Categorical characterizations of the natural numbers require primitive recursion

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Abstract

Simpson and Yokoyama [Ann. Pure Appl. Logic 164 (2012), 284–293] asked whether there exists a characterization of the natural numbers by a second-order sentence which is provably categorical in the theory RCA_0^*. We answer in the negative, showing that for any characterization of the natural numbers which is provably true in WKL_0^*, the categoricity theorem implies Σ^0_1 induction.

On the other hand, we show that RCA_0^* does make it possible to characterize the natural numbers categorically by means of a set of second-order sentences. We also show that a certain Π^1_2-conservative extension of RCA_0^* admits a provably categorical single-sentence characterization of the naturals, but each such characterization has to be inconsistent with $\mathsf{WKL}_0^* + \text{superexp}$.

Inspired by a question of Väänänen (see e.g. [Vää12] for some related work), Simpson and the second author [SY12] studied various second-order characterizations of $\langle \mathbb{N}, S, 0\rangle$, with the aim of determining the reverse-mathematical strength of their respective categoricity theorems. One of the general conclusions is that the strength of a categoricity theorem depends heavily on the characterization. Strikingly, however, each of the categoricity theorems considered in [SY12] implies RCA_0, even over the much weaker base theory RCA_0^*, that is, RCA_0 with Σ^0_1 induction replaced by Δ^0_0 induction in the language with exponentiation. (For RCA_0^*, see [SS86].)

This leads to the following question.

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Question 1. [SY12, Question 5.3] Does RCA_0^* prove the existence of a second-order sentence or set of sentences T such that $\mathbb{N}, 0, S$ is a second-order model of T and all second-order models of T are isomorphic to $\mathbb{N}, 0, S$? One may also consider the same question with RCA_0^* replaced by systems which are Π^0_2-equivalent to RCA_0^*.

The question as stated admits multiple versions depending on whether we focus on RCA_0^* or consider other Π^0_2-equivalent theories and whether we want the characterizations of the natural numbers to be sentences or sets of sentences. The most basic version, restricted to RCA_0^* and single-sentence characterizations, would read as follows:

Question 2. Does there exist a second-order sentence ψ in the language with one unary function f and one constant c such that RCA_0^* proves: (i) $\langle \mathbb{N}, S, 0\rangle \models \psi$, and (ii) for every $\langle A, f, c\rangle$, if $\langle A, f, c\rangle \models \psi$, then there exists an isomorphism between $\langle \mathbb{N}, S, 0\rangle$ and $\langle A, f, c\rangle$?

We answer Question 2 in the negative. In fact, characterizing $\langle \mathbb{N}, S, 0\rangle$ not only up to isomorphism, but even just up to *equicardinality of the universe*, requires the full strength of RCA_0. More precisely:

Theorem 1. *Let ψ be a second-order sentence in the language with one unary function f and one individual constant c. If WKL_0^* proves that $\langle \mathbb{N}, S, 0\rangle \models \psi$, then over RCA_0^* the statement "for every $\langle A, f, c\rangle$, if $\langle A, f, c\rangle \models \psi$, then there exists a bijection between $\mathbb{N}$ and A" implies RCA_0.*

Since RCA_0 is equivalent over RCA_0^* to a statement expressing the correctness of defining functions by primitive recursion [SS86, Lemma 2.5], Theorem 1 may be intuitively understood as saying that, for provably true single-sentence characterizations at least, "categorical characterizations of the natural numbers require primitive recursion".

Do less stringent versions of Question 1 give rise to "exceptions" to this general conclusion? As it turns out, they do. Firstly, characterizing the natural numbers by a *set* of sentences is already possible in RCA_0^*:

Theorem 2. *There exists a Δ_0-definable (and polynomial-time recognizable) set Ξ of $\Sigma^1_1 \wedge \Pi^1_1$ sentences such that RCA_0^* proves: for every $\langle A, f, c\rangle$, $\langle A, f, c\rangle$ satisfies all $\xi \in \Xi$ if and only if it is isomorphic to $\langle \mathbb{N}, S, 0\rangle$.*

Secondly, even a single-sentence characterization is possible in a Π^1_2-conservative extension of RCA_0^*, at least if one is willing to consider rather peculiar theories:

Theorem 3. *There is a Σ^1_2 sentence which is a categorical characterization of $\langle \mathbb{N}, S, 0\rangle$ provably in $\mathsf{RCA}_0^* + \neg\mathrm{WKL}$.*

Theorem 3 is not quite satisfactory, as the theory and characterization it speaks of are false in $\langle \omega, \mathscr{P}(\omega) \rangle$. So, another natural question to ask is whether a single-sentence characterization of the natural numbers can be provably categorical in a *true* Π^0_2-conservative extension of RCA^*_0. We show that under an assumption just a little stronger than Π^0_2-conservativity, the characterization from Theorem 3 is actually "as true as possible":

Theorem 4. *Let T be an extension of RCA^*_0 conservative for first-order $\forall\Delta_0(\Sigma_1)$ sentences. Let η be a second-order sentence consistent with $\mathsf{WKL}^*_0 + \mathrm{superexp}$. Then it is not the case that η is a categorical characterization of $\langle \mathbb{N}, S, 0 \rangle$ provably in T.*

The proofs of our theorems make use of a weaker notion of isomorphism to $\langle \mathbb{N}, S, 0 \rangle$ studied in [SY12], that of "almost isomorphism". Intuitively speaking, a structure $\langle A, f, c \rangle$ satisfying some basic axioms is almost isomorphic to $\langle \mathbb{N}, S, 0 \rangle$ if it is "equal to or shorter than" the natural numbers. The two crucial facts we prove and exploit are that almost isomorphism to $\langle \mathbb{N}, S, 0 \rangle$ can be characterized by a single sentence provably in RCA^*_0, and that structures almost isomorphic to $\langle \mathbb{N}, S, 0 \rangle$ correspond to Σ^0_1-definable cuts.

The paper is structured as follows. After a short preliminary Section 1, we conduct our study of almost isomorphism to $\langle \mathbb{N}, S, 0 \rangle$ in Section 2. We then prove Theorem 1 in Section 3, Theorems 2 and 3 in Section 4, and Theorem 4 in Section 5.

