

# Computability-Theoretic Properties of Injection Structures

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## Abstract

We study computability-theoretic properties of computable injection structures and the complexity of isomorphisms between these structures. We prove that a computable injection structure is computably categorical if and only if it has finitely many infinite orbits. We also prove that a computable injection structure is  $\Delta_2^0$ -categorical if and only if it has finitely many orbits of type  $\omega$  or finitely many orbits of type  $Z$ . Furthermore, every computably categorical injection structure is relatively computably categorical, and every  $\Delta_2^0$ -categorical injection structure is relatively  $\Delta_2^0$ -categorical. We investigate analogues of these results for  $\Sigma_1^0$ ,  $\Pi_1^0$ , and  $n$ -c.e. injection structures.

We study the complexity of the set of elements with orbits of a given type in computable injection structures. For example, we show that for every c.e. Turing degree  $\mathbf{b}$ , there is a computable injection structure  $\mathcal{A}$  in which the set of all elements with finite orbits has degree  $\mathbf{b}$  and, for every  $\Sigma_2^0$  Turing degree  $\mathbf{c}$ , there is a computable injection structure  $\mathcal{B}$  in which the set of elements with orbits of type  $\omega$  has degree  $\mathbf{c}$ . We also have various index set results for infinite computable injection structures. For example, we show that the index set of infinite computably categorical injection structures is a  $\Sigma_3^0$ -complete set and that the index set of infinite  $\Delta_2^0$ -categorical injection structures is a  $\Sigma_4^0$ -complete set.

We also explore the connection between the complexity of the character and the first-order theory of a computable injection structure. We show that for an injection structure with a computable character, there is a decidable structure isomorphic to it. However, there are computably categorical injection structures with undecidable theories.

**Keywords:** computability theory, injections, permutations, effective categoricity, computable model theory

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## 1 Introduction

Computable algebra uses the tools of computability theory to explore effectiveness of notions and constructions in algebra. We are interested in the complexity of isomorphisms between a computable structure and its isomorphic copies. The main notion in this area of investigation is that of computable categoricity. This concept has been part of computable algebra since 1956 when Fröhlich and Shepherdson produced examples of computable fields that are isomorphic but not computably isomorphic. That is, these fields are not computably categorical. Here we investigate computable and higher level categoricity of computable injection structures. Let us first recall some basic definitions.

Let  $\mathbb{N} = \{0, 1, 2, \dots\}$  denote the natural numbers and  $\mathbb{Z} = \{0, \pm 1, \pm 2, \dots\}$  denote the integers. We let  $\omega$  denote the order type of  $\mathbb{N}$  under the usual ordering, and  $Z$  denote the order type of  $\mathbb{Z}$  under the usual ordering. In this paper, we restrict our attention to countable structures for computable languages. Hence, if a structure is infinite, we can assume that its universe is  $\mathbb{N}$ . If  $\mathcal{A}$  is a structure with universe  $A$  for a language  $\mathcal{L}$ , then  $\mathcal{L}^A$  is the language obtained by expanding  $\mathcal{L}$  by constants for all elements of  $A$ . The *atomic diagram* of  $\mathcal{A}$  is the set of all atomic sentences and negations of atomic sentences from  $\mathcal{L}^A$ , which are true in  $\mathcal{A}$ . The *elementary diagram* of  $\mathcal{A}$  is the set of all first-order sentences of  $\mathcal{L}^A$ , which are true in  $\mathcal{A}$ . A structure is *computable* if its atomic diagram is computable, and a structure is *decidable* if its elementary diagram is computable.

We call two structures *computably isomorphic* if there is a computable function that is an isomorphism between them. A computable structure  $\mathcal{A}$  is *relatively computably isomorphic* to a (possibly noncomputable) structure  $\mathcal{B}$  if there is an isomorphism between them which is computable in the atomic diagram of  $\mathcal{B}$ . A computable structure  $\mathcal{A}$  is called *computably categorical* if every computable structure that is isomorphic to  $\mathcal{A}$  is computably isomorphic to  $\mathcal{A}$ . A computable structure  $\mathcal{A}$  is called *relatively computably categorical* if  $\mathcal{A}$  is relatively computably isomorphic to every structure that is isomorphic to  $\mathcal{A}$ . Similar definitions arise for other naturally definable classes of structures and their isomorphisms. For example, for any  $n \in \mathbb{N}$ , a structure is  $\Delta_n^0$  if its atomic diagram is  $\Delta_n^0$ , two  $\Delta_n^0$  structures are  $\Delta_n^0$ -isomorphic if there is a  $\Delta_n^0$  isomorphism between them, and a computable structure  $\mathcal{A}$  is  $\Delta_n^0$ -categorical if every computable structure isomorphic to  $\mathcal{A}$  is  $\Delta_n^0$ -isomorphic to  $\mathcal{A}$ .

For a Turing degree  $\mathbf{d}$ , a computable structure  $\mathcal{A}$  is called  $\mathbf{d}$ -computably categorical if for every computable structure  $\mathcal{B}$  isomorphic to  $\mathcal{A}$ , there exists a  $\mathbf{d}$ -computable isomorphism from  $\mathcal{B}$  onto  $\mathcal{A}$ . Hence, for example,  $\mathbf{0}$ -computably categorical structures are the same as computably categorical ones. In [8], Fokina, Kalimullin, and Miller introduced and first studied  $\mathbf{d}$ -computable categoricity. They defined the *degree of categoricity* of a computable structure  $\mathcal{A}$ , if it exists, to be the least Turing degree  $\mathbf{d}$  for which  $\mathcal{A}$  is  $\mathbf{d}$ -computably categorical. Since there are only countably many computable structures, most Turing degrees are not degrees of categoricity. Fokina, Kalimullin, and Miller investigated which Turing degrees can be the degrees of categoricity. Their investigation was

further extended by Csima, Franklin, and Shore in [6]. In [10], Miller studied  $\mathbf{d}$ -computable categoricity for computable algebraic fields.

Among the simplest nontrivial structures are equivalence structures, that is, structures of the form  $\mathcal{A} = (A, E)$ , where  $E$  is an equivalence relation on  $A$ . The complexity of isomorphisms between computable equivalence structures was recently studied by Calvert, Cenzer, Harizanov, and Morozov in [2] where they characterized computably categorical equivalence structures and also relatively  $\Delta_2^0$ -categorical equivalence structures. Cenzer, LaForte, and Rimmel [4] extended this work by investigating equivalence structures in the Ershov hierarchy. More recently, Cenzer, Harizanov, and Rimmel [3] studied  $\Sigma_1^0$  and  $\Pi_1^0$  equivalence structures.

For any equivalence structure  $\mathcal{A}$ , we let  $Fin(\mathcal{A})$  denote the set of elements of  $\mathcal{A}$  that belong to finite equivalence classes. For equivalence structures, it is natural to consider different sizes of the equivalence classes of the elements in  $Fin(\mathcal{A})$  since such sizes code information into the equivalence relation. The *character* of an equivalence structure  $\mathcal{A}$  is a subset of  $(\mathbb{N} - \{0\}) \times (\mathbb{N} - \{0\})$  defined by:

$$\chi(\mathcal{A}) = \{(k, n) : n, k > 0 \text{ and } \mathcal{A} \text{ has at least } n \text{ equivalence classes of size } k\}.$$

This set provides a kind of skeleton for  $Fin(\mathcal{A})$ . Any set  $K \subseteq (\mathbb{N} - \{0\}) \times (\mathbb{N} - \{0\})$  such that for all  $n > 0$  and  $k$ ,  $(k, n + 1) \in K$  implies  $(k, n) \in K$ , is simply called a *character*. We say that a character  $K$  is *bounded* if there is some finite  $k_0$  such that for all  $(k, n) \in K$ , we have  $k < k_0$ .

Khisamiev [9] introduced the concepts of an  $s$ -function and an  $s_1$ -function in his work on Abelian  $p$ -groups with computable isomorphic copies. In their book [1], Ash and Knight investigated equivalence structures in the context of Khisamiev's results.

**Definition 1.1.** *Let  $f : \mathbb{N}^2 \rightarrow \mathbb{N}$ . The function  $f$  is an  $s$ -function if*

1. *for every  $i, s \in \mathbb{N}$ ,  $f(i, s) \leq f(i, s + 1)$ , and*
2. *for every  $i \in \mathbb{N}$ , the limit  $m_i = \lim_{s \rightarrow \infty} f(i, s)$  exists.*

*We say that  $f$  is an  $s_1$ -function if, in addition,*

3. *for every  $i \in \mathbb{N}$ ,  $m_i < m_{i+1}$ .*

Calvert, Cenzer, Harizanov, and Morozov [2] gave conditions under which a given character  $K$  can be the character of a computable equivalence structure. In particular, they observed that if  $K$  is a bounded character and  $\alpha \leq \omega$ , then there is a computable equivalence structure with character  $K$  and exactly  $\alpha$  infinite equivalence classes. To prove the existence of computable equivalence structures for unbounded characters  $K$ , they needed additional information given by  $s$ -functions and  $s_1$ -functions. They showed that if  $K$  is a  $\Sigma_2^0$  character,  $r \in \mathbb{N}$ , and either

- (a) there is an  $s$ -function  $f$  such that

$$(k, n) \in K \Leftrightarrow \text{card}(\{i : k = \lim_{s \rightarrow \infty} f(i, s)\}) \geq n, \text{ or}$$

(b) there is an  $s_1$ -function  $f$  such that for every  $i \in \mathbb{N}$ ,  $(\lim_{s \rightarrow \infty} f(i, s), 1) \in K$ , then there is a computable equivalence structure with character  $K$  and exactly  $r$  infinite equivalence classes.

In this paper, we study injection structures. Here, an injection is, as usual, a one-to-one function, and an *injection structure*  $\mathcal{A} = (A, f)$  consists of a set  $A$  and an injection  $f : A \rightarrow A$ . The structure  $\mathcal{A}$  is a *permutation structure* if  $f$  is a permutation of  $A$ . Given  $a \in A$ , the *orbit of  $a$  under  $f$*  is

$$\mathcal{O}_f(a) = \{b \in A : (\exists n \in \mathbb{N})[f^n(a) = b \vee f^n(b) = a]\}.$$

Clearly, the isomorphism type of a permutation structure  $\mathcal{A}$  is determined by the number of orbits of size  $k$  for  $k = 1, 2, \dots, \omega$ . By analogy with characters of equivalence structures, we define the *character*  $\chi(\mathcal{A})$  of an injection structure  $\mathcal{A}$  as

$$\chi(\mathcal{A}) = \{(k, n) \in (\mathbb{N} - \{0\}) \times (\mathbb{N} - \{0\}) : \mathcal{A} \text{ has at least } n \text{ orbits of size } k\}.$$

We let  $\text{Ran}(f)$  denote the range of  $f$ .

An injection structure  $(A, f)$  may have two types of infinite orbits:  $Z$ -orbits, which are isomorphic to  $(\mathbb{Z}, S)$  and in which every element is in  $\text{Ran}(f)$ , and  $\omega$ -orbits, which are isomorphic to  $(\omega, S)$  and have the form  $\mathcal{O}_f(a) = \{f^n(a) : n \in \mathbb{N}\}$  for some  $a \notin \text{Ran}(f)$ . Thus, injection structures are characterized by the number of orbits of size  $k$  for each finite  $k$  and by the number of orbits of types  $Z$  and  $\omega$ . We will examine the complexity of the set of elements with orbits of a given type in an injection structure  $\mathcal{A} = (A, f)$ . In particular, we will study the complexity of  $\text{Fin}(\mathcal{A}) = \{a : \mathcal{O}_f(a) \text{ is finite}\}$ . It is clear from the definitions above that any computable injection structure  $(A, f)$  will induce a  $\Sigma_1^0$  equivalence structure  $(A, E)$  in which the equivalence classes are simply the orbits of  $(A, f)$ .

The outline of this paper is as follows. In Section 2, we investigate algorithmic properties of computable injection structures and their characters, characterize computably categorical injection structures, and show that all computably categorical injection structures are relatively computably categorical. More specifically, we prove that a computable injection structure  $\mathcal{A}$  is computably categorical if and only if it has finitely many infinite orbits. In Section 3, we characterize  $\Delta_2^0$ -categorical injection structures as those with finitely many orbits of type  $\omega$  or with finitely many orbits of type  $Z$ . We show that they coincide with the relatively  $\Delta_2^0$ -categorical structures. Finally, we prove that every computable injection structure is relatively  $\Delta_3^0$ -categorical.

In Section 4, we consider the *spectrum question*, which is to determine the possible sets (or degrees of sets) that can be the set  $\text{Fin}(\mathcal{A})$  for some computable injection structure  $\mathcal{A}$  of a given isomorphism type. For example, we show that for any c.e. degree  $\mathbf{b}$ , there is a computable injection structure  $\mathcal{A}$  such that  $\text{Fin}(\mathcal{A})$  has degree  $\mathbf{b}$ . In Section 5, we study the complexity of the theory  $\text{Th}(\mathcal{A})$  of a computable injection structure  $\mathcal{A}$ , as well as the complexity of its elementary diagram  $\text{FTh}(\mathcal{A})$ . We prove that the character  $\chi(\mathcal{A})$  and the theory  $\text{Th}(\mathcal{A})$  have the same Turing degree. We also show that there is a computably

categorical injection structure the theory of which is not decidable. In Section 6, we study index sets for infinite computable injection structures. That is, let  $\phi_e$  denote the  $e$ th partial computable function and let  $\mathcal{A}_e = (\mathbb{N}, \phi_e)$ . For any property  $\mathcal{P}$  of injection structures, we let

$$\text{Inj}(\mathcal{P}) = \{e : \mathcal{A}_e \text{ has property } \mathcal{P}\}.$$

Then let  $\mathcal{P}_{cc}$  be the property of being a (computable) computably categorical injection structure, and  $\mathcal{P}_{\Delta_2^0 c}$  be the property of being a (computable)  $\Delta_2^0$ -categorical injection structure. We show that  $\text{Inj}(\mathcal{P}_{cc})$  is  $\Sigma_3^0$ -complete and  $\text{Inj}(\mathcal{P}_{\Delta_2^0 c})$  is  $\Sigma_4^0$ -complete. We also establish that for infinite computable injection structures, the isomorphism problem is  $\Pi_4^0$ -complete, while the computable isomorphism problem is  $\Sigma_3^0$ -complete.

In Section 7, we consider  $\Sigma_1^0$  injection structures, that is, the injection structures  $\mathcal{A} = (A, f)$  where  $A$  is an infinite  $\Sigma_1^0$  set and  $f$  is the restriction of a partial computable function to  $A$ . We show that every  $\Sigma_1^0$  injection structure is computably isomorphic to a computable injection structure. Hence if two  $\Sigma_1^0$  injection structures are isomorphic, then they are isomorphic via a  $\Delta_3^0$  isomorphism. In Section 8, we consider  $\Pi_1^0$  injection structures, that is, the injection structures  $\mathcal{A} = (A, f)$  where  $A$  is an infinite  $\Pi_1^0$  set and  $f$  is the restriction of a partial computable function to  $A$ . We show that there are  $\Pi_1^0$  injection structures that have arbitrary non-trivial  $\Sigma_2^0$  characters. Hence there are  $\Pi_1^0$  injection structures which are not isomorphic to any computable injection structure. In Section 9, we consider  $n$ -c.e. injection structures. We prove that for any  $n$ -c.e. injection structure  $\mathcal{A}$ , there exist a  $\Pi_1^0$  structure  $\mathcal{B}$  and a computable injection that maps  $\mathcal{B}$  onto  $\mathcal{A}$ . The notions and notation of computability theory are standard and as in Soare [11]. For more background on computable model theory and categoricity see Ash and Knight [1] and Ershov and Goncharov [7].

## 2 Computably Categorical Structures

In this section, we first show that the characters of computable injection structures are exactly the c.e. characters. We then characterize computably categorical injection structures and show that they coincide with relatively computably categorical injection structures.

**Lemma 2.1.** *For every computable injection structure  $\mathcal{A} = (A, f)$ :*

- (a)  $\{(k, a) : a \in \text{Ran}(f^k)\}$  is a  $\Sigma_1^0$  set,
- (b)  $\{(a, k) : \text{card}(\mathcal{O}_f(a)) \geq k\}$  is a  $\Sigma_1^0$  set,
- (c)  $\{a : \mathcal{O}_f(a) \text{ is infinite}\}$  is a  $\Pi_1^0$  set,
- (d)  $\{a : \mathcal{O}_f(a) \text{ has type } Z\}$  is a  $\Pi_2^0$  set,
- (e)  $\{a : \mathcal{O}_f(a) \text{ has type } \omega\}$  is a  $\Sigma_2^0$  set, and

(f)  $\chi(\mathcal{A})$  is a  $\Sigma_1^0$  set.

*Proof.* Parts (a) and (b) are straightforward.

(c)  $\mathcal{O}_f(a)$  is infinite if and only if  $(\forall n)[f^n(a) \neq a]$ .

(d)  $\mathcal{O}_f(a)$  has type  $Z$  if and only if  $\mathcal{O}_f(a)$  is infinite and  $(\forall n)(\exists b)[f^n(b) = a]$ .

(e)  $\mathcal{O}_f(a)$  has type  $\omega$  if and only if  $\mathcal{O}_f(a)$  is infinite and not of type  $Z$ .

(f) First notice that  $\text{card}(\mathcal{O}_f(a)) = k$  if and only if  $f^k(a) = a$  and  $(\forall i < k)[f^i(a) \neq a]$ . Hence the property that  $\text{card}(\mathcal{O}_f(a)) = k$  is computable.

