

# LINEAR ORDERS REALIZED BY C.E. EQUIVALENCE RELATIONS

EKATERINA FOKINA, BAKHADYR KHOUSSAINOV, PAVEL SEMUKHIN,  
AND DANIEL TURETSKY

ABSTRACT. Let  $E$  be a computably enumerable (c.e.) equivalence relation on the set  $\omega$  of natural numbers. We say that the quotient set  $\omega/E$  (or equivalently, the relation  $E$ ) *realizes* a linearly ordered set  $\mathcal{L}$  if there exists a c.e. relation  $\trianglelefteq$  respecting  $E$  such that the induced structure  $(\omega/E; \trianglelefteq)$  is isomorphic to  $\mathcal{L}$ . Thus, one can consider the class of all linearly ordered sets that are realized by  $\omega/E$ ; formally,  $\mathcal{K}(E) = \{\mathcal{L} \mid \text{the order-type } \mathcal{L} \text{ is realized by } E\}$ . In this paper we study the relationship between computability-theoretic properties of  $E$  and algebraic properties of linearly ordered sets realized by  $E$ . One can also define the following pre-order  $\leq_{lo}$  on the class of all c.e. equivalence relations:  $E_1 \leq_{lo} E_2$  if every linear order realized by  $E_1$  is also realized by  $E_2$ . Following the tradition of computability theory, the *lo*-degrees are the classes of equivalence relations induced by the pre-order  $\leq_{lo}$ . We study the partially ordered set of *lo*-degrees. For instance, we construct various chains and anti-chains and show the existence of a maximal element among the *lo*-degrees.

## 1. INTRODUCTION

In this paper we are interested in countable linearly ordered sets, their computably enumerable (c.e.) representations, and dependency of these representations on the underlying domains. By linear orders we always mean reflexive, transitive, and anti-symmetric binary relations such that any two elements in their domain are comparable. To explain our set-up, we start with the following known folklore result about countable linearly ordered set. For every countable linearly ordered set  $\mathcal{L} = (L; \leq_L)$  there exists a mapping  $h$  from the linearly ordered set  $(Q; \leq)$  of rational numbers onto  $\mathcal{L}$ ,  $h : Q \rightarrow L$ , such that  $h(x) \leq_L h(y)$  whenever  $x \leq y$ . Consider the kernel  $E$  of this homomorphism:

$$E = \{(x, y) \mid h(x) = h(y)\}.$$

The natural order relation  $\leq$  *respects*  $E$ , that is, for all  $x, y, x', y'$  if  $xEx'$  and  $yEy'$  then  $x \leq y$  if and only if  $x' \leq y'$ ; in addition, the induced quotient linearly ordered set  $(Q/E; \leq)$  is isomorphic to  $\mathcal{L}$ . Furthermore,  $\leq$  is a computable relation. Thus, for every countable linearly ordered set  $\mathcal{L}$  there exists an equivalence relation  $E$  on  $\omega$  and a computable relation  $\trianglelefteq$  such that  $\trianglelefteq$  respects  $E$  and the induced structure  $(\omega/E; \trianglelefteq)$  is isomorphic to  $\mathcal{L}$ . Note that if a binary relation  $\trianglelefteq$  respects  $E$  then  $\trianglelefteq$  naturally induces a relation on the quotient set  $\omega/E$ ; we use the same notation  $\trianglelefteq$  for the induced relation on  $\omega/E$ .

---

The authors acknowledge the support of the Austrian Science Fund FWF through the projects V 206 and I 1238. The second author also acknowledges partial support of Marsden Fund of Royal Society of New Zealand.

Let us refer to the isomorphism types of linearly ordered sets as *order-types*. We give the following definition central to this paper:

**Definition 1.** Let  $E$  be an equivalence relation on  $\omega$  and let  $\mathcal{L}$  be an order-type.

- (1) An  $E$ -linear order is a structure of the type  $(\omega/E; \trianglelefteq)$  where  $\trianglelefteq$  is a c.e. relation respecting  $E$  such that the induced structure  $(\omega/E; \trianglelefteq)$  is linearly ordered. We sometimes call  $(\omega/E, \trianglelefteq)$  a *linear ordering on  $E$* .
- (2) We say that  $E$  *realizes*  $\mathcal{L}$  if there exists an  $E$ -linear order isomorphic to  $\mathcal{L}$ . Otherwise, we say that  $E$  *omits* the order-type  $\mathcal{L}$ .