1 Preliminaries

We assume familiarity with subtheories of second-order arithmetic, as presented in [Sim09]. Of the "big five" theories featuring prominently in that book, we only need the two weakest: RCA_0, axiomatized by Δ^0_1 comprehension and Σ^0_1 induction (and a finite list of simple basic axioms), and WKL_0, which extends RCA_0 by the axiom WKL stating that an infinite binary tree has an infinite branch.

We also make use of some well-known fragments of first-order arithmetic, principally $\mathrm{I}\Delta_0 + \exp$, which extends induction for Δ_0 formulas by an axiom exp stating the totality of exponentiation; $\mathrm{B}\Sigma_1$, which extends $\mathrm{I}\Delta_0$ by the Σ_1 collection (bounding) principle; and $\mathrm{I}\Sigma_1$. For a comprehensive treatment of these and other subtheories of first-order arithmetic, refer to [HP93]. To distinguish a class of first-order formulas from its second-order analogue, we use notation without the superscript "^{0}". Thus, for instance, a Σ_1 formula is a first-order formula containing a single block of existential quantifiers followed by a bounded part, whereas a Σ^0_1 formula has the same quantifier structure, but may additionally contain second-order parameters. Such a formula is $\Sigma_1(\bar{X})$ if all its second-order parameters are among $\bar{X}$.

A formula is $\Delta_0(\Sigma_1)$ if it belongs to the closure of Σ_1 under boolean operations and bounded first-order quantifiers.

The theory RCA_0^* was introduced in [SS86]. It differs from RCA_0 in that the Σ^0_1 induction axiom is replaced by $\mathrm{I}\Delta^0_0 + \exp$. WKL_0^* is RCA_0^* plus the WKL axiom. Both RCA_0^* and WKL_0^* have $\mathrm{B}\Sigma_1 + \exp$ as their first-order part, while the first-order part of RCA_0 and WKL_0 is $\mathrm{I}\Sigma_1$.

We let superexp denote both the "tower of exponents" function defined by $\mathrm{superexp}(x) = \exp_x(2)$ (where $\exp_0(2) = 1, \exp_{x+1}(2) = 2^{\exp_x(2)}$) and the axiom saying that for every x, $\mathrm{superexp}(x)$ exists. $\Delta_0(\exp)$ stands for the class of bounded formulas in the language extending the language of Peano Arithmetic by a symbol for x^y. $\mathrm{I}\Delta_0(\exp)$ is a definitional extension of $\mathrm{I}\Delta_0 + \exp$.

In any model M of a first-order arithmetic theory (possibly the first-order part of a second-order structure), a *cut* is a nonempty subset of M which is downwards closed and closed under successor. For a cut J, we sometimes abuse notation and also write J to denote the structure $\langle J, S, 0\rangle$, or even $\langle J, +, \cdot, \leq, 0, 1\rangle$ if J happens to be closed under multiplication. A set $A \subseteq M$ is *bounded* if there exists $a \in M$ such that $A \subseteq \{0, \dots, a\}$, and it is *unbounded* otherwise. Assuming that $M \models \exp$ and M satisfies $\Delta_0(A)$ induction, we can refer to a bounded set A as *M-finite* (or simply *finite*), and to an unbounded set A as *(M)-infinite*. Under the same assumptions, it makes sense to speak of the *internal cardinality* $|A|_{\mathscr{M}}$ of A, which is defined to be $\sup(\{x \in M : A \text{ contains a finite subset with at least } x \text{ elements}\})$. $|A|_{\mathscr{M}}$ is an element of M if A is finite, and a cut in M otherwise.

If $\langle M, \mathscr{X}\rangle \models \mathsf{RCA}_0^*$ and J is a cut in M, then $\mathscr{X}_J$ will denote the family of sets $\{X \cap J : X \in \mathscr{X}\}$. Theorem 4.8 of [SS86] states that if J is a proper cut closed under exp, then $\langle J, \mathscr{X}_J\rangle \models \mathsf{WKL}_0^*$.

The letter $\mathbb{A}$ will always stand for a structure $\mathbb{A} = \langle A, f, c\rangle$ for the language with one unary function and one constant. $\mathbb{N}$ stands for the set of numbers defined by the formula $x = x$; in other words, $\mathbb{N}_M = M$. To refer to the set of standard natural numbers, we use the symbol ω.

The general notational conventions regarding cuts apply also to $\mathbb{N}$: for instance, if there is no danger of confusion, we sometimes write that some $\mathbb{A}$ is "isomorphic to $\mathbb{N}$" rather than "isomorphic to $\langle \mathbb{N}, S, 0\rangle$".

2 Almost isomorphism

The structure $\mathbb{A} = \langle A, f, c\rangle$ is a *Peano system* if f is one-to-one, $c \notin \mathrm{rng}(f)$, and $\mathbb{A}$ satisfies the natural formulation of the second-order induction axiom with c as the least element and f as successor. A Peano system is said to be *almost isomorphic to* $\langle \mathbb{N}, S, 0\rangle$ if for every $a \in A$ there is some $x \in \mathbb{N}$ such that $f^x(c) = a$. Since RCA_0^*

is too weak to prove that any function can be iterated an arbitrary number of times, $f^x(c) = a$ needs to be expressed in such a way as to imply the existence of the sequence $\langle c, f(c), f^2(c), \ldots, f^x(c)\rangle$.

Being almost isomorphic to $\mathbb{N}$ is a definable property:

Lemma 5. *There exists a $\Sigma^1_1 \wedge \Pi^1_1$ sentence ξ in the language with one unary function f and one individual constant c such that RCA^*_0 proves: for every $\mathbb{A}$, $\mathbb{A} \models \xi$ if and only if $\mathbb{A}$ is a Peano system almost isomorphic to $\langle \mathbb{N}, S, 0\rangle$.*

Proof. By definition, $\mathbb{A}$ is a Peano system precisely if it satisfies the Π^1_1 sentence ξ_{peano}:

$$f \text{ is 1-1} \wedge c \notin \text{rng}(f) \wedge \forall X\,[X(c) \wedge \forall a\,[X(a) \to X(f(a))] \to \forall a\, X(a)]\,.$$

The sentence ξ will be the conjunction of ξ_{peano}, the Σ^1_1 sentence $\xi_{\preccurlyeq,\Sigma}$:

there exists a discrete linear ordering $\preccurlyeq$
for which c is the least element and f is the successor function,

and the Π^1_1 sentence $\xi_{\Pi,\preccurlyeq}$:

for every linear ordering $\preccurlyeq$ with c as least element and f as successor
and for every a, the set of elements $\preccurlyeq$-below a is Dedekind-finite.