Then  $(k, n) \in \chi(\mathcal{A})$  if and only if

$$(\exists x_1) \cdots (\exists x_n) \left( \bigwedge_{i=1}^n \text{card}(\mathcal{O}_f(x_i)) = k \wedge \bigwedge_{i \neq j} (\forall t < k)[f^t(x_i) \neq x_j] \right)$$

□

**Proposition 2.2.** *For any  $\Sigma_1^0$  character  $K$ , there is a computable injection structure  $\mathcal{A} = (A, f)$  with character  $K$  and with any specified finite or countably infinite number of orbits of types  $\omega$  and  $Z$ . Furthermore,  $\text{Fin}(\mathcal{A})$  is computable and  $\text{Ran}(f)$  is computable.*

*Proof.* First we build  $(A, f)$  with character  $K$  and no infinite orbits. If  $K$  is finite, this is trivial. If  $K$  is infinite, let  $(k_0, n_0), (k_1, n_1), \dots$  be a computable enumeration of  $K$  without repetition. For each  $i > 0$ , let  $s_i = k_0 + k_1 + \dots + k_{i-1}$ . Let  $s_0 = 0$ . Define  $f$  to have orbits  $\mathcal{O}_f(s_i) = \{s_i, s_i + 1, \dots, s_i + k_i - 1\}$ . Given  $a \in \mathbb{N}$ , let  $i$  be the least such that  $s_i \leq a < s_{i+1}$ . Then  $f(a) = a + 1$  if  $a < s_{i+1} - 1$  and  $f(s_{i+1} - 1) = s_i$ .

For any  $m \leq \omega$  and  $n \leq \omega$ , we can easily create a computable injection structure consisting of exactly  $m$  orbits of type  $\omega$  and  $n$  orbits of type  $Z$ . For example, to have  $\omega$  orbits of type  $\omega$  and 3 orbits of type  $Z$ , let the orbits of type  $Z$  be  $\{0, 1, 2, 4, \dots\}$ ,  $\{3, 6, 12, \dots\}$  and  $\{5, 10, 20, \dots\}$ , and let the orbits of type  $\omega$  have the form  $\{2a + 7, 4a + 14, 8a + 28, \dots\}$  for  $a \in \mathbb{N}$ . In the orbits of type  $\omega$ , let  $f(x) = 2x$ . In the orbit of 0, let  $f(0) = 1$ ,  $f(2) = 0$  and for each  $i$ , let  $f(2^{2i}) = 2^{2i+2}$  and  $f(2^{2i+3}) = 2^{2i+1}$ . For the other two orbits of type  $Z$ , let  $f(a \cdot 2^{2i}) = a \cdot 2^{2i+2}$  and  $f(a \cdot 2^{2i+3}) = 2^{2i+1}$ .

If  $K$  is infinite, then let  $\mathcal{A} = (A, f)$  have character  $K$  and no infinite orbits, let  $\mathcal{B} = (B, g)$  have the desired number of infinite orbits, and define the disjoint union  $\mathcal{A} \oplus \mathcal{B}$  in the natural way by mapping  $A$  to the even numbers and  $B$  to the odd numbers. If  $K$  is finite of cardinality  $c$ , we may assume that  $(A, f)$  has universe  $\{0, 1, \dots, c - 1\}$ , and then build a copy of  $(B, g)$  to have universe  $\{c, c + 1, \dots\}$  by mapping  $b$  to  $b + c$ . It is easy to construct  $\mathcal{B}$  so that the range of  $f$  is computable. The only difficult case is when  $\mathcal{B}$  has infinitely many orbits of type  $\omega$ . For example, if there are no other orbits, then we can take a standard model such as  $f(x) = 2x$  with universe  $\mathbb{N} - \{0\}$ . □

Proposition 2.2 shows that injection structures are simpler than equivalence structures in an important way. The characters are simpler, i.e., they are  $\Sigma_1^0$

rather than  $\Sigma_2^0$ , and there is no distinction between characters that have or do not have  $s_1$ -functions.

**Theorem 2.3.** *If  $\mathcal{A} = (\mathbb{N}, f)$  is a computable injection structure with finitely many infinite orbits, then  $\mathcal{A}$  is relatively computably categorical.*

*Proof.* Assume that  $\mathcal{A}$  has  $m$  orbits of type  $\omega$  and  $n$  orbits of type  $Z$ , where  $m, n \in \mathbb{N}$ . Let  $a_1, \dots, a_m$  be elements of the  $m$  orbits of type  $\omega$ , each not in  $\text{Ran}(f)$ . Let  $b_1, \dots, b_n$  be representatives of the  $n$  orbits of type  $Z$ . A Scott formula for a finite sequence  $c_0, \dots, c_r$  of elements distinct from  $a_1, \dots, a_m, b_1, \dots, b_n$  is a conjunction of  $\Delta_1^0$  formulas of the following kinds. First, for each  $t \leq r$ , we have either

- (1)  $f^k(c_t) = c_t$  for some minimal  $k$ , or
- (2)  $f^k(a_i) = c_t$  for some unique  $i$  and  $k$ , or
- (3)  $f^k(b_i) = c_t$  for some unique  $i$  and  $k$ , or
- (4)  $f^k(c_t) = b_i$  for some unique  $i$  and  $k$ .

Nothing more needs to be said about the elements  $c_t$  which fall into cases (2), (3) or (4). For two elements  $c_s$  and  $c_t$  which fall into case (1) with the same value of  $k$ , we need to add either

- (5)  $f^j(c_s) = c_t$  for some unique  $j < k$ , or
- (6)  $(\forall j < k)[f^j(c_s) \neq c_t]$ .

If two finite sequences satisfy the same Scott formula as defined above, then it is clear that there exists an automorphism of  $\mathcal{A}$  mapping one sequence to the other, while preserving the infinite orbits.  $\square$

Our next result will show that these are the only computably categorical injection structures.

**Theorem 2.4.** *If a computable injection structure  $\mathcal{A}$  has infinitely many infinite orbits, then it is not computably categorical.*

*Proof.* First, consider the cases where either  $\mathcal{A}$  consists of an infinite number of orbits of type  $\omega$  and no orbits of type  $Z$ , or  $\mathcal{A}$  consists of an infinite number of orbits of type  $Z$  and no orbits of type  $\omega$ .

Suppose first that  $\mathcal{A} = (\mathbb{N} - \{0\}, f)$  consists of infinitely many orbits of type  $\omega$ , where  $f((2i+1)2^n) = (2i+1)2^{n+1}$  for each  $i \geq 0$  and  $n \geq 0$ . Thus,  $\text{Ran}(f)$  is a computable set. Now we build a computable structure  $\mathcal{B} = (\mathbb{N} - \{0\}, g)$  isomorphic to  $\mathcal{A}$  such that  $\text{Ran}(g)$  is not computable, so that  $\mathcal{A}$  cannot be computably isomorphic to  $\mathcal{B}$ .

Let  $C$  be a noncomputable c.e. set that does not contain 0 or 1. Let  $C = \bigcup_s C_s$ , where  $\{C_s : s \in \mathbb{N}\}$  is a computable sequence of finite sets such that  $C_s \subseteq \{2, \dots, s-1\}$  and  $\text{card}(C_{s+1} - C_s) \leq 1$  for all  $s$ . The injection  $g$  is defined in stages. At stage  $s$ , we define a finite partial function  $g_s$  such that:

- (i) if  $i \in \{1, \dots, s\} - C_s$ , then  $g_s((2i+1)2^n) = (2i+1)2^{n+1}$  for  $0 \leq i \leq s$ ,

- (ii) if  $i \in C_s$ , then  $(2i + 1)$  will be in the orbit of 1 under  $g_s$ , and
- (iii)  $\{(2i + 1)2^n : i, n \leq s\} \subseteq \text{Dom}(g_s)$ .

Initially, we have  $g_0(1) = 2$ . Now assume that at stage  $s$ , we have defined  $g_s$  so that it satisfies (i)–(iii). Then at stage  $s + 1$ , we first extend  $g_s$  as follows. If  $i \in \{1, \dots, s + 1\} - C_{s+1}$ , let  $g_{s+1}((2i + 1)2^n) = (2i + 1)2^{n+1}$  for  $0 \leq i \leq s + 1$ . Next, add elements to the end of the current orbit of 1 if necessary so that we ensure that  $\{(2i + 1)2^n : i, n \leq s + 1\} \subseteq \text{Dom}(g_{s+1})$ . Finally, if  $i \in C_{s+1} - C_s$ , then let  $m$  be the unique element of the current orbit of 1 for which  $g_{s+1}(m)$  is not defined, and let  $g_{s+1}(m) = 2i + 1$ . This has the effect of adding the current orbit of  $2i + 1$  at the end of the current orbit of 1. It is clear that if  $g = \bigcup_{s \geq 0} g_s$ , then  $(\mathbb{N} - \{0\}, g)$  is a computable injection structure isomorphic to  $\mathcal{A}$  and that  $(\mathbb{N} - \{0, 1\}) - \text{Ran}(g) = \{2i + 1 : i \notin C\}$ . Thus,  $\mathcal{B} = (\mathbb{N} - \{0\}, g)$  is not computably isomorphic to  $\mathcal{A}$ .

Next, suppose that  $\mathcal{A} = (\mathbb{N} - \{0\}, f)$  consists of infinitely many orbits of type  $Z$ , where every orbit of type  $Z$  is computable. We shall build a structure  $\mathcal{B} = (\mathbb{N} - \{0\}, g)$  in which the orbit of 1 is not computable. The construction is similar to that given above with several modifications. First, to make the orbits have type  $Z$ , we extend the orbits at stage  $s + 1$  to the right when  $s$  is even and to the left when  $s$  is odd. Second, when  $i$  appears in  $C_{s+1} - C_s$ , we append the orbit of  $2i + 1$  to the orbit of 1. In this way, we have  $i \in C$  if and only if  $2i + 1 \in \mathcal{O}_g(1)$ , so that  $\mathcal{O}_g(1)$  is not computable.

Now, let  $\mathcal{A} = (\mathbb{N} - \{0\}, f)$  be a computable injection structure with infinitely many infinite orbits. Suppose first that  $\mathcal{A}$  has infinitely many orbits of type  $\omega$  and that  $\text{Ran}(f)$  is computable. Let  $\mathcal{A}_0$  be the restriction of  $\mathcal{A}$  to the orbits of type  $\omega$ , and let  $\mathcal{B}_0$  be a computable structure isomorphic to  $\mathcal{A}_0$ , but not computably isomorphic to  $\mathcal{A}_0$ , as above. By Proposition 2.2, there is a computable injection structure  $\mathcal{C}$  with  $\chi(\mathcal{C}) = \chi(\mathcal{A})$  and such that  $\mathcal{C}$  has the same number of orbits of type  $Z$  as  $\mathcal{A}$ . Let  $\mathcal{B} = \mathcal{B}_0 \oplus \mathcal{C}$ . Then  $\mathcal{B}$  is a computable injection structure that is isomorphic to  $\mathcal{A}$ , but is not computably isomorphic to  $\mathcal{A}$ , since any isomorphism would have to map  $\mathcal{A}_0$  to  $\mathcal{B}_0$ . Note that in  $\mathcal{B}_0 \oplus \mathcal{C}$  the element 1 in  $\mathcal{B}_0$  gets mapped to 2. Thus the orbit of 2 in  $\mathcal{B}$  is of type  $\omega$  and is Turing equivalent to  $\mathcal{C}$ . The argument when  $\mathcal{A}$  has infinitely many orbits of type  $Z$  is similar.  $\square$

The following corollary is immediate.

**Corollary 2.5.** *Let  $\mathcal{A}$  be a computable injection structure.*

1. *The structure  $\mathcal{A}$  is computably categorical if and only if  $\mathcal{A}$  is relatively computably categorical.*
2. *The structure  $\mathcal{A}$  is computably categorical if and only if  $\mathcal{A}$  has finitely many infinite orbits.*

We also have the following corollary to the proof of Theorem 2.4.

**Corollary 2.6.** *Let  $\mathbf{d}$  be a c.e. degree.*

1. Let  $\mathcal{A} = (\mathbb{N}, f)$  be a computable injection structure that has infinitely many orbits of type  $\omega$ . Then there is a computable injection structure  $\mathcal{B} = (\mathbb{N}, g)$  isomorphic to  $\mathcal{A}$  in which  $\text{Ran}(g)$  is a c.e. set of degree  $\mathbf{d}$ , there is an  $x \in \mathbb{N}$  such that  $\mathcal{O}_g(x)$  is of type  $\omega$  and is a c.e. set of degree  $\mathbf{d}$ , and for all  $y \in \mathbb{N} - \mathcal{O}_g(x)$ , if  $\mathcal{O}_g(y)$  is of type  $\omega$ , then  $\mathcal{O}_g(y)$  is computable.
2. Let  $\mathcal{A} = (\mathbb{N}, f)$  be a computable injection structure that has infinitely many infinite orbits of type  $Z$ . Then there is a computable injection structure  $\mathcal{B} = (\mathbb{N}, g)$  isomorphic to  $\mathcal{A}$  such that there is an  $x \in \mathbb{N}$  for which  $\mathcal{O}_g(x)$  is of type  $Z$  and is a c.e. set of degree  $\mathbf{d}$ , and for all  $y \in \mathbb{N} - \mathcal{O}_g(x)$ , if  $\mathcal{O}_g(y)$  is of type  $Z$ , then  $\mathcal{O}_g(y)$  is computable.

*Proof.* Parts (1) and (2) are immediate from the proof of Theorem 2.4.  $\square$

### 3 $\Delta_2^0$ -Categorical Structures

**Theorem 3.1.** *Suppose that a computable injection structure  $\mathcal{A}$  does not have infinitely many orbits of type  $\omega$  or does not have infinitely many orbits of type  $Z$ . Then  $\mathcal{A}$  is relatively  $\Delta_2^0$ -categorical.*

*Proof.* Recall from Lemma 2.1 that  $\{a : \mathcal{O}(a) \text{ is infinite}\}$  is a  $\Pi_1^0$  set. Under the assumption of our theorem,  $\{a : \mathcal{O}(a) \text{ has type } \omega\}$  and  $\{a : \mathcal{O}(a) \text{ has type } Z\}$  are  $\Delta_2^0$  sets. Thus, given isomorphic computable structures  $\mathcal{A} = (A, f)$  and  $\mathcal{B} = (B, g)$ , we can use an oracle for  $\mathbf{0}'$  to partition  $A$  and  $B$  into three sets each: the orbits of finite type, the orbits of type  $\omega$ , and the orbits of type  $Z$ .

First suppose that  $\mathcal{A}$  consists of infinitely many orbits of type  $\omega$  and only finitely many orbits of type  $Z$ . We shall construct an isomorphism  $h : A \rightarrow B$ , which is computable in  $\mathbf{0}'$ . Let  $c_1 < \dots < c_t$  be representatives of the orbits of type  $Z$  in  $\mathcal{A}$ , and let  $d_1 < \dots < d_t$  be the representatives of the orbits of type  $Z$  in  $\mathcal{B}$ . Then define  $h(c_i) = d_i$  for  $i = 1, \dots, t$  and extend  $h$  in the obvious way to map the orbits of  $c_1, \dots, c_t$  to the orbits of  $d_1, \dots, d_t$ , respectively. This map will be computable in  $\mathbf{0}'$  since the orbit of each  $c_i$  and  $d_i$  is computable in  $\mathbf{0}'$ .

Next, a simple back-and-forth argument will allow us to show that we can construct an isomorphism from  $(\text{Fin}(\mathcal{A}), f)$  onto  $(\text{Fin}(\mathcal{B}), g)$ , which is computable in  $\mathbf{0}'$ . That is, at any given stage  $s$ , assume that we have defined an isomorphism  $h_s$  on a finite set of orbits of  $(\text{Fin}(\mathcal{A}), f)$  onto a finite set of orbits of  $(\text{Fin}(\mathcal{B}), g)$ . Then let  $a \in \text{Fin}(\mathcal{A})$  be the least element not in  $\text{Dom}(h_s)$ . We can compute its orbit  $\{a, f(a), f^2(a), \dots, f^{n-1}(a)\}$  in  $(\text{Fin}(\mathcal{A}), f)$ . Then search through the elements of  $(\text{Fin}(\mathcal{B}), g)$  until we find  $b$  not in  $\text{Ran}(h_s)$  such that  $b$  has an orbit of size  $n$ , and define  $h_{s+1}(f^i(a)) = g^i(b)$  for  $i = 0, 1, \dots, n-1$ . Next, let  $d$  be the least element of  $\text{Fin}(\mathcal{B})$ , which is not in  $\text{Ran}(h_s)$  and not in the orbit of  $b$ . We can compute the orbit of  $d$ ,  $\{d, g(d), g^2(d), \dots, g^{m-1}(d)\}$ , in  $(\text{Fin}(\mathcal{B}), g)$ . Then we search for  $c$  in  $\text{Fin}(\mathcal{A})$  such that  $c$  is not in  $\text{Dom}(h_s)$  nor in the orbit of  $a$ , and has an orbit of size  $m$ . Then we set  $h_{s+1}(f^i(c)) = g^i(d)$  for  $i = 0, 1, \dots, m-1$ . Since  $\text{Fin}(\mathcal{A})$  and  $\text{Fin}(\mathcal{B})$  are c.e. sets, it follows that  $h$  restricted to  $\text{Fin}(\mathcal{A})$  is computable in  $\mathbf{0}'$ .

