Hilbert's tenth problem

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Theorem (Matiyasevich-Robinson-Davis-Putnam)

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Positive results

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Degree one: yes.

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Degree three: unknown.

Degree four: as hard as general equation (Skolem), and thus undecidable by MRDP.

Sum of three cubes

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1955: Miller and Woollett used the EDSAC computer to find solution for all $n <\leq 100$ (that are not $\pm 4 \mod 9$) except $n = 30, 33, 39, 42, 52, 74, 75, 84, 87$. They suggested maybe some of these are not sums of three cubes.

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$33 = 8\ 866\ 128\ 975\ 287\ 528^3 + (-8\ 778\ 405\ 442\ 862\ 239)^3 + (-2\ 736\ 111\ 468\ 807\ 040)^3$

Diophantine equation

A simple observation: there is an algorithm deciding whether $f \in \mathbb{Z}[X_1, \ldots, X_n]$ has integer solution $\Leftrightarrow$ there is an algorithm deciding whether $f \in \mathbb{Z}[X_1, \ldots, X_n]$ has natural number solution.

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$\Rightarrow$: Lagrange's four-square theorem says every natural number is the sum of four squares of integers. So $f(X_1, \ldots, X_n)$ has natural number solution iff the following has integer solution.

$$f(X_{11}^2 + X_{12}^2 + X_{13}^2 + X_{14}^2, \ldots, X_{n1}^2 + X_{n2}^2 + X_{n3}^2 + X_{n4}^2)$$

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$\Leftarrow$: For example, $f(X, Y)$ has integer solution iff one of $f(X, Y)$, $f(X, -Y)$, $f(-X, Y)$ and $f(-X, -Y)$ has natural number solution.

Diophantine equation

A subset of $\mathbb{N}^m$ is *Diophantine* if it is of the form

$\{\bar{a} \in \mathbb{N}^m : \exists \bar{x} \in \mathbb{N}^n \ f(\bar{a}, \bar{x}) = 0\}$

for some $f \in \mathbb{Z}[A_1, \ldots, A_m, X_1, \ldots, X_n]$

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Theorem (Matiyasevich-Robinson-Davis-Putnam)

Diophantine sets are exactly the recursively enumerable sets.

There is an r.e. set $S \subseteq \mathbb{N}^m$ that is not recursive. If S is defined by $f(\overline{A}, \overline{X})$, then there is no algorithm that determines whether $f(\bar{a}, \overline{X})$ has natural number solution for a given $\bar{a} \in \mathbb{N}^m$.

History of MRDP theorem

1949: Davis showed Diophantine sets are not closed under complementation.

1950: Robinson realized if there is a function such that: (i) its graph is Diophantine, (ii) it grows exponentially, then certain sets (such as the set of all primes) are Diophantine.

1959: Davis and Putnam improved Robinson's "certain sets" to all r.e. sets, conditional on the then unproven Green-Tao theorem.

1960: Robinson removed the dependence on Green-Tao.

1961-1969: People found various other reductions.

1970: Matiyasevich showed the function $n \mapsto F_{2n}$ works, where F_n is the n-th Fibonacci number.

Outline of the proof

We follow Lou's notes for the proof of MRDP theorem.

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Define $x_a(n)$, $y_a(n)$ by $x_a(n) + y_a(n)\sqrt{a^2-1} = (a + \sqrt{a^2-1})^n$, i.e., $(x_a(n), y_a(n))$ is the n-th solution to he Pell's equation $x^2 - (a^2-1)y^2 = 1$.

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Use intricate congruence properties of these numbers to show $(a, n) \mapsto y_a(n)$ is Diophantine, which in turn implies that $n \mapsto 2^n$ is Diophantine.

Basic properties

Convention: polynomials $f(\overline{X})$ have integer coefficients; variables $a, b, c, x, y, z, m, n, u, \ldots$ range over natural numbers.