We say that a set X is *Dedekind-finite* if there is no bijection between X and a proper subset of X. Note that provably in RCA^*_0, a set $X \subseteq A$ is finite exactly if $A \models$ "X is Dedekind-finite".

We first prove that Peano systems almost isomorphic to $\mathbb{N}$ satisfy $\xi_{\preccurlyeq,\Sigma}$ and $\xi_{\preccurlyeq,\Pi}$. Let $\mathbb{A}$ be almost isomorphic to $\mathbb{N}$. Every $a \in A$ is of the form $f^x(c)$ for some $x \in \mathbb{N}$. Moreover, x is unique. To see this, assume that $a = f^x(c) = f^{x+y}(c)$ and that $\langle c, f(c), \ldots, f^x(c) = a, f^{x+1}(c), \ldots, f^{x+y}(c) = a\rangle$ is the sequence witnessing that $f^{x+y}(c) = a$ (by Δ^0_0-induction, this sequence is unique and its first $x+1$ elements comprise the unique sequence witnessing $f^x(c) = a$). If $y > 0$, then we have $c \neq f^y(c)$ and then Δ^0_0-induction coupled with the injectivity of f gives $f^w(c) \neq f^{w+y}(c)$ for all $w \leq x$. So, $y = 0$.

Because of the uniqueness of the $f^x(c)$ representation for $a \in A$, we can define $\preccurlyeq$ on A by Δ^0_1-comprehension in the following way:

$$a \preccurlyeq b := \exists x\, \exists y\, (a = f^x(c) \wedge b = f^y(c) \wedge x \leq y).$$

Clearly, $\preccurlyeq$ is a discrete linear ordering on A with c as the least element and f as the successor function, so $\mathbb{A}$ satisfies $\xi_{\preccurlyeq,\Sigma}$.

For each $a \in A$, the set of elements $\preccurlyeq$-below a is finite. Moreover, if $\lessdot$ is any ordering of A with c as least element and f as successor, then for each $a \in A$ the set

$$\{b \in A : b \preccurlyeq a \Leftrightarrow b \lessdot a\}$$

contains c and is closed under f. Since $\mathbb{A}$ is a Peano system, $\lessdot$ has to coincide with $\preccurlyeq$. Thus, $\mathbb{A}$ satisfies $\xi_{\preccurlyeq,\Pi}$.

For a proof in the other direction, let $\mathbb{A}$ be a Peano system satisfying $\xi_{\preccurlyeq,\Sigma}$ and $\xi_{\preccurlyeq,\Pi}$. Let $\preccurlyeq$ be an ordering on A witnessing $\xi_{\preccurlyeq,\Sigma}$. Take some $a \in A$. By $\xi_{\preccurlyeq,\Pi}$, the set $[c,a]_{\preccurlyeq}$ of elements $\preccurlyeq$-below a is finite. Let ℓ be the cardinality of $[c,a]_{\preccurlyeq}$ and let b be the $\leq$-maximal element of $[c,a]_{\preccurlyeq}$. By $\Delta^0_0(\exp)$-induction on x prove that there is an element below b^{x+1} coding a sequence $\langle s_0, \ldots, s_x\rangle$ such that $s_0 = c$ and for all $y < x$, either $s_{y+1} = f(s_y) \preccurlyeq a$ or $s_{y+1} = s_y = a$. Take such a sequence for $x = \ell - 1$. If a does not appear in the sequence, then by $\Delta^0_0(\exp)$-induction the sequence has the form $\langle c, f(c), \ldots, f^{\ell-1}(c)\rangle$ and all its entries are distinct elements of $[c,a]_{\preccurlyeq} \setminus \{a\}$; an impossibility, given that $[c,a]_{\preccurlyeq} \setminus \{a\}$ only has $\ell - 1$ elements. So, a must appear somewhere in the sequence. Taking w to be the least such that $a = s_w$, we easily verify that $a = f^w(c)$. □

Remark. We do not know whether in RCA^*_0 it is possible to characterize $\langle \mathbb{N}, S, 0\rangle$ up to almost isomorphism by a Π^1_1 sentence. This does become possible in the case of $\langle \mathbb{N}, \leq\rangle$ (given a suitable definition of almost isomorphism, cf. [SY12]), where there is no need for the Σ^1_1 part of the characterization which guarantees the existence of a suitable ordering.

An important fact about Peano systems almost isomorphic to $\mathbb{N}$ is that their isomorphism types correspond to Σ^0_1-definable cuts. This correspondence, which will play a major role in the proofs of our main theorems, is formalized in the following definition and lemma.

Definition 6. Let $\mathscr{M} = \langle M, \mathscr{X}\rangle$ be a model of RCA^*_0. For a Peano system $\mathbb{A}$ in $\mathscr{M}$ which is almost isomorphic to $\langle \mathbb{N}, S, 0\rangle$, let $J(\mathbb{A})$ be the cut defined in $\mathscr{M}$ by the Σ^0_1 formula $\varphi(x)$:

$$\exists a \in A\, f^x(c) = a.$$

For a Σ^0_1-definable cut J in $\mathscr{M}$, let the structure $\mathbb{A}(J)$ be $\langle A_J, f_J, c_J\rangle$, where the set A_J consists of all the pairs $\langle x, y_x\rangle$ such that y_x is the smallest witness for the formula $x \in J$, the function f_J maps $\langle x, y_x\rangle$ to $\langle x+1, y_{x+1}\rangle$, and c_J equals $\langle 0, y_0\rangle$.

