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P vs NP

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Abstract

P versus NP is one of the most important and unsolved problems in computer science. This consists in knowing the answer of the following question: Is P equal to NP? This incognita was first mentioned in a letter written by Kurt Gödel to John von Neumann in 1956. However, the precise statement of the P versus NP problem was introduced in 1971 by Stephen Cook in a seminal paper. Under the assumption of P = NP, we show that P = EXP is also hold. Since P is not equal to EXP, we prove that P is not equal to NP by the Reductio ad absurdum rule.

Keywords: P, NP, EXP, NP-complete, SUBSET-PRODUCT, SUBSET-SUM

2000 MSC: 68-XX, 68Qxx, 68Q15

1. Introduction

P versus NP is a major unsolved problem in computer science. This problem was introduced in 1971 by Stephen Cook [1]. It is considered by many to be the most important open problem in the field [2]. 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 [2].

The argument made by Alan Turing in the twentieth century states that for any algorithm we can create an equivalent Turing machine [3]. There are some definitions related to this model such as the deterministic Turing machine. A deterministic Turing machine has only one next action for each step defined in its program or transition function [4].

Another huge advance in the last century was 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].

In computational complexity theory, the class $P$ contains those languages that can be decided in polynomial-time by a deterministic Turing machine [6]. A language $L$ is in class $NP$ if there is a polynomial-time decidable and polynomially balanced relation $R_L$ such that for all strings $x$: There is a string $y$ in $R_L(x, y)$ if and only if $x \in L$ [4]. The string $y$ is known as the certificate.

The biggest open question in theoretical computer science concerns the relationship between these two classes:

Is $P$ equal to $NP$?

In a 2002 poll of 100 researchers, 61 believed the answer to be no, 9 believed the answer is yes, and 22 were unsure; 8 believed the question may be independent of the currently accepted axioms and so impossible to prove or disprove [7].

Email address: vega.frank@gmail.com (Frank Vega)

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We shall define an interesting problem called \textsc{MAS}. We show \textsc{MAS} is a succinct version of the known problem \textsc{Subset–Product}. When we accept or reject the succinct instances of \textsc{MAS}, then we are accepting or rejecting the equivalent large instances of \textsc{Subset–Product}. If we assume that $P = NP$, then the problems \textsc{MAS} and \textsc{Subset–Product} could be in $P$–complete. However, this would imply that \textsc{MAS} is also in $EXP$–complete, because \textsc{MAS} is a succinct version of \textsc{Subset–Product} and \textsc{Subset–Product} would be in $P$–complete. Indeed, in Papadimitriou’s book is proved the following statement: “$NEXP$ and $EXP$ are nothing else but $P$ and $NP$ on exponentially more succinct input” [4]. Nevertheless, \textsc{MAS} cannot be in $EXP$–complete and $P$–complete at the same time, because this will be a contradiction. Therefore, we can claim that $P \neq NP$ as a result of applying the Reductio ad absurdum rule.

2. The class $NP$–complete

We say that a language $L_1$ is polynomial-time reducible to a language $L_2$, written $L_1 \leq_p L_2$, if there exists a polynomial-time computable function $f : \{0, 1\}^* \rightarrow \{0, 1\}^*$ such that for all $x \in \{0, 1\}^*$,

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

A fundamental complexity class is $NP$–complete [8]. A language $L \subseteq \{0, 1\}^*$ is $NP$–complete if

1. $L \in NP$, and
2. $L' \leq_p L$ for every $L' \in NP$.

Furthermore, if $L$ is a language such that $L' \leq_p L$ for some $L' \in NP$–complete, then $L$ is $NP$–hard [5]. Moreover, if $L \in NP$, then $L \in NP$–complete [5]. No polynomial-time algorithm has yet been discovered for any $NP$–complete problem [2].

