

Undecidability in the Ramsey theory of polynomial equations

Combinatorics and Interactions Seminar
IMPAN Krakow

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Overview

- 1 Partition Ramsey Theory
- 2 Decidability and the lightface Borel hierarchy
- 3 Hilbert's 10th problem
- 4 Main result for partition regularity
- 5 Density Ramsey Theory
- 6 References

Partition regularity

Definition

Let R be an integral domain, let $S \subseteq R$, let $n, m \in \mathbb{N}$ and $p_1, \dots, p_m \in R[x_1, \dots, x_n]$ be arbitrary. The system of equations

$$\begin{aligned} p_1(x_1, \dots, x_n) &= 0 \\ &\vdots \\ p_m(x_1, \dots, x_n) &= 0 \end{aligned} \tag{1}$$

is **ℓ -partition regular (p.r.) over S** if for any partition $S = \bigcup_{i=1}^{\ell} C_i$, there is some $1 \leq i_0 \leq \ell$ for which C_{i_0} contains a solution to the system of equations in (1). The system of equations is **partition regular** if it is ℓ -partition regular for all $\ell \in \mathbb{N}$.

Positive results 1/2

The following systems of equations **are** partition regular over \mathbb{N} .

1) $x + y = z$, Schur 1916 [24]

2) van der Waerden 1927 [25] (arithmetic progressions or A.P.s)

$$x_1 - x_2 = x_2 - x_3$$

⋮

$$x_{n-2} - x_{n-1} = x_{n-1} - x_n, \text{ or equivalently,}$$

$$\sum_{i=1}^{n-2} (x_{i+2} - 2x_{i+1} + x_i)^2 = 0.$$

3) Brauer 1928 [6] (A.P.s and their common difference)

$$x_1 - x_2 = x_0$$

⋮

$$x_{n-1} - x_n = x_0$$

Positive results 2/2

- 4) Rado 1933 [22] classified which finite systems of linear equations are p.r.
- 5) $x - y = p(z)$ with $p(z) \in z\mathbb{Z}[z]$, Bergelson 1996 [3, page 53]
- 6) Bergelson, Moreira, and Johnson 2017 [4], for $p_i(x) \in x\mathbb{Z}[x]$

$$\begin{aligned} x_1 - x_2 &= p_1(x_0) \\ &\vdots \\ x_{n-1} - x_n &= p_{n-1}(x_0) \end{aligned}$$

- 7) $x^2 - y^2 = z$, Moreira 2017 [19]
- 8) $z = x^y$, Sahasrabudhe 2018 [23]

Negative results

The following systems of equations **are not** partition regular over \mathbb{N} .

- 1) $2x + 3y = z$, Rado 1933 [22]
- 2) Rado 1933 [22]

$$\begin{aligned}x + 3y &= z_1 \\x + 2y &= 2z_2\end{aligned}$$

- 3) $x + y = z^2$ (ignoring $2 + 2 = 2^2$), Csikvári, Gyarmati, and Sárközy 2012 [9] (see also [17])
- 4) $x - 2y = z^2$, Di Nasso and Luperi Baglini 2018 [12]
- 5) $x^2 - 2y^2 = z$, Di Nasso and Luperi Baglini 2018 [12]
- 6) $x + y = w^3z^2$, F. and Magner 2022 [14]
- 7) $2x + 3y = wz^2$, F. and Magner 2022 [14]
- 8) F. and Magner 2022 [14]

$$\begin{aligned}x_1 + 17y_1 &= w_1 z_1^{100} \\9x_2 + 18y_2 &= w_2 z_2^2\end{aligned}$$

Open problems

The partition regularity of the following systems of equations over \mathbb{N} is **not known**.

- 1) $x^2 + y^2 = z^2$ (**VERY** popular, [13, 18, 15, 16])
- 2) $a(x^2 - y^2) = bz^2 + dw$ (important, cf. [21])
- 3) $x^3 + y^3 + z^3 = w^3$ (cf. [8])
- 4) $x^3 + y^3 + z^3 - 3xyz = w^3$
- 5) $x^4 + y^4 + z^4 = w^4$ (cf. [8])
- 6) (**VERY** popular, cf. [19, 1, 2, 5])

$$\begin{aligned} w &= xy \\ z &= x + y \end{aligned}$$

- 7) $2x - 8y = wz^3$ (cf. [14])
- 8) (cf. [14])

$$\begin{aligned} 16x_1 + 17y_1 &= w_1 z_1^8 \\ 33x_2 - 17y_2 &= w_2 z_2^8 \end{aligned}$$

Computable sets

Definition

A set $A \subseteq \mathbb{N}$ is **computable** if there exists an algorithm (Turing machine) that halts on every input, and outputs 1 if and only if the input is an element of A . If S is a countably infinite set, then $A \subseteq S$ is **computable** if there exists a computable bijection $\phi : S \rightarrow \mathbb{N}$ for which the set $\phi(A)$ is computable.