In order to consider effective linearly ordered sets we consider domains of the type  $(\omega/E)$  where  $E$  is a c.e. equivalence relation. We formalise this as follows:

**Definition 2.** A linear ordered set  $\mathcal{L}$  is *computably enumerable (c.e.)* if  $\mathcal{L}$  is an  $E$ -linear order for some computably enumerable equivalence relation  $E$ . Often we abuse this definition, and refer to an order-type as c.e. if it is isomorphic to a c.e. linearly ordered set.

From now on throughout the paper all our equivalence relations  $E$  are computably enumerable; furthermore, the domains  $\omega/E$  are infinite. In particular, any  $E$ -linear order is a c.e. linear order with infinite domain  $\omega/E$ .

Given a c.e. equivalence relation  $E$ , the natural class of linear orders associated with  $E$  is the following:

$$\mathcal{K}(E) = \{\mathcal{L} \mid \text{the order-type } \mathcal{L} \text{ is realized by } E\}.$$

Informally, the class  $\mathcal{K}(E)$  represents an algebraic content of the domain  $\omega/E$  in terms of linearly ordered sets realized by  $E$ . A typical question one might now ask is to describe the isomorphism types of order types realized by  $E$ .

We now provide several simple notations and results that explain the definitions given above. Some of the examples are taken from [5]. In [5] it is proved that for any  $E$ -linear order  $(\omega/E; \trianglelefteq)$  there exists a computable linear order  $(\omega; \trianglelefteq')$  such that  $\trianglelefteq'$  respects  $E$  and every  $E$ -equivalence class is an interval of the linear order  $(\omega; \trianglelefteq')$ . It is not too hard to see that if each equivalence class of  $E$  is an infinite set then the order  $(\omega; \trianglelefteq')$  can be made isomorphic to the order of the rational numbers.

Let  $X_1, \dots, X_n$  be pairwise disjoint c.e. sets such that  $\omega \setminus (X_1 \cup \dots \cup X_n)$  is infinite. Define the following c.e. equivalence relation:

$$(i, j) \in E(X_1, \dots, X_n) \iff (i = j) \vee (i, j \in X_1) \vee \dots \vee (i, j \in X_n).$$

Thus, the equivalence classes of  $E(X_1, \dots, X_n)$  are either sets  $X_1, \dots, X_n$  or singletons  $\{k\}$ , where  $k \notin X_1 \cup \dots \cup X_n$ . Equivalence relations of the form  $E(X_1, \dots, X_n)$  have been widely studied, though in a different context, e.g., in [1, 3, 4].

Note that in every  $E(X_1, \dots, X_n)$ -linear order the sets  $X_1, \dots, X_n$  represent pairwise distinct points of the order. In [5] it is proved that every linear order realized by  $E(X_1, \dots, X_n)$  is also realized by  $E(X_1, \dots, X_{n-1})$ . Furthermore, it is shown that the converse of this implication does not hold. As a consequence, one obtains that every linear order realized by  $E(X_1, \dots, X_n)$  is (isomorphic to) a computable linear order.

Consider the equivalence relation  $E(X)$ . In [5], it is shown that  $E(X)$  realizes a linear order if and only if  $X$  is one-reducible to a join of two semi-recursive sets.

Semi-recursive sets are introduced by Jockusch [7], and a set  $X$  is called semi-recursive if there exists a computable total function  $f$  of two variables such that for all  $x, y \in \omega$  we have the following:  $f(x, y) \in \{x, y\}$  and if  $\{x, y\} \cap X \neq \emptyset$  then  $f(x, y) \in X$ . The mentioned result, for instance, implies that the equivalence relation  $E(X)$  omits linear orders in each of the following cases:  $X$  is maximal,  $r$ -maximal, simple and not hypersimple, and creative.