A principal $NP$–complete problem is $\textsc{Subset–Sum}$ [5]. In this problem we are given a finite set $S \subseteq \mathbb{N}$ and a target $t \in \mathbb{N}$. We ask whether there is a subset $S' \subseteq S$ whose elements sum to $t$. We may define this problem as a language:

$$\textsc{Subset–Sum} = \{ \langle S; t \rangle : \exists S' \subseteq S \text{ such that } t = \sum_{k \in S'} k \}.$$ 

Another important $NP$–complete problem is $\textsc{Subset–Product}$ [9]. An instance of this problem is a finite list $L$ of natural numbers not necessarily distinct and a target $t \in \mathbb{N}$. We ask whether there is a sublist $L' \subseteq L$ such that the product of the elements in $L'$ is exactly $t$. This problem is defined as a language in the following way:

$$\textsc{Subset–Product} = \{ \langle L; t \rangle : \exists L' \subseteq L \text{ such that } t = \prod_{k \in L'} k \}.$$ 

3. The problem $\textsc{Multiple-Arrays-Sum}$

We will define a new problem as follows:
Definition 3.1. MULTIPLE-ARRAYS-SUM (MAS)

INSTANCE: A matrix $M$ of $m \times n$ dimensions, $M[i, j] \in \mathbb{Z}^+$ for each $1 \leq i \leq m$ and $1 \leq j \leq n$, and array $B$ where length($B$) = $m$ and $B[i] \in \mathbb{Z}^+$ for each $1 \leq i \leq m$.

QUESTION: Is there a subset $T \subseteq \{1, 2, 3, \ldots, n-1, n\}$ such that $B[1] = \sum_{j \in T} M[1, j]$, $B[2] = \sum_{j \in T} M[2, j]$, $B[3] = \sum_{j \in T} M[3, j]$, $\ldots$, $B[m] = \sum_{j \in T} M[m, j]$?

Theorem 3.2. $MAS \in NP$.

Proof. Given an instance $\langle M; B \rangle$ of MAS, we could verify whether a subset $T \subseteq \{1, 2, 3, \ldots, n-1, n\}$ is a certificate for $\langle M; B \rangle$ in polynomial-time. We verify whether each element of $T$ is an integer between 1 and $n$. Then, we check whether $B[1] = \sum_{j \in T} M[1, j]$, $B[2] = \sum_{j \in T} M[2, j]$, $B[3] = \sum_{j \in T} M[3, j]$, $\ldots$, $B[m] = \sum_{j \in T} M[m, j]$. Since this iteration over the elements in the set $T$ and matrix $M$ just comparing or summing their values can be done in polynomial time, we obtain that $MAS \in NP$.  

Theorem 3.3. SUBSET–SUM $\leq_P$ MAS.

Proof. Given an arbitrary instance $\langle S; t \rangle$ of SUBSET–SUM, we will do the following actions:

1. We create a one-to-one function $\kappa_x$ which maps to a single integer between 1 and $|S|$ each element of $S$. This means $\kappa_x(x) \neq \kappa_x(y)$ if and only if $x \neq y$ for $x, y \in S$.
2. Next, we create a matrix $M$ of $|S| \times |S|$ dimensions.
3. After that, we iterate for each $x \in S$ and $i = 1, 2, 3, \ldots, |S|$ assigning the value of $x$ in $M$ as follows: $M[i, \kappa_x(x)] = x$.
4. Finally, we create the array $B$ of length $|S|$ such that for each $i = 1, 2, 3, \ldots, |S|$ we have that $B[i] = t$.