Let  $A_\omega$  and  $B_\omega$  denote the sets of elements that are in orbits of type  $\omega$  in  $\mathcal{A}$  and  $\mathcal{B}$ , respectively. It is easy to see that  $A - A_\omega$  and  $B - B_\omega$  are c.e. sets. Since  $\text{Ran}(f)$  and  $\text{Ran}(g)$  are c.e. sets, we can use an oracle for  $\mathbf{O}'$  to compute a list  $a_0, a_1, \dots$  of  $A_\omega - \text{Ran}(f)$ , and similarly a list  $b_0, b_1, \dots$  of  $B_\omega - \text{Ran}(g)$ . Then we extend the isomorphism  $h$  by mapping  $A_\omega$  to  $B_\omega$  as follows. Given  $a \in A_\omega$ , compute the unique  $i$  and  $n$  such that  $a = f^n(a_i)$ , and let  $h(a) = g^n(b_i)$ .

Next, suppose that  $\mathcal{A}$  consists of infinitely many orbits of type  $Z$  and only finitely many orbits of type  $\omega$ . Then, again, we shall construct an isomorphism  $h : A \rightarrow B$  that is computable in  $\mathbf{O}'$ . Let  $c_1 < \dots < c_t$  be the first elements of the orbits of type  $\omega$  in  $\mathcal{A}$ , and let  $d_1 < \dots < d_t$  be the first elements of the orbits of type  $\omega$  in  $\mathcal{B}$ . Then define  $h(c_i) = d_i$  for  $i = 1, \dots, t$ , and extend  $h$  in the obvious way to map the orbits of  $c_1, \dots, c_t$  to the orbits of  $d_1, \dots, d_t$ , respectively. This function will be computable in  $\mathbf{O}'$  since  $A - \text{Ran}(f)$  and  $B - \text{Ran}(g)$  are computable in  $\mathbf{O}'$ . Then we can use the back-and-forth argument to define an isomorphism  $h$  from  $\text{Fin}(\mathcal{A})$  onto  $\text{Fin}(\mathcal{B})$ , computable in  $\mathbf{O}'$ .

Let  $A_Z$  and  $B_Z$  be the sets of elements that lie in the orbits of type  $Z$  in  $\mathcal{A}$  and  $\mathcal{B}$ , respectively. In this case, it is easy to see that  $A - A_Z$  and  $B - B_Z$  are c.e. sets. Since the orbit of any element in  $\mathcal{A}$  or  $\mathcal{B}$  is computable in  $\mathbf{O}'$ , it follows that we can use an oracle for  $\mathbf{O}'$  to compute a list  $a_0, a_1, \dots$  of representatives for the orbits. That is, observe that  $\{(x, y) : \mathcal{O}(x) = \mathcal{O}(y)\}$  is a c.e. set. Let  $a_0$  be the least element in  $A_Z$ , and for each  $i$ , let  $a_{i+1}$  be the least  $a \in A_Z$  that is not in the same orbit as any of  $a_0, \dots, a_i$ . Similarly, we can compute a list  $b_0, b_1, \dots$  of representatives for the orbits of  $B_Z$ . Then an isomorphism  $h$  can be defined on  $A_Z$  as follows. Given  $a \in A_Z$ , compute the unique  $i$  and  $n$  such that either  $a = f^n(a_i)$  or  $a_i = f^n(a)$ . In the first instance, let  $h(a) = g^n(b_i)$ , and in the second instance, let  $h(a) = b$  for the unique  $b$  such that  $g^n(b) = b_i$ .

In each case, if  $\mathcal{B}$  is not computable, we can nevertheless use an oracle for  $(\text{deg}(\mathcal{B}))'$  to compute the isomorphisms described above. Hence  $\mathcal{A}$  is, in fact, relatively  $\Delta_2^0$ -categorical.  $\square$

**Theorem 3.2.** *Suppose that a computable injection structure  $\mathcal{A}$  has infinitely many orbits of type  $\omega$  and infinitely many orbits of type  $Z$ . Then  $\mathcal{A}$  is not  $\Delta_2^0$ -categorical.*

*Proof.* Clearly, it suffices to consider only the case when  $\mathcal{A}$  has no finite orbits. Let  $\mathcal{A} = (A, f)$  be an injection structure in which the union of the orbits of type  $\omega$  is a computable subset of  $A$ . We will construct a computable injection structure  $\mathcal{B} = (\mathbb{N} - \{0\}, g)$ , which is isomorphic to  $\mathcal{A}$ , but in which the union of orbits of type  $\omega$  is a  $\Sigma_2^0$  set that is not  $\Delta_2^0$ , so that  $\mathcal{A}$  and  $\mathcal{B}$  cannot be  $\Delta_2^0$ -isomorphic.

It is well-known that  $\text{Fin} = \{e : W_e \text{ is finite}\}$  is a  $\Sigma_2^0$ -complete set (see [11]). Thus, for any  $\Sigma_2^0$  set  $C$ , there is a computable function  $F : \mathbb{N} \times \mathbb{N} \rightarrow \{0, 1\}$  such that for all  $i$ ,

$$i \in C \Leftrightarrow (\{s : F(i, s) = 1\} \text{ is finite}).$$

Fix an arbitrary  $\Sigma_2^0$  set  $C$  and a corresponding  $F$ . We will define  $g$  such that

$$i \in C \Leftrightarrow (\mathcal{O}_g(2i+1) \text{ has type } \omega).$$

The orbits of  $\mathcal{B} = (B, g)$  will be exactly  $\{\mathcal{O}_g(2i+1) : i \in \mathbb{N}\}$ .

Initially, we have  $g_0(1) = 2$ . After stage  $s$ , the function  $g_s$  will have orbits  $\mathcal{O}_{g_s}(2i+1) = \{(2i+1)2^n : n \leq 2s+2\}$  for  $i \leq s$ . At stage  $s+1$ , we first extend each orbit of  $g_s$  as follows. Fix  $i \leq s$ . Let  $a$  be the unique element of  $\mathcal{O}(2i+1)$  not in  $\text{Ran}(g_s)$ , and let  $b$  be the unique element of  $\mathcal{O}(2i+1)$  not in  $\text{Dom}(g_s)$ . In either case, we let  $g_{s+1}(b) = (2i+1)2^{2s+3}$ . If  $F(i, s+1) = 0$ , then  $g_{s+1}((2i+1)2^{2s+3}) = (2i+1)2^{2s+4}$ , and if  $F(i, s+1) = 1$ , then let  $g_{s+1}((2i+1)2^{2s+4}) = a$ . Next, we add a new orbit by letting  $g((2s+3)2^n) = (2s+3)2^{n+1}$  for all  $n \leq 2s+3$ . Let  $g = \bigcup_s g_s$ . If  $i \in C$ , then  $\{s : F(i, s) = 1\}$  is finite, say of cardinality  $m$ . Then, by the construction, there is no element  $b$  such that  $g^{m+1}(b) = 2i+1$ , and hence  $\mathcal{O}(2i+1)$  has type  $\omega$ . If  $i \notin C$ , then  $\{s : F(i, s) = 1\}$  is infinite. Thus, for any  $m$ , there is an element  $b$  such that  $g^{m+1}(b) = 2i+1$ , and hence  $\mathcal{O}(2i+1)$  has type  $Z$ . It is clear that  $(\mathbb{N} - \{0\}, g)$  is a computable injection structure all orbits of which are infinite, and  $\mathcal{O}_g(2i+1)$  is of type  $\omega$  if and only if  $i \in C$ . If  $C$  is not a  $\Delta_2^0$  set, then  $\mathcal{B}$  cannot be  $\Delta_2^0$ -isomorphic to  $\mathcal{A}$ .  $\square$

The following corollary is immediate.

**Corollary 3.3.** *Let  $\mathcal{A}$  be a computable injection structure.*

1. *The structure  $\mathcal{A}$  is  $\Delta_2^0$ -categorical if and only if  $\mathcal{A}$  is relatively  $\Delta_2^0$ -categorical.*
2. *The structure  $\mathcal{A}$  is  $\Delta_2^0$ -categorical if and only if  $\mathcal{A}$  has finitely many orbits of type  $\omega$  or finitely many orbits of type  $Z$ .*

We also have the following corollary to the proof of Theorem 3.2.

**Corollary 3.4.** *For any  $\Sigma_2^0$  set  $C$ , there exists a computable injection structure  $\mathcal{A} = (A, f)$  in which the set of elements with orbits of type  $\omega$  is a  $\Sigma_2^0$  set with Turing degree equal to  $\text{deg}(C)$ .*

The next theorem shows that  $\mathbf{0}'$  is the degree of categoricity of an injection structure.

**Theorem 3.5.** *Let  $\mathcal{M}$  be a computable  $\Delta_2^0$ -categorical injection structure, which is not computably categorical. Then there is a computable injection structure  $\mathcal{A}$  isomorphic to  $\mathcal{M}$  such that the degree of categoricity of  $\mathcal{A}$  is  $\mathbf{0}'$ .*

*Proof.* Let  $K \subseteq (\mathbb{N} - \{0, 1\})$  be a c.e. set such that  $\text{deg}(K) = \mathbf{0}'$ . First, consider the case when  $\mathcal{M}$  has infinitely many orbits of type  $\omega$ . Let  $\mathcal{M}_0$  be the restriction of  $\mathcal{M}$  to the orbits of type  $\omega$ . Let  $\mathcal{A}_0 = (\mathbb{N} - \{0\}, f)$  be isomorphic to  $\mathcal{M}_0$  and such that  $(\mathbb{N} - \{0\}) - \text{Ran}(f) = \{2i+1 : i \in \mathbb{N}\}$ . Then, by the proof of Theorem 2.4, we obtain a computable structure  $\mathcal{B} = (\mathbb{N} - \{0\}, g)$  isomorphic to  $\mathcal{A}_0$ , such that for an isomorphism  $G : \mathcal{A}_0 \rightarrow \mathcal{B}$  we have

$$(\forall i)[i \in K \Leftrightarrow 2i+3 \in \text{Ran}(g) \Leftrightarrow 2i+3 \in G(\text{Ran}(f))].$$

Since  $\text{Ran}(f)$  is a computable set, we have  $K \leq_T G$ , and thus  $\mathbf{0}' \leq \text{deg}(G)$ . Hence the degree of categoricity of  $\mathcal{A}_0$  is  $\mathbf{0}'$ . Let  $\mathcal{C}$  be a computable injection structure with  $\chi(\mathcal{C}) = \chi(\mathcal{M})$  and with the same number of orbits of type  $Z$  as  $\mathcal{M}$ . Let  $\mathcal{A} = \mathcal{A}_0 \oplus \mathcal{C}$ . Then  $\mathcal{A}$  is a computable injection structure isomorphic to  $\mathcal{M}$  such that the degree of categoricity of  $\mathcal{A}$  is  $\mathbf{0}'$ .

Now, assume that  $\mathcal{M}$  has infinitely many orbits of type  $Z$ . Let  $\mathcal{M}_0$  be the restriction of  $\mathcal{M}$  to the orbits of type  $Z$ . Assume that  $\mathcal{A}_0$  is an injection structure isomorphic to  $\mathcal{M}_0$  such that every orbit of  $\mathcal{A}_0$  of type  $Z$  is computable and  $\{2i + 1 : i \in \mathbb{N}\}$  is a set of representatives for the orbits of  $\mathcal{A}_0$ . Then, by the proof of Theorem 2.4, we obtain a computable structure  $\mathcal{B} = (\mathbb{N} - \{0\}, g)$  isomorphic to  $\mathcal{A}_0$ , such that for an isomorphism  $G : \mathcal{A}_0 \rightarrow \mathcal{B}$  we have

$$(\forall i)[i \in K \Leftrightarrow 2i + 1 \in G(\text{Orb}_{\mathcal{A}_0}(a))],$$

where  $G(a) = 1$ . Since  $\text{Orb}_{\mathcal{A}_0}(a)$  is a computable set, we have  $K \leq_T G$ , and thus,  $\mathbf{0}' \leq \text{deg}(G)$ . Hence the degree of categoricity of  $\mathcal{A}_0$  is  $\mathbf{0}'$ . We now continue as in the previous case.  $\square$

**Theorem 3.6.** *Every computable injection structure  $\mathcal{A}$  is relatively  $\Delta_3^0$ -categorical.*

*Proof.* Let  $\mathcal{A}$  be a computable injection structure and let  $\mathcal{B}$  be isomorphic to  $\mathcal{A}$ . It follows from Lemma 2.1 that, using an oracle for  $\mathbf{0}''$ , we can partition  $\mathcal{A}$  into three  $\Delta_3^0$  sets, that is, the orbits of finite type, the orbits of type  $\omega$ , and the orbits of type  $Z$ . Using an oracle for  $(\text{deg}(\mathcal{B}))''$ , we can similarly partition  $\mathcal{B}$ . It then follows from the proofs of Theorems 2.3 and 3.1 that we can compute from  $(\text{deg}(\mathcal{B}))''$  isomorphisms between the three substructures of  $\mathcal{A}$  and  $\mathcal{B}$ .  $\square$

The next theorem shows that  $\mathbf{0}''$  is the degree of categoricity of an injection structure.

**Theorem 3.7.** *Let  $\mathcal{M}$  be a computable injection structure, which is not  $\Delta_2^0$ -categorical. Then there is a computable injection structure  $\mathcal{A}$  isomorphic to  $\mathcal{M}$  such that the degree of categoricity of  $\mathcal{A}$  is  $\mathbf{0}''$ .*

*Proof.* Let  $C \subseteq \mathbb{N}$  be a  $\Sigma_2^0$  set such that  $\text{deg}(C) = \mathbf{0}''$ . Without loss of generality, based on the proof of Theorem 3.5, assume that  $\mathcal{M}$  has no finite orbits. Then  $\mathcal{M}$  has infinitely many orbits of type  $\omega$ , and infinitely many orbits of type  $Z$ . Let  $\mathcal{A}$  be an injection structure isomorphic to  $\mathcal{M}$  such that  $A_\omega$  (the set of all elements of  $\mathcal{A}$  the orbits of which have type  $\omega$ ) is a computable set. Then, by the proof of Theorem 3.2, we obtain a computable structure  $\mathcal{B}$  isomorphic to  $\mathcal{A}$  such that for an isomorphism  $G : \mathcal{A} \rightarrow \mathcal{B}$  we have

$$(\forall i)[i \in C \Leftrightarrow 2i + 1 \in G(A_\omega)].$$

Since the set  $A_\omega$  is computable, we have  $C \leq_T G$ , and thus  $\mathbf{0}'' \leq \text{deg}(G)$ . Hence the degree of categoricity of  $\mathcal{A}$  is  $\mathbf{0}''$ .  $\square$

One of the most common finer classifications of the class of  $\Delta_2^0$  objects is the difference hierarchy of Ershov. Recall that a set  $A \subseteq \mathbb{N}$  is said to be *n-c.e.* for  $n \in \mathbb{N}$ , if there is a computable function  $f : \mathbb{N} \times \mathbb{N} \rightarrow \{0, 1\}$  such that for every  $x \in \mathbb{N}$ :

1.  $f(x, 0) = 0$ ;
2.  $\lim_{s \rightarrow \infty} f(x, s) = A(x)$ ;
3.  $\text{card}(\{s : f(x, s+1) \neq f(x, s)\}) \leq n$ .

2-c.e. sets are also called d.c.e., for difference of c.e. sets. The set  $A$  is  $\omega$ -c.e. if instead of property 3 above there is a computable function  $h$  such that for all  $x$ ,  $|\{x : A_{s+1}(x) \neq A_s(x)\}| \leq h(x)$ .

**Definition 3.8.** (a) Let  $g(x) = \lim_{s \rightarrow \infty} f(x, s)$ , where  $f$  is a computable function.

1. The function  $g$  is an *n-c.e.* function if for all  $x \in \mathbb{N}$ ,

$$\text{card}(\{s : f(x, s) \neq f(x, s+1)\}) < n.$$

2. The function  $g$  is an  $\omega$ -c.e. function if there is a computable function  $h$  such that for all  $x \in \mathbb{N}$ ,

$$\text{card}(\{s : f(x, s) \neq f(x, s+1)\}) \leq h(x).$$

- (b) For  $\alpha \leq \omega$ , a function  $p$  is graph- $\alpha$ -c.e. if the graph of  $p$  is an  $\alpha$ -c.e. set.

In [4], Cenzer, LaForte, and Rummel investigated  $\alpha$ -c.e. and graph- $\alpha$ -c.e. functions.

**Theorem 3.9.** *There exist two computable injection structures that are not  $\omega$ -c.e. isomorphic.*

*Proof.* We will diagonalize against all possible  $\omega$ -c.e. isomorphisms  $h_e$  from a standard computable injection structure  $\mathcal{A}$  with domain  $\mathbb{N}$ , consisting of infinitely many orbits of type  $Z$ , to another isomorphic computable structure  $\mathcal{B} = (\mathbb{N}, g)$  that we shall construct. That is, we diagonalize over all pairs of partial computable functions  $h_e = (f_e, g_e)$ . Then we have to ensure that if  $f_e$  and  $g_e$  are total functions and for all  $x \in \mathbb{N}$ ,  $\text{card}(\{s : f_e(x, s) \neq f_e(x, s+1)\}) \leq g_e(x)$ , then  $f^{(e)}$  is not an isomorphism from  $\mathcal{A}$  onto  $\mathcal{B}$ , where  $f^{(e)}(x) = \lim_{s \rightarrow \infty} f_e(x, s)$  for all  $x$ . We then have two sets of requirements.