Based on the characterisation result mentioned above, it turns out that one can give a full description of linearly ordered sets realized over  $E(X)$  in case  $X$  is a simple set [5]. Namely, in case  $X$  is a simple set any of the following three cases occurs: (1)  $E(X)$  realizes no linear order; (2) The only linear order realized over  $E(X)$  is of the type  $\omega + 1 + \omega^*$ ; (3) The linear orders realized over  $E(X)$  are precisely those of the form  $\omega + 1 + \omega^*$ ,  $\omega + n$  or  $n + \omega^*$ , where  $n \in \omega$ . There are simple sets that exhibit each of these three cases. Case (2) implies that for every  $n > 1$  there exists equivalence relation  $E_n$  such that the only linear order realized over  $E$  is  $n \cdot (\omega + 1 + \omega^*)$ .

Let  $\mathcal{L} = (L; \leq_L)$  be a linear order. An element  $a \in L$  is called *discrete* if either  $a$  is the rightmost element and  $a$  has an immediate predecessor, or  $a$  is the leftmost element and  $a$  has an immediate successor, or  $a$  has both immediate successor and predecessor. Otherwise, we say that  $a$  is a *limit point* of  $\mathcal{L}$ . The following is easy to note [5]. If a c.e. equivalence relation  $E$  has a c.e. and non-computable equivalence class, say  $A$ , then any linear order realized over  $E$  must have at least one limit point; in fact the equivalence class  $A$  represents a limit point of the order.

We now can compare equivalence relations in terms of order-types that they realize:

**Definition 3.** Let  $E_1$  and  $E_2$  be c.e. equivalence relations. We say that  $E_1$  is *lo-reducible* to  $E_2$ , written  $E_1 \leq_{lo} E_2$ , if  $\mathcal{K}(E_1) \subseteq \mathcal{K}(E_2)$ . In other words,  $E_1$  is *lo-reducible* to  $E_2$  if every order-type realized by  $E_1$  is also realized by  $E_2$ .

It is clear that  $\leq_{lo}$  is transitive and reflexive. Two equivalence relations  $E_1$  and  $E_2$  are *lo-equivalent*, written  $E_1 \equiv_{lo} E_2$ , if  $E_1 \leq_{lo} E_2$  and  $E_2 \leq_{lo} E_1$ . Following the terminology from computability theory, we refer to the equivalence classes of this relation as *lo-degrees*. Thus,  $\leq_{lo}$  induces a partial order on *lo-degrees*, and thus determines a degree structure on c.e. equivalence relations. This partial order has the least element, consisting of c.e. equivalence relations realizing no order-types. Such equivalence relations exists as mentioned above, e.g.  $E(X)$  where  $X$  is a maximal set. This partial order is infinite as it has an infinite anti-chain. Indeed, above we mentioned that for each  $n$  there exists equivalence relation  $E_n$  such that the only linear order realized over  $E$  is  $n \cdot (\omega + 1 + \omega^*)$ . This sequence  $E_n$  of equivalence relations is clearly an anti-chain. Moreover, these are atoms in the partial order of *lo-degrees*. Furthermore, the partial order  $\leq_{lo}$  has an infinite chain. This is witnessed by the result that we mentioned above: there exists a sequence c.e. sets  $X_1, X_2, \dots$  such that  $E(X_1, \dots, X_n) <_{lo} E(X_1, \dots, X_{n-1})$  [5]. In this paper we continue our study of the partial order of *lo-degrees* and its sub-orders. We note that paper [6] investigates a related topic for the various classes of graphs.

## 2. AN $\leq_{LO}$ -ANTI-CHAIN ON EQUIVALENCE RELATIONS $E(X)$

In this section we study the partial order  $\leq_{lo}$  restricted to the *lo-degrees* of equivalence relations of the type  $E(X)$ , where  $X$  is an infinite and co-infinite c.e.

set. Namely, we consider the partial order  $\leq_{lo}$  restricted to the following set

$$\mathcal{P} = \{E(X)/\equiv_{lo} \mid X \text{ is an infinite and co-infinite c.e. set}\}.$$

Our goal is to study some of the properties of this partial order. For instance, we will prove that this set has infinite chains and anti-chains.