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Examples:

- $\{(a, b) : a < b\} \subseteq \mathbb{N}^2$ is Diophantine: $\exists x\ a + x + 1 - b = 0$.
- $\{(a, b) : a \mid b\} \subseteq \mathbb{N}^2$ is Diophantine: $\exists x\ a \cdot x - b = 0$
- $\{(a, b, c) : a \equiv b \mod c\} \subseteq \mathbb{N}^3$ is Diophantine: $\exists x\ (a - b - cx) \cdot (b - a - cx) = 0$.

Basic properties

Diophantine sets are closed under union and intersection: consider $f \cdot g$ and $f^2 + g^2$ resp.

A function is Diophantine if its graph is. $\gcd(a, b)$ and $\mathrm{rem}(a, b)$ are Diophantine. For $\gcd(a, b)$ consider $\exists x \exists y\ (ax - by = c \vee by - ax = c) \wedge c \mid a \wedge c \mid b$.

Diophantine functions are closed under composition. Preimage or image of Diophantine set under Diophantine function is Diophantine.

Basic properties

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Recall that r.e. sets are defined by $\exists \bar{x} \varphi$ where φ is bounded. To show that r.e. sets are Diophantine, it suffices to show that Diophantine sets are closed under bounded universal quantification. To show this we temporarily assume that $n \mapsto 2^n$ is Diophantine.

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Lemma: If 2^x is Diophantine, so are x^y, $\binom{x}{y}$ and $x!$.

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Lemma: If 2^x is Diophantine, so are x^y, $\binom{x}{y}$ and $x!$.

$2^{xy} \equiv x \mod 2^{xy} - x$

$2^{xy^2} \equiv x^y \mod 2^{xy} - x$

$x^y = \mathrm{rem}(2^{xy^2}, 2^{xy} - x)$ if $y > 1$ (since $x^y < 2^{xy} - x$)

Bounded quantification theorem

A small further reduction: we want to show a set of form

$\forall u \leq x \exists \bar{v}\ F(\bar{a}, x, u, \bar{v}) = 0$

is Diophantine, where
$F(\overline{A}, X, U, \overline{V}) \in \mathbb{Z}[A_1, \ldots, A_m, X, U, V_1, \ldots, V_n]$.

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Note that

$\forall u \leq x \exists \bar{v}\ F(\bar{a}, x, u, \bar{v}) = 0 \Leftrightarrow \exists y \forall u \leq x \exists \bar{v} \leq y\ F(\bar{a}, x, u, \bar{v}) = 0$

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For simplicity assume $n = 1$.

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Idea: this holds iff there are b and coprime p_u's for $u \le x$ s.t. $\mathrm{rem}(b, p_u) \le y$ and $F(\bar{a}, x, y, u, \mathrm{rem}(b, p_u)) = 0$.

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To express this for all $u \le x$, find a large number M s.t. $M \equiv u \mod p_u$, and the above implies

$F(\bar{a}, x, y, M, b) \equiv 0 \mod \prod_{u \le x} p_u$.

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Choose p_u carefully plus some other stuff to make this sufficient.

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$$F(\overline{A}, X, Y, U, V) \in \mathbb{Z}[A_1, \ldots, A_m, X, Y, U, V].$$

Choose $G(\overline{A}, X, Y)$ s.t. $G(\bar{a}, x, y) > 2x + 2$, $G(\bar{a}, x, y) > y + 1$, and $G(\bar{a}, x, y) > |F(\bar{a}, x, y, u, v)|$ for all $u \le x$ and $v \le y$. E.g., let $G(\overline{A}, X, Y) = F^*(\overline{A}, X, Y, X, Y) + 2X + Y + 3$ where F^* replaces all coefficients in F by absolute values.

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BQT: $\forall u \le x \exists v \le y \; F(\bar{a}, x, y, u, v) = 0 \Leftrightarrow$
$\exists b \left[\binom{b}{y+1} \equiv F(\bar{a}, x, y, g! - 1, b) \equiv 0 \mod \binom{g! - 1}{x+1} \right]$

where $g = G(\bar{a}, x, y)$.