$N_e$ :  $\mathcal{B}$  has at least  $e$  different  $Z$ -orbits, and

$P_e$ : Either  $f_e$  is not total,  $g_e$  is not total, there is an  $x$  such that  $\text{card}(\{s : f_e(x, s) \neq f_e(x, s+1)\}) > g_e(x)$ , or there exists a pair  $a_e$  and  $b_e$  such that  $a_e$  and  $b_e$  are in different  $Z$ -orbits in  $\mathcal{A}$ , but  $f^{(e)}(a_e)$  and  $f^{(e)}(b_e)$  are in the same  $Z$ -orbit in  $\mathcal{B}$ .

We construct  $g$  in stages. Initially, we let  $g(0) = 1$  and our intention is to use  $\{(2i+1)2^n : n \in \mathbb{N}\}$  to build a  $Z$ -orbit by adding elements to the end of chains at even stages and elements at the beginning of chains at odd stages. To meet a negative requirement  $N_e$ , at any stage  $s \geq e$ , we shall have  $e$   $\Gamma_e$ -markers on elements of the form  $(2i+1)$ , which are currently in different orbits relative to  $g_s$ . We then allow two orbits with  $\Gamma_e$ -markers on an element in an orbit to be merged only for the sake of meeting the requirements  $P_0, \dots, P_{e-1}$ .

To meet a requirement  $P_e$ , at any stage  $s \geq e$ , we note that there can be at most  $\Gamma_j$ -markers for  $j \leq e$  on at most  $1 + 2 + \dots + e = \binom{e+1}{2}$  different orbits. Then we specify  $2 + \binom{e+1}{2}$  elements from pairwise distinct  $Z$ -orbits in  $\mathcal{A}$  and place  $\Delta_e$ -markers on these elements. Then if  $a_e$  and  $b_e$  are two elements with  $\Delta_e$ -markers on them such that  $f_e(a_e, s)$  and  $f_e(b_e, s)$  are defined and are currently in two different  $g_s$ -orbits which do not have any  $\Gamma_j$ -markers on them for some  $j \leq e$ , then we will define  $g_{s+1}$  so that we merge the orbits of  $f_e(a_e, s)$  and  $f_e(b_e, s)$ .

A standard finite injury priority argument will show that we can meet all of the requirements  $N_e$  and  $P_e$  to construct the desired computable injection structure  $\mathcal{B}$ .  $\square$

## 4 Relation Spectrum Problem

Corollaries 2.6 and 3.4 are results about the *spectra* of natural relations on computable injection structures. For a computable injection structure  $\mathcal{A} = (A, f)$  and any cardinal  $k \leq \omega$ , we may consider the possible Turing degrees of  $\{a : \text{card}(\mathcal{O}_f(a)) = k\}$ , as well as of  $\{a : \mathcal{O}_f(a) \text{ has type } \omega\}$  and  $\{a : \mathcal{O}_f(a) \text{ has type } Z\}$ . For example, we know that for any computable injection structure  $\mathcal{A}$ ,  $\text{Fin}(\mathcal{A})$  is a c.e. set. Thus, a natural question is to ask whether for any computable injection structure  $\mathcal{A}$  and any c.e. Turing degree  $\mathbf{c}$ , there exists a computable injection structure  $\mathcal{B}$  isomorphic to  $\mathcal{A}$  such that  $\text{Fin}(\mathcal{B})$  has degree  $\mathbf{c}$ . Clearly, this is not possible for any computable injection structure. For example, if  $\mathcal{A}$  has only finitely many infinite orbits, then  $A - \text{Fin}(\mathcal{A})$  is c.e., so  $\text{Fin}(\mathcal{A})$  must be computable. Similarly, if  $\mathbf{c} \neq \mathbf{0}$ , then  $\text{Fin}(\mathcal{A})$  must be infinite if we are to have a computable injection structure  $\mathcal{B}$  isomorphic to  $\mathcal{A}$  such that  $\text{Fin}(\mathcal{B})$  is of degree  $\mathbf{c}$ . However, we can prove the following theorem.

**Theorem 4.1.** *Let  $\mathbf{c}$  be a c.e. Turing degree. Let  $\mathcal{A}$  be a computable injection structure such that  $\mathcal{A}$  has infinitely many orbits of size  $k$  for every  $k \in \mathbb{N}$ , and also has infinitely many infinite orbits. Then there is a computable structure  $\mathcal{B}$  isomorphic to  $\mathcal{A}$  such that  $\text{Fin}(\mathcal{B})$  is of degree  $\mathbf{c}$ .*

*Proof.* Without loss of generality, assume that  $\mathcal{A} = (\mathbb{N}, f)$  is such that we can find a computable set of representatives  $a_0, a_1, \dots$  of the finite orbits of  $\mathcal{A}$ , a computable set of representatives  $b_0, b_1, \dots$  of the orbits of type  $Z$  of  $\mathcal{A}$ , and a computable set  $c_0, c_1, \dots$  of the first elements of all orbits of type  $\omega$  in  $\mathcal{A}$ .

First, consider the case when  $\mathcal{A}$  has infinitely many orbits of type  $\omega$ . Thus, in this case, the list  $b_0, b_1, \dots$  may be finite. Let  $C$  be a noncomputable c.e. set,

and let  $C = \bigcup_s C_s$ , where  $\{C_s : s \in \mathbb{N}\}$  is a computable sequence of finite sets such that for every  $s$ ,  $C_s \subseteq \{0, 1, \dots, s-1\}$  and  $\text{card}(C_{s+1} - C_s) \leq 1$ . The construction of  $\mathcal{B} = (\mathbb{N}, g)$  is quite simple. First, define  $g$  so that the orbits of each  $a_i$  and  $b_i$  in  $\mathcal{B}$  is the same as the orbits of  $a_i$  and  $b_i$  in  $\mathcal{A}$ , respectively, by having  $f$  and  $g$  agree on such orbits. Next, we define  $g$  so that the orbit of each  $c_{2i+1}$  in  $\mathcal{B}$  is the same as the orbit of  $c_{2i+1}$  in  $\mathcal{A}$  by having  $f$  and  $g$  agree on the orbit of  $c_{2i+1}$ .

For each  $i \in \mathbb{N}$ , we define  $g$  on the orbit of  $c_{2i}$  in stages. At stage  $s$ , if  $i \notin C_s$ , then we define  $g^k(c_{2i}) = f^k(c_{2i})$  for  $k \leq s$ . If  $i \in C_{t+1} - C_t$ , then we define  $g(f^{t+1}(c_{2i})) = c_{2i}$  and set  $g(f^r(c_{2i})) = f^{r+1}(c_{2i})$  for  $r > t+1$ . This will make the orbit of  $c_{2i}$  split into two orbits in  $\mathcal{B}$ , one that is finite and one that is of type  $\omega$ . If  $i \notin C$ , then  $f$  and  $g$  will agree on the orbit of  $c_{2i}$ . It then easily follows that  $c_{2i} \in \text{Fin}(\mathcal{B})$  if and only if  $i \in C$ . Thus,  $C \leq_T \text{Fin}(\mathcal{B})$ . However, if we know  $C$ , then we can easily compute  $\text{Fin}(\mathcal{B})$ . Hence  $\text{Fin}(\mathcal{B}) \equiv_T C$ . Finally, it is easy to see that our assumptions ensure that  $\mathcal{A}$  is isomorphic to  $\mathcal{B}$ .

The construction when  $\mathcal{A}$  has only finitely many orbits of type  $\omega$ , but infinitely many orbits of type  $Z$  is similar. In that case, we split each orbit of  $b_{2i}$  into two orbits, one finite containing  $b_{2i}$  and one infinite of type  $Z$  if  $i \in C$ , and otherwise we will have  $g$  and  $f$  agree on the orbit of  $b_{2i}$ . We also have that  $f$  and  $g$  agree on the orbits of each  $a_i$ , each  $c_i$ , and each  $b_{2i+1}$ .  $\square$

Note that in the proof of Theorem 4.1, we used the assumption that  $\mathcal{A}$  had infinitely many orbits of size  $k$  for each  $k$ , to ensure that  $\mathcal{B}$  we constructed is isomorphic to  $\mathcal{A}$ , since in such a situation adding an extra finite orbit does not change the isomorphism type. However, in general, we cannot do this for an arbitrary injection structure  $\mathcal{A}$ . We can, however, easily modify the construction of Theorem 4.1 to prove a similar result in the case when  $\mathcal{A}$  has infinitely many orbits of different sizes. Similarly, it is easy to see that we can modify the construction to produce a computable injection structure  $\mathcal{A} = (\mathbb{N}, f)$  such that  $\text{Fin}(\mathcal{A})$  has degree  $\mathbf{c}$  and the sizes of the finite orbits of elements of  $\mathcal{A}$  are pairwise distinct. A more general question is to characterize the possible characters of computable injection structures  $\mathcal{A}$  which have  $\text{Fin}(\mathcal{A})$  of degree  $\mathbf{c}$  for any given c.e. degree  $\mathbf{c}$ .

A more refined question is what sets can be realized as  $\text{Fin}(\mathcal{A})$  for a computable injection structure. An easy observation here is that  $\text{Fin}(\mathcal{A})$  can never be a simple c.e. set. That is, if  $\text{Fin}(\mathcal{A})$  is not computable, then  $\text{Fin}(\mathcal{A})$  must be infinite and also there must be some infinite orbits. But then each infinite orbit of  $\mathcal{A}$  is a c.e. set in the complement of  $\text{Fin}(\mathcal{A})$ . Similarly, no infinite orbit of  $\mathcal{A}$  can be a simple c.e. set. We next show that there is a non-simple c.e. set that cannot be  $\text{Fin}(\mathcal{A})$  for any computable injection structure  $\mathcal{A}$ .

**Theorem 4.2.** *Let  $C$  be a simple c.e. set. Then there is no computable injection structure  $\mathcal{A} = (\mathbb{N}, f)$  such that  $2C = \text{Fin}(\mathcal{A})$  or  $2C$  is an orbit of  $\mathcal{A}$ , where  $2C = \{2c : c \in C\}$ .*

*Proof.* Suppose, for a contradiction, that  $\mathcal{A} = (\mathbb{N}, g)$  is a computable injection structure such that  $2C = \text{Fin}(\mathcal{A})$  or  $2C$  is an orbit of  $\mathcal{A}$ . Then for  $c \in C$ ,

the orbit  $\mathcal{O}_f(2C) \subseteq 2C$ , and hence every element of  $\mathcal{O}_f(2C)$  is even. Let  $D = \{n : (\exists m)(2m + 1 \in \mathcal{O}_f(2n))\}$ . Hence  $D$  is a c.e. set disjoint from  $C$ , and therefore finite. Thus, there are only finitely many even numbers,  $2a_1, \dots, 2a_n$ , which have odd numbers in their orbits. It follows that if  $2x \notin \{2a_1, \dots, 2a_n\}$ , then  $\mathcal{O}_f(2x)$  consists entirely of even numbers.

Now suppose that  $2C = \text{Fin}(\mathcal{A})$ . If there is an  $x \notin C \cup \{a_1, \dots, a_n\}$  such that  $\mathcal{O}_f(2x)$  is infinite, then  $\{m : 2m \in \mathcal{O}_f(2x)\}$  would be an infinite c.e. set in the complement of  $C$ , which would violate our assumption that  $C$  is simple. It then follows that if  $x \notin C \cup \{a_1, \dots, a_n\}$ ,  $\mathcal{O}_f(2x)$  is finite. This would imply that  $2C = \{2n : n \in \mathbb{N}\} - \{2a_1, \dots, 2a_n\}$ , which would imply that  $C = \mathbb{N} - \{a_1, \dots, a_n\}$ , again violating our assumption that  $C$  is simple.

Finally, suppose that  $2C = \mathcal{O}_f(2m)$ . Again, if there is an  $x \notin C \cup \{a_1, \dots, a_n\}$  such that  $\mathcal{O}_f(2x)$  is infinite, then  $\{m : 2m \in \mathcal{O}_f(2x)\}$  would be an infinite c.e. set in the complement of  $C$ , which would violate our assumption that  $C$  is simple. Thus we must assume that for all  $x \notin C \cup \{a_1, \dots, a_n\}$ ,  $\mathcal{O}_f(2x)$  is finite. But then  $\{n : 2n \in \text{Fin}(\mathcal{A})\}$  is an infinite c.e. set disjoint from  $C$ , which again violates our assumption that  $C$  is simple.  $\square$

Now, for a computable injection structure  $\mathcal{A} = (\mathbb{N}, g)$ , the range  $\text{Ran}(g)$  is always a c.e. set, so a natural question to ask is whether  $\text{Ran}(g)$  can be *any* c.e. set. There are some obvious restrictions, namely, if  $\mathcal{A}$  has only finitely many orbits of type  $\omega$ , then  $\text{Ran}(g)$  is computable.

**Theorem 4.3.** *Let  $C$  be any infinite, co-infinite c.e. set and let  $K$  be any c.e. character.*

- (i) *There is a computable injection structure  $(\mathbb{N}, g)$  with  $\text{Ran}(g) = C$ .*
- (ii) *If  $C$  is not simple, then there is a computable injection structure  $(\mathbb{N}, h)$  with character  $K$ , with  $\text{Ran}(h) \equiv_T C$ , and with an arbitrary number of orbits of type  $Z$ .*

*Proof.* Let  $C$  be an infinite, co-infinite c.e. set and let  $c_0, c_1, \dots$  be a computable enumeration of  $C$  without repetitions.

(i) The function  $g$  is defined in stages  $g_s$  as follows. Initially,  $g_0 = \emptyset$ . At stage 1, there are three cases. If  $c_0 \neq 0$ , then we let  $g_1 = \{(0, c_0)\}$ . If  $c_0 = 0$  and  $c_1 \neq 1$ , then we let  $g_1(0) = c_1$  and  $g_1(1) = 0$ . If  $c_0 = 0$  and  $c_1 = 1$ , then we let  $g_1(0) = 1$  and  $g_1(1) = 0$ .

Suppose that after  $s$  steps, we have defined a finite function  $g_s$  such that  $\{0, 1, \dots, s-1\} \subseteq \text{Dom}(g_s)$  and  $\{c_0, c_1, \dots, c_{s-1}\} \subseteq \text{Ran}(g_s) \subset C$ . At stage  $s+1$ , let  $i$  be the least element not in  $\text{Dom}(g_s)$ , and let  $m$  be the least index such that  $c_m \notin \text{Ran}(g_s)$ . If  $i \neq c_m$ , let  $g_{s+1}(i) = c_m$ . If  $i = c_m$ , let  $j$  be the least element such that  $j > i$  and  $j \notin \text{Dom}(g_s)$ , and let  $n$  be the least index such that  $n > m$  and such that  $c_n \notin \text{Ran}(g_s)$ . Now define  $g_{s+1}(j) = c_m$  and  $g_{s+1}(i) = c_n$ . In this way we ensure that  $s \in \text{Dom}(g_{s+1})$  and  $c_s \in \text{Ran}(g_{s+1})$ .

(ii) Let  $A$  be an infinite computable set, disjoint from  $C$ . Then both  $A$  and  $\mathbb{N} - A$  are computably isomorphic to  $\mathbb{N}$ , so we can build a computable structure

$(\mathbb{N}-A, g)$  with range computably isomorphic to  $C$ . Then, by Proposition 2.2, we can build a computable structure  $(A, f)$  with character  $K$  and with the desired number of orbits of type  $Z$ . Now,  $(\mathbb{N}, h)$  is defined so that  $h(x) = f(x)$  if  $x \in A$ , and  $h(x) = g(x)$  if  $x \notin A$ .  $\square$

Next, we consider the infinite orbits of an injection structure. Since each infinite orbit is a c.e. set, and also the union of all finite orbits forms a c.e. set, any noncomputable orbit will have a c.e. set in its complement. We can show that every c.e. degree contains a c.e. set that is an orbit of some computable injection structure.

**Theorem 4.4.** *For every c.e. set  $C$  and every computable injection structure  $\mathcal{A}$  with infinitely many infinite orbits, there is a computable injection structure  $\mathcal{B}$  isomorphic to  $\mathcal{A}$  such that  $C$  is 1 – 1 reducible to an orbit of  $\mathcal{B}$ .*

*Proof.* First, suppose that  $\mathcal{A}$  has infinitely many orbits of type  $\omega$ . Clearly, it suffices to build  $\mathcal{B} = (\mathbb{N}, g)$ , consisting exactly of infinitely many orbits of type  $\omega$ , and having an orbit, say the orbit of 0, such that  $C$  is 1 – 1 reducible to it. The construction of  $\mathcal{B}$  is as follows. For each  $n$ , we start to build an orbit of type  $\omega$  with the first element  $2n$ , using the odd numbers to extend the orbits. When a number  $n$  appears in  $C$ , we attach the chain beginning with  $2n$  to the end of the chain beginning with 0. Thus, we see that for any  $n$ , we have  $n \in C$  if and only if  $2n \in \mathcal{O}_g(0)$ .

If  $\mathcal{A}$  has infinitely many orbits of type  $Z$ , then we can similarly define  $\mathcal{B}$ , consisting of infinitely many orbits of type  $Z$ , and such that  $(n \in C \Leftrightarrow 2n \in \mathcal{O}(0))$ , by extending each chain both forward and backward.  $\square$

## 5 Decidability of Structures and Theories

Recall that for any structure  $\mathcal{A}$ ,  $Th(\mathcal{A})$  denotes the first-order theory of  $\mathcal{A}$  and  $FTh(\mathcal{A})$  denotes the elementary diagram of  $\mathcal{A}$ . In the case of equivalence structures, Cenzer, Harizanov, and Remmel [3] showed that the character of an equivalence structure together with the number of infinite classes effectively determine its theory. Similarly, they showed that the character together with the function mapping any element to the size of its equivalence class effectively determine its elementary diagram.

