THE COMPLEXITY OF THE INDEX SETS OF
$\aleph_0$-CATEGORICAL THEORIES AND OF
EHRENFEUCHT THEORIES

STEFFEN LEMPP AND THEODORE A. SLAMAN

Abstract. We classify the computability-theoretic complexity of
two index sets of classes of first-order theories: We show that the
property of being an $\aleph_0$-categorical theory is $\Pi_3^0$-complete; and the
property of being an Ehrenfeucht theory $\Pi_1^1$-complete. We also
show that the property of having continuum many models is $\Sigma_1^1$-
hard. Finally, as a corollary, we note that the properties of having
only decidable models, and of having only computable models, are
both $\Pi_1^1$-complete.

1. The Main Theorem

Measuring the complexity of mathematical notions is one of the main
tasks of mathematical logic. Two of the main tools to classify com-
plexity are provided by Kleene's arithmetical and analytical hierarchy.
These two hierarchies provide convenient ways to determine the exact
complexity of properties by various notions of completeness, and to give
lower bounds on the complexity by various notions of hardness. (See,
e.g., Kleene [1], Soare [10] or Odifreddi [4, 5] for the definitions.)

This paper will investigate the complexity of properties of a first-
order theory, more precisely, the complexity of a countable first-order
theory having a certain number of models. Recall that a theory is called
$\aleph_0$-categorical if it has only one countable model up to isomorphism,
and an Ehrenfeucht theory if it has more than one but only finitely
many countable models up to isomorphism. In order to measure the
complexity of these notions, we will use decidable first-order theories,
i.e., sets $T$ of first-order sentences closed under inference such that membership in $T$ can be determined effectively.

The principal result of this paper is now the following

**Main Theorem.** We classify the complexity of some properties of decidable first-order theories as follows:

1. The property “$T$ is an $\aleph_0$-categorical theory” is $\Pi^0_3$-complete.
2. The property “$T$ is an Ehrenfeucht theory” is $\Pi^1_1$-complete.
3. The property “$T$ has continuum many pairwise nonisomorphic models” is $\Sigma^1_1$-hard.

In this paper, a theory will be a set of first-order sentences closed under inference (so that $T \vdash \sigma$ iff $\sigma \in T$ for any sentence $\sigma$).

The rest of this paper is devoted to the proof of our Main Theorem. In section 2, we will prove clause (1) of our Main Theorem. In section 3, we will show that the property of a theory being an Ehrenfeucht theory is $\Pi^1_1$, giving the upper bound for clause (2) of our Main Theorem. Finally, in section 4, we will prove a simultaneous reduction

$$(\Pi^1_1, \Sigma^1_1) \leq_m (\text{Ehrenfeucht}, \text{Continuum})$$

(where Ehrenfeucht and Continuum are (the index sets of) the properties of being an Ehrenfeucht theory or a theory having continuum many models, respectively). This reduction gives the lower bound for clause (2) and proves clause (3) of our Main Theorem.

**2. The Proof for $\aleph_0$-Categoricity**

We first show that “$T$’s being $\aleph_0$-categorical” is $\Pi^0_3$ to obtain the upper bound: A theory $T$ (with a characteristic function given by a partial computable function $\varphi_e$) is $\aleph_0$-categorical iff, by the Ryll-Nardzewski Theorem,

$\varphi_e$ is a total function, $T$ is a complete consistent theory and

$$\forall n (T \text{ has only finitely many } n\text{-types}),$$

i.e., iff

$$e \in \text{Tot and } \forall \sigma (T \vdash \sigma \text{ implies } \sigma \in T) \text{ and }$$
$$\forall \sigma (T \not\vdash \sigma \land \neg \sigma) \text{ and } \forall \sigma (T \vdash \sigma \text{ or } T \not\vdash \neg \sigma) \text{ and }$$
$$\forall n \exists m \exists \sigma_0, \ldots, \sigma_m [\forall i \leq m (T \not\vdash \sigma_i) \text{ and }$$
$$\forall i \leq m \forall \tau (T \vdash \sigma_i \rightarrow \tau \text{ or } T \vdash \sigma_i \rightarrow \neg \tau)].$$

(where $\sigma$ ranges over all first-order sentences, and $\sigma_i$ and $\tau$ range over all first-order formulas in $n$ variables $\overline{x}$ which we suppress above, respectively). Now, since “$T \vdash \sigma$” is $\Delta^0_1$ for decidable theories, inspection
shows that “$T$’s being $\aleph_0$-categorical” is $\Pi^0_3$. (Recall here that we assume that $T$ is closed under inference.)