Lemma 7. *Let $\mathscr{M} = \langle M, \mathscr{X}\rangle$ be a model of RCA^*_0. The following holds:*

(a) for a Σ^0_1-definable cut J in $\mathscr{M}$, the structure $\mathbb{A}(J)$ is a Peano system almost isomorphic to $\langle \mathbb{N}, S, 0\rangle$, and $J(\mathbb{A}(J)) = J$,

(b) *if $\mathbb{A} \in \mathscr{X}$ is a Peano system almost isomorphic to $\langle \mathbb{N}, S, 0\rangle$, then there is an isomorphism in $\mathscr{M}$ between $\mathbb{A}(J(\mathbb{A}))$ and $\mathbb{A}$,*

(c) *if $\mathbb{A} \in \mathscr{X}$ is a Peano system almost isomorphic to $\langle \mathbb{N}, S, 0\rangle$, then there is an isomorphism in $\mathscr{M}$ between $\mathbb{A}$ and $J(\mathbb{A})$, which also induces an isomorphism between the second-order structures $\langle \mathbb{A}, \mathscr{X} \cap \mathscr{P}(A)\rangle$ and $\langle J(\mathbb{A}), \mathscr{X}_{J(\mathbb{A})}\rangle$.*

Although all the isomorphisms between first-order structures mentioned in Lemma 7 are elements of $\mathscr{X}$, a cut is not itself an element of $\mathscr{X}$ unless it equals M (because induction fails for the formula $x \in J$ whenever J is a proper cut). Obviously, the isomorphism between second-order structures mentioned in part (c) is also outside $\mathscr{X}$.

Proof. For a Σ^0_1-definable cut J in $\mathscr{M}$, it is clear that A_J and f_J are elements of $\mathscr{X}$, that f_J is an injection from A_J into A_J, and that c_J is outside the range of f_J. Furthermore, for every $\langle x, y_x\rangle \in A_J$, Σ^0_1 collection in $\mathscr{M}$ guarantees that there is a common upper bound on $y_0, \dots, y_x$, so Δ^0_0 induction is enough to show that the sequence $\langle c_J, f_J(c_J), \dots, f^x_J(c_J) = \langle x, y_x\rangle\rangle$ exists. If $X \subset A_J$, $X \in \mathscr{X}$, is such that $c_J \in X$ but $f^x_J(c_J) \notin X$, then Δ^0_0 induction along the sequence $\langle c_J, f_J(c_J), \dots, f^x_J(c_J)\rangle$ finds some $w < x$ such that $f^w_J(c_J) \in X$ but $f_J(f^w_J(c_J)) \notin X$. Thus, $\mathbb{A}(J)$ is a Peano system almost isomorphic to $\mathbb{N}$, and clearly $J(\mathbb{A}(J))$ equals J, so part (a) is proved.

For part (b), if $\mathbb{A}$ is almost isomorphic to $\mathbb{N}$, then each $a \in A$ has the form $a = f^x(c)$ for some $x \in J(\mathbb{A})$, and we know from the proof of Lemma 5 that the element x is unique. Thus, the mapping which takes $f^x(c) \in \mathbb{A}$ to $\langle x, y_x\rangle \in \mathbb{A}(J(\mathbb{A}))$ is guaranteed to exist in $\mathscr{M}$ by Δ^0_1 comprehension. It follows easily from the definitions of $J(\mathbb{A})$ and $\mathbb{A}(J)$ that the mapping $f^x(c) \mapsto \langle x, y_x\rangle$ is an isomorphism between $\mathbb{A}$ and $\mathbb{A}(J(\mathbb{A}))$.

For part (c), we assume that $\mathbb{A}$ equals $\mathbb{A}(J(\mathbb{A}))$, which we may do w.l.o.g. by part (b). The isomorphism between $\mathbb{A}$ and $J(\mathbb{A})$ is given by $\langle x, y_x\rangle \mapsto x$. To prove that this also induces an isomorphism between $\langle \mathbb{A}, \mathscr{X} \cap \mathscr{P}(A)\rangle$ and $\langle J(\mathbb{A}), \mathscr{X}_{J(\mathbb{A})}\rangle$, we have to show that for any $X \subseteq A$, it holds that $X \in \mathscr{X}$ exactly if $\{x : \langle x, y_x\rangle \in X\}$ has the form $Z \cap J(\mathbb{A})$ for some $Z \in \mathscr{X}$.

The "if" direction is immediate: given $Z \in \mathscr{X}$, the set $\{\langle x, y_x\rangle : x \in Z\}$ is $\Delta_0(Z)$ and thus belongs to $\mathscr{X}$.

To deal with the other direction, we assume that $\mathscr{M}$ is countable. We can do this w.l.o.g. because $J(\mathbb{A})$ is a definable cut, so the existence of a counterexample in some model would imply the existence of a counterexample in a countable model by a downwards Skolem-Löwenheim argument.

By [SS86, Theorem 4.6], the countability of $\mathscr{M}$ means that we can extend $\mathscr{X}$ to a family $\mathscr{X}^+ \supseteq \mathscr{X}$ such that $\langle M, \mathscr{X}^+\rangle \models \mathsf{WKL}^*_0$. Note that there are no (M)-

finite sets in $\mathscr{X}^+ \setminus \mathscr{X}$. This is because a finite set in $\mathscr{X}^+$ actually has the form $\{x : \mathrm{bit}(z,x) = 1\}$ for some $z \in M$, and each such set is Δ_0-definable and thus in $\mathscr{X}$.