**Proposition 5.1.** *For any injection structure  $\mathcal{A}$ , the character  $\chi(\mathcal{A})$  is computable from the theory  $Th(\mathcal{A})$ . Hence if  $Th(\mathcal{A})$  is decidable, then  $\chi(\mathcal{A})$  is computable.*

*Proof.* It follows from the proof of Lemma 2.1 that for all finite  $n$  and  $k$ , there are formulas  $\psi_k(x)$  and sentences  $\phi_{n,k}$  (in the language of injection structures) such that:

1. For any injection structure  $\mathcal{A}$  and any element  $a \in \mathcal{A}$ ,  $\mathcal{A} \models \psi_k(a)$  if and only if  $card(\mathcal{O}_f(a)) = k$ ;

2. For any injection structure  $\mathcal{A}$ ,  $\mathcal{A} \models \phi_{n,k}$  if and only if  $(n, k) \in \chi(\mathcal{A})$ .

Furthermore, the formulas  $\psi_k(x)$  and sentences  $\phi_{n,k}$  are computable from  $k$  and  $n$ .

It follows from the argument above that, in fact,  $\chi(\mathcal{A})$  is many-one reducible to  $Th(\mathcal{A})$ .  $\square$

Given an injection structure  $\mathcal{A} = (A, f)$ , let the relation  $R(\mathcal{A}) \subseteq \mathbb{N} \times A$  be defined by

$$(n, a) \in R(\mathcal{A}) \Leftrightarrow (\exists x)[f^n(x) = a].$$

**Theorem 5.2.** *For any injective structure  $\mathcal{A}$ , the elementary diagram of  $\mathcal{A}$  is Turing reducible to the join of the relation  $R(\mathcal{A})$  with the atomic diagram of  $\mathcal{A}$ .*

*Proof.* The proof is by quantifier elimination and is a straightforward modification of the classical proof for the decidability of the theory of successor. We first expand the language by adding the relation symbols  $\gamma_n$  such that  $\mathcal{A} \models \gamma_n(a)$  if and only if  $(n, a) \in R(\mathcal{A})$ . Let  $\psi(x, t_1, \dots, t_k)$  be any conjunction of literals in this expanded language, where  $t_1, \dots, t_k$  are either variables or elements of  $\mathcal{A}$ , and let  $\theta$  be  $(\exists x)\psi$ . Atomic formulas contain the basic terms  $x, t_1, \dots, t_k$ , as well as terms  $f^j(t)$  for one of those basic terms. The atomic formulas have one of two forms:  $\gamma_n(s)$  for some term  $s$ , or  $s = t$  for some terms  $s$  and  $t$ . Since  $f$  is an injection, we can ensure that all occurrences of  $x$  in any equality have the form  $f^j(x)$  for the same  $j$ , by applying  $f$  to each equality. Similarly, the formula  $\gamma_n(f^i(x))$  is equivalent to  $\gamma_{n+1}(f^{i+1}(x))$ , so that each such occurrence of  $x$  is equivalent to some  $\gamma_m(f^j(x))$ . Now, the formula  $(\exists x)\psi(f^j(x))$  is equivalent to the formula  $(\exists y)[\gamma_j(y) \wedge \psi(y)]$ . We may assume that for every term  $s$  of  $\psi$ , either  $y = s$  or  $y \neq s$  occurs among the literals of  $\psi$ .

Now, there are two cases. First, suppose that one of the literals has the form  $y = s$ . Then the formula  $(\exists y)\psi(y)$  is equivalent to the formula  $\psi(s)$ . Second, suppose that for all terms  $s$ , the literal  $y \neq s$  occurs in  $\psi$ . Then the fact that  $\mathcal{A}$  is infinite means that such  $y$  must exist, so  $(\exists y)\psi$  is equivalent to the formula obtained by deleting the quantifier  $\exists y$  and all literals containing  $y$ .

At the end of quantifier elimination, we can determine whether the reduced, quantifier-free formula  $\phi$  holds in  $\mathcal{A}$  by consulting the atomic diagram of  $\mathcal{A}$  as well as  $R(\mathcal{A})$ .  $\square$

**Theorem 5.3.** *For any injection structure  $\mathcal{A}$ , there is a structure  $\mathcal{B}$  isomorphic to  $\mathcal{A}$ , such that  $\mathcal{B}$  and  $R(\mathcal{B})$  are computable from  $\chi(\mathcal{B})$ .*

*Proof.* We may assume, without loss of generality, that  $\mathcal{A}$  has no infinite orbits, since, if needed, we can simply adjoin either infinitely many or some fixed finite number of computable infinite orbits of either type. The structure  $\mathcal{B}$  will contain a distinct orbit  $\mathcal{O}(\langle k, n \rangle)$  for each  $(k, n) \in \chi(\mathcal{A})$ , where we let  $\langle k, n \rangle = 2^{k+1} \cdot 3^{n+1}$ . Let  $\chi(\mathcal{A})$  be enumerated numerically as  $\langle k_0, n_0 \rangle, \langle k_1, n_1 \rangle, \dots$ , and let  $b_0, b_1, \dots$  enumerate  $\mathbb{N} - \chi(\mathcal{A})$ . Then the function  $f = f^{\mathcal{B}}$  is defined by using the elements  $b_0, b_1, \dots$  to fill out the orbits  $[\langle k_0, n_0 \rangle], [\langle k_1, n_1 \rangle], \dots$  in order as needed. It is easy to see that  $\mathcal{B}$  and  $R(\mathcal{B})$  are computable from  $\chi(\mathcal{B})$ .  $\square$

Putting the previous results together, we have the next two theorems along with some immediate corollaries.

**Theorem 5.4.** *For any injection structure  $\mathcal{A}$ ,  $Th(\mathcal{A})$  and  $\chi(\mathcal{A})$  have the same Turing degree.*

*Proof.* It follows from Proposition 5.1 that  $\chi(\mathcal{A})$  is Turing reducible to  $Th(\mathcal{A})$ . Conversely, let  $\mathcal{A}$  be an injection structure, and let  $\mathcal{B}$ , isomorphic to  $\mathcal{A}$ , be given by Theorem 5.3 so that  $\mathcal{B}$  and  $R(\mathcal{B})$  are both computable from  $\chi(\mathcal{B})$  (which, of course, equals  $\chi(\mathcal{A})$ ). It follows from Theorem 5.2 that  $FTh(\mathcal{B})$  is computable from  $\chi(\mathcal{A})$ . Now,  $Th(\mathcal{B})$ , which equals  $Th(\mathcal{A})$ , is computable from  $FTh(\mathcal{B})$ , and hence  $Th(\mathcal{A})$  is computable from  $\chi(\mathcal{A})$ , as desired.  $\square$

**Corollary 5.5.** *For any injection structure  $\mathcal{A}$ ,  $Th(\mathcal{A})$  is decidable if and only if  $\chi(\mathcal{A})$  is computable.*

**Theorem 5.6.** *For any injection structure  $\mathcal{A}$  with computable character  $\chi(\mathcal{A})$ , there is a decidable structure  $\mathcal{B}$  isomorphic to  $\mathcal{A}$ . (Hence  $Th(\mathcal{A})$  is decidable.)*

*Proof.* Again, it suffices to assume that  $\mathcal{A}$  has no infinite orbits. By Theorem 5.3, there is a structure  $\mathcal{B}$  isomorphic to  $\mathcal{A}$ , which is computable from  $\chi(\mathcal{B})$ , and hence  $\mathcal{B}$  and  $R(\mathcal{B})$  are also computable. It now follows from Theorem 5.2 that  $FTh(\mathcal{B})$  is decidable, and hence  $Th(\mathcal{B})$ , which equals  $Th(\mathcal{A})$ , is decidable.  $\square$

Clearly, any bounded character is computable.

**Corollary 5.7.** *If the injection structure  $\mathcal{A}$  has bounded character, then  $Th(\mathcal{A})$  is decidable.*

In contrast to the result for equivalence structures [3] that every computably categorical structure is decidable, here we have the following negative result.

**Proposition 5.8.** *There is a computably categorical injection structure  $\mathcal{A}$  such that  $Th(\mathcal{A})$  is not decidable.*

*Proof.* Simply, let  $W$  be a noncomputable c.e. set, and let  $\mathcal{A}$  have character  $\{(n, 1) : n \in W\}$  and no infinite orbits, by Proposition 2.2. Then  $\chi(\mathcal{A})$  is not computable and hence, by Proposition 5.1,  $Th(\mathcal{A})$  is also not decidable.  $\square$

**Proposition 5.9.** *For any computable character  $K$ , there is a decidable injection structure  $\mathcal{A}$  with character  $K$  and with any specified countable number of orbits of types  $\omega$  and  $Z$ . Furthermore,  $Fin(\mathcal{A})$  is computable.*

*Proof.* It suffices to construct  $\mathcal{A}$  with no infinite orbits. By Proposition 2.2, there is a computable injection structure  $\mathcal{B}$  with character  $K$ . Now, by Theorem 5.6, there is a decidable structure  $\mathcal{A}$  isomorphic to  $\mathcal{B}$ .  $\square$

**Corollary 5.10.** *If  $\mathcal{B}$  is a computable injection structure with computable character and with no infinite orbits, then  $\mathcal{B}$  is decidable.*

*Proof.* It follows from Proposition 5.9 that there is a decidable structure  $\mathcal{A}$  that is isomorphic to  $\mathcal{B}$ . Since  $\mathcal{A}$  has no infinite orbits, it is computably categorical, and hence  $\mathcal{A}$  and  $\mathcal{B}$  are computably isomorphic. Thus,  $\mathcal{B}$  is also decidable.  $\square$

## 6 Index Sets for Infinite Injection Structures

In this section, we develop the theory of index sets for infinite computable injection structures. Fix an enumeration of structures,  $\mathcal{A}_e = (\mathbb{N}, \phi_e)$ , where  $\phi_e$  is the usual  $e$ th partial computable function. Clearly, this list includes every computable injection structure with universe  $\mathbb{N}$ . We avoid consideration of structures with computable universe  $A \subset \mathbb{N}$  since we want to focus on the properties of the structure and not on the universe. Of course, every computable structure with an infinite universe  $A \subset \mathbb{N}$  is computably isomorphic to a structure with universe  $\mathbb{N}$ .

We say that a set  $A$  is  $D_n^0$  if  $A$  is the difference of two  $\Sigma_n^0$  sets, or, equivalently,  $A$  is the intersection of a  $\Sigma_n^0$  and a  $\Pi_n^0$  set. We say that  $A$  is  $D_n^0$ -complete if  $A$  is  $D_n^0$ , and for any  $D_n^0$  set  $B$ , there is a computable function  $f$  such that  $e \in B \Leftrightarrow f(e) \in A$ . If  $A \subseteq B \subseteq \mathbb{N}$ , then we say that  $A$  is  $\Sigma_n^0$  within  $B$  if  $A$  is the intersection of  $B$  with a  $\Sigma_n^0$  set. We say that  $A$  is  $\Sigma_n^0$ -complete within  $B$  if for any  $\Sigma_n^0$  set  $C$ , there is a computable function  $f$  such that for every  $e$ ,  $f(e) \in B$  and  $e \in C \Leftrightarrow f(e) \in A$ . Similar definitions apply to  $\Pi_n^0$  sets and other notions of complexity.

We want to consider properties of computable injection structures, which indicate the number of orbits of types  $\omega$  and  $Z$ . Let  $Inv_m$  ( $Inv_{\leq m}$ ) be the set of indices  $e$  such that  $\mathcal{A}_e$  is a computable injection structure with exactly  $m$  ( $\leq m$ ) orbits of type  $\omega$ . The sets  $Inv_{< m}$ ,  $Inv_{\geq m}$  and  $Inv_{> m}$  are defined similarly. Let  $Inv^n$  ( $Inv^{\leq n}$ ) be the set of indices  $e$  such that  $\mathcal{A}_e$  is a computable injection structure with exactly  $n$  ( $\leq n$ ) orbits of type  $Z$ . The sets  $Inv^{< n}$ ,  $Inv^{\geq n}$  and  $Inv^{> n}$  are defined similarly. Let  $Inv_m^n$  be the set of indices  $e$  such that  $\mathcal{A}_e$  is a computable injection structure with exactly  $m$  orbits of type  $\omega$  and  $n$  orbits of type  $Z$ . We can replace  $m$  by either  $\leq m$ ,  $< m$ ,  $\geq m$ ,  $> m$ , and  $n$  by either  $\leq n$ ,  $< n$ ,  $\geq n$ ,  $> n$  in the definition of  $Inv_m^n$  to define similar sets. For example, the set  $Inv_{\leq m}^{> n}$  is the set of all indices  $e$  such that  $\mathcal{A}_e$  is an injection structure with no more than  $m$  orbits of type  $\omega$  and more than  $n$  orbits of type  $Z$ .

**Theorem 6.1.** *The set  $Inv = \{e : \mathcal{A}_e \text{ is a computable injection structure}\}$  is  $\Pi_2^0$ -complete. The set  $Inv_0^0$  of injection structures with no infinite orbits is  $\Pi_2^0$ -complete, and also  $\Pi_2^0$ -complete within  $Inv$ .*

*Proof.* It is easy to see that  $Inv$  is a  $\Pi_2^0$  set. That is,  $e \in Inv$  if and only if  $\phi_e$  is total and injective, which is a  $\Pi_2^0$  condition. It follows from part (c) of Lemma 2.1 that  $Inv_0^0$  is also a  $\Pi_2^0$  set.

For the completeness of  $Inv$  and also of  $Inv_{0,0}$ , we define a reduction  $f$  of the  $\Pi_2^0$ -complete set  $Inf = \{e : W_e \text{ is infinite}\}$  to  $Inv$ . Define the structure  $\mathcal{A}_{f(e)} = (\mathbb{N}, \phi_{f(e)})$  as follows. Let  $s_0 < s_1 < \dots$  enumerate the (possibly finite) set of stages at which a new element appears in the standard enumeration of  $W_e$ . Here

we assume that at most one element enters  $W_e$  at any stage. To define  $\phi = \phi_{f(e)}$ , wait until  $s_0$  appears and then let  $\phi(0) = 1, \phi(1) = 2, \dots, \phi(s_0 - 1) = s_0$  and  $\phi(s_0) = 0$ . Next, wait until  $s_1$  appears and let  $\phi(s_0 + 1) = s_0 + 2, \dots, \phi(s_1 - 1) = s_1$  and  $\phi(s_1) = s_0 + 1$ . If  $W_e$  is finite and  $s_k$  is the last stage at which an element enters  $W_e$ , then  $\phi_{f(e)}(s_k + 1)$  is undefined, so  $f(e) \notin \text{Inj}$ . If  $W_e$  is infinite, then  $\phi_{f(e)}$  is total and  $\text{Fin}(\mathcal{A}_{f(e)}) = \mathbb{N}$ .

For the  $\Pi_2^0$ -completeness of  $\text{Inj}_0^0$  within  $\text{Inj}$ , modify the construction above to produce a computable function  $g$  as follows. Begin by letting  $\phi_{g(e)}(0) = 1, \phi_{g(e)}(1) = 2, \dots$  until  $s_0$  appears and then let  $\phi_{g(e)}(s_0) = 0$ . Next, let  $\phi_{g(e)}(s_0 + 1) = s_0 + 2, \phi_{g(e)}(s_0 + 2) = s_0 + 3, \dots$  again until  $s_1$  appears and then let  $\phi_{g(e)}(s_1) = s_0 + 1$ . If  $s_k$  is the last stage at which an element enters  $W_e$ , then  $\phi_{g(e)}(s_k + n + 1) = s_k + n + 2$  for all  $n$ . It follows from this construction that if  $W_e$  is infinite, then all orbits of  $\mathcal{A}_{g(e)}$  are finite, whereas if  $W_e$  is finite, then  $\mathcal{A}_{g(e)}$  has a finite number of finite orbits together with one orbit of type  $\omega$ . Then  $g$  shows that  $\text{Inj}_0^0$  is  $\Pi_2^0$ -complete within  $\text{Inj}$ .  $\square$

Before giving further results for the above index sets, we first observe that the property of being in the same orbit under  $f$ , that is, the relation “ $\mathcal{O}_f(a) = \mathcal{O}_f(b)$ ”, is  $\Sigma_1^0$ .

**Theorem 6.2.** *For each  $m \geq 0$ ,  $\text{Inj}_{\leq m}$  is  $\Pi_2^0$ -complete, and the relations  $\text{Inj}_{> m}$  and  $\text{Inj}_{m+1}$  are  $D_2^0$ -complete.*

*Proof.* The set  $\text{Inj}_{> m}$  is  $\Sigma_2^0$  within  $\text{Inj}$ , that is, it is the intersection of the  $\Sigma_2^0$  set  $S$  with  $\text{Inj}$ , where  $S$  is the set of indices  $e$  such that there exist at least  $m + 1$  elements  $x \notin \text{Ran}(\phi_e)$ . The other upper complexity bounds follow from this fact.

Let  $\text{Fin} = \{e : W_e \text{ is finite}\}$  and  $\text{Inf} = \{e : W_e \text{ is infinite}\}$ . Then  $\text{Fin}$  is a  $\Sigma_2^0$ -complete set,  $\text{Inf}$  is a  $\Pi_2^0$ -complete set, and  $D = \{\langle a, b \rangle : a \in \text{Fin} \wedge b \in \text{Inf}\}$  is a  $D_2^0$ -complete set. For the  $\Pi_2^0$ -completeness of  $\text{Inj}_{\leq 0}$ , we can use the same proof that we used to prove that  $\text{Inj}_0^0$  is  $\Pi_2^0$ -complete.