A subset $S' \subseteq S$ whose elements sum to $t$ can be interpreted as a subset $T' \subseteq \{1, 2, 3, \ldots, |S| - 1, |S|\}$ such that $x \in S'$ if and only if $\kappa_x(x) \in T'$. Certainly, if $S'$ is a certificate of $\langle S; t \rangle$, then the instance $\langle M; B \rangle$ belongs to MAS, because $t = B[1] = \sum_{j \in T'} M[1, j] = B[2] = \sum_{j \in T'} M[2, j] = \ldots = B[|S|] = \sum_{j \in T'} M[|S|, j]$. Moreover, if $T'$ is a certificate of $\langle M; B \rangle$, then the instance $\langle S; t \rangle$ belongs to SUBSET–SUM, since there will be $|T'|$ elements in $S$ that sums $t$. The reason is because the elements of $M[i, j]$ for some fixed $1 \leq i \leq |S|$ and iterating through all $j$ between 1 and $|S|$ is exactly the set $S$ and $t = B[1] = B[2] = B[3] = \ldots = B[|S|]$. Hence, we obtain the following result:

$\langle S; t \rangle \in$ SUBSET–SUM if and only if $\langle M; B \rangle \in$ MAS.

In addition, the construction of matrix $M$ and array $B$ can be done in polynomial-time, and thus, SUBSET–SUM $\leq_P$ MAS.  

Theorem 3.4. MAS $\in$ NP–complete.

Proof. Since SUBSET–SUM $\leq_P$ MAS, then $MAS \in$ NP–hard. Furthermore, $MAS \in$ NP, and therefore, $MAS \in$ NP–complete.
4. P versus NP

We will state our principal result:

**Theorem 4.1.** MAS is actually SUBSET–PRODUCT on exponentially more succinct representation.

**Proof.** Given an arbitrary instance \(\langle L, t \rangle\) of SUBSET–PRODUCT, we will do the following actions:

1. We create a function \(\kappa_i\) which maps to a single integer between 1 and \(|L|\) each element of \(L\), such that if we pick two elements \(x, y \in L\), then they will have different values on \(\kappa_i\), even though they might represent the same number.

2. If the number \(N\) is the amount of different prime factors in \(t\), then we create a one-to-one function \(\kappa_i\) which maps to a single integer between 1 and \(N\) each prime factor of \(t\). This means \(\kappa_i(p) \neq \kappa_i(q)\) if and only if \(p \neq q\) for every two primes \(p\) and \(q\) that divide to \(t\).

3. Next, we create a matrix \(M\) of \((N + 1) \times |L|\) dimensions.

4. After that, we iterate for each \(x \in L\) filling the cells of \(M\) as follows: If \(x\) can be expressed as \(p^i \times r\) where \(p\) is a prime factor of \(t\), \(w \in \mathbb{N}\) and \(r\) is not divisible by \(p\), then \(M[\kappa_i(p), \kappa_i(x)] = w\) otherwise we make \(M[\kappa_i(p), \kappa_i(x)] = 0\).

5. Then, we iterate for each \(x \in L\) filling the cells of row \((N + 1)\) in \(M\) in the following way: If \(x\) has at least one prime factor \(p\) such that \(p\) does not divide to \(t\), then \(M[N + 1, \kappa_i(x)] = 1\) otherwise we make \(M[N + 1, \kappa_i(x)] = 0\).

6. Finally, we create the array \(B\) of length \(N + 1\) such that if the number \(t\) can be expressed as \(p^i \times r\) where \(p\) is a prime factor, \(w \in \mathbb{N}\) and \(r\) is not divisible by \(p\), then we assign \(B[\kappa_i(p)] = w\). In addition, we make \(B[N + 1] = 0\).

A sublist \(L' \subseteq L\) whose elements multiplication is exactly \(t\) can be interpreted as a subset \(T' \subseteq \{1, 2, 3, \ldots, |L| - 1, |L|\}\) such that \(x \in L'\) if and only if \(\kappa_i(x) \in T'\). Since \(t\) is equal to the product of the powers of its different prime factors as \(p^{\kappa_i(p)} \times r^{\kappa_i(r)}\), we obtain that \(B[\kappa_i(p)] = \sum_{j \in T'} M[\kappa_i(p), j]\), \(B[\kappa_i(q)] = \sum_{j \in T'} M[\kappa_i(q), j]\), \(\ldots\), \(B[\kappa_i(r)] = \sum_{j \in T'} M[\kappa_i(r), j]\), because the product of powers \(A'\) and \(A'\) under the same base \(A\) will imply the addition of their exponents \(i\) and \(j\) in the result \(A'^{i+j}\). In addition, the row \((N + 1)\) in \(M\) guarantees there will not be included any other prime in the multiplication which is not a prime factor of \(t\), since \(0 = B[N + 1] = \sum_{j \in T'} M[N + 1, j]\). Indeed, \(T'\) will be a certificate for \(\langle M; B \rangle\) in MAS.