Now consider some $X \in \mathscr{X}$, $X \subseteq A$. Let T be the set consisting of the finite binary strings s satisfying:

$$\forall a,x<\mathrm{lh}(s) \left[(a=\langle x,y_x\rangle \wedge a\in X \to (s)_x = 1) \wedge (a=\langle x,y_x\rangle \wedge a\in A\setminus X \to (s)_x = 0)\right].$$

T is $\Delta_0(X)$-definable, so it belongs to $\mathscr{X}$, and it is easy to show that it is an infinite tree. Let $B \in \mathscr{X}^+$ be an infinite branch of T. Then $\{x : \langle x,y_x\rangle \in X\} = B \cap J(\mathbb{A})$. However, $B\cap J(\mathbb{A})$ can also be written as $(B \cap \{0,\dots,z\}) \cap J(\mathbb{A})$ for an arbitrary $z \in M \setminus J(\mathbb{A})$, and $B \cap \{0,\dots,z\}$, being a finite set, belongs to $\mathscr{X}$. □

Corollary 8. *Let $\mathscr{M} = (M,\mathscr{X})$ be a model of RCA_0^*. Let $\mathbb{A} \in \mathscr{X}$ be a Peano system almost isomorphic to $\langle \mathbb{N}, S, 0\rangle$. Assume that $J(\mathbb{A})$ is a proper cut closed under* exp*, that $\preccurlyeq$ is a linear ordering on A with least element c and successor function f, and that $\oplus,\otimes$ are operations on A which satisfy the usual recursive definitions of addition* resp. *multiplication with respect to least element c and successor f. Then $\langle\langle \mathbb{A},\oplus,\otimes,\preccurlyeq,c,f(c)\rangle, \mathscr{X}\cap\mathscr{P}(A)\rangle \models \mathsf{WKL}_0^*$.*

Proof. Write $\mathring{\mathbb{A}}$ for $\langle \mathbb{A},\oplus,\otimes,\leq,c,f(c)\rangle$. By Lemma 7 part (b), we can assume w.l.o.g. that $\mathbb{A} = \mathbb{A}(J(\mathbb{A}))$. Using the fact that $\mathbb{A}$ is a Peano system, we can prove that for every $x,z \in J(\mathbb{A})$ we have

$$\begin{aligned} \langle x,y_x\rangle \oplus \langle z,y_z\rangle &= \langle x+z, y_{x+z}\rangle, \\ \langle x,y_x\rangle \otimes \langle z,y_z\rangle &= \langle x\cdot z, y_{x\cdot z}\rangle, \\ \langle x,y_x\rangle \preccurlyeq \langle z,y_z\rangle &\text{ iff } x \leq z. \end{aligned}$$

By the obvious extension of Lemma 7 part (c) to structures with addition, multiplication and ordering, $\langle \mathring{\mathbb{A}}, \mathscr{X}\cap\mathscr{P}(A)\rangle$ is isomorphic to $\langle J(A), \mathscr{X}_{J(A)}\rangle$. Since $J(\mathbb{A})$ is proper and closed under exp, this means that $\langle \mathring{\mathbb{A}}, \mathscr{X}\cap\mathscr{P}(A)\rangle \models \mathsf{WKL}_0^*$. □

Remark. It was shown in [SY12, Lemma 2.2] that in RCA_0 a Peano system almost isomorphic to $\mathbb{N}$ is actually isomorphic to $\mathbb{N}$. In light of Lemma 7, this is a reflection of the fact that in RCA_0 there are no proper Σ^0_1-definable cuts.

Informally speaking, a Peano system which is not almost isomorphic to $\mathbb{N}$ is "too long", since it contains elements which cannot be obtained by starting at zero and iterating successor finitely many times. On the other hand, a Peano system which is almost isomorphic but not isomorphic to $\mathbb{N}$ is "too short". The results of this section, together with our Theorem 1, give precise meaning to the intuitive idea strongly suggested by Table 2 of [SY12], that the problem with characterizing the natural numbers in RCA_0^* is ruling out structures that are "too short" rather than "too long".

3 Characterizations: basic case

In this section, we prove Theorem 1.

Theorem 1 (restated). *Let ψ be a second-order sentence in the language with one unary function f and one individual constant c. If* WKL_0^* *proves that* $\langle \mathbb{N}, S, 0\rangle \models \psi$*, then over* RCA_0^* *the statement "for every* $\mathbb{A}$*, if* $\mathbb{A} \models \psi$*, then there exists a bijection between* $\mathbb{N}$ *and A" implies* RCA_0.

We use a model-theoretic argument based on the work of Section 2 and a lemma about cuts in models of $\mathrm{I}\Delta_0 + \exp + \neg \mathrm{I}\Sigma_1$.

Lemma 9. *Let* $M \models \mathrm{I}\Delta_0 + \exp + \neg\mathrm{I}\Sigma_1$*. There exists a proper* Σ_1*-definable cut* $J \subseteq M$ *closed under* exp.

Note that a proper cut closed under exp satisfies $\mathrm{B}\Sigma_1 + \exp$, the first-order part of RCA_0^* and WKL_0^*.

Proof. We need to consider a few cases.

Case 1. $M \models$ superexp. Since $M \not\models \mathrm{I}\Sigma_1$, there exists a Σ_1 formula $\varphi(x)$, possibly with parameters, which defines a proper subset of M closed under successor. Replacing $\varphi(x)$ by the formula $\hat{\varphi}(x)$: "there exists a sequence witnessing that for all $y \leq x$, $\varphi(y)$ holds", we obtain a proper Σ_1-definable cut $K \subseteq M$. Define:

$$J := \{y : \exists x \in K\, (y < \mathrm{superexp}(x))\}.$$

J is a cut closed under exp because K is a cut, and it is proper because it does not contain superexp(b) for any $b \notin K$.

The remaining cases all assume that $M \not\models$ superexp. Let $\mathrm{Log}^*(M)$ denote the domain of superexp in M. By the case assumption and the fact that $M \models \exp$, $\mathrm{Log}^*(M)$ is a proper Σ_1-definable cut in M.

Case 2. $\mathrm{Log}^*(M)$ is closed under exp. Define $J := \mathrm{Log}^*(M)$.

Case 3. $\mathrm{Log}^*(M)$ is closed under addition but not under exp. Let $\mathrm{Log}(\mathrm{Log}^*(M))$ be the subset of M defined as $\{x : \exp(x) \in \mathrm{Log}^*(M)\}$. Since $\mathrm{Log}^*(M)$ is closed under addition, $\mathrm{Log}(\mathrm{Log}^*(M))$ is a cut. Moreover, $\mathrm{Log}(\mathrm{Log}^*(M)) \subsetneq \mathrm{Log}^*(M)$, because $\mathrm{Log}^*(M)$ is not closed under exp. Define:

$$J := \{y : \exists x \in \mathrm{Log}(\mathrm{Log}^*(M))\, (y < \mathrm{superexp}(x))\}.$$

J is a cut closed under exp because $\mathrm{Log}(\mathrm{Log}^*(M))$ is a cut, and it is proper because it does not contain superexp(b) for any $b \in \mathrm{Log}^*(M) \setminus \mathrm{Log}(\mathrm{Log}^*(M))$.