For the  $\Pi_2^0$ -completeness of  $\text{Inj}_{\leq m}$  where  $m \geq 1$ , first consider the computable function  $g$  that we used to show that  $\text{Inj}_0^0$  is  $\Pi_2^0$ -complete within  $\text{Inj}$ . That is, we constructed a computable function  $g$  such that if  $W_e$  is finite, then  $\mathcal{A}_{g(e)}$  is a computable injection structure with one infinite orbit of type  $\omega$  and finitely many finite orbits, and if  $W_e$  is infinite, then all orbits of  $\mathcal{A}_{g(e)}$  are finite. Now, let  $g_{m+1}(e)$  be the computable function such that  $\mathcal{A}_{g_{m+1}(e)}$  is the disjoint union of  $m + 1$  computable copies of  $\mathcal{A}_{g(e)}$ . It follows that  $e \in \text{Inf} \Leftrightarrow g_{m+1}(e) \in \text{Inj}_{\leq m}$ , so that  $\text{Inj}_{\leq m}$  is  $\Pi_2^0$ -complete.

For  $D_2^0$ -completeness of  $\text{Inj}_{m+1}$ , we can define a computable function  $h$  such that  $\mathcal{A}_{h(\langle a, b \rangle)} = \mathcal{A}_{g_{m+1}(a)} \oplus (\mathcal{A}_{g_{m+1}(b)} \oplus \mathcal{A}_{g_{m+1}(b)})$ . Now if  $\langle a, b \rangle \in D$ , then  $\mathcal{A}_{g_{m+1}(a)}$  has exactly  $m + 1$  infinite orbits of type  $\omega$  and  $\mathcal{A}_{g(b)}$  has no infinite orbits, so  $\mathcal{A}_{h(\langle a, b \rangle)}$  will have exactly  $m + 1$  orbits of type  $\omega$ . If  $a \in \text{Inf}$ , then  $\mathcal{A}_{h(\langle a, b \rangle)}$  has no infinite orbits if  $b \in \text{Inf}$ , and will have  $2m + 2$  orbits of type  $\omega$  if  $b \in \text{Fin}$ . Thus,  $h$  shows that  $D$  is many-one reducible to  $\text{Inj}_{m+1}$ .

For  $D_2^0$ -completeness of  $Inj_{>m}$ , we can define a computable function  $q$  such that  $\mathcal{A}_{q(\langle a,b \rangle)} = \mathcal{A}_{g_{m+1}(a)} \oplus (\mathcal{A}_{f(b)} \oplus \mathcal{A}_{f(b)})$ , where  $f$  is the computable function constructed in Theorem 6.1 such that  $\mathcal{A}_{f(e)}$  is a computable injection structure with no infinite orbits if  $e \in Inf$ , and  $\phi_{f(e)}$  is not total if  $e \in Fin$ . Now if  $\langle a,b \rangle \in D$ , then  $\mathcal{A}_{g_{m+1}(a)}$  has exactly  $m+1$  infinite orbits of type  $\omega$  and  $\mathcal{A}_{g(b)}$  has no infinite orbits, so that  $\mathcal{A}_{q(\langle a,b \rangle)}$  will be a computable injection structure with exactly  $m+1$  orbits of type  $\omega$ . If  $b \in Fin$ , then  $\mathcal{A}_{q(\langle a,b \rangle)}$  will not be a computable injection structure. Thus,  $q$  shows that  $Inj_{>m}$  is  $D_2^0$ -complete.  $\square$

**Theorem 6.3.** *For each  $n \geq 0$ ,  $Inj^{\leq n}$  is  $\Pi_3^0$ -complete,  $Inj^{>n}$  is  $\Sigma_3^0$ -complete, and  $Inj^{n+1}$  is  $D_3^0$ -complete.*

*Proof.* The set  $Inj^{>n}$  is  $\Sigma_3^0$ , since it is the set of indices  $e$  such that there exist  $n+1$  elements  $x_0, \dots, x_n$ , each having an orbit of type  $Z$  and no two being in the same orbit. The other upper complexity bounds follow from this fact.

First we show that  $Inj^{>0}$  is  $\Sigma_3^0$ -complete and  $Inj^{\leq 0}$  is  $\Pi_3^0$ -complete. Let  $Cof = \{e : W_e \text{ is co-finite}\}$ . It is well-known that  $Cof$  is a  $\Sigma_3^0$ -complete set. We define a computable function  $r$  such that  $\mathcal{A}_{r(e)}$  is built by the following construction. We start to build  $\omega$  chains going forward from each number  $2m+1$  by mapping  $x$  to  $2x$ . When a number  $m$  comes into  $W_e$  at stage  $s+1$ , we find the longest sequence,  $k, k+1, \dots, m, m+1, \dots, n$ , which includes  $m$  and is contained in  $W_{e,s+1}$ . We take the chains from  $2(m+1)+1$  to  $2n+1$  and put them at the end of the  $(2m+1)$ -chain, removing them from any further activity. If  $k < m$ , then we put the newly expanded  $(2m+1)$ -chain at the end of the  $(2k+1)$ -chain. Finally, we add an element to the beginning of the  $(2k+1)$ -chain.

If  $W_e$  is co-finite, there will be a least  $m$  such that every  $n \geq m$  belongs to  $W_e$ . In that case, the orbit of  $2m+1$  will be a  $Z$ -chain, all of the  $(2n+1)$ -chains for  $n > m$  will be included in this orbit, and there will be finitely many orbits of type  $\omega$  for the numbers  $k < m$ . If  $W_e$  is co-infinite, then  $W_e$  will be an infinite union of finite consecutive sequences, each of which will have an orbit of type  $\omega$  and these orbits will include all elements. Thus  $e \in Cof \Leftrightarrow r(e) \in Inj^{>0}$ , so that  $Inj^{>0}$  is  $\Sigma_3^0$ -complete and  $Inj^{\leq 0}$  is  $\Pi_3^0$ -complete.

To show that  $Inj^{>m}$  is  $\Sigma_3^0$ -complete and  $Inj^{\leq m}$  is  $\Pi_3^0$ -complete for  $m \geq 1$ , let  $r_m(e)$  be the computable function such that  $\mathcal{A}_{r_m(e)}$  is  $\mathcal{A}_{r(e)} \oplus \mathcal{B}_m$ , where  $\mathcal{B}_m$  is a computable injection structure that has  $m$   $Z$ -chains and no other orbits. Then  $e \in Cof \Leftrightarrow r_m(e) \in Inj^{>m}$ , so that  $Inj^{>m}$  is  $\Sigma_3^0$ -complete and  $Inj^{\leq m}$  is  $\Pi_3^0$ -complete.

To show that  $Inj^m$  is  $D_3^0$ -complete for  $m \geq 1$ , we reduce to it the  $D_3^0$ -complete set  $E = \{\langle a,b \rangle : a \in Cof \wedge b \notin Cof\}$ . Let  $k$  be the computable function such that  $\mathcal{A}_{k(\langle a,b \rangle)} = \mathcal{A}_{r_{m-1}(a)} \oplus (\mathcal{A}_{r_{m-1}(b)} \oplus \mathcal{A}_{r_{m-1}(b)})$ . Then it is easy to check that  $\mathcal{A}_{k(\langle a,b \rangle)}$  has exactly  $m$   $Z$ -chains if and only if  $a \in Cof$  and  $b \notin Cof$ .  $\square$

**Theorem 6.4.** *The property of being a computably categorical (computable) injection structure over  $\mathbb{N}$  is  $\Sigma_3^0$ -complete. That is,*

$$CCI = \{e : \mathcal{A}_e \text{ is an injection structure with finitely many infinite orbits}\}$$

is a  $\Sigma_3^0$ -complete set.

*Proof.* The set  $CCI$  is  $\Sigma_3^0$  since  $\mathcal{A}_e$  has finitely many infinite orbits if and only if there exists a finite sequence  $a_0, \dots, a_k$  such that for every  $b$ , if  $b \notin \mathcal{O}(a_i)$  for any  $i \leq k$ , then  $\mathcal{O}(b)$  is finite. The details follow from Lemma 2.1.

For completeness, consider the  $\Sigma_3^0$ -complete set  $Cof = \{e : W_e \text{ is co-finite}\}$ . We define a computable function  $f$  such that for every  $e$ ,  $\mathcal{A}_{f(e)}$  will have finitely many infinite orbits if and only if  $W_e$  is co-finite. The orbits of  $\mathcal{A}_{f(e)}$  will be exactly the orbits  $\mathcal{O}(2i+1)$  for  $i \in \mathbb{N}$ , and the even numbers will be used to fill out the orbits. The injection  $\phi_{f(e)}$  will be defined in stages, as  $\phi_{f(e)}^s$ , so that for  $i \leq s$ , we have defined  $\phi_{f(e)}^t(2i+1)$  for all  $t \leq s$ .

At stage  $s+1$ , we do the following. For  $i \leq s$ , we have three cases. If  $i \notin W_{e,s+1}$ , then at stage  $s+1$  we simply define  $\phi_{f(e)}^{s+1}(2i+1)$  to be the next available even number. If  $i \in W_{e,s+1} - W_{e,s}$ , then we define  $\phi_{f(e)}^{s+1}(2i+1) = 2i+1$ . If we already have  $i \in W_{e,s}$ , there is nothing to do. That is, if  $i \in W_{e,s}$ , then  $\phi_{f(e)}^t(2i+1) = 2i+1$  for some  $t \leq s$ , and hence  $\phi_{f(e)}^s(2i+1)$  is automatically defined for all  $s \geq t$ . For  $i = s+1$ , we choose the next  $s+1$  available even numbers, say  $2n_1, 2n_2, \dots, 2n_{s+1}$ , and let  $\phi_{f(e)}^t(2s+3) = 2n_t$  for all  $t \leq s+1$ .

The following facts are immediate from the construction.

1. The orbit  $\mathcal{O}_{f(e)}(2i+1)$  is finite if and only if  $i \in W_e$ .
2. The function  $\phi_{f(e)}$  is total and one-to-one.

It follows from Fact 2 that  $f(e) \in Inj$  for all  $e$ . It follows from Fact 1 that  $\mathcal{A}_{f(e)}$  has finitely many infinite orbits if and only if  $W_e$  is co-finite.  $\square$

**Theorem 6.5.** *The property of being  $\Delta_2^0$ -categorical (computable) injection structure is  $\Sigma_4^0$ -complete. That is,*

$$DCI = \{e : \mathcal{A}_e \text{ is an injection structure with finitely many orbits of type } \omega \\ \text{or finitely many orbits of type } Z\}$$

is a  $\Sigma_4^0$ -complete set.

*Proof.* The set  $DCI$  is  $\Sigma_4^0$  since  $\mathcal{A}_e$  has finitely many infinite orbits of type  $\omega$  or of type  $Z$  if and only if one of the following two cases holds.

*Case I:* There exists a finite sequence  $a_0, \dots, a_k$  such that for every  $b$ , if  $b \notin \mathcal{O}(a_i)$  for any  $i \leq k$ , then  $\mathcal{O}(b)$  does not have type  $\omega$ .

*Case II:* There exists a finite sequence  $a_0, \dots, a_k$  such that for every  $b$ , if  $b \notin \mathcal{O}(a_i)$  for any  $i \leq k$ , then  $\mathcal{O}(b)$  does not have type  $Z$ .

It follows from Lemma 2.1 that the condition in Case I is  $\Sigma_3^0$ , and the condition in Case II is  $\Sigma_4^0$ . For completeness, let  $C$  be any  $\Pi_4^0$  set. Then there is a  $\Pi_2^0$  relation  $Q$  such that for every  $e$ , we have  $e \in C$  if and only if  $\{n : Q(e, n)\}$  is infinite. Since  $Q$  is  $\Pi_2^0$ , there is a computable relation  $R$  such that  $Q(e, n)$  if and only if  $\{r : R(e, n, r)\}$  is infinite. That is,  $e \in C$  if and only if there are infinitely many  $n$  such that there are infinitely many  $r$  for which  $R(e, n, r)$  holds. We may

assume that  $R$  is defined in stages, as  $R_s$ , so that  $R_{s+1} - R_s$  contains at most one element  $(e, n, r)$  for each  $s$  and that  $e + n + r \leq s$ .

We now define a reduction  $g$  such that for any  $e$ ,  $\mathcal{A}_{g(e)}$  has only infinite orbits, and has infinitely many orbits of type  $Z$  if and only if  $e \in C$ . We first define a reduction  $f$  so that  $\mathcal{A}_{f(e)}$  has infinitely many orbits of type  $Z$  if and only if  $e \in C$ , and then modify the construction to obtain  $\mathcal{A}_{g(e)}$  as the disjoint union of  $\mathcal{A}_{f(e)}$  with a computable structure consisting of an infinite number of orbits of type  $\omega$ .

As in the proof of Theorem 6.4, the orbits of  $\mathcal{A}_{f(e)}$  will be exactly the orbits  $\mathcal{O}(2i+1)$  for  $i \in \mathbb{N}$ , and the even numbers will be used to fill out the orbits. The injection  $\phi_{f(e)}$  will be defined in stages, as  $\phi_{f(e)}^s$ , so that for  $i \leq s$ , we have defined  $\phi_{f(e)}^t(2i+1)$  for all  $t \leq s$ .

At stage  $s+1$ , we do the following. For  $i \leq s$ , we extend each orbit  $\mathcal{O}(2i+1)$  by defining  $\phi_{f(e)}^{s+1}(2i+1)$  to be the next available even number. We begin the orbit  $\mathcal{O}(2s+3)$  by defining  $\phi_{f(e)}^t(2s+3)$  for  $t \leq s+1$  as the next  $s+1$  even numbers.

Finally, if  $(e, n, r)$  enters  $R$  at stage  $s+1$ , then we add a new element to the front of  $\mathcal{O}(2n+1)$ . That is, let  $b$  be the unique element of  $\mathcal{O}(2n+1)$  at stage  $s$  that is not in  $\text{Ran}(\phi_{f(e),s})$ , let  $2a$  be the next available even number, and let  $\phi_{f(e)}^{s+1}(2a) = b$ .

The following facts are immediate from the construction.

1. For every  $n$ ,  $\mathcal{O}_{f(e)}(2n+1)$  is infinite and has type  $Z$  if and only if  $\{r : R(e, n, r)\}$  is infinite.
2. The function  $\phi_{f(e)}$  is total, one-to-one, and onto.

It follows from Fact 2 that  $f(e) \in \text{Inj}$  for all  $e$ . It follows from Fact 1 that  $\mathcal{A}_{f(e)}$  has infinitely many orbits of type  $Z$  if and only if  $e \in C$ .

Finally, let  $\mathcal{B}$  be a computable structure consisting of an infinite number of orbits, each of type  $\omega$ , and let  $\mathcal{A}_{g(e)}$  be the disjoint union of  $\mathcal{B}$  with  $\mathcal{A}_{f(e)}$ . It follows that  $g(e) \in \text{DCI} \Leftrightarrow e \notin C$ . Therefore,  $\text{DCI}$  is  $\Sigma_4^0$ -complete.  $\square$

Next, we consider the complexity of the *isomorphism problem* for infinite computable injection structures.

**Theorem 6.6.** *The set  $\{(i, j) : \mathcal{A}_i \text{ is isomorphic to } \mathcal{A}_j\}$  is  $\Pi_4^0$ -complete.*

*Proof.* For the upper bound on the complexity, observe that  $\mathcal{A}_i$  is isomorphic to  $\mathcal{A}_j$  if and only if they have the same character and the same number of infinite orbits of each type. In particular, for the most complicated case, it must be that for every  $n$ , if  $\mathcal{A}_i$  has at least  $n$  orbits of type  $Z$ , then in  $\mathcal{A}_j$  there must exist at least  $n$  elements, all in different orbits of type  $Z$ . Since being in an orbit of type  $Z$  is  $\Pi_2^0$ , it is easy to see that the overall definition is  $\Pi_4^0$ .

For completeness, fix a structure  $\mathcal{A}_j$  with infinitely many orbits of type  $\omega$  and infinitely many orbits of type  $Z$ . Let  $Q$  be an arbitrary unary  $\Pi_4^0$  relation, so that there is a computable ternary relation  $R$  such that for every  $e$ ,

$$e \in Q \Leftrightarrow (\exists^\infty n)(\exists^\infty k)R(n, k, e),$$

where the quantifier  $\exists^\infty$  stands for “there exist infinitely many.”

Define a computable function  $f$  by constructing  $\mathcal{A}_{f(e)}$  as follows. Each orbit will be  $\mathcal{O}(4n)$  for some  $n$ . Odd numbers will be used to fill out the orbits. At each stage  $s$ , we will have finite chains of length  $\geq s$  containing  $4n$  for each  $n < s$ . At stage  $s + 1$ , we do the following:

(i) Start a new chain for  $4s$  of length  $s + 1$  by letting  $t_1 < \dots < t_s$  be the least odd numbers which have not been used in the construction up to this point, and define  $f_e(4s) = t_1$  and  $f_e(t_i) = t_{i+1}$  for  $1 \leq i < s$ ;

(ii) Add a new odd number at the end of each previous chain starting at  $4n$  for  $n < s$ ; and

(iii) For every  $n < s$ , if  $R(n, s + 1, e)$  holds, then add a new odd number at the beginning of the finite chain containing  $4n$ .