Examples of computable subsets of \mathbb{N} include the set of squares, the set of primes, the set of powers of 2, and the set of square free numbers. If $S \subseteq \mathbb{Z}[x]$ denotes the collection of polynomials of degree at most 2, and $A \subseteq S$ is those polynomials that have an integer root, then A is a computable set. Rado's Theorem [22] shows us that if S is the set of finite systems of linear equations with coefficients in \mathbb{Z} , and $A \subseteq S$ consists of those systems that are partition regular over \mathbb{N} , then A is computable.

Computably enumerable sets

Definition

A set $A \subseteq \mathbb{N}$ is **computably enumerable** if there exists an algorithm (Turing machine) such that the set of inputs for which the algorithm halts is exactly A . Equivalently, A is computably enumerable if there exists an algorithm that enumerates the members of A .

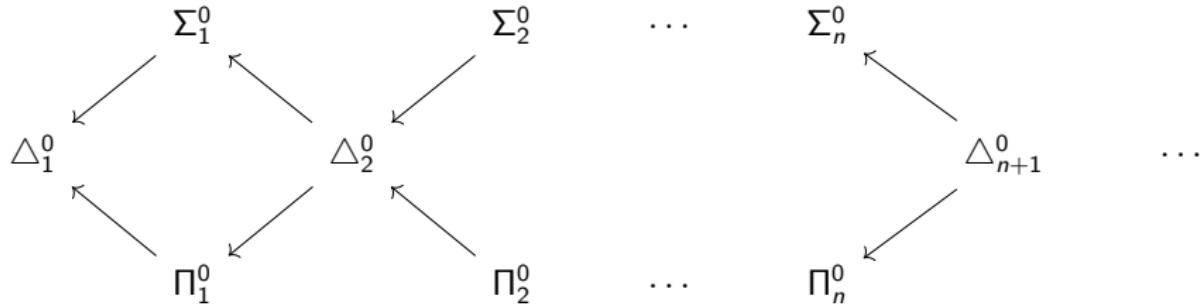
Given a polynomial $p \in \mathbb{Z}[x_1, \dots, x_n]$, the set Z_p of integer roots of p is seen to be computably enumerable from the second of the given definitions. If $S = \bigcup_{n=1}^{\infty} \mathbb{Z}[x_1, \dots, x_n]$, and $A \subseteq S$ is those polynomials that possess an integer root, then A is seen to be computably enumerable from the first of the given definitions.

Lemma

A set $A \subseteq \mathbb{N}$ is computable if and only if A and A^c are both computably enumerable.

The lightface hierarchy

We denote the collection of computable subsets of \mathbb{N} by Δ_1^0 , the collection of computably enumerable subsets of \mathbb{N} by Σ_1^0 , and we let Π_1^0 denote the collection of sets whose complement is in Σ_1^0 . We inductively define Σ_{n+1}^0 to be the collection of sets that are reducible to a set in Π_n^0 in a “computably enumerable fashion”, Π_{n+1}^0 is the complement of Σ_{n+1}^0 , and $\Delta_{n+1}^0 = \Sigma_{n+1}^0 \cap \Pi_{n+1}^0$.



Hilbert's 10th problem (HTP)

At the International Congress of Math in 1900, David Hilbert presented 10 important problems in mathematics, and 2 years later published a completed list of 23 problems now known as Hilbert's problems. The 10th of the 23 problems (published but not presented) asked if the set $A \subseteq S := \bigcup_{n=1}^{\infty} \mathbb{Z}[x_1, \dots, x_n]$ of polynomials that have an integer root is computable.

Theorem (Matiyasevič, 1971)

The set A is not computable.

See the survey of Davis [10] for an exposition of the proof of this result and the history.

Open Problem: Is the set $A_{\mathbb{Q}} \subseteq S$ of polynomials that have a root in \mathbb{Q} computable?

The latter problem is referred to as Hilbert's 10th problem over \mathbb{Q} . It is generally believed that $A_{\mathbb{Q}}$ is not computable.

Variations of Hilbert's 10th problem

Given a **computable** integral domain R , we let $HTP(R)$ refer to the following statement:

HTP(R): There does not exist a computable procedure to determine if a given $p \in R[x_1, \dots, x_n]$ has a root in R .

The statement $HTP(R)$ can be true, or false depending on the integral domain R .