Bounded quantification theorem

Let $g = G(\bar{a}, x, y)$, then $\forall u \leq x \exists v \leq y \; F(\bar{a}, x, y, u, v) = 0 \Leftrightarrow$
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$$\binom{g!-1}{x+1} = \frac{(g!-1)(g!-2)\cdots(g!-x-1)}{1\cdot 2\cdots(x+1)}$$
$$= \frac{g!-1}{1} \cdot \frac{g!-2}{2} \cdots \frac{g!-x-1}{x+1}$$
$$= \left(\frac{g!}{1} - 1\right) \cdot \left(\frac{g!}{2} - 1\right) \cdots \left(\frac{g!}{x+1} - 1\right)$$

Claim: each prime factor of $\binom{g!-1}{x+1}$ is $> g$, and $\frac{g!}{u+1} - 1$ are coprime.

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Claim: each prime factor of $\binom{g!-1}{x+1}$ is $> g$, and $\frac{g!}{u+1} - 1$ are coprime.

For each $u \leq x$ let p_u be a prime factor of $\frac{g!}{u+1} - 1$. So $g! - 1 \equiv u \mod p_u$, and for any b we have
$F(\bar{a}, x, y, g! - 1, b) \equiv F(\bar{a}, x, y, u, \mathrm{rem}(b, p_u)) \mod p_u$

Bounded quantification theorem

Let $g = G(\bar{a}, x, y)$, then $\forall u \le x \exists v \le y \; F(\bar{a}, x, y, u, v) = 0 \Leftrightarrow$
$\exists b \left[\binom{b}{y+1} \equiv F(\bar{a}, x, y, g! - 1, b) \equiv 0 \mod \binom{g!-1}{x+1} \right]$

$\Leftarrow$: Suppose such a b exists, in particular $p_u \mid \binom{b}{y+1}$ for each $u \le x$, so $p_u \mid b \cdot (b-1) \cdots (b-y)$, so $p_u \mid (b-k)$ for some $k \le y$. Thus $\mathrm{rem}(b, p_u) \le y$, and by assumption on g we have

$$|F(\bar{a}, x, y, u, \mathrm{rem}(b, p_u))| < g < p_u,$$

but this is also congruent mod p_u to $F(\bar{a}, x, y, g! - 1, b)$, so it's 0.

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$\exists b \left[\binom{b}{y+1} \equiv F(\bar{a}, x, y, g! - 1, b) \equiv 0 \mod \binom{g!-1}{x+1} \right]$

$\Rightarrow$: Suppose for every $u \leq x$ there exists such a $v_u \leq y$. By CRT there is a $b < \binom{g!-1}{x+1}$ s.t. $\mathrm{rem}(b, \frac{g!}{u+1} - 1) = v_u$. Thus

$\frac{g!}{u+1} - 1 \mid (b - v_u) \mid b \cdot (b-1) \cdots (b-y)$

Then $\binom{g!-1}{x+1} \mid \binom{b}{y+1}$ since each prime factor of $\binom{g!-1}{x+1}$ is $> g$ and $g > y + 1$. Also easy to check $g! - 1 \equiv u \mod \frac{g!}{u+1} - 1$, so $F(\bar{a}, x, y, g! - 1, b) \equiv 0 \mod \frac{g!}{u+1} - 1$ for each $u \leq x$, and the result follows.

Pell's equation

It remains to show $n \mapsto 2^n$ is Diophantine. For this we use the properties of Pell's equation

$$x^2 - dy^2 = 1$$

$(x, y) \in \mathbb{N}^2$ is a solution iff $x + y\sqrt{d}$ is a unit in the ring $O_{\mathbb{Q}(\sqrt{d})}$; if $x_1 + y_1\sqrt{d}$ and $x_2 + y_2\sqrt{d}$ are units then so is their product, so $(x_1x_2 + dy_1y_2, x_1y_2 + x_2y_1)$ is a solution.

