THE NUMBER OF SOLUTIONS OF A DIOPHANTINE EQUATION OVER A RECURSIVE RING

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Abstract. Let $R$ be a recursive ring whose quotient field is not algebraically closed with the property that Hilbert’s Tenth Problem over $R$ is undecidable, and let $A$ be a non-empty proper subset of $\{0, 1, 2, \ldots\} \cup \{\aleph_0\}$. We prove that it is not decidable whether the number of solutions of a diophantine equation with coefficients in $R$ is in $A$.

Hilbert’s Tenth Problem asked for an algorithm which would decide whether an arbitrary diophantine equation is solvable. It was solved by Ju. V. Matijasevič [6], who built on earlier work by M. Davis, H. Putnam and J. Robinson [4] and showed that it is undecidable. An elementary introduction to the problem and its solution and ramifications can be found, e.g., in the textbook [7]. In the decades following this breakthrough a large number of consequences and extensions of Hilbert’s Tenth Problem have been studied and proved.

We fix the following notation for the remainder of this paper: if $R$ is an enumerable ring and $p \in R[X_1, \ldots, X_n]$, let

$$#(p) = |\{(a_1, \ldots, a_n) \in R^n \mid p(a_1, \ldots, a_n) = 0\}|.$$ 

Furthermore, set $C = \{0, 1, 2, \ldots\} \cup \{\aleph_0\}$.

M. Davis [3] proved the following surprising result in the case $R = \mathbb{Z}$.

Theorem. Let $A$ be a non-empty proper subset of $C$. Then there is no algorithm for testing whether $#(p) \in A$ where $p$ denotes a polynomial with integer coefficients.

A simplification of Davis’ proof can be found in C. Smoryński’s textbook [10] (see also [9]).

Hilbert’s Tenth Problem has also been extended to a large number of rings, most notably rings of integers in number fields. The most prominent problem in this direction is Hilbert’s Tenth Problem over $\mathbb{Q}$, which remains open in spite of dramatic recent progress made by B. Poonen [1]. His survey paper [2] is an excellent introduction to this field. Much more information and further references can be found in the conference proceedings [5] and in A. Shlapentokh’s monograph [8].

In order to be able to transfer notions from recursion theory to a ring it has to be recursive, which intuitively says that its elements can be represented by a computer and that its addition, subtraction and multiplication can be carried out by a computer.

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Definition. A countable integral domain $R$ will be called a recursive ring if there is an injection $J : R \to \mathbb{N}$ such that $J(R)$ is recursive and the functions translating addition, subtraction and multiplication are recursive. (For example, there is a computable function $J_+ : \mathbb{N}^2 \to \mathbb{N}$ such that $J_+(J(x), J(y)) = J(x + y)$ for all $x, y \in R$.)

The map $J$ is called a recursive presentation of $R$. A set $A \subseteq R$ is called recursive (recursively enumerable) under the presentation $J$ if $J(A)$ is recursive (recursively enumerable).

A function $f : A(\subseteq \mathbb{N}^n) \to R$ is called recursive under a presentation $J$ if its translation is recursive (i.e., there is a recursive function $J_f : \mathbb{N}^n \to \mathbb{N}$ such that $J_f(J(x_1), \ldots, J(x_n)) = J(f(x_1, \ldots, x_n))$ for all $(x_1, \ldots, x_n) \in A$).

It is known that every polynomial function $\mathbb{N}^n \to \mathbb{R}$ is recursive. If $R$ is a finitely generated ring, then being recursive does not depend on the presentation [8, Appendix A].

It is the purpose of this note to extend Davis’ theorem to suitable recursive rings $R$ for which Hilbert’s Tenth Problem is undecidable; i.e., there is no algorithm for testing whether an equation $p(X_1, \ldots, X_n) = 0$ with $n \in \mathbb{N}$ and $p \in R[X_1, \ldots, X_n]$ has a solution.

Theorem 1. Let $R$ be a recursive ring whose quotient field is not algebraically closed with the property that Hilbert’s Tenth Problem over $R$ is undecidable and let $\emptyset \subseteq A \subseteq \mathbb{C}$. Then there is no algorithm for testing whether $\#(p) \in A$ for an arbitrary polynomial $p$ with coefficients in $R$.

Lemma 2. Let $R$ be an integral domain whose quotient field $K$ is not algebraically closed and let $p_1, \ldots, p_m \in R[X_1, \ldots, X_n]$. Then there is a polynomial

$$H_m(p_1, \ldots, p_m) \in R[X_1, \ldots, X_n]$$

such that the system of equations

$$p_1(X_1, \ldots, X_n) = \cdots = p_m(X_1, \ldots, X_n) = 0$$

has a solution in $\mathbb{R}^n$ if and only if $H_m(p_1, \ldots, p_m)(X_1, \ldots, X_n) = 0$ has a solution in $\mathbb{R}^n$.

The proof of this lemma can be found, e.g., as Lemma 1.2.3 in [8]. We sketch the proof for the reader’s convenience.