In order to show that “$T$’s being $\aleph_0$-categorical” is $\Pi^0_3$-complete, we present the following construction of a decidable theory $T_e$ (uniformly in an index $e$) such that

$$\forall n \ (W_f(n) \text{ is finite}) \iff T_e \text{ is } \aleph_0\text{-categorical},$$

where $f = f_e$ is a computable function such that

$$\forall n \ (W_f(n) \text{ is finite})$$

is a $\Pi^0_3$-complete predicate (see, e.g., Soare [10, p. 68]). Without of loss of generality, we may assume that for every stage $s$, there is exactly one pair $\langle n, x \rangle$ such that $x$ enters $W_f(n)$ at stage $s$. We denote this $n$ by $n_s$.

The signature of our theory $T_e$ now consists of relation symbols $R^n_s$ (for all $n, s \in \omega$) where each $R^n_s$ is an $n$-ary relation symbol. At stage $s$, we completely specify the relations $R^n_s$ for all $n \in \omega$ as follows: For all $n \neq n_s$, we let the relation $R^n_s$ be empty. For $n = n_s$, we let the relation $R^n_s$ be “random” over all $R^{n'}_{s'}$ (for $s' < s$) in the sense that all finite extensions consistent with the theory enumerated before stage $s$ (in the relation symbols $R^{n'}_{s'}$ for all $n$ and all $s' < s$) are realized by the relation symbol $R^n_s$ added at stage $s$.

To verify that the construction yields the theory $T_e$ with the desired properties, first assume that for some $n$, $W_f(n)$ is infinite. Then $R^n_s$ is nonempty for infinitely many $s$, and in fact the reduct of $T_e$ to these $n$-ary relations has continuum many consistent $n$-types, making $T_e$ not $\aleph_0$-categorical.

On the other hand, assume that $W_f(n)$ is finite for all $n$. Then the $n$-type of any $n$-tuple $\bar{x}$ is determined by the finitely many nonempty relations of arity $\leq n$ satisfied by $\bar{x}$, so there are only finitely many $n$-types, and $\aleph_0$-categoricity follows.

In fact, it is not hard to see that the theory $T_e$ admits elimination of quantifiers (effectively uniformly in $e$) and is decidable (again uniformly in $e$).

3. The Upper Bound for Ehrenfeucht theories

**Proposition 1.** The set $\{ e : T_e \text{ is an Ehrenfeucht theory} \}$ is $\Pi^1_1$.

**Proof.** Proposition 1 follows from Sacks’s [8] proof that every countable model of an Ehrenfeucht theory has a hyperarithmetic representation.

Suppose that $T$ is a recursive, complete, first-order, Ehrenfeucht theory. From Sacks’s theorem, each of the finitely many isomorphism
types of models of $T$ has a representative which is hyperarithmetically coded. In the same paper, Sacks shows that any model $A$ of $T$ completes its canonical Scott analysis in finitely many steps. Consequently, the canonical Scott sentence for $A$ is uniformly hyperarithmetic in any representation $A$ of $A$. Further, if $A$ and $H$ are representations of countable first-order structures and have the same finite-rank canonical Scott sentence, then there is an isomorphism $\pi$ between the models coded by $A$ and $H$ which is uniformly hyperarithmetically definable from $A$ and $H$. See, for example, [3] in which Nadel analyzes of Scott sentences and isomorphisms between countable models within admissible sets. Thus, for $T$ with the given properties, there are finitely many hyperarithmetic presentations $H_1, \ldots, H_k$ of models of $T$ such that for every representation $A$ of a model of $T$, there is an isomorphism between the models coded by $A$ one of the $H_i$’s which is hyperarithmetic relative to $A$ and $H_1, \ldots, H_k$.

Conversely, for any recursive, complete, first-order theory $T$, if there is a hyperarithmetic finite sequence $H_1, \ldots, H_k$ of representations of models of $T$ such that for every $A$, if $A$ codes a model of $T$ then there is an isomorphism $\pi$ between the model coded by $A$ and that coded by one of the $H_i$’s, then $T$ is an Ehrenfeucht theory.