We start with the following two simple observations. Consider the following subset  $\mathcal{S}$  of  $lo$ -degrees from  $\mathcal{P}$ :

$$\mathcal{S} = \{E(X)/\equiv_{lo} \mid X \text{ is simple}\}.$$

The results mentioned in the previous section give us the following corollary:

**Corollary 4.** The partial order  $\leq_{lo}$  on  $\mathcal{S}$  is a 3-element linear order.

*Proof.* Let  $X_1$ ,  $X_2$ , and  $X_3$  be simple sets such that (1)  $E(X_1)$  realizes no linear order (for example, a maximal set); (2) The only linear order realized over  $E(X_2)$  is of the type  $\omega + 1 + \omega^*$ ; (3) The only linear orders realized over  $E(X_3)$  are of the form,  $\omega + 1 + \omega^*$ ,  $\omega + n$  or  $n + \omega^*$ , where  $n \in \omega$ . Clearly,  $E(X_1) <_{lo} E(X_2) <_{lo} E(X_3)$ . As mentioned above, these are the only possibilities that occur for simple sets.  $\square$

Another corollary that follows from the introduction is this:

**Corollary 5.** The partial order  $\leq_{lo}$  on  $\mathcal{P}$  has a least and greatest element.

*Proof.* The least element is witnessed by  $E(X)$ , where  $X$  is a maximal set. The largest element  $E(Y)$  is witnessed by a computable set  $Y$ , as every linear order realized over any  $E(Z)$  has a computable copy, that is, realized over  $E(Y)$ .  $\square$

**Corollary 6.**  $\mathcal{S}$  is an initial segment of  $\mathcal{P}$ .

*Proof.* Suppose  $X$  is a non-simple set such that  $(\omega/E(X), \leq)$  is a linear order. Fix infinite computable  $C \subseteq \omega \setminus X$ . We can construct a new linear order by restricting to  $\leq$  on  $\omega \setminus C$  and placing  $C$  to the right of  $\omega \setminus C$ . That is, we define  $a \hat{\leq} b \iff a \leq b$  for  $a, b \in \omega \setminus C$ , and  $a \hat{\leq} b$  for  $a \in \omega \setminus C$  and  $b \in C$ . Then we can define  $\hat{\leq}$  on  $C$  to be any computable linear order we like. Thus  $E(X)$  realizes infinitely many linear orders, and so is not  $\leq_{lo}$ -below any  $lo$ -degree in  $\mathcal{S}$ .  $\square$

We would like to say a few words by comparing the standard degree structures (e.g.  $m$ -degrees and  $T$ -degrees) with the  $lo$ -degrees. First, the definition of  $lo$ -reducibility is a  $\Pi_1^1$ -definition while the definition of  $m$ -reducibility is an arithmetic definition on c.e. sets. Second, all the c.e.  $m$ -degrees (and  $T$ -degrees) are  $m$ -reducible to the  $m$ -degree of the creative set. In contrast, if  $X$  is creative then  $E(X)$  forms the least  $lo$ -degree. From this view point,  $lo$ -reducibility behaves somewhat orthogonally to  $m$ -reducibility. Third, every non-computable  $T$ -degree is witnessed by a simple set. In contrast, the simple sets  $X$ , via the mapping  $X \rightarrow E(X)$ , exhibit only three elements in the partial order  $\mathcal{P}$  by our first corollary.

Now our goal is to show that the set  $\mathcal{P}$  is infinite. We prove this by exhibiting that the partial order  $\mathcal{P}$  contains an infinite anti-chain with respect to  $lo$ -reducibility. Moreover, any two elements of the anti-chain form a minimal pair. We start with the following definition about linear orders.

**Definition 7.** A *block* in a linear order  $L$  is a subset  $B \subseteq L$  which is maximal with the property that for any two points  $x, y \in B$ , the interval  $[x, y]_L$  is finite.

Note that singletons have the described property, and thus every point from  $L$  is contained in a block. Note also that blocks are necessarily convex, and they partition  $L$  such that the ordering of  $L$  induces an ordering on the blocks. Finally, observe that every block is either finite or has order-type  $\omega, \omega^*$  or  $\zeta$  (here  $\zeta$  is the order-type of the integers).

**Definition 8.** For  $A \subseteq \{\omega, \omega^*, \zeta\} \cup \omega/\{0\}$ , the *shuffle-sum* of  $A$ , denoted  $\sigma(A)$ , is the order-type in which:

- Every block has an order-type appearing in  $A$ ;
- There is no greatest or least block; and
- For every  $\nu \in A$ , and every pair of distinct blocks  $B_0 < B_1$ , there is a block  $B_2$  with order-type  $\nu$  such that  $B_0 < B_2 < B_1$ .