Proof. Let $m = 2$ and let $h(X) = a_k X^k + \cdots + a_1 X + a_0 \in R[X]$ (with $k \neq 0$ and $a_k \neq 0$) denote a polynomial without roots in $K$. Then $a_0 \neq 0$ and $g(X) = a_0 X^k + \cdots + a_{k-1} X + a_k$ has no roots in $K$ either. Set

$$H_2(p_1, p_2)(X_1, \ldots, X_n) = \sum_{i=0}^{k} a_i p_1^{k-i}(X_1, \ldots, X_n) p_2^i(X_1, \ldots, X_n).$$

Let $(b_1, \ldots, b_n) \in \mathbb{R}^n$. If $p_1(b_1, \ldots, b_n) = p_2(b_1, \ldots, b_n) = 0$, then

$$H_2(p_1, p_2)(b_1, \ldots, b_n) = 0.$$

Conversely, let $H_2(p_1, p_2)(b_1, \ldots, b_n) = 0$. If $p_1(b_1, \ldots, b_n) \neq 0$, then

$$h \left( \frac{p_2(b_1, \ldots, b_n)}{p_1(b_1, \ldots, b_n)} \right) = 0,$$
and if \( p_2(b_1, \ldots, b_n) \neq 0 \), then
\[
g\left( \frac{p_1(b_1, \ldots, b_n)}{p_2(b_1, \ldots, b_n)} \right) = 0,
\]
both of which are impossible. For \( m > 2 \) let
\[
H_m(p_1, \ldots, p_m) = H_2(H_{m-1}(p_1, \ldots, p_{m-1}), p_m).
\]
Finally, let \( H_1(p) = p \).

**Lemma 3.** Let \( R \) be a recursive ring whose quotient field is not algebraically closed and let \( k \in \{0,1,2,\ldots\} \). Then there is a recursive operation \( T^k \) on the set \( \bigcup_{n=0}^{\infty} R[X_1, \ldots, X_n] \) such that \( \#(T^k(p)) = \#(p) + k \) for all \( p \in \bigcup_{n=0}^{\infty} R[X_1, \ldots, X_n] \).

**Proof.** If \( k = 0 \), let \( T^k(p) = p \). If \( k \geq 1 \), let
\[
(T^k(p))(X_1, \ldots, X_n, Y) = H_2(p(X_1, \ldots, X_n), Y) \cdot \prod_{i=1}^k H_{n+1}(X_1, \ldots, X_n, Y - a_i),
\]
where \( Y \) is a new variable and \( a_1, a_2, a_3, \ldots \) is a recursive enumeration of an infinite subset of \( R \setminus \{0\} \). Then \((b_1, \ldots, b_n, c) \in R^{n+1} \) is a solution of
\[
(T^k(p))(X_1, \ldots, X_n, Y) = 0
\]
if and only if either \( p(b_1, \ldots, b_n) = c = 0 \) or \( b_1 = \cdots = b_n = 0 \) and \( c \in \{a_1, \ldots, a_k\} \).

**Remark.** If the characteristic of \( R \) is zero, we can use \( a_i = 1 + \cdots + 1 \) (with \( i \) summands). One can also use the following variant: let
\[
(T^1(p))(X_1, \ldots, X_n, Y) = H_2(p(X_1, \ldots, X_n), Y) \cdot H_{n+1}(X_1, \ldots, X_n, Y - 1)
\]
and \( T^k(p) = T^1(T^{k-1}(p)) \) for \( k \geq 2 \).

**Lemma 4.** Let \( R \) be a recursive ring whose quotient field is not algebraically closed. Then there is a recursive operation \( T^\infty \) on \( \bigcup_{n=0}^{\infty} R[X_1, \ldots, X_n] \) such that
\[
\#(T^\infty(p)) = \begin{cases} 0, & \text{if } \#(p) = 0, \\ \aleph_0, & \text{if } \#(p) > 0, \end{cases}
\]
for all \( p \in \bigcup_{n=0}^{\infty} R[X_1, \ldots, X_n] \).

**Proof.** Let \( (T^\infty(p))(X_1, \ldots, X_n, Y) = p(X_1, \ldots, X_n) \cdot h(Y) \), where \( Y \) is a new variable and \( h \in R[Y] \) is a non-constant polynomial without roots in the quotient field of \( R \). If \( p(X_1, \ldots, X_n) = 0 \) is unsolvable, then so is \( p(X_1, \ldots, X_n)h(Y) = 0 \). If \((b_1, \ldots, b_n) \in R^n \) satisfies \( p(b_1, \ldots, b_n) = 0 \), then \( p(b_1, \ldots, b_n)h(c) = 0 \) for all \( c \in R \).

**Proof of Theorem 1.** We first assume that \( \aleph_0 \notin A \). As \( A 
eq C \) there is a \( k \in \{0,1,2,\ldots\} \) such that \( k \notin A \). Then \( \#(p) = 0 \) if and only if \( \#(T^k(T^\infty(p))) \notin A \). This means that Hilbert’s Tenth Problem over \( R \) would be decidable if we could decide whether the number of solutions of a diophantine equation is in \( A \). If \( \aleph_0 \notin A \), then \( \aleph_0 \in C \setminus A \). If we could decide whether \( \#(p) \in A \) for every polynomial \( p \), we could also decide whether \( \#(p) \in C \setminus A \), which is impossible by the first case.
References


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