Now, the proposition follows. $T_e$’s being a complete first-order theory is an arithmetic property and hence $\Pi^1_1$. By the Spector-Gandy Theorem, see Sacks [9], the $\Pi^1_1$ predicates are closed under existential quantification over the hyperarithmetic sets. Thus, the condition above, that there exist hyperarithmetic sets $H_1, \ldots, H_k$, for all sets $A$, there exists $\pi$ hyperarithmetic in $H_1, \ldots, H_k$ and $A$, with arithmetically described properties, is a $\Pi^1_1$ condition. $\square$

4. A Simultaneous Reduction for Ehrenfeucht Theories and Theories with Continuum Many Models

In this section, we will establish the simultaneous reduction

$$(\Pi^1_1, \Sigma^1_1) \leq_m (3\text{Models}, \text{Continuum})$$

where 3Models and Continuum are (the index sets of) the properties of being an Ehrenfeucht theory with exactly three countable models, and a theory having continuum many countable models, respectively. Our proof will be based largely on Reed [7], which in turn used previous work of Peretyat’kin [6] and Millar [2]. (Since our proof uses the rather involved machinery of Reed [7] so heavily and mostly without changes, we will assume familiarity with this paper throughout the rest of the proof.)
We first observe that one can easily modify the proof of the $\Sigma^1_1$-completeness of the property of a computable tree $\text{Tr} \subseteq \omega^{<\omega}$ having an infinite path to obtain a reduction

$$(\Pi^1_1, \Sigma^1_1) \leq_m (\text{NoPath}, \text{InfPath}) \quad (2)$$

where NoPath and InfPath are (the index sets of) the properties of being a computable tree $\text{Tr} \subseteq \omega^{<\omega}$ having no infinite path, and having continuum many infinite paths, respectively.

We now compose the reduction from (2) with the reduction given in Reed [7]: Reed defines, for each computable tree $\text{Tr} \subseteq \omega^{<\omega}$, and uniformly in an index $e$ of $\text{Tr}$, a complete decidable theory $T_e$ “coding” the tree $\text{Tr}$ into a “dense tree”. (Actually, Reed only defines $T_e$ for trees $\text{Tr}$ having exactly one infinite path, but his definition in Part II of [7] can be applied to any computable $\text{Tr} \subseteq \omega^{<\omega}$ and always yields a complete decidable theory $T_e$.)

Checking over Reed’s analysis of 1-types over $T_e$ in Part III of [7], one can now easily verify the following: If $\text{Tr}$ has no infinite path then $T_e$ has exactly three countable models, namely, the countable computable models omitting the type $\Gamma^*(x)$ (since $\text{Tr}$ contains no infinite paths). On the other hand, if $\text{Tr}$ has infinitely many infinite paths then $T_e$ admits a partial type $\Gamma^*_f = \{c_\xi < x \mid \xi \subseteq f\}$ for each infinite path $f \in [\text{Tr}]$, and by an argument analogous to that for Corollary 15.1 in Reed [7] (which shows that the type $\Delta(x)$ can be realized without the type $\Gamma^*(x)$ being realized), for any two distinct paths $f, g \in [\text{Tr}]$, the partial types $\Gamma^*_f$ and $\Gamma^*_g$ can be realized independently of each other. Thus $T_e$ has continuum many types and so also continuum many countable models.

To finish off, we note an easy corollary of our proof as well as two remarks:

**Corollary 2.** The property of a decidable theory having only decidable models is $\Pi^1_1$-hard, as is the property of a decidable theory having only computable models.

**Remark 3.**

1. Our proof actually shows that the property of being an Ehrenfeucht theory with exactly three models is already $\Pi^1_1$-complete.

2. The first-order language used in our proof is not fixed; i.e., the language depends on the tree $\text{Tr}$ and thus on the index $e$ used for the construction. However, we can simply add constant symbols $c_\eta$ (for $\eta \in \omega^{<\omega} - T$) denoting a fixed element of our model, and empty relations $E^\eta_\xi$, etc. (for $\eta$ or $\xi \in \omega^{<\omega} - T$), to achieve a fixed language.


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DEPARTMENT OF MATHEMATICS, UNIVERSITY OF WISCONSIN, MADISON, WI 53706-1388, USA
E-mail address: lempp@math.wisc.edu

DEPARTMENT OF MATHEMATICS, UNIVERSITY OF CALIFORNIA, BERKELEY, CA 94720-3840, USA
E-mail address: slaman@math.berkeley.edu