**Theorem 9.** *The partial order  $\mathcal{P}$  contains an infinite anti-chain. Furthermore, any two distinct elements of the anti-chain exhibit a minimal pair.*

*Proof.* Let  $A \subseteq \omega/\{0\}$  be non-empty and computable. Let  $K$  be any nice presentation of  $1 + \sigma(A) + 1 + \sigma(A) + 1$ . By nice, we mean that  $K$  is computable, and given a point we can effectively determine the order-type of its block, and given two points we can effectively determine whether they are in the same block. Such a presentation exists since  $A$  is computable.

We will construct a set  $X$  as a c.e. interval of  $K$ . Our goal is to ensure that in any linear ordering  $(\omega/E(X), \preceq)$  on  $E(X)$ , there is an interval to the immediate left of  $X$  and an interval to the immediate right of  $X$  both of order-type  $\sigma(A)$ . We construct  $X$  using a finite-injury priority construction, which we now describe.

Let  $0$  denote the central 1-block of  $K$ . At stage  $0$ , let  $X_0 = \{0\}$ . We will grow  $X$  by expanding to the left and right of  $0$ , always maintaining a 0-1-law on blocks. That is, for any block of  $K$ , either that block is a subset of  $X$  or it is disjoint from  $X$ . So when we enumerate a point into  $X$ , we will be sure to also enumerate any other points in the same block. Indeed, at every stage  $s$ ,  $X_s$  will consist of two blocks from  $K$  and all the points between them.

We have strategies for dealing with each c.e. relation  $\preceq_e$ . Each strategy will receive a restraint  $(B_L, B_R)$  consisting of two blocks, one to the left of  $X$  and one to the right, indicating blocks that that strategy is forbidden from enumerating into  $X$ .

Given restraint  $(B_L, B_R)$ , our strategy for  $\preceq_e$  begins at stage  $s_0$  by choosing arbitrary blocks  $C_L, C_R \not\subseteq X_{s_0}$  with  $B_L <_K C_L <_K 0 <_K C_R <_K B_R$  and setting  $(C_L, C_R)$  as the restraint for lower priority strategies. Let  $H$  be the  $e$ th block of  $K$ , in some effective numbering. If  $H \not\subseteq X_{s_0}$ , then we choose  $C_L$  and  $C_R$  such that either  $H <_K C_L$  or  $C_R <_K H$ . Note that such blocks always exist, since  $X_{s_0}$  has a leftmost and rightmost block.

At stage  $s$ , we search for a pair of points  $(a, b)$  such that:

- $a, b \in \omega \setminus X_s$ ;
- $a$  and  $b$  are not in the same block;
- $0 \preceq_e b \preceq_e a$  or  $a \preceq_e b \preceq_e 0$ ; and
- We can enumerate  $a$  into  $X$  without enumerating  $b$ . That is, we must have  $B_L <_K a <_K B_R$  and one of:
  - $0 <_K a <_K b$ ;
  - $b <_K a <_K 0$ ;
  - $b <_K 0 <_K a$ ; or

$$- a <_K 0 <_K b.$$

Having found such points, we enumerate  $a$  into  $X_{s+1}$ , along with all other points in the same block as  $a$ , and all points between  $X_s$  and  $a$ . We let  $B$  be the block of  $b$ . We choose new blocks  $C'_L, C'_R \not\subseteq X_{s+1}$  such that  $B_L <_K C'_L <_K 0 <_K C'_R <_K B_R$  and either  $B <_K C'_L$  or  $C'_R <_K B$ . If  $H \not\subseteq X_{s+1}$ , then we again require that either  $H <_K C'_L$  or  $C'_R <_K H$ . We injure all lower priority strategies and set  $(C'_L, C'_R)$  as their new restraint. We then end the action for this strategy.

We arrange these strategies into a standard priority construction. Let  $-\infty$  and  $\infty$  be the leftmost and rightmost points of  $K$ . We begin by giving the highest priority strategy restraint  $(\{-\infty\}, \{\infty\})$ . Note that between injuries, each strategy acts and injures lower priority strategies at most once, and so this is finite injury.