Case 4. $\mathrm{Log}^*(M)$ is not closed under addition. Let $\frac{1}{2}\mathrm{Log}^*(M)$ be the subset of M defined as $\{x : 2x \in \mathrm{Log}^*(M)\}$. Since $\mathrm{Log}^*(M)$ is closed under successor,

$\frac{1}{2}\mathrm{Log}^*(M)$ is a cut. Moreover, $\frac{1}{2}\mathrm{Log}^*(M) \subsetneq \mathrm{Log}^*(M)$, because $\mathrm{Log}^*(M)$ is not closed under addition. Define:

$$J := \{y : \exists x \in \frac{1}{2}\mathrm{Log}^*(M)\,(y < \mathrm{superexp}(x))\}.$$

J is a cut closed under exp because $\frac{1}{2}\mathrm{Log}^*(M)$ is a cut, and it is proper because it does not contain superexp(b) for any $b \in \mathrm{Log}^*(M) \setminus \frac{1}{2}\mathrm{Log}^*(M)$. $\square$

Remark. Inspection of the proof reveals immediately that Lemma 9 relativizes, in the sense that in a model of $\mathrm{I}\Delta_0(X) + \exp + \neg\mathrm{I}\Sigma_1(X)$ there is a $\Sigma_1(X)$-definable proper cut closed under exp.

Remark. The method used to prove Lemma 9 shows the following result: for any $n \in \omega$, there is a definable cut in $\mathrm{I}\Delta_0 + \exp$ which is provably closed under exp and proper in all models of $\mathrm{I}\Delta_0 + \exp + \neg\mathrm{I}\Sigma_n$. In contrast, there is no definable cut in $\mathrm{I}\Delta_0 + \exp$ provably closed under superexp; otherwise, $\mathrm{I}\Delta_0 + \exp$ would prove its consistency relativized to a definable cut, which would contradict a result of [Pud85].

We can now complete the proof of Theorem 1. Assume that ψ is a second-order sentence true of $\langle \mathbb{N}, S, 0\rangle$ provably in WKL_0^*. Let $\mathscr{M} = \langle M, \mathscr{X}\rangle$ be a model of $\mathsf{RCA}_0^* + \neg\mathrm{I}\Sigma_1^0$. Assume for the sake of contradiction that according to $\mathscr{M}$, the universe of any structure satisfying ψ can be bijectively mapped onto $\mathbb{N}$.

Let J be the cut in M guaranteed to exist by the relativized version of Lemma 9. Since $|A_J|_{\mathscr{M}} = J$, the model $\mathscr{M}$ believes that there is no bijection between A_J and $\mathbb{N}$, and hence also that $\mathbb{A}(J) \models \neg\psi$.

By Lemma 7 and its proof, the mapping $f^x(c) \mapsto x$ induces an isomorphism between $\langle \mathbb{A}(J), \mathscr{X} \cap \mathscr{P}(A_J)\rangle$ and $\langle J, \mathscr{X}_J\rangle$. Since J is closed under addition and multiplication, we can define the operation $\oplus$ on A_J by setting $f^x(c) \oplus f^z(c) = f^{x+z}(c)$, and we can define $\otimes$ and $\preccurlyeq$ analogously. By the uniqueness of the $f^x(c)$ representation, $\oplus, \otimes, \preccurlyeq$ are all elements of $\mathscr{X}$. Write $\mathring{\mathbb{A}}(J)$ for $\langle \mathbb{A}(J), \oplus, \otimes, \preccurlyeq, c_J, f_J(c_J)\rangle$.

Clearly, A_J with the structure given by $\oplus, \otimes, \preccurlyeq$ satisfies the assumptions of Corollary 8, which means that $\langle \mathring{\mathbb{A}}(J), \mathscr{X} \cap \mathscr{P}(A_J)\rangle$ is a model of WKL_0^*. We also claim that $\langle \mathring{\mathbb{A}}(J), \mathscr{X} \cap \mathscr{P}(A_J)\rangle$ believes $\mathbb{N} \models \neg\psi$. This is essentially an immediate consequence of the fact that $\mathscr{M}$ thinks $\mathbb{A}(J) \models \neg\psi$, since the subsets of A_J are exactly the same in $\langle \mathring{\mathbb{A}}(J), \mathscr{X} \cap \mathscr{P}(A_J)\rangle$ as in $\mathscr{M}$. There is one minor technical annoyance related to non-unary second-order quantifiers in ψ, as the integer pairing function in $\mathring{\mathbb{A}}(J)$ does not coincide with that of M. The reason this matters is that the language of second-order arithmetic officially contains only unary set variables, so e.g. a binary relation is represented by a set of pairs, but a set of M-pairs of elements of A_J might not even be a subset of A_J. Clearly, however, since the graph of the $\mathring{\mathbb{A}}(J)$-pairing function is $\Delta_0^0(\exp)$-definable in $\mathscr{M}$, a given set of M-pairs of elements of A_J belongs to $\mathscr{X}$ exactly if the corresponding set of Å-pairs belongs to $\mathscr{X} \cap \mathscr{P}(A_J)$; and likewise for tuples of greater constant length.

Thus, our claim holds, and we have contradicted the assumption that ψ is true of $\mathbb{N}$ provably in WKL_0^*. □ (Theorem 1)

We point out the following corollary of the proof.

Corollary 10. *The following are equivalent over* RCA_0^**:*

(1) $\neg\mathsf{RCA}_0$.

(2) There exists $\mathscr{M} = (M, \mathscr{X})$ *satisfying* WKL_0^* *such that* $|M| \neq |\mathbb{N}|$.

Proof. RCA_0 proves that all infinite sets have the same cardinality, which gives $(2) \Rightarrow (1)$. To prove $(1) \Rightarrow (2)$, work in a model of $\mathsf{RCA}_0^* + \neg\mathsf{RCA}_0$ and take the inner model of WKL_0^* provided by the proof of Theorem 1. □

Remark. The type of argument described above can be employed to strengthen Theorem 1 in two ways.

