

## req.1 Undecidability

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We call a theory  $\mathbf{T}$  *undecidable* if there is no computational procedure which, after finitely many steps and unfailingly, provides a correct answer to the question “does  $\mathbf{T}$  prove  $\varphi$ ?” for any sentence  $\varphi$  in the language of  $\mathbf{T}$ . So  $\mathbf{Q}$  would be decidable iff there were a computational procedure which decides, given a sentence  $\varphi$  in the language of arithmetic, whether  $\mathbf{Q} \vdash \varphi$  or not. We can make this more precise by asking: Is the relation  $\text{Prov}_{\mathbf{Q}}(y)$ , which holds of  $y$  iff  $y$  is the Gödel number of a sentence provable in  $\mathbf{Q}$ , recursive? The answer is: no.

**Theorem req.1.**  $\mathbf{Q}$  is undecidable, i.e., the relation

$$\text{Prov}_{\mathbf{Q}}(y) \Leftrightarrow \text{Sent}(y) \wedge \exists x \text{Prf}_{\mathbf{Q}}(x, y)$$

is not recursive.

*Proof.* Suppose it were. Then we could solve the halting problem as follows: Given  $e$  and  $n$ , we know that  $\varphi_e(n) \downarrow$  iff there is an  $s$  such that  $T(e, n, s)$ , where  $T$  is Kleene’s predicate from ???. Since  $T$  is primitive recursive it is representable in  $\mathbf{Q}$  by a formula  $\psi_T$ , that is,  $\mathbf{Q} \vdash \psi_T(\bar{e}, \bar{n}, \bar{s})$  iff  $T(e, n, s)$ . If  $\mathbf{Q} \vdash \psi_T(\bar{e}, \bar{n}, \bar{s})$  then also  $\mathbf{Q} \vdash \exists y \psi_T(\bar{e}, \bar{n}, y)$ . If no such  $s$  exists, then  $\mathbf{Q} \vdash \neg \psi_T(\bar{e}, \bar{n}, \bar{s})$  for every  $s$ . But  $\mathbf{Q}$  is  $\omega$ -consistent, i.e., if  $\mathbf{Q} \vdash \neg \varphi(\bar{n})$  for every  $n \in \mathbb{N}$ , then  $\mathbf{Q} \not\vdash \exists y \varphi(y)$ . We know this because the axioms of  $\mathbf{Q}$  are true in the standard model  $\mathfrak{N}$ . So,  $\mathbf{Q} \not\vdash \exists y \psi_T(\bar{e}, \bar{n}, y)$ . In other words,  $\mathbf{Q} \vdash \exists y \psi_T(\bar{e}, \bar{n}, y)$  iff there is an  $s$  such that  $T(e, n, s)$ , i.e., iff  $\varphi_e(n) \downarrow$ . From  $e$  and  $n$  we can compute  $\# \exists y \psi_T(\bar{e}, \bar{n}, y) \#$ , let  $g(e, n)$  be the primitive recursive function which does that. So

$$h(e, n) = \begin{cases} 1 & \text{if } \text{Prov}_{\mathbf{Q}}(g(e, n)) \\ 0 & \text{otherwise.} \end{cases}$$

This would show that  $h$  is recursive if  $\text{Prov}_{\mathbf{Q}}$  is. But  $h$  is not recursive, by ??, so  $\text{Prov}_{\mathbf{Q}}$  cannot be either.  $\square$

**Corollary req.2.** *First-order logic is undecidable.*

*Proof.* If first-order logic were decidable, provability in  $\mathbf{Q}$  would be as well, since  $\mathbf{Q} \vdash \varphi$  iff  $\vdash \omega \rightarrow \varphi$ , where  $\omega$  is the conjunction of the axioms of  $\mathbf{Q}$ .  $\square$

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## Bibliography