**Claim 9.1.** *If our strategy for  $\trianglelefteq_e$  acts and is then never injured,  $(\omega/E(X), \trianglelefteq_e)$  is not a linear order on  $E(X)$ .*

*Proof.* Let  $(a, b)$  be the pair the strategy found which caused it to act. Then  $a \in X$ , and so  $a \sim_{E(X)} 0$ . Meanwhile, since the strategy is never again injured, no higher priority strategy will enumerate  $b$  into  $X$ . By the choice of restraint, no lower priority strategy will enumerate  $b$  into  $X$ . Thus  $b \notin X$ , but since either  $0 \trianglelefteq_e b \trianglelefteq_e a$  or  $a \trianglelefteq_e b \trianglelefteq_e 0$ ,  $\trianglelefteq_e$  cannot be a linear order on  $E(X)$ .  $\square$

**Claim 9.2.** *If  $(\omega/E(X), \trianglelefteq_e)$  is a linear order on  $E(X)$ , then there is an interval of  $(\omega/E(X), \trianglelefteq_e)$  of order-type  $\sigma(A) + 1 + \sigma(A)$  and containing  $X$ .*

*Proof.* Let  $(B_L, B_R)$  be the final restraint imposed on the strategy for  $\trianglelefteq_e$ . By the previous claim, the strategy for  $\trianglelefteq_e$  never acts after this restraint is imposed.

Let  $I_L = \{a \in K : B_L <_K a <_K X\}$  and  $I_R = \{a \in K : X <_K a <_K B_R\}$ . Note that  $C_L \subset I_L$  and  $C_R \subset I_R$ , so in particular these are nonempty. Moreover, if  $(B_L^f, B_R^f)$  is the final restraint imposed by the strategy for  $\trianglelefteq_f$ , and  $H \not\subseteq X$  is some block of  $K$ , then for some  $f$  either  $H <_K B_L^f$  or  $B_R^f <_K H$ . Thus  $I_L$  has no rightmost element, and  $I_R$  no leftmost, and so  $(I_L, <_K)$  and  $(I_R, <_K)$  both have order-type  $\sigma(A)$ .

Suppose there were  $a \in I_L$  and  $b \in I_R$  with  $a \trianglelefteq_e X$  and  $b \trianglelefteq_e X$ . Without loss of generality,  $a \trianglelefteq_e b \trianglelefteq_e X$ . But then  $(a, b)$  would be of one of the forms we are searching for, and the strategy would eventually see them and act, contrary to hypothesis. Symmetric reasoning holds for  $X \trianglelefteq_e a$  and  $X \trianglelefteq_e b$ . So it must be that the  $\trianglelefteq_e$  ordering places all elements of  $I_L$  on one side of  $X$ , and all elements of  $I_R$  on the other. Without loss of generality,  $I_L \trianglelefteq_e X \trianglelefteq_e I_R$ .

Now, suppose there were some  $b \in \omega/(I_L \cup X \cup I_R)$  and  $a \in I_R$  with  $X \trianglelefteq_e b \trianglelefteq_e a$ . Then either  $I_R <_K b$  and so  $a <_K b$ , or  $b <_K I_L$ , and so  $b <_K 0$ . Again,  $(a, b)$  is of one of the forms we are searching for, contrary to hypothesis. Symmetric reasoning holds for  $a \in I_L$ . So  $I_L \cup \{X\} \cup I_R$  is convex in  $(\omega/E(X), \trianglelefteq_e)$ .

Now, fix  $a \in I_R$ , and let  $D$  be the block of  $K$  containing  $a$ , and let  $G$  be the block of  $(\omega/E(X), \trianglelefteq_e)$  containing  $a$ .

**Claim 9.2.1.**  $D = G$ .

*Proof.* Suppose there is  $b \in D \setminus G$ . Without loss of generality,  $a \trianglelefteq_e b$ . Since  $b \notin G$ , there must be infinitely many points  $c$  with  $a \trianglelefteq_e c \trianglelefteq_e b$ . Choose such a  $c \notin D$ . If  $c <_K D$ , then the pair  $(c, a)$  is of one of the forms we are searching for, contrary to hypothesis. If  $D <_K c$ , then  $(b, c)$  is of the form we are searching for, contrary to hypothesis.