Firstly, it is clear that $\langle \mathbb{N}, S, 0 \rangle$ could be replaced in the statement of Theorem 1 by, for instance, $\langle \mathbb{N}, \leq, +, \cdot, 0, 1 \rangle$. In other words, the extra structure provided by addition and multiplication does not help in characterizing the natural numbers without $\mathrm{I}\Sigma_1^0$.

Secondly, for any fixed $n \in \omega$, the theories $\mathsf{RCA}_0^*/\mathsf{WKL}_0^*$ appearing in the statement could be extended (both simultaneously) by an axiom expressing the totality of f_n, the n-th function in the Grzegorczyk-Wainer hierarchy (e.g., the totality of f_2 is exp, the totality of f_3 is superexp). The proof remains essentially the same, except that the argument used to show Lemma 9 now splits into $n+2$ cases instead of four.

By compactness, $\mathsf{RCA}_0^*/\mathsf{WKL}_0^*$ could also be replaced in the statement of the theorem by $\mathsf{RCA}_0^* + \mathrm{PRA}/\mathsf{WKL}_0^* + \mathrm{PRA}$, where PRA is primitive recursive arithmetic.

4 Characterizations: exceptions

In this section, we prove Theorems 2 and 3.

Theorem 2 (restated). *There exists a* Δ_0*-definable (and polynomial-time recognizable) set* Ξ *of* $\Sigma_1^1 \wedge \Pi_1^1$ *sentences such that* RCA_0^* *proves: for every* $\mathbb{A}$*,* $\mathbb{A}$ *satisfies all* $\xi \in \Xi$ *if and only if it is isomorphic to* $\langle \mathbb{N}, S, 0 \rangle$.

Proof of Theorem 2. Let the set Ξ consist of the sentence ξ from Lemma 5 and the sentences

$$\exists a_0 \exists a_1 \ldots \exists a_{x-1} \exists a_x \left[a_0 = c \wedge a_1 = f(a_0) \wedge \ldots \wedge a_x = f(a_{x-1}) \right],$$

for every $x \in \mathbb{N}$. (Note that in a nonstandard model of RCA_0^*, the set Ξ will contain sentences of nonstandard length.)

Provably in RCA_0^*, a structure $\mathbb{A}$ satisfies all sentences in Ξ exactly if it is a Peano system almost isomorphic to $\mathbb{N}$ such that for every $x \in \mathbb{N}$, $f^x(c)$ exists. Clearly then, $\mathbb{N}$ satisfies all sentences in Ξ. Conversely, if $\mathbb{A}$ satisfies all sentences in Ξ, then $J(\mathbb{A}) = \mathbb{N}$ and so $\mathbb{A}$ is isomorphic to $\mathbb{N}$. □

Theorem 3 (restated) . *There is a Σ^1_2 sentence which is a categorical characterization of $\langle \mathbb{N}, S, 0 \rangle$ provably in $\mathsf{RCA}_0^* + \neg$WKL.*

Before proving the theorem, we verify that the theory it mentions is a Π^1_2-conservative extension of RCA_0^*.

Proposition 11. *The theory $\mathsf{RCA}_0^* + \neg$WKL is a Π^1_2-conservative extension of RCA_0^*.*

Proof. Let $\exists X \forall Y \varphi(X,Y)$ be a Σ^1_2 sentence consistent with RCA_0^*. Take $(M, \mathscr{X})$ and $A \in \mathscr{X}$ such that $(M, \mathscr{X}) \models \mathsf{RCA}_0^* + \forall Y \varphi(A,Y)$. Let $\Delta_1(A)$-$\mathfrak{Def}$ stand for the collection of the $\Delta_1(A)$-definable subsets of M. $\Delta_1(A)$-$\mathfrak{Def} \subseteq \mathscr{X}$, so obviously $(M, \Delta_1(A)\text{-}\mathfrak{Def}) \models \mathsf{RCA}_0^* + \forall Y \varphi(A,Y)$. Moreover, by a standard argument, there is a $\Delta_1(A)$-definable infinite binary tree without a $\Delta_1(A)$-definable branch, so $(M, \Delta_1(A)\text{-}\mathfrak{Def}) \models \neg$WKL. □

Proof of Theorem 3. Work in $\mathsf{RCA}_0^* + \neg$WKL. The sentence ψ, our categorical characterization of $\mathbb{N}$, is very much like the the sentence ξ described in the proof of Lemma 5, which expressed almost isomorphism to $\mathbb{N}$. The one difference is that the Σ^1_1 conjunct of ξ:

there exists a discrete linear ordering $\preccurlyeq$
for which c is the least element and f is the successor function,

is strengthened in ψ to the Σ^1_2 sentence:

there exist binary operations $\oplus, \otimes$ and a discrete linear ordering $\preccurlyeq$ such that
$\preccurlyeq$ has c as the least element and f as the successor function,
$\oplus$ and $\otimes$ satisfy the usual recursive definition of addition and multiplication,
and such that $\mathrm{I}\Delta_0 + \exp + \neg$WKL holds.

$\mathrm{I}\Delta_0 + \exp$ is finitely axiomatizable, so there is no problem with expressing this as a single sentence. Note that ψ is Σ^1_2.

Since $\neg$WKL holds, the usual $+$, $\cdot$ and ordering on $\mathbb{N}$ witness that $\mathbb{N}$ satisfies the new Σ^1_2 conjunct of ψ. Of course, $\mathbb{N}$ is a Peano system almost isomorphic to $\mathbb{N}$, and thus it satisfies ψ.

Now let $\mathbb{A}$ be a structure satisfying ψ. Then $\mathbb{A}$ is a Peano system almost isomorphic to $\mathbb{N}$, so we may consider $J(\mathbb{A})$. The existence of $\oplus, \otimes, \preccurlyeq$ witnessing the Σ^1_2 conjunct of ψ guarantees that $J(\mathbb{A})$ is closed under exp. Moreover, Corollary 8 implies that $J(\mathbb{A})$ cannot be a proper cut, because otherwise $\mathbb{A}$ with the additional structure given by $\oplus, \otimes, \preccurlyeq$ would have to satisfy WKL. So, $J(\mathbb{A}) = \mathbb{N}$ and thus $\mathbb{A}$ is isomorphic to $\mathbb{N}$. □

5 Characterizations: exceptions are exotic

To conclude the paper, we prove Theorem 4 and some corollaries.