Theorem ([26, 20, 11])

Suppose that R is a finite degree algebraic extension of $\mathbb{F}_{p^k}(t_1, \dots, t_n)$ for some prime $p > 2$ and some $n, k \in \mathbb{N}$.

- ① $HTP(R)$ is true.
- ② There does not exist a computable procedure for determining whether or not a given polynomial $p \in R[x_1, \dots, x_n]$ has an integer root $(z_1, \dots, z_n) \in (R \setminus \{0\})^n$.

First main result

Theorem (F., Jackson, Mance, 2024+)

- ① Let us assume that $HTP(\mathbb{Q})$ is true. For $\ell \in \mathbb{N}$, the set $A_\ell \subseteq \bigcup_{n=1}^{\infty} \mathbb{Z}[x_1, \dots, x_n]$ of (homogeneous) polynomials p for which the equation $p(x_1, \dots, x_n) = 0$ is ℓ -partition regular over $\mathbb{Z} \setminus \{0\}$ is computably enumerable but not computable, so it is Σ_1^0 -complete. The set $A := \bigcap_{\ell=1}^{\infty} A_\ell$ is Π_2^0 -complete.
- ② Suppose that R is as in the Theorem on the last slide (or just $R = \mathbb{F}_p(t)$). For $\ell \in \mathbb{N}$, the set $A_\ell \subseteq \bigcup_{n=1}^{\infty} R[x_1, \dots, x_n]$ of (homogeneous) polynomials p for which the equation $p(x_1, \dots, x_n) = 0$ is ℓ -partition regular over $R \setminus \{0\}$ is Σ_1^0 -complete. The set $A := \bigcap_{\ell=1}^{\infty} A_\ell$ is Π_2^0 -complete.

Reducing partition regularity to HTP

Lemma (cf. Krawczyk, Byszewski, 2021 [7])

Let R be an integral domain with field of fractions K . For any $m \in \mathbb{N}$ and any $k_1, \dots, k_m \in K$, the system of equations

$$\frac{z_{3i-2} - z_{3i-1}}{z_{3i}} = k_i \text{ for all } 1 \leq i \leq m, \quad (2)$$

is partition regular over $R \setminus \{0\}$.

Corollary

Given an integral domain R , and a polynomial $p \in R[x_1, \dots, x_n]$, p has a root in K if and only if the equation $p'(x_1, \dots, x_{3n}) = 0$ with

$$p'(x_1, \dots, x_{3n}) := p \left(\frac{x_1 - x_2}{x_3}, \dots, \frac{x_{3n-2} - x_{3n-1}}{x_{3n}} \right) \left(\prod_{i=1}^n x_{3i} \right)^{\deg(p)}$$

is partition regular over $R \setminus \{0\}$.

Implications 1/3

Observe that if R is a countably infinite integral domain, then there are only countably many polynomials p with coefficients in R . Consequently, the set B of such polynomials that are not partition regular over $R \setminus \{0\}$ is countable, so for each $p \in B$ there exists a partition P_p of $R \setminus \{0\}$ that does not contain a root of p . Consequently, to determine whether or not a polynomial p is partition regular over $R \setminus \{0\}$, it suffices check whether or not p has a root in some cell of each partition in the family $\{P_b\}_{b \in B}$. The fact that the set of "partition regular polynomials" is Π_2^0 -complete, means that there does not exist a simpler method of determining whether or not the equation $p(x_1, \dots, x_n) = 0$ is partition regular over $R \setminus \{0\}$.

Conjecture

Let R be a computable integral domain. There exists a computable collection of finite partitions $\{\mathcal{C}_n\}_{n=1}^{\infty}$ of $R \setminus \{0\}$ such that p is partition regular over $R \setminus \{0\}$ if and only if for every $n \in \mathbb{N}$, p has a root in some cell of \mathcal{C}_n .

Implications 3/3

The following statement is false since it is describing a Σ_1^0 set, but the set of "partition regular polynomials" is (conditionally) a Π_2^0 -complete set.

False Statement: Let R be a countably infinite integral domain. For each $p \in R[x_1, \dots, x_n]$, there exists $q \in R[x_1, \dots, x_m]$ that is a computable function of p such that $p(x_1, \dots, x_n) = 0$ is partition regular over $R \setminus \{0\}$ if and only if q has a root in K .

However, the following result is true.

Theorem

For each $p \in R[x_1, \dots, x_n]$ and each $r \in \mathbb{N}$, there exists $q_r \in R[x_1, \dots, x_m]$ that is a computable function of p and r such that $p(x_1, \dots, x_n) = 0$ is r -partition regular over $R \setminus \{0\}$ if and only if q_r has a root in K .

Density Ramsey Theory

Everything that we have considered so far for partition regularity, we have also considered for density Ramsey theory. See the paper for more details.

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