We can make the reverse transformation in the other direction too. Certainly, if \(\langle M; B \rangle\) is an arbitrary instance of MAS where the matrix \(M\) has \(m \times n\) dimensions, then we could translate it into an instance \(\langle L; t \rangle\) of SUBSET–PRODUCT. For this purpose, we create a one-to-one function \(\kappa_i\) which maps to a single prime number the integers between 1 and \(m\) in the following way: \(\kappa_i(i) = p\) if and only if \(i\) is the \(i\)-th prime. Now, we iterate for each \(j = 1, 2, 3, \ldots, n\) defining the elements of list \(L\) as follows: \(((\kappa_i(1))^{M[1, j]} \times (\kappa_i(2))^{M[2, j]} \times (\kappa_i(3))^{M[3, j]} \times \ldots \times (\kappa_i(m))^{M[m, j]}\). Finally, we define \(t\) as \(((\kappa_i(1))^{B[1]} \times (\kappa_i(2))^{B[2]} \times (\kappa_i(3))^{B[3]} \times \ldots \times (\kappa_i(m))^{B[m]}\). Now, if \(\langle M; B \rangle\) is in MAS, then there is a sublist \(L' \subseteq L\) whose elements multiplication is exactly \(t\). In conclusion, we can affirm that we can always find for every instance \(\langle L; t \rangle\) of SUBSET–PRODUCT another equivalent instance \(\langle M; B \rangle\) of MAS and viceversa. Consequently, we obtain that

\[\langle L; t \rangle \in \text{SUBSET–PRODUCT} \text{ if and only if } \langle M; B \rangle \in \text{MAS}\]
Theorem 4.2.  $P \neq NP$.

Proof. We start assuming that $P = NP$. But, if $P = NP$, then $MAS$ and $SUBSET–PRODUCT$ would be in $P–complete$, because they are $NP–complete$. A succinct version of a problem that is complete for $P$ can be shown not to lie in $P$, because it will be complete for $EXP$ [4]. Since $MAS$ is a succinct version of $SUBSET–PRODUCT$ and $SUBSET–PRODUCT$ would be in $P–complete$, then we obtain that $MAS$ should be also in $EXP–complete$.

Since the classes $P$ and $EXP$ are closed under reductions, and $MAS$ is complete for both $P$ and $EXP$, then we could state that $P = EXP$ [4]. However, as result of Hierarchy Theorem the class $P$ cannot be equal to $EXP$ [4]. To sum up, we obtain a contradiction under the assumption that $P = NP$, and thus, we can claim that $P \neq NP$ as a direct consequence of the Reductio ad absurdum rule.

5. Conclusions

This proof explains why after decades of studying the $NP$ problems no one has been able to find a polynomial-time algorithm for any of more than 300 important known $NP–complete$ problems [9]. Indeed, it shows in a formal way that many currently mathematically problems cannot be solved efficiently, so that the attention of researchers can be focused on partial solutions or solutions to other problems.

Although this demonstration removes the practical computational benefits of a proof that $P = NP$, it would represent a very significant advance in computational complexity theory and provide guidance for future research. In addition, it proves that could be safe most of the existing cryptosystems such as the public-key cryptography [8]. On the other hand, we will not be able to find a formal proof for every theorem which has a proof of a reasonable length by a feasible algorithm.

References