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Logarithmic Space Verifiers on NP-complete

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Abstract

P versus NP is considered as one of the most important open problems in computer science. This consists in knowing the answer of the following question: Is P equal to NP? A precise statement of the P versus NP problem was introduced independently by Stephen Cook and Leonid Levin. Since that date, all efforts to find a proof for this problem have failed. NP is the complexity class of languages defined by polynomial time verifiers M such that when the input is an element of the language with its certificate, then M outputs a string which belongs to a single language in P. Another major complexity classes are L and NL. The certificate-based definition of NL is based on logarithmic space Turing machine with an additional special read-once input tape: This is called a logarithmic space verifier. NL is the complexity class of languages defined by logarithmic space verifiers M such that when the input is an element of the language with its certificate, then M outputs 1. To attack the P versus NP problem, the NP-completeness is a useful concept. We demonstrate there is an NP-complete language defined by a logarithmic space verifier M such that when the input is an element of the language with its certificate, then M outputs a string which belongs to a single language in L.

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1 Introduction

The P versus NP problem is a major unsolved problem in computer science [4]. This is considered by many to be the most important open problem in the field [4]. 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 [4]. It was essentially mentioned in 1955 from a letter written by John Nash to the United States National Security Agency [1]. However, the precise statement of the $P = NP$ problem was introduced in 1971 by Stephen Cook in a seminal paper [4]. In 2012, a poll of 151 researchers showed that 126 (83%) believed the answer to be no, 12 (9%) believed the answer is yes, 5 (3%) believed the question may be independent of the currently accepted axioms and therefore impossible to prove or disprove, 8 (5%) said either do not know or do not care or don't want the answer to be yes nor the problem to be resolved [7]. It is fully expected that $P \neq NP$ [11]. Indeed, if $P = NP$ then there are stunning practical consequences [11]. For that reason, $P = NP$ is considered as a very unlikely event [11]. Certainly, P versus NP is one of the greatest open problems in science and a correct solution for this incognita will have a great impact not only in computer science, but for many other fields as well [1]. Whether $P = NP$ or not is still a controversial and unsolved problem [1]. In this work, we show some results that might be helpful in facing one of the most important open problems in computer science.

2 Preliminaries

In 1936, Turing developed his theoretical computational model [13]. The deterministic and nondeterministic Turing machines have become in two of the most important definitions

related to this theoretical model for computation [13]. A deterministic Turing machine has only one next action for each step defined in its program or transition function [13]. 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 [13].

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 $M(w) = 1$ (when M outputs 1 on the input w) [3]. Note that M fails to accept w either if this computation ends in the rejecting state, that is $M(w) = 0$, 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 [5]. A complexity class is a set of problems, which are represented as a language, grouped by measures such as the running time, memory, etc [5]. The language accepted by a Turing machine M , denoted $L(M)$, has an associated alphabet Σ and is defined by:

$$L(M) = \{w \in \Sigma^* : M(w) = 1\}.$$

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 [5]. A verifier for a language L_1 is a deterministic Turing machine M , where:

$$L_1 = \{w : M(w, c) = 1 \text{ for some string } c\}.$$

We measure the time of a verifier only in terms of the length of w , so a polynomial time verifier runs in polynomial time in the length of w [3]. A verifier uses additional information, represented by the symbol c , to verify that a string w is a member of L_1 . This information is called certificate. NP is the complexity class of languages defined by polynomial time verifiers [11].

► **Lemma 1.** *Given a language $L_1 \in P$, a language L_2 is in NP if there is a deterministic Turing machine M , where:*

$$L_2 = \{w : M(w, c) = y \text{ for some string } c \text{ such that } y \in L_1\}$$

and M runs in polynomial time in the length of w . In this way, NP is the complexity class of languages defined by polynomial time verifiers M such that when the input is an element of the language with its certificate, then M outputs a string which belongs to a single language in P .