Observe that for each  $n$ , if there exist infinitely many  $k$  such that  $R(n, k, e)$ , then in the construction we will add a new element to the front of  $\mathcal{O}(4n)$  infinitely often, so that  $\mathcal{O}(4n)$  will have type  $Z$ . Finally, use the numbers that are equivalent to  $2 \pmod{4}$  to build infinitely many orbits of type  $\omega$ .

Suppose first that  $e \in Q$ . Then, by the argument above,  $\mathcal{A}_{f(e)}$  will have infinitely many orbits of type  $Z$ , in addition to having infinitely many orbits of type  $\omega$ . It follows that  $\mathcal{A}_{f(e)}$  will be isomorphic to  $\mathcal{A}_j$ . On the other hand, if  $e \notin Q$ , then only finitely many of the orbits  $\mathcal{O}(4n)$  will have type  $Z$ , so  $\mathcal{A}_{f(e)}$  will not be isomorphic to  $\mathcal{A}_j$ .  $\square$

Next, we investigate the complexity of the *computable isomorphism problem* for injection structures.

**Theorem 6.7.** *The set  $\{(i, j) : \mathcal{A}_i \text{ is computably isomorphic to } \mathcal{A}_j\}$  is  $\Sigma_3^0$ -complete.*

*Proof.* As usual, this set is  $\Sigma_3^0$  since its description asks for the existence of a total computable function that is an isomorphism. For completeness, let  $\mathcal{A}_j = (\mathbb{N}, f)$  be a fixed structure with infinitely many orbits of type  $\omega$  and infinitely many orbits of type  $Z$ , in which  $\text{Ran}(f)$  is a computable set, the set of all elements belonging to orbits of type  $Z$  is computable, and the set  $\{(a, b) : a, b \text{ are in the same orbit}\}$  is also computable. Note that any two injection structures with these properties will be computably isomorphic.

Recall that the set  $\text{Comp} = \{e : W_e \text{ is computable}\}$  is  $\Sigma_3^0$ -complete. We shall define a computable function  $f$  so that for every  $e \in \mathbb{N}$ ,  $e \in \text{Comp}$  if and only if  $\mathcal{A}_{f(e)}$  is computably isomorphic to  $\mathcal{A}_j$ . We begin with a copy  $\mathcal{A}^*$  of  $\mathcal{A}_j$  containing the odd numbers as elements and with the nice properties described above. Next, we construct  $\mathcal{B}_{f(e)}$  as follows. Every orbit of  $\mathcal{A}_{f(e)}$  will be  $\mathcal{O}(4n)$  for some  $n$ . Numbers of the form  $4n + 2$  will be used to fill out the orbits. At stage  $s$ , each orbit will extend forward and backward from  $4n$ . At stage  $s + 1$ , if  $n$  comes into  $W_e$ , then we stop adding elements to the front of the orbit  $\mathcal{O}(4n)$ . Thus, if  $n \in W_e$ , then  $\mathcal{O}(4n)$  will have type  $\omega$ , and otherwise it will have type

$Z$ . The structure  $\mathcal{A}_{f(e)}$  is defined to be the disjoint union of the structures  $\mathcal{A}^*$  and  $\mathcal{B}_{f(e)}$ . Notice that for every  $n$ ,  $\mathcal{O}(4n)$  has type  $Z$  if and only if  $n \in W_e$ . Thus, if  $e \notin \text{Comp}$ , then  $\mathcal{A}_{f(e)}$  cannot be computably isomorphic to  $\mathcal{A}_j$ . On the other hand, if  $e \in \text{Comp}$ , then  $\mathcal{A}_{f(e)}$  will have the properties described above, and hence will be computably isomorphic to  $\mathcal{A}_j$ .  $\square$

## 7 $\Sigma_1^0$ Injection Structures

Recall that an injection structure  $(A, f)$  is said to be a  $\Sigma_1^0$  *injection structure* if  $A$  is an infinite  $\Sigma_1^0$  set and  $f$  is the restriction of a partial computable function to  $A$ . The complexities of orbits and the character for  $\Sigma_1^0$  injection structures are unchanged from those for computable structures.

**Lemma 7.1.** *For every  $\Sigma_1^0$  injection structure  $\mathcal{A} = (A, f)$ :*

- (a)  $\{(k, a) : a \in \text{Ran}(f^k)\}$  is a  $\Sigma_1^0$  set,
- (b)  $\{(a, k) : \text{card}(\mathcal{O}_f(a)) \geq k\}$  is a  $\Sigma_1^0$  set,
- (c)  $\{a : \mathcal{O}_f(a) \text{ is infinite}\}$  is a  $D_1^0$  set, in fact, the intersection of a  $\Pi_1^0$  set with  $A$ ,
- (d)  $\{a : \mathcal{O}_f(a) \text{ has type } Z\}$  is a  $\Pi_2^0$  set,
- (e)  $\{a : \mathcal{O}_f(a) \text{ has type } \omega\}$  is a  $\Sigma_2^0$  set, and
- (f)  $\chi(\mathcal{A})$  is a  $\Sigma_1^0$  set.

*Proof.* It is a straightforward extension of the proof of Lemma 2.1.  $\square$

Since the character of any  $\Sigma_1^0$  structure is  $\Sigma_1^0$ , the following result is immediate from Proposition 2.2.

**Proposition 7.2.** *Any  $\Sigma_1^0$  injection structure is isomorphic to a computable injection structure.*

In fact, there is always a computable isomorphism.

**Proposition 7.3.** *For any  $\Sigma_1^0$  injection structure  $\mathcal{A}$ , there exists a computable injection structure  $\mathcal{B}$  and a computable isomorphism from  $\mathcal{B}$  onto  $\mathcal{A}$ .*

*Proof.* Let  $A$  be a  $\Sigma_1^0$  set and let  $f$  be a partial computable function such that the restriction of  $f$  to  $A$  is an injection. Let  $\phi$  be a computable one-to-one enumeration of  $A$ . Then define  $\mathcal{B} = (\mathbb{N}, g)$  by letting  $g(b) = \phi^{-1}(f(\phi(b)))$ . The mapping  $\phi : \mathcal{B} \rightarrow \mathcal{A}$  is the desired computable isomorphism. The inverse mapping  $\phi^{-1}$  maps  $\mathcal{A}$  onto  $\mathcal{B}$  and is partial computable with domain  $A$ .  $\square$

**Theorem 7.4.** *If  $\mathcal{A}_1$  and  $\mathcal{A}_2$  are isomorphic  $\Sigma_1^0$  injection structures with finitely many infinite orbits, then there is an isomorphism  $\psi : \mathcal{A}_1 \rightarrow \mathcal{A}_2$  such that both  $\psi$  and  $\psi^{-1}$  are partial computable.*

*Proof.* Let the computable structures  $\mathcal{B}_1$  and  $\mathcal{B}_2$  be given by Proposition 7.3, together with partial computable isomorphisms  $\phi_i : \mathcal{B}_i \rightarrow \mathcal{A}_i$  for  $i = 1, 2$ . Since  $\mathcal{B}_1$  is computably categorical, there is a computable isomorphism  $g : \mathcal{B}_1 \rightarrow \mathcal{B}_2$ . Now define  $\psi : \mathcal{A}_1 \rightarrow \mathcal{A}_2$  by  $\psi(a) = \phi_2(g(\phi_1^{-1}(a)))$ .  $\square$

The following result is proved similarly, using Theorem 3.1.

**Theorem 7.5.** *If  $\mathcal{A}_1$  and  $\mathcal{A}_2$  are isomorphic  $\Sigma_1^0$  injection structures with finitely orbits of type  $Z$  or finitely many orbits of type  $\omega$ , then there is a  $\Delta_2^0$  isomorphism  $\psi : \mathcal{A}_1 \rightarrow \mathcal{A}_2$ .*

Now we can use Theorem 3.6 and Proposition 7.3 to establish the following results.

**Theorem 7.6.** *If  $\mathcal{A}_1$  and  $\mathcal{A}_2$  are isomorphic  $\Sigma_1^0$  injection structures, then there is a  $\Delta_3^0$  isomorphism  $\psi : \mathcal{A}_1 \rightarrow \mathcal{A}_2$ .*

**Proposition 7.7.** *For any d.c.e. set  $B$ , there is a  $\Sigma_1^0$  injection structure  $\mathcal{A} = (A, f)$  such that  $B$  is 1 – 1 reducible to  $A - Fin(\mathcal{A})$ .*

*Proof.* Let  $B = C - D$ , where  $C$  and  $D$  are c.e. sets and  $D \subset C$ . Let  $A = \{2n + 1 : n \in C\} \cup \{2n : n \in \mathbb{N}\}$ . For each  $n$ , we begin to define the orbit of  $2n + 1$  in  $\mathcal{A}$  by setting  $f(2n + 1) = 2(2n + 1)$ ,  $f(2(2n + 1)) = 2^2(2n + 1)$ , and so on, until we see that  $n \in D$  at some stage  $s + 1$ . Then let  $f(2^s(2n + 1)) = 2n + 1$ , and for  $t > s$ , let  $f(2^t(2n + 1)) = 2^{t+1}(2n + 1)$ . It follows that for each  $n$ ,  $n \in B \Leftrightarrow 2n + 1 \in A - Fin(\mathcal{A})$ .  $\square$

## 8 $\Pi_1^0$ Injection Structures

Recall that an injection structure  $(A, f)$  is a  $\Pi_1^0$  injection structure if  $A$  is an infinite  $\Pi_1^0$  set and  $f$  is the restriction of a partial computable function to  $A$ . The complexities of orbits and the character for  $\Pi_1^0$  injection structures are higher than those for computable structures.

**Lemma 8.1.** *For every  $\Pi_1^0$  injection structure  $\mathcal{A} = (A, f)$ :*

- (a)  $\{(k, a) : a \in Ran(f^k)\}$  is a  $\Sigma_2^0$  set, although each orbit of  $\mathcal{A}$  is a d.c.e. set,
- (b)  $\{(a, k) : card(\mathcal{O}_f(a)) \geq k\}$  is a  $\Pi_1^0$  set,
- (c)  $\{a : \mathcal{O}_f(a) \text{ is finite}\}$  is a  $D_1^0$  set, the intersection of  $A$  with a c.e. set,
- (d)  $\{a : \mathcal{O}_f(a) \text{ has type } Z\}$  is a  $\Pi_3^0$  set,
- (e)  $\{a : \mathcal{O}_f(a) \text{ has type } \omega\}$  is a  $\Sigma_3^0$  set, and
- (f)  $\chi(\mathcal{A})$  is a  $\Sigma_2^0$  set.

*Proof.* In the first part of (a) and in (d), (e) and (f), we are quantifying over the  $\Pi_1^0$  set  $A$ , which increases the complexity. For the second part of (a), the orbit of any  $a \in A$  is

$$\{x : (\exists n)[f^n(a) = x] \vee [x \in A \wedge (\exists n)(f^n(x) = a)]\}.$$

□

Next, we show that there are  $\Pi_1^0$  injection structures that have arbitrary non-trivial  $\Sigma_2^0$  characters, so there are  $\Pi_1^0$  injection structures that are not isomorphic to computable injection structures.

**Theorem 8.2.** *For any  $\Sigma_2^0$  character  $K$ , which is both infinite and co-infinite, there is a  $\Pi_1^0$  injection structure with character  $K$  and with any finite or countably infinite number of orbits of type  $Z$  and type  $\omega$ .*

*Proof.* Let  $K$  be a  $\Sigma_2^0$  character, which is both infinite and co-infinite. Clearly, it suffices to construct a  $\Pi_1^0$  injection structure  $\mathcal{A} = (A, f)$  with character  $K$  and with no infinite orbits. Let  $R$  be a computable relation so that for all  $n, k > 0$ ,  $(n, k) \in K$  if and only if  $\{t : R(n, k, t)\}$  is finite. We may assume that for each  $t$ , there is at most one pair  $(n, k)$  such that  $R(n, k, t)$ . We begin with a computable injection structure  $\mathcal{A} = (\mathbb{N}, f)$  consisting of infinitely many orbits of size  $k$  for each  $k$ . For example, for all  $k$ , let  $f(\langle k, nk + k + i \rangle) = \langle k, nk + k + i + 1 \rangle$  for  $i < k$  and let  $f(\langle k, nk + 2k \rangle) = \langle k, nk + k \rangle$ . The  $\Pi_1^0$  set  $A$  will be defined in stages, as  $A_s$ , so that  $A_{s+1} \subseteq A_s$  and  $A = \bigcap_s A_s$ . At each stage  $s$ , there will be uniformly computable families of infinitely many orbits  $\mathcal{O}_{k,n}^s$  of size  $k$ , for each  $k \geq 1$ .

At stage  $s + 1$ , we look for the unique  $\langle n, k \rangle$  such that  $R(n, k, s + 1)$  and delete the orbit  $\mathcal{O}_{k,n}$  from the set  $A_s$  to obtain the set  $A_{s+1}$ . The remaining orbits are renamed so that  $\mathcal{O}_{k,i}^{s+1} = \mathcal{O}_{k,i}^s$  for  $i < n$ , and  $\mathcal{O}_{k,i}^{s+1} = \mathcal{O}_{k,i+1}^s$  for  $i \geq n$ .

Suppose that  $(n, k) \in K$ . Then for all  $m \leq n$ , there are just finitely many  $t$  such that  $R(m, k, t)$  so that after some stage  $s$ , we will retain the  $m$ th orbit of size  $k$  at each successive stage. Hence  $\mathcal{A}$  will have at least  $n$  orbits of size  $k$ .

Suppose that  $(n, k) \notin K$ . Then there are infinitely many  $t$  such that  $R(n, k, t)$  so that the  $n$ th orbit of size  $k$  at any stage  $s$  is eventually deleted from  $A$ . Since  $K$  is a character, this also happens for any  $i > n$ , so  $\mathcal{A}$  has at most  $n - 1$  orbits of size  $k$ . □

Now, we will consider the complexity of isomorphisms for  $\Pi_1^0$  injection structures. Since computable injection structures with finitely many infinite orbits are relatively computably categorical, we obtain the following theorem.

**Theorem 8.3.** *If  $\mathcal{A}$  and  $\mathcal{B}$  are isomorphic  $\Pi_1^0$  injection structures with only finitely many infinite orbits, then  $\mathcal{A}$  and  $\mathcal{B}$  are  $\Delta_2^0$ -isomorphic.*

In contrast to the previous positive results for  $\Pi_1^0$  equivalence structures in [3], the results for  $\Pi_1^0$  injection structures that are isomorphic to  $\Delta_2^0$ -categorical structures are mixed.

**Lemma 8.4.** *Let  $\mathcal{A} = (A, f)$  be a  $\Pi_1^0$  injection structure. Define the relation  $R_{\mathcal{A}}$  by  $R_{\mathcal{A}}(a, b)$  holds if and only if  $a$  and  $b$  are in the same orbit. Then  $\{\langle a, b \rangle : R_{\mathcal{A}}(a, b)\}$  is a d.c.e. set.*

*Proof.* Just observe that

$$R(a, b) \Leftrightarrow [a \in A \wedge b \in A \wedge (\exists n)(f^n(a) = b \vee f^n(b) = a)].$$

□

**Theorem 8.5.** *Let  $\mathcal{A} = (A, f)$  be a  $\Pi_1^0$  injection structure, which has only finitely many orbits of type  $\omega$ , such that  $\chi(\mathcal{A})$  is a  $\Sigma_1^0$  set. Then  $\mathcal{A}$  is  $\Delta_2^0$ -isomorphic to a computable structure.*

*Proof.* Suppose that  $\mathcal{A}$  has  $n$  orbits of type  $\omega$ , and  $a_1, \dots, a_n$  are the unique elements in these orbits, which are in  $A$  but not in the range of  $f$  restricted to  $A$ . It follows from Lemma 8.1 that if we are given an oracle for  $\mathbf{O}'$ , we can effectively list  $Fin(\mathcal{A}) = \{b_0 < b_1 < \dots\}$ , and we can effectively list the elements  $c_0 < c_1 < \dots$  that are in  $A - (Fin(\mathcal{A}) \cup \mathcal{O}_{\mathcal{A}}(a_1) \cup \dots \cup \mathcal{O}_{\mathcal{A}}(a_n))$ . Now let  $\mathcal{B} = (\mathbb{N}, g)$  be a computable injection structure isomorphic to  $\mathcal{A}$  such that  $Fin(\mathcal{B})$  is computable and the set of elements that lie in the  $Z$ -orbits is computable. Let  $x_1, \dots, x_n$  be the representatives of the  $\omega$ -orbits, which are not in  $Ran(g)$ , let  $Fin(\mathcal{B}) = \{y_0 < y_1 < \dots\}$ , and let  $z_0 < z_1 < \dots$  be an effective list of the elements in  $\mathbb{N}$ , which are in  $\mathbb{N} - (Fin(\mathcal{B}) \cup \mathcal{O}_{\mathcal{B}}(x_1) \cup \dots \cup \mathcal{O}_{\mathcal{B}}(x_n))$ .