Suppose instead there is  $b \in G \setminus D$ . Without loss of generality,  $a <_K b$ . Since  $b \notin D$ , there must be infinitely many points  $c$  with  $a <_K c <_K b$ . Since the interval  $[a, b]_{\leq_e}$  is finite, choose such a  $c$  which is not in this interval, and is in neither  $D$  nor  $b$ 's block in  $K$ . If  $c \leq_e a$ , then  $(a, c)$  is of one of the forms we are searching for, contrary to hypothesis. If  $b \leq_e c$ , then  $(c, b)$  is of one of the forms we are searching for, contrary to hypothesis.  $\square$

The symmetric claim holds for  $a \in I_L$ .

Thus the set of blocks in  $(I_R, <_K)$  equals the set of blocks in  $(I_R, \leq_e)$ . Consider now the ordering induced on these blocks by  $<_K$  and  $\leq_e$ . If there were blocks  $H, J$  with  $H <_K J$  and  $J \leq_e H$ , then for any  $a \in H$  and  $b \in J$ ,  $(a, b)$  would be one of the forms we are searching for, contrary to hypothesis. So the two orders induce the same orderings on the blocks. Thus  $(I_R, \leq_e)$  has order-type  $\sigma(A)$ .

By symmetric reasoning,  $(I_L, \leq_e)$  has order-type  $\sigma(A)$ .  $\square$

Now, take any infinite collection of distinct computable sets  $(A_i : i \in \omega)$ , and let  $X_i$  be the c.e. set obtained by running the above construction for  $A_i$ . Then for each  $i$ , there is a linear ordering on  $E(X_i)$  (namely,  $(K_i/E(X_i), \leq_{K_i})$ , where  $K_i$  is the  $K$  of the above construction), and so  $E(X_i)$  is not the least element of our degree structure.

Further, any linear ordering on  $E(X_i)$  contains an interval around  $X$  of order-type  $\sigma(A_i) + 1 + \sigma(A_i)$ . Since  $A_i \neq A_j$  for  $i \neq j$ , it follows that there is no linear order realized on both  $E(X_i)$  and  $E(X_j)$ , and therefore  $E(X_i)$  and  $E(X_j)$  form a minimal pair. Thus  $(E(X_i) : i \in \omega)$  forms an anti-chain in  $\mathcal{P}$ .  $\square$

**Remark 10.** If  $X$  is non-computable, then every linear order realized by  $E(X)$  has a limit point represented by  $X$ . Thus, each such linear order must have at least one limit point. The linear orders constructed in this section give examples of equivalence relations of the form  $E(X)$  that only realize linear orders with infinitely many limit points. In fact, one can show that if a relation  $E(X)$  does not realize a linear order with exactly one limit point, it only realizes linear orders with infinitely many limit points.

### 3. AN $\leq_{LO}$ -CHAIN ON EQUIVALENCE RELATIONS $E(X)$

In the first paragraph of the proof of Claim 9.2.1, we made implicit use of the fact that all order-types in  $A$  were finite, which allowed us to find  $c \notin D$ . Our construction of an infinite chain will be similar, but we will use sets  $A$  containing  $\zeta$ .

**Theorem 11.** *The partial order  $\mathcal{P}$  contains an infinite chain of lo-degrees.*

*Proof.* Fix  $(A_i : i \in \mathbb{Z})$  a uniformly computable sequence of sets with  $A_i \subset A_j$  for  $i > j$ . For definiteness, let  $A_i = \{2n : n \geq i\}$  and  $A_{-i} = \{2n : n \in \omega\} \cup \{2n+1 : n < i\}$ , for  $i \in \omega$ .

Let  $K_i$  be a nice presentation of  $1 + \sigma(A_i \cup \{\zeta\}) + 1 + \sigma(A_i \cup \{\zeta\}) + 1$  uniformly in  $i$ . By nice, we again mean that given a point we can effectively determine the order-type of its block, and given two points we can effectively determine whether they are in the same block. We let  $0_i$  denote the central 1-block of  $K_i$ .