Proof. If L_1 can be decided by the Turing machine M' in polynomial time, then the deterministic Turing machine $M''(w, c) = M'(M(w, c))$ will output 1 when $w \in L_2$. Consequently, M'' is a polynomial time verifier of L_2 and thus, L_2 is in NP . ◀

3 Hypothesis

A function $f : \Sigma^* \rightarrow \Sigma^*$ is a polynomial time computable function if some deterministic Turing machine M , on every input w , halts in polynomial time with just $f(w)$ on its tape [13]. Let $\{0, 1\}^*$ be the infinite set of binary strings, we say that a language $L_1 \subseteq \{0, 1\}^*$ is polynomial time reducible to a language $L_2 \subseteq \{0, 1\}^*$, written $L_1 \leq_p L_2$, if there is a polynomial time computable function $f : \{0, 1\}^* \rightarrow \{0, 1\}^*$ such that for all $x \in \{0, 1\}^*$:

$$x \in L_1 \text{ if and only if } f(x) \in L_2.$$

An important complexity class is *NP-complete* [8]. A language $L_1 \subseteq \{0, 1\}^*$ is *NP-complete* if:

- $L_1 \in NP$, and
- $L' \leq_p L_1$ for every $L' \in NP$.

If L_1 is a language such that $L' \leq_p L_1$ for some $L' \in NP\text{-complete}$, then L_1 is *NP-hard* [5]. Moreover, if $L_1 \in NP$, then $L_1 \in NP\text{-complete}$ [5]. A principal *NP-complete* problem is *SAT* [6]. An instance of *SAT* is a Boolean formula ϕ which is composed of:

1. Boolean variables: x_1, x_2, \dots, x_n ;
2. Boolean connectives: Any Boolean function with one or two inputs and one output, such as \wedge (AND), \vee (OR), \neg (NOT), \Rightarrow (implication), \Leftrightarrow (if and only if);
3. and parentheses.

A truth assignment for a Boolean formula ϕ is a set of values for the variables in ϕ . A satisfying truth assignment is a truth assignment that causes ϕ to be evaluated as true. A formula with a satisfying truth assignment is a satisfiable formula. The problem *SAT* asks whether a given Boolean formula is satisfiable [6]. We define a *CNF* Boolean formula using the following terms:

A literal in a Boolean formula is an occurrence of a variable or its negation [5]. A Boolean formula is in conjunctive normal form, or *CNF*, if it is expressed as an AND of clauses, each of which is the OR of one or more literals [5]. A Boolean formula is in 3-conjunctive normal form or *3CNF*, if each clause has exactly three distinct literals [5].

For example, the Boolean formula:

$$(x_1 \vee \neg x_1 \vee \neg x_2) \wedge (x_3 \vee x_2 \vee x_4) \wedge (\neg x_1 \vee \neg x_3 \vee \neg x_4)$$

is in *3CNF*. The first of its three clauses is $(x_1 \vee \neg x_1 \vee \neg x_2)$, which contains the three literals x_1 , $\neg x_1$, and $\neg x_2$. Another relevant *NP-complete* language is *3CNF* satisfiability, or *3SAT* [5]. In *3SAT*, it is asked whether a given Boolean formula ϕ in *3CNF* is satisfiable.

A logarithmic space Turing machine has a read-only input tape, a write-only output tape, and read/write work tapes [13]. The work tapes may contain at most $O(\log n)$ symbols [13]. In computational complexity theory, L is the complexity class containing those decision problems that can be decided by a deterministic logarithmic space Turing machine [11]. NL is the complexity class containing the decision problems that can be decided by a nondeterministic logarithmic space Turing machine [11].

A logarithmic space transducer is a Turing machine with a read-only input tape, a write-only output tape, and read/write work tapes [13]. The work tapes must contain at most $O(\log n)$ symbols [13]. A logarithmic space transducer M computes a function $f : \Sigma^* \rightarrow \Sigma^*$, where $f(w)$ is the string remaining on the output tape after M halts when it is started with

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w on its input tape [13]. We call f a logarithmic space computable function [13]. We say that a language $L_1 \subseteq \{0, 1\}^*$ is logarithmic space reducible to a language $L_2 \subseteq \{0, 1\}^*$, written $L_1 \leq_l L_2$, if there exists a logarithmic space computable function $f : \{0, 1\}^* \rightarrow \{0, 1\}^*$ such that for all $x \in \{0, 1\}^*$,

$$x \in L_1 \text{ if and only if } f(x) \in L_2.$$

The logarithmic space reduction is frequently used for L and NL [11]. A Boolean formula is in 2-conjunctive normal form, or $2CNF$, if it is in CNF and each clause has exactly two distinct literals. There is a problem called $2SAT$, where we asked whether a given Boolean formula ϕ in $2CNF$ is satisfiable. $2SAT$ is complete for NL [11]. Another special case is the class of problems where each clause contains XOR (i.e. exclusive or) rather than (plain) OR operators. This is in P , since an $XOR SAT$ formula can also be viewed as a system of linear equations mod 2, and can be solved in cubic time by Gaussian elimination [9]. We denote the XOR function as \oplus . The $XOR 2SAT$ problem will be equivalent to $XOR SAT$, but the clauses in the formula have exactly two distinct literals. $XOR 2SAT$ is in L [2], [12].