The Indian mathematician Bhāskara II (c. 1114–1185) was the first to show that there always exist nontrivial solutions. In modern language, the group of units of $O_{\mathbb{Q}(\sqrt{d})}$ is isomorphic to $\{-1, 1\} \times \mathbb{Z}$, and the generator for $\mathbb{Z}$ is the element $x + y\sqrt{d}$ with $x > 1$ minimal.

Pell's equation

The minimal solution to Pell's equation varies wildly, e.g., when $d = 61$ it's $x = 1766319049,\ y = 226153980$, due to Fermat.

We are going to consider the family $x^2 - (a^2 - 1)y^2 = 1$, whose minimal solution is obviously $(a, 1)$. Define $x_a(n)$, $y_a(n)$ by

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They satisfy various formulas, such as

$$y_a(m + n) = x_a(m)y_a(n) + x_a(n)y_a(m)$$

$$y_a(n + 2) = 2ay_a(n + 1) - y_a(n)$$

Pell's equation

Growth rate: $(2a-1)^n \leq y_a(n+1) < (2a)^2$, $2n \leq y_a(n)$ for $n \geq 2$

Congruence rules: $y_a(n) \equiv n \mod a-1$,
$y_a(n) \equiv y_b(n) \mod a-b$

Periodicity: if $y_a(n) \equiv 0 \mod m$ then $y_a(k) \equiv y_a(l) \mod m$ for any $k = l \mod 2n$

1st step-down lemma: $y_a(m) \mid y_a(n) \Leftrightarrow m \mid n$
$y_a(m)^2 \mid y_a(n) \Leftrightarrow my_a(m) \mid n$

2nd step-down lemma: if $y_a(k) \equiv y_a(l) \mod x_a(n)$ then $k \equiv \pm l \mod 2n$

Pell's equation

Claim: for $a, y, n \geq 2$, we have $y = y_a(n)$ iff there are x, u, v, s, t, b such that

(i) $2n \leq y$

(ii) $x^2 - (a^2 - 1)y^2 = 1$

(iii) $v \geq 1$ & $u^2 - (a^2 - 1)v^2 = 1$

(iv) $b \geq 2$ & $s^2 - (b^2 - 1)t^2 = 1$

(v) $b \equiv a \mod u$

(vi) $b \equiv 1 \mod y$

(vii) $t \equiv y \mod u$

(viii) $t \equiv n \mod y$

(ix) $y^2 \mid v$

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(vii) $t \equiv y \mod u$
(viii) $t \equiv n \mod y$
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Idea?: (ii) implies $y = y_a(k)$ for some k. By the growth bound we have $2k \leq y$, and some intricate (but completely elementary) arguments show $n \equiv \pm k \mod y$.

Exponentiation is Diophantine

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Some simple estimation shows if $a \geq 2ny_3(n+1)+1$ then

$$\left|\frac{y_{2a}(n+1)}{y_a(n+1)} - 2^n\right| < \frac{1}{2},$$

so $2^n = m \Leftrightarrow 2|y_{2a}(n+1) - my_a(n+1)| < y_a(n+1)$

Variants

One can also ask about solutions in other rings or fields. The theories of $\mathbb{Q}_p$, $\mathbb{R}$ and $\mathbb{C}$ are decidable, so there exist algorithm for checking, e.g., whether a given polynomial with integer coefficients has real solution.

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MRDP extends to many (but currently not all) number rings.

An important open case is Hilbert tenth for rationals. Robinson proved in 1949 that $\mathbb{Z}$ is definable in $\mathbb{Q}$, using a formula of form $\forall\bar{x}\exists\bar{y}\forall\bar{z} f(n, \bar{x}, \bar{y}, \bar{z}) = 0$. Consequently, the theory of $\mathbb{Q}$ is undecidable.

Poonen improved this to $\forall\exists$, and Koenigsmann found a $\forall$-definition. If there is an $\exists$-definition then Hilbert tenth for rationals would have a negative answer, but this is impossible assuming the Bombieri-Lang conjecture in number theory.

Reference

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