Theorem 4 (restated). *Let T be an extension of RCA^*_0 conservative for first-order $\forall\Delta_0(\Sigma_1)$ sentences. Let η be a second-order sentence consistent with $\mathsf{WKL}^*_0 +$ superexp. Then it is not the case that η is a categorical characterization of $\langle \mathbb{N}, S, 0\rangle$ provably in T.*

Proof. Let $\mathscr{M} = (M, \mathscr{X})$ be a countable recursively saturated model of $\mathsf{WKL}^*_0 +$ superexp $+ \eta$.

Tanaka's self-embedding theorem [Tan97] is stated for countable models of WKL_0, but it is part of the folklore that the same proof works for countable recursively saturated models of WKL^*_0. Thus, there is a cut I in M such that $(M, \mathscr{X})$ and $(I, \mathscr{X}_I)$ are isomorphic. In particular, $(I, \mathscr{X}_I) \models \eta$.

Let $a \in M \setminus I$. Define the cut K in M to be

$$\{y : \exists x \in I\,(y < \exp_{a+x}(2))\}.$$

$(K, \mathscr{X}_K)$ is a model of WKL^*_0 and I is a Σ_1-definable proper cut in K.

T is conservative over RCA^*_0 for first-order $\forall\Delta_0(\Sigma_1)$ sentences, so there is a model $(L, \mathscr{Y}) \models T$ such that $K \preccurlyeq_{\Delta_0(\Sigma_1)} L$. We claim that in $(L, \mathscr{Y})$ there is a Peano system $\mathbb{A}$ satisfying η but not isomorphic to $\mathbb{N}$. This will imply that T does not prove η to be a categorical characterization of $\mathbb{N}$. It remains to prove the claim.

We can assume that η does not contain a second-order quantifier in the scope of a first-order quantifier. This is because we can always replace first-order quantification by quantification over singleton sets, at the cost of adding some new first-order quantifiers with none of the original quantifiers of η in their scope.

Note that $(K, \mathscr{X}_K)$ contains a proper Σ_1 definable cut, namely I, which satisfies η. Using the universal Σ_1 formula, we can express this fact by a first-order $\exists\Delta_0(\Sigma_1)$ sentence η^{FO}. The sentence η^{FO} says the following:

there exists a triple "Σ_1 formula $\varphi(x,w)$, parameter p, bound b" such that b does not satisfy $\varphi(x,p)$, the set defined by $\varphi(x,p)$ below b is a cut, and this cut satisfies η.

To state the last part, replace the second-order quantifiers of η by quantifiers over subsets of $\{0,\dots,b-1\}$ (these are bounded first-order quantifiers) and replace the first-order quantifiers by first-order quantifiers relativized to elements below b satisfying $\varphi(x,p)$. By our assumptions about the syntactical form of η, this ensures that η^{FO} is $\exists\Delta_0(\Sigma_1)$.

L is a $\Delta_0(\Sigma_1)$-elementary extension of K, so L also satisfies η^{FO}. Therefore, $(L,\mathscr{Y})$ also contains a proper Σ_1-definable cut satisfying η. By Lemma 7, this means that in $(L,\mathscr{Y})$ there is a Peano system $\mathbb{A}$ satisfying η but not isomorphic to $\mathbb{N}$. The claim, and the theorem, is thus proved. □

Remark. The assumption that η is consistent with $\mathsf{WKL}_0^* + \text{superexp}$ rather than just WKL_0^* is only needed to ensure that there is a model of RCA_0^* with a proper Σ_1-*definable* cut satisfying η. The assumption can be replaced by consistency with WKL_0^* extended by a much weaker first-order statement, but we were not able to make the proof work assuming only consistency with WKL_0^*.

One idea used in the proof of Theorem 4 seems worth stating as a separate corollary.

Corollary 12. *Let η be a second order sentence. The statement "there exists a Peano system $\mathbb{A}$ almost isomorphic but not isomorphic to $\langle\mathbb{N},S,0\rangle$ such that $\mathbb{A}\models\eta$" is Σ^1_1 over* RCA_0^*.

Proof. By Lemma 7, a Peano system satisfying η and almost isomorphic but not isomorphic to $\mathbb{N}$ exists exactly if there is a proper Σ^0_1-definable cut satisfying η. This can be expressed by a sentence identical to the first-order sentence η^{FO} from the proof of Theorem 4 except for an additional existential second-order quantifier to account for the possible set parameters in the formula defining the cut. □

Theorem 4 also has the consequence that if we restrict our attention to Π^1_1-conservative extensions of RCA_0^*, then the characterization from Theorem 3 is not only the "truest possible", but also the "simplest possible" provably categorical characterization of $\mathbb{N}$.

Corollary 13. *Let T be a Π^1_1-conservative extension of RCA^*_0. Assume that the second-order sentence η is a categorical characterization of $\langle \mathbb{N}, S, 0\rangle$ provably in T. Then*

(a) η is not Π^1_2,

(b) T is not Π^1_2-axiomatizable.

Proof. We first prove (b). Assume that T is Π^1_2-axiomatizable and Π^1_1-conservative over RCA^*_0. As observed in [Yok09], this means that $T + \mathsf{WKL}^*_0$ is Π^1_1-conservative over RCA^*_0, so T is consistent with $\mathsf{WKL}^*_0 + \text{superexp}$. Hence, Theorem 4 implies that there can be no provably categorical characterization of $\mathbb{N}$ in T.

Turning now to part (a), assume that η is Π^1_2. Since T is Π^1_1-conservative over RCA^*_0 and proves that $\mathbb{N} \models \eta$, then $\mathsf{RCA}^*_0 + \eta$ must also be Π^1_1-conservative over RCA^*_0. But then, by a similar argument as above, η is consistent with $\mathsf{WKL}^*_0 +$ superexp, which contradicts Theorem 4. □

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