We can give a certificate-based definition for NL [3]. The certificate-based definition of NL assumes that a logarithmic space Turing machine has another separated read-only tape [3]. On each step of the machine the machine's head on that tape can either stay in place or move to the right [3]. In particular, it cannot reread any bit to the left of where the head currently is [3]. For that reason this kind of special tape is called "read once" [3].

► **Definition 2.** A language L_1 is in NL if there exists a deterministic logarithmic space Turing machine M with an additional special read-once input tape polynomial $p : \mathbb{N} \rightarrow \mathbb{N}$ such that for every $x \in \{0, 1\}^*$,

$$x \in L_1 \Leftrightarrow \exists u \in \{0, 1\}^{p(|x|)} \text{ such that } M(x, u) = 1$$

where by $M(x, u)$ we denote the computation of M where x is placed on its input tape and u is placed on its special read-once tape, and M uses at most $O(\log |x|)$ space on its read/write tapes for every input x where $|\dots|$ is the bit-length function [3]. M is called a logarithmic space verifier [3].

We state the following Hypothesis:

▷ **Hypothesis 3.** Given a language $L_1 \in L$, there is a language L_2 in NP -complete with a deterministic Turing machine M , where:

$$L_2 = \{w : M(w, u) = y \text{ for some string } u \text{ such that } y \in L_1\}$$

when M runs in logarithmic space in the length of w , u is placed on the special read-once tape of M , and u is polynomially bounded by w . In this way, there is an NP -complete language defined by a logarithmic space verifier M such that when the input is an element of the language with its certificate, then M outputs a string which belongs to a single language in L .

4 Results

We show a previous known NP -complete problem:

► **Definition 4.** *MONOTONE NAE 3SAT*

INSTANCE: A Boolean formula ϕ in 3CNF such that each clause has no negation variables.

QUESTION: Is there a truth assignment for ϕ such that each clause has at least one true literal and at least one false literal?

REMARKS: This is equivalent to the special case of the NP-complete problem known as SET SPLITTING when the sets in the input have exactly three elements and therefore, MONOTONE NAE 3SAT \in NP-complete [6].

We define a new problem:

► **Definition 5. MINIMUM EXCLUSIVE-OR 2-SATISFIABILITY**

INSTANCE: A positive integer K and a Boolean formula ϕ that is an instance of XOR 2SAT such that each clause has no negation variables.

QUESTION: Is there a truth assignment in ϕ such that at most K clauses are unsatisfiable?

REMARKS: We denote this problem as $MIN \oplus 2SAT$.

► **Theorem 6.** $MIN \oplus 2SAT \in NP$ -complete.

Proof. It is trivial to see $MIN \oplus 2SAT \in NP$ [11]. Given a Boolean formula ϕ in 3CNF with n variables and m clauses such that each clause has no negation variables, we create three new variables a_{c_i} , b_{c_i} and d_{c_i} for each clause $c_i = (x \vee y \vee z)$ in ϕ , where x , y and z are positive literals, in the following formula:

$$P_i = (a_{c_i} \oplus b_{c_i}) \wedge (b_{c_i} \oplus d_{c_i}) \wedge (a_{c_i} \oplus d_{c_i}) \wedge (x \oplus a_{c_i}) \wedge (y \oplus b_{c_i}) \wedge (z \oplus d_{c_i}).$$

We can see P_i has at most one unsatisfiable clause for some truth assignment if and only if at least one member of $\{x, y, z\}$ is true and at least one member of $\{x, y, z\}$ is false for the same truth assignment. Hence, we can create the Boolean formula ψ as the conjunction of the P_i formulas for every clause c_i in ϕ , such that $\psi = P_1 \wedge \dots \wedge P_m$. Finally, we obtain that

$$\phi \in \text{MONOTONE NAE 3SAT} \text{ if and only if } (\psi, m) \in \text{MIN} \oplus 2SAT.$$