Then using the lists  $b_0 < b_1 < \dots$  and  $y_0 < y_1 < \dots$  and the fact that  $f$  and  $g$  are partial computable, we can effectively construct an isomorphism  $h_2 : (Fin(\mathcal{A}), f) \rightarrow (Fin(\mathcal{B}), g)$ . Thus,  $h_1$  will be computable in  $\mathbf{O}'$ . We can extend  $h_1$  to include the  $\omega$ -orbits by defining  $h_1(f^m(a_i)) = g^m(x_i)$  for all  $1 \leq i \leq n$  and  $m \geq 0$ . Finally, we can use the lists  $c_0 < c_1 < \dots$  and  $z_0 < z_1 < \dots$  to construct an isomorphism  $h_2$  that maps the  $Z$ -orbits of  $\mathcal{A}$  onto the  $Z$ -orbits of  $\mathcal{B}$  as follows. First if  $\mathcal{A}$  has only finitely many  $Z$ -orbits, then we let  $r_1, \dots, r_p$  be a list of representatives from the  $Z$ -orbits of  $\mathcal{A}$ , and  $s_1, \dots, s_p$  be a list of representatives of the  $Z$ -orbits of  $\mathcal{B}$ . Then we define  $h_2(r_i) = s_i$  for  $i = 1, \dots, p$  and extend  $h_2$  to the  $Z$ -orbits in the obvious way. If  $\mathcal{A}$  has infinitely many  $Z$ -orbits, then using an oracle for  $\mathbf{O}'$  and Lemma 8.4, we can effectively construct a sequence  $i_0 < i_1 < \dots$  such that  $i_0 = 0$ , and  $i_1$  is the least  $i$  such that  $c_i \notin \mathcal{O}_{\mathcal{A}}(c_{i_0})$ , and for all  $k \geq 1$ ,  $i_{k+1}$  is the least  $i$  such that  $c_i \notin \bigcup_{s=0}^k \mathcal{O}_{\mathcal{A}}(c_{i_s})$ . Similarly, using an oracle for  $\mathbf{O}'$ , we can effectively construct a sequence  $j_0 < j_1 < \dots$  such that  $j_0 = 0$ , and  $j_1$  is the least  $i$  such that  $z_i \notin \mathcal{O}_{\mathcal{B}}(z_{i_0})$ , and for all  $k \geq 1$ ,  $j_{k+1}$  is the least  $i$  such that  $z_i \notin \bigcup_{s=0}^k \mathcal{O}_{\mathcal{B}}(z_{j_s})$ . Then we can define  $h_2(c_{i_s}) = z_{j_s}$  for all  $s \geq 0$ , and extend  $h_2$  so that it maps  $\mathcal{O}_{\mathcal{A}}(c_{i_s})$  to  $\mathcal{O}_{\mathcal{B}}(z_{j_s})$  in the obvious way.

Then  $h = h_1 \cup h_2$  will be computable in  $\mathbf{O}'$  so that  $h$  will be the desired  $\Delta_2^0$  isomorphism from  $\mathcal{A}$  onto  $\mathcal{B}$ . □

Note that in the proof of Theorem 8.5, if  $\mathcal{A}$  and  $\mathcal{B}$  are isomorphic  $\Pi_1^0$  injection structures, then  $h$  will still be a  $\Delta_2^0$  isomorphism because we can use an oracle for  $\mathbf{O}'$  to effectively construct the lists  $y_0 < y_1 < \dots$  and  $z_0 < z_1 < \dots$ . Thus, we have the following corollary.

**Corollary 8.6.** *If  $\mathcal{A}$  and  $\mathcal{B}$  are isomorphic  $\Pi_1^0$  injection structures with only finitely many orbits of type  $\omega$ , then  $\mathcal{A}$  and  $\mathcal{B}$  are  $\Delta_2^0$ -isomorphic.*

For  $\Pi_1^0$  injection structures with infinitely many orbits of type  $\omega$ , it is not always possible to have a  $\Delta_2^0$  isomorphism.

**Proposition 8.7.** *For any infinite, co-infinite  $\Sigma_2^0$  set  $C$ , there is a  $\Pi_1^0$  injection structure  $\mathcal{A} = (A, f)$  consisting of infinitely many orbits of type  $\omega$  and such that  $C \leq_T \text{Ran}(f)$ .*

*Proof.* Let  $C$  be a  $\Sigma_2^0$  set, which is both infinite and co-infinite. Let  $R$  be a computable relation so that for all  $n$ , we have  $n \in C$  if and only if  $\{t : R(n, t)\}$  is finite. We construct  $\mathcal{A}$  so that for each  $n$ , the element  $2(2n + 1)$  belongs to the  $n$ th orbit and will be the first element of its orbit if and only if  $n \notin C$ . At each stage  $s$  of the construction, every orbit will begin with an odd number, but this odd number will be deleted from  $A$  whenever a new  $t$  is found so that  $R(n, t)$ . Thus, if  $n \in C$ , then  $2(2n + 1) = f(a)$  for some fixed odd number  $a$ . If  $n \notin C$ , then every  $a$  such that  $f(a) = 2(2n + 1)$  at some stage  $s$  is eventually removed from  $A$ , so that  $2(2n + 1) \notin \text{Ran}(f)$ .

Here are the details of the construction. The  $\Pi_1^0$  set  $A$  will be defined in stages, as  $A_s$ , so that  $A_{s+1} \subseteq A_s$  and  $A = \bigcap_s A_s$ . The computable function  $f$  will be defined in stages, as  $f_s$ , such that  $(A_s, f_s)$  has exactly  $s$  orbits of size  $s$ . At stage 0,  $A = \mathbb{N}$  and  $f_0$  is the empty function.

There are two parts to the construction at stage  $s + 1$ . First, we add a new orbit of size  $s + 1$  as follows. Select the next available odd number  $2a + 1$ , and let  $f_{s+1}(2a + 1) = 2(2(s + 1) + 1)$ , and  $f_{s+1}(2^i(2(s + 1) + 1)) = 2^{i+1}(2(s + 1) + 1)$  for  $i = 1, 2, \dots, s - 1$ . Next, we check for  $i \leq s$ , whether  $R(i, s + 1)$  holds. If it does, then we remove the initial odd number from the orbit of  $2i + 1$  and replace it with the next available odd number  $b$ , so that  $f_{s+1}(b) = 2(2i + 1)$ . Finally, we add the  $(s + 1)$ st element  $2^s(2i + 1)$  to the orbit of  $2(2i + 1)$ , and let  $f_{s+1}(2^{s-1}(2i + 1)) = 2^s(2i + 1)$ .

Let  $A = \bigcap_s A_s$ . Then, clearly,  $A$  is a  $\Pi_1^0$  set and  $f$  is a partial computable function with domain  $A$  so that  $(A, f)$  is a  $\Pi_1^0$  injection structure. As indicated above, we have  $n \in C \Leftrightarrow 2(2n + 1) \in \text{Ran}(f)$ , so  $C \leq_T \text{Ran}(f)$ .  $\square$

**Theorem 8.8.** *For any  $\Sigma_1^0$  character  $K$ , there is a  $\Pi_1^0$  injection structure  $\mathcal{B}$  with character  $K$ , with infinitely many orbits of type  $\omega$ , and any finite number of orbits of type  $Z$ , such that  $\mathcal{B}$  is not  $\Delta_2^0$ -isomorphic to any  $\Sigma_1^0$  injection structure.*

*Proof.* Let  $C$  be a  $\Sigma_2^0$  set, which is not  $\Delta_2^0$ , and let  $\mathcal{B}_0 = (B, g_0)$  be given by Proposition 8.7 so that  $\text{Ran}(g_0)$  is not  $\Delta_2^0$ . Now build  $\mathcal{B} = (B, g)$  by adjoining a natural computable structure with character  $K$  and with the desired number of orbits of type  $Z$ . Then the range of  $g$  is the disjoint union of the range of  $g_0$  with a computable set, and is still not a  $\Delta_2^0$  set. Let  $\mathcal{A} = (A, f)$  be a computable structure given by Proposition 2.2 so that  $\mathcal{A}$  is isomorphic to  $\mathcal{B}$ , but  $\text{Ran}(f)$  is computable. If  $\phi$  were a  $\Delta_2^0$  isomorphism from  $\mathcal{A}$  onto  $\mathcal{B}$ , then  $\text{Ran}(g) = \phi[\text{Ran}(f)]$  and is, therefore, a  $\Sigma_2^0$  set. However,  $B - \text{Ran}(g) = \phi[\mathbb{N} - \text{Ran}(f)]$

and is, therefore, also a  $\Sigma_2^0$  set. It would then follow that  $\text{Ran}(g)$  is, in fact, a  $\Delta_2^0$  set. Thus  $\mathcal{A}$  and  $\mathcal{B}$  cannot be  $\Delta_2^0$ -isomorphic.

By Theorem 7.5, any  $\Sigma_1^0$  structure  $\mathcal{D}$  that is isomorphic to  $\mathcal{A}$  is, in fact,  $\Delta_2^0$ -isomorphic to  $\mathcal{A}$ . It follows that  $\mathcal{D}$  cannot be  $\Delta_2^0$ -isomorphic to  $\mathcal{B}$ .  $\square$

**Proposition 8.9.** *For any d.c.e. set  $B$ , there is a  $\Pi_1^0$  injection structure  $\mathcal{A} = (A, f)$  such that  $B$  is 1 – 1 reducible to  $\text{Fin}(\mathcal{A})$ .*

*Proof.* Let  $B = C \cap D$ , where  $C$  is a  $\Pi_1^0$  set,  $D$  is a c.e. set, and  $D \cup C = \mathbb{N}$ . Let  $A = \{2n + 1 : n \in C\} \cup \{2n : n \in \mathbb{N}\}$ . For each  $n$ , start to define the orbit of  $2n + 1$  in  $\mathcal{A}$  by having  $f(2n + 1) = 2(2n + 1)$ ,  $f(2(2n + 1)) = 4(2n + 1)$ , and so on, until we see that  $n \in D$  at some stage  $s + 1$ . Then let  $f(2^s(2n + 1)) = 2n + 1$ , and for  $t > s$ , let  $f(2^t(2n + 1)) = 2^{t+1}(2n + 1)$ . It follows that for each  $n$ ,  $n \in B \Leftrightarrow 2n + 1 \in \text{Fin}(\mathcal{A})$ .  $\square$

## 9 Injection Structures in the Ershov Hierarchy

In this section, we consider injection structures  $(A, f)$ , where  $A$  is an infinite  $n$ -c.e. set and  $f$  is the restriction of a partial computable function to  $A$ , which defines an injection on  $A$ . The complexities of orbits for  $n$ -c.e. injection structures are almost the same as that of  $\Pi_1^0$  structures.

**Lemma 9.1.** *Let  $n \geq 2$ . For every  $n$ -c.e. injection structure  $\mathcal{A} = (A, f)$ :*

- (a)  $\{(k, a) : a \in \text{Ran}(f^k)\}$  is a  $\Sigma_2^0$  set, although each orbit of  $\mathcal{A}$  is an  $n$ -c.e. set,
- (b)  $\{(a, k) : \text{card}(\mathcal{O}_f(a)) \geq k\}$  is an  $n$ -c.e. set, in fact, the intersection of  $A$  with a computable set,
- (c)  $\{a : \mathcal{O}_f(a) \text{ is infinite}\}$  is the intersection of  $A$  with a  $\Pi_1^0$  set, and is therefore  $n$ -c.e. if  $n$  is even, and  $(n + 1)$ -c.e. if  $n$  is odd,
- (d)  $\{a : \mathcal{O}_f(a) \text{ has type } Z\}$  is a  $\Pi_3^0$  set,
- (e)  $\{a : \mathcal{O}_f(a) \text{ has type } \omega\}$  is a  $\Sigma_3^0$  set, and
- (f)  $\chi(\mathcal{A})$  is a  $\Sigma_2^0$  set.

*Proof.* We only consider parts (a) and (c) since all other proofs are as before. Part (a) easily follows by writing out the definition of  $\{(k, a) : a \in \text{Ran}(f^k)\}$  and using the fact that  $A$  is a  $\Delta_2^0$  set. Note that since  $f$  is partial computable,  $\mathcal{O}_f(a) = \{x : (\exists k)(f^k(a) = x) \vee (\exists m)(f^m(x) = a)\}$  is a c.e. set. Thus,  $\mathcal{O}_A(a) = A \cap \mathcal{O}_f(a)$  is  $n$ -c.e. since the intersection of an  $n$ -c.e. set and a c.e. set is  $n$ -c.e. set. The result in (c) follows in a similar manner using the fact that for an even  $n$ , the family of  $n$ -c.e. sets is closed under intersection with  $\Pi_1^0$  sets, while for an odd  $n$ , the intersection of a  $\Pi_1^0$  set with an  $n$ -c.e. set is an  $(n + 1)$ -c.e. set.  $\square$

**Lemma 9.2.** *Let  $n \geq 1$ . For every infinite  $n$ -c.e. set  $B$ , there is a  $\Pi_1^0$  set  $A$  and a (total) computable  $1-1$  function  $\phi$  mapping  $A$  onto  $B$ .*

*Proof.* The proof is by induction on  $n$ . Certainly, for  $n = 1$ , every infinite c.e. set has a  $1-1$  enumeration. Now, let  $B$  be an infinite  $(n+1)$ -c.e. set. By induction, there are a  $\Pi_1^0$  set  $A_1$  and a computable  $1-1$  function  $\phi_1$  mapping  $A_1$  onto  $B_1$ . There are two cases. If  $n$  is odd, then  $B = B_1 \cup E$ , where  $E$  is a c.e. set, and we may assume that  $E$  is infinite and disjoint from  $B_1$ . Let  $\phi_2$  be a computable  $1-1$  enumeration of  $E$ . Now, let  $A = \{2n : n \in A_1\} \cup \{2n+1 : n \in \mathbb{N}\}$ , and define  $\phi(2n) = \phi_1(n)$  and  $\phi(2n+1) = \phi_2(n)$ . Note that  $\phi$  is a computable  $1-1$  function.

If  $n$  is even, then  $B = B_1 \cap A_2$ , where  $A_2$  is a  $\Pi_1^0$  subset of  $B_1$ . Now let  $A = \{n : \phi_1(n) \in A_2\}$ . Then  $\phi_1$  maps  $A$  onto  $B$ , as desired.  $\square$

This lemma leads to the following proposition.

**Proposition 9.3.** *For every  $n$ -c.e. injection structure  $\mathcal{A}$ , there exist a  $\Pi_1^0$  structure  $\mathcal{B}$  and a computable injection  $\phi : \mathbb{N} \rightarrow \mathbb{N}$  that maps  $\mathcal{B}$  onto  $\mathcal{A}$ .*

*Proof.* Let  $\mathcal{A} = (A, f)$  be an  $n$ -c.e. structure, so that  $f$  is a partial computable function such that the restriction of  $f$  to  $A$  is an injection. Let  $B$  be a  $\Pi_1^0$  set, and let  $\phi$  be a computable  $1-1$  function mapping  $B$  onto  $A$ . Then define  $\mathcal{B} = (B, g)$  by letting  $g(b) = \phi^{-1}(f(\phi(b)))$ . Observe that for  $b \in B$ ,  $\phi(b) \in A$ , so  $f(\phi(b)) \in A$ , and thus  $\phi^{-1}(f(\phi(b)))$  is defined and can be computed since  $\phi$  is a computable  $1-1$  function. Hence the mapping  $\phi : \mathcal{B} \rightarrow \mathcal{A}$  is the desired computable isomorphism. The inverse mapping  $\phi^{-1}$  maps  $\mathcal{A}$  onto  $\mathcal{B}$  and is partial computable with domain  $A$ .  $\square$

Combining Proposition 9.3 with Corollary 8.6, we obtain the following result.

**Corollary 9.4.** *If  $\mathcal{A}$  and  $\mathcal{B}$  are isomorphic  $n$ -c.e. injection structures with only finitely many orbits of type  $\omega$ , then  $\mathcal{A}$  and  $\mathcal{B}$  are  $\Delta_2^0$ -isomorphic.*

**Theorem 9.5.** *Let  $K$  be a  $\Sigma_2^0$  character.*

(a) *There is a 2-c.e. injection  $f$  such that  $(\mathbb{N}, f)$  has character  $K$  and infinitely many infinite orbits.*

(b) *If  $K$  has an  $s_1$ -function, then there is a 2-c.e. injection  $f$  such that  $(\mathbb{N}, f)$  has character  $K$  and no infinite orbits.*

*Proof.* (a) By a previous result from [2], there exists a computable equivalence structure  $\mathcal{B} = (\mathbb{N}, E)$  with character  $K$  and with infinitely many infinite equivalence classes. Define the injection structure  $\mathcal{A} = (\mathbb{N}, f)$  as follows. At each stage  $s$ , there will be a finite injection  $f_s : \{0, 1, \dots, s\} \rightarrow \{0, 1, \dots, s\}$  forming a collection of finite orbits. In each orbit, the largest element will have a value  $f_s(m)$ , which has never changed since being defined. At stage 0, we have  $f_0(0) = 0$ . At stage  $s+1$ , there are two cases. If  $E(i, s+1)$  holds for some  $i \leq s$ , we insert  $s+1$  into the orbit of  $i$  by taking the largest element  $m$  of this orbit and making  $f_{s+1}(m) = s+1$  and  $f_{s+1}(s+1) = f_s(m)$ . If  $E(i, s+1)$  does not hold for all  $i \leq s$ , let  $f_{s+1}(s+1) = s+1$ .

It is clear that if the equivalence class of  $a$  in  $\mathcal{B}$  is of finite size  $k$ , then  $\mathcal{O}(a)$  in  $\mathcal{A}$  will also have size  $k$ .

If the equivalence class of  $a$  is infinite, then, by the construction, if  $[a] = \{a_0 < a_1 < \dots\}$ , then in  $\mathcal{A}$ ,  $f(a_i) = a_{i+1}$  for all  $i$ , so  $\mathcal{O}(a)$  is infinite.

(b) In this case,  $\mathcal{B} = (\mathbb{N}, E)$  with no infinite orbits exists, so the construction will produce  $\mathcal{A}$  with character  $K$  and no infinite orbits.  $\square$

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