of an integer [14].

▶ **Theorem 16.** *$FACTORIZATION \notin NSPACE(S(n))$ for all $S(n) = o(\log n)$.*

Proof. Since it is necessary that $FACTORIZATION$ checks whether the factorization is compose of solely prime numbers, then $FACTORIZATION \notin NSPACE(S(n))$ for all $S(n) = o(\log n)$. The reason is because $PRIMES \notin NSPACE(S(n))$ for all $S(n) = o(\log n)$ as result of Theorem 9. ◀

▶ **Theorem 17.** *$L_{VB} \notin NSPACE(S(n))$ for all $S(n) = o(\log n)$.*

Proof. The complement coL_{VB} needs obligatorily to check the factorizations of the roots in order to prove the three numbers are co-primes. Certainly, coL_{VB} should contain the possible counterexamples of the Beal's conjecture for the chosen exponents (x, y, z) in L_B. Since coL_{VB} uses the $FACTORIZATION$ in order to accept its elements, then $coL_{VB} \notin NSPACE(S(n))$ for all $S(n) = o(\log n)$. Since $NSPACE(S(n))$ is closed under complement for $S(n) \geq \log n$ [18], then $L_{VB} \notin NSPACE(S(n))$ for all $S(n) = o(\log n)$. ◀

▶ **Theorem 18.** *The Beal's conjecture is true.*

Proof. If the Beal's conjecture is false, then $L_B \in REG$ or L_B is non-regular and its complement is infinite, since every finite set is regular and REG is also closed under complement [21]. However, this implies that the exponentially more succinct version of L_B, that is L_{VB}, 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 L_B in $NSPACE(o(\log\log n))$ could be easily transformed into a slightly modified algorithm that decides L_{VB} in $NSPACE(S(n))$ for some $S(n) = o(\log n)$ [18]. Actually, L_B could be reduced to L_{SB} in a nondeterministic constant space following the steps of Theorem 7 and L_{SB} is the unary version of L_{VB} due to Lemma 15. As we mentioned before, the standard space translation between the unary and binary languages actually works for nondeterministic machines with small space [12]. This means that if some unary language belongs to $NSPACE(S(\log n))$, then the binary version of that language belongs to $NSPACE(S(n))$ [12]. In this way, we obtain that $L_B \notin REG$, since it is not possible that $L_B \in NSPACE(o(\log\log n))$ under the result of $L_{VB} \notin NSPACE(S(n))$ for all $S(n) = o(\log n)$ as a consequence of Theorem 17. Consequently, we obtain a contradiction just assuming that the Beal's conjecture is false and $L_B \in REG$. In contraposition, we have the Beal's conjecture is true or this has an infinite number of counterexamples for a specific choice of exponents (x, y, z), since L_B uses a specific choice of exponents (x, y, z). The Darmon-Granville theorem uses Faltings's theorem to show that for every specific choice of exponents (x, y, z), there are at most finitely many co-prime solutions for (A, B, C) [9], [11]. In conclusion, we obtain that necessarily the Beal's conjecture is true as the remaining only option. ◀

4 Conclusions

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.

Peter Norvig, Director of Research at Google, have conducted a series of numerical searches for counterexamples to Beal's conjecture. Among his results, he excluded all possible solutions having each of $x, y, z = 7$ and each of $A, B, C = 250,000$, as well as possible solutions having each of $x, y, z = 100$ and each of $A, B, C = 10,000$ [20]. We conclude announcing the failure in the prolonged search of counterexamples since the Beal's conjecture is true.

Fermat's Last Theorem established that $A^n + B^n = C^n$ has no solutions for $n > 2$ for positive integers A, B, and C. If any solutions had existed to Fermat's Last Theorem, then by dividing out every common factor, there would also exist solutions with A, B, and C co-prime which would mean they do not have a common prime factor [14]. Hence, Fermat's Last Theorem can be seen as a special case of the Beal's conjecture restricted to $x = y = z$ [4].

The Fermat-Catalan conjecture is that $A^x + B^y = C^z$ has only finitely many solutions with A, B, and C being positive integers with no common prime factor and x, y, and z being positive integers satisfying $\frac{1}{x} + \frac{1}{y} + \frac{1}{z} < 1$ [29]. Beal's conjecture can be restated as "All Fermat-Catalan conjecture solutions will use 2 as an exponent".

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