Consequently, we prove $\text{MONOTONE NAE 3SAT} \leq_p \text{MIN} \oplus 2SAT$ where we already know the language $\text{MONOTONE NAE 3SAT} \in NP$ -complete [6]. To sum up, we show $MIN \oplus 2SAT \in NP$ -hard and $MIN \oplus 2SAT \in NP$ and thus, $MIN \oplus 2SAT \in NP$ -complete. ◀

► **Theorem 7.** There is a deterministic Turing machine M , where:

$$MIN \oplus 2SAT = \{w : M(w, u) = y \text{ for some string } u \text{ such that } y \in \text{XOR 2SAT}\}$$

when M runs in logarithmic space in the length of w , u is placed on the special read-once tape of M , and u is polynomially bounded by w .

Proof. Given a valid instance (ψ, K) for $MIN \oplus 2SAT$ when ψ has m clauses, we can create a certificate array A which contains K different natural numbers in ascending order which represents the indexes of the clauses in ψ that we are going to remove from the instance. We read at once the elements of the array A and we reject whether this is not a valid certificate: That is when the numbers are not sorted in ascending order, or the array A does not contain exactly K elements, or the array A contains a number that is not between 1 and m . While we read the elements of the array A , we remove the clauses from the instance (ψ, K) for $MIN \oplus 2SAT$ just creating another instance ϕ for XOR 2SAT where the Boolean formula

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ϕ does not contain the K different indexed clauses ψ represented by the numbers in A . Therefore, we obtain that:

$(\psi, K) \in MIN \oplus 2SAT$ if and only if $\phi \in XOR 2SAT$.

Furthermore, we can make this verification in logarithmic space such that the array A is placed on the special read-once tape, because we read at once the elements in the array A and we assume the clauses in the input ψ are indexed from left to right. Hence, we only need to iterate from the elements of the array A to verify whether the array is a valid certificate and also remove the K different clauses from the Boolean formula ψ when we write the final clauses to the output. This logarithmic space verification will be the Algorithm 1. We assume whether a value does not exist in the array A into the cell of some position i when $A[i] = \text{undefined}$. In addition, we reject immediately when the following comparisons

$$A[i] \leq \max \vee A[i] < 1 \vee A[i] > m$$

hold at least into one single binary digit. Note, in the loop j from min to $max - 1$, we do not output any clause when $max - 1 < min$.

Algorithm 1 Logarithmic space verifier

```

1: /*A valid instance for  $MIN \oplus 2SAT$  with its certificate*/
2: procedure  $VERIFIER((\psi, K), A)$ 
3:   /*Initialize minimum and maximum values*/
4:    $min \leftarrow 1$ 
5:    $max \leftarrow 0$ 
6:   /*Iterate for the elements of the certificate array  $A$ */
7:   for  $i \leftarrow 1$  to  $K + 1$  do
8:     if  $i = K + 1$  then
9:       /*There exists a  $K + 1$  element in the array*/
10:      if  $A[i] \neq \text{undefined}$  then
11:        /*Reject the certificate*/
12:        return 0
13:      end if
14:      /* $m$  is the number of clauses in  $\psi$ */
15:       $max \leftarrow m + 1$ 
16:    else if  $A[i] = \text{undefined} \vee A[i] \leq \max \vee A[i] < 1 \vee A[i] > m$  then
17:      /*Reject the certificate*/
18:      return 0
19:    else
20:       $max \leftarrow A[i]$ 
21:    end if
22:    /*Iterate for the clauses of the Boolean formula  $\psi$ */
23:    for  $j \leftarrow min$  to  $max - 1$  do
24:      /*Output the indexed  $j$  clause in  $\psi$ */
25:      output “  $\wedge c_j$  ”
26:    end for
27:     $min \leftarrow max + 1$ 
28:  end for
29: end procedure

```

▶ **Theorem 8.** *The Hypothesis 3 is true.* ◀

Proof. This is a consequence of Theorems 6 and 7. ◀

5 Materials and Methods

This work is implemented into a GitHub Project programmed in Scala [14]. In this GitHub Project, we use the Assertion on the properties of the instances of each problem and the Unit Test for checking the correctness of every reduction [14]. We need to install JDK 8 in order to test the Scala Project [10]. In addition, we need to install SBT to run the unit test (we could run the unit test with the `sbt test` command) [10].

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