Homogeneous Diophantine Equation of Degree Two in NP-Complete

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Abstract

In mathematics, a Diophantine equation is a polynomial equation, usually involving two or more unknowns, such that the only solutions of interest are the integer ones. A homogeneous Diophantine equation is a Diophantine equation that is defined by a homogeneous polynomial. Solving a homogeneous Diophantine equation is generally a very difficult problem. However, homogeneous Diophantine equations of degree two are considered easier to solve. Certainly, using the Hasse principle we may able to decide whether a homogeneous Diophantine equation of degree two has an integer solution. We prove that this decision problem is actually in *NP–complete* under the constraint that the each variable is required to be evaluated in $\{0, 1\}$.

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1 Introduction

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 $f : \{0,1\}^* \to \{0,1\}^*$ such that for all $x \in \{0,1\}^*$:

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

An important complexity class is *NP–complete* [3]. 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* [1]. Moreover, if $L_1 \in NP$, then $L_1 \in NP\text{–}complete$ [1]. A principal *NP–complete* problem is SAT [3]. An instance of SAT is a Boolean formula ϕ which is composed of:

1. Boolean variables: $x_1, x_2, \ldots, x_n$;
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 Boolean formula with a satisfying truth assignment is satisfiable. The problem SAT asks whether a given Boolean formula is satisfiable [3]. 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 [1]. 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 [1]. A Boolean formula is in 3-conjunctive normal form or $3CNF$, if each clause has exactly three distinct literals [1]. 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 $\neg x_2$. In computational complexity, not-all-equal 3-satisfiability

(*NAE–3SAT*) is an *NP–complete* variant of SAT over $3CNF$ Boolean formulas. *NAE–3SAT* consists in knowing whether a Boolean formula ϕ in $3CNF$ has a truth assignment such that for each clause at least one literal is true and at least one literal is false [3]. *NAE–3SAT* remains *NP–complete* when all clauses are monotone (meaning that variables are never negated), by Schaefer's dichotomy theorem [6]. We know that the variant of $XOR\ 2SAT$ that uses the logic operator $\oplus$ (XOR) instead of $\vee$ (OR) within the clauses of $2CNF$ Boolean formulas can be decided in polynomial time [4, 5]. Despite of its feasible computation, we announce another problem very similar to this one but in *NP–complete*.

▶ **Definition 1.** ***Monotone Exact XOR 2SAT (EX2SAT)***
INSTANCE: A Boolean formula φ in $2CNF$ with monotone clauses between logic operators $\oplus$ and a positive integer K.
QUESTION: Does φ has a truth assignment such that there are exactly K satisfied clauses?

▶ **Theorem 2.** *$EX2SAT \in$ NP–complete.*

A homogeneous Diophantine equation is a Diophantine equation that is defined by a polynomial whose nonzero terms all have the same degree [2]. The degree of a term is the sum of the exponents of the variables that appear in it, and thus is a non-negative integer [2]. From general homogeneous Diophantine equations of degree two, we can reject an instance when there is no solution reducing the equation modulo p. We define our finally decision problem:

▶ **Definition 3.** ***ZERO-ONE Homogeneous Diophantine Equation (HDE)***
INSTANCE: A homogeneous Diophantine equation of degree two $P(x_1, x_2, \ldots, x_n) = B$ with the unknowns $x_1, x_2, \ldots, x_n$ and a positive integer B.
QUESTION: Does $P(x_1, x_2, \ldots, x_n) = B$ has a solution $u_1, u_2, \ldots, u_n$ on $\{0, 1\}^n$?

▶ **Theorem 4.** *$HDE \in$ NP–complete.*

2 Proof of Theorem 2

Proof. Take a Boolean formula ϕ in $3CNF$ with n variables and m clauses when all clauses are monotone. Iterate for each clause $c_i = (a \vee b \vee c)$ and create the conjunctive normal form formula

$$d_i = (a \oplus a_i) \wedge (b \oplus b_i) \wedge (c \oplus c_i) \wedge (a_i \oplus b_i) \wedge (a_i \oplus c_i) \wedge (b_i \oplus c_i)$$

where a_i, b_i, c_i are new variables linked to the clause c_i in ϕ. Note that, the clause c_i has exactly at least one true literal and at least one false literal if and only if d_i has exactly one unsatisfied clause. Finally, we obtain a new formula

$$\varphi = d_1 \wedge d_2 \wedge d_3 \wedge \ldots \wedge d_m$$

where there is not any repeated clause. In this way, we made a polynomial time reduction from ϕ in *NAE–3SAT* to $(\varphi, 5 \cdot m)$ in $EX2SAT$. Certainly, $\phi \in$ *NAE–3SAT* if and only if $(\varphi, 5 \cdot m) \in EX2SAT$, where the new instance $(\varphi, 5 \cdot m)$ is polynomially bounded by the bit-length of ϕ. At the end, we see that $EX2SAT$ is trivially in NP since we could check when there are exactly K satisfied clauses for a single truth assignment in polynomial time. ◀

3 Proof of Theorem 4

Proof. Take a Boolean formula φ in $XOR\ 2CNF$ with n variables and m clauses when all clauses are monotone and a positive integer K. Iterate for each clause $c_i = (a \oplus b)$ and create the Homogeneous Diophantine Equation of degree two

$$P(x_a, x_b) = x_a^2 - 2 \cdot x_a \cdot x_b + x_b^2$$

where x_a, x_b are variables linked to the positive literals a, b in the Boolean formula φ. When the literals a, b are evaluated in $\{false, true\}$, then we assign the respective values $\{0, 1\}$ to the variables x_a, x_b (1 if it is true and 0 otherwise). Note that, the clause c_i is satisfied if and only if $P(x_a, x_b) = 1$. Finally, we obtain a polynomial

$$P(x_1, x_2, \ldots, x_n) = P(x_a, x_b) + P(x_c, x_d) + \ldots + P(x_e, x_f)$$

that is a Homogeneous Diophantine Equation of degree two. Indeed, K satisfied clauses in φ correspond to K distinct small pieces of Homogeneous Diophantine Equation of degree two $P(x_i, x_j)$ which are equal to 1. In this way, we made a polynomial time reduction from (φ, K) in $EX2SAT$ to $(P(x_1, x_2, \ldots, x_n), K)$ in HDE. Certainly, $(\varphi, K) \in EX2SAT$ if and only if $(P(x_1, x_2, \ldots, x_n), K) \in HDE$, where the new instance $(P(x_1, x_2, \ldots, x_n), K)$ is polynomially bounded by the bit-length of (φ, K). At the end, we see that HDE is trivially in NP since we could check whether an evaluation of $x_1, x_2, \ldots, x_n$ in the solution $u_1, u_2, \ldots, u_n$ on $\{0, 1\}^n$ could be equal to K in polynomial time. ◀

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