We will uniformly construct  $X_i$  a c.e. interval of  $K_i$  containing  $0_i$ , similar to the construction for the previous theorem. Simultaneously, we will construct functions  $f_i$  mapping blocks of  $K_i$  to intervals of  $K_{i-1}$  satisfying the following properties:

- (1)  $f_i$  is total on the blocks of  $K_i - X_i$ ;
- (2)  $f_i$  maps blocks of  $K_i - X_i$  to intervals of  $K_{i-1} - X_{i-1}$ ;
- (3) If  $B_0$  and  $B_1$  are distinct blocks of  $K_i - X_i$  with  $B_0 <_{K_i} B_1$ , then  $f(B_0)$  and  $f(B_1)$  are disjoint intervals of  $K_{i-1} - X_{i-1}$  with  $f(B_0) <_{K_{i-1}} f(B_1)$ ;
- (4) If  $B$  is a block of  $K_i - X_i$  with  $0_i <_{K_i} B$ , then  $0_{i-1} <_{K_{i-1}} f_i(B)$ , where  $0_i$  and  $0_{i-1}$  are the central points of  $K_i$  and  $K_{i-1}$ , respectively;
- (5) If  $B$  is a block of  $K_i - X_i$  with  $B <_{K_i} 0_i$ , then  $f_i(B) <_{K_{i-1}} 0_{i-1}$ ;
- (6) Every block of  $K_{i-1} - X_{i-1}$  is contained in some  $f(B)$  for  $B$  a block of  $K_i - X_i$ ;
- (7) If  $B$  is a block of  $K_i - X_i$  with  $|B| < \infty$ , then  $f(B)$  is a block of  $K_{i-1} - X_{i-1}$  of the same size; and
- (8) If  $B$  is a block of  $K_i - X_i$  of order-type  $\zeta$ , then  $f(B)$  has a leftmost block and a rightmost block and infinitely many elements (we allow the possibility that  $f(B)$  is a single block of order-type  $\zeta$ ).

The function  $f_i$  will be used to demonstrate that every order-type realized by  $E(X_{i-1})$  is also realized by  $E(X_i)$ . The idea is that we will pull-back linear orderings on  $E(X_{i-1})$  using  $f_i$ .

Most of the desired properties of  $f_i$  will be satisfied simply by how we choose to define  $f_i(B)$ . The only two properties that cause concern are properties 2 and 6. We will use strategies to satisfy property 6. Every block of  $K_{i-1}$  will have some strategy which waits until that block is contained in  $f_i(B)$  for some  $B$ , then restrains  $B$  from entering  $X_i$ . Of course, this restraint may be injured by higher priority strategies, but this will occur only finitely many times.

To satisfy property 2, when we define  $f_i(B)$ , we will make the promise that if  $X_{i-1}$  contains any block from  $f_i(B)$ , then  $B \subset X_i$ . So any strategy that enumerates part of  $f_i(B)$  into  $X_{i-1}$  will simultaneously enumerate  $f_i(B)$  into  $X_i$ . This means that when strategies place restraint on  $K_i$ , they are also placing restraint on  $K_{i-1}$ : if some strategy restrains  $B$  from entering  $X_i$ , it also restrains all  $C \subseteq f_i(B)$  from entering  $X_{i-1}$ . And in turn, this restrains all  $D \subseteq f_{i-1}(C)$  from entering  $X_{i-2}$ , etc.

To properly track this restraint, we will introduce additional functions  $g_{i,j}$  for  $i \geq j$ :

- We define  $g_{i,i}(B) = B$  for all blocks  $B$  of  $K_i$ ;
- If  $0_i <_{K_i} B$ , we define  $g_{i,j-1}(B)$  to be the leftmost block of  $f_j(g_{i,j}(B))$ ;
- If  $B <_{K_i} 0_i$ , we define  $g_{i,j-1}(B)$  to be the rightmost block of  $f_j(g_{i,j}(B))$ .

As we are defining the various  $f_i$  during the construction, this will simultaneously define the various  $g_{i,j}$ . By induction,  $g_{i,j}$  will be defined on all blocks of  $K_i - X_i$ , and if  $0_i <_{K_i} B$  then  $0_j <_{K_j} g_{i,j}(B)$ . If a strategy restrains  $B$  from entering  $X_i$ , then it will simultaneously restrain  $g_{i,j}(B)$  from entering  $X_j$ .

Note that restraint only propagates down the  $K_i$ : a restraint on  $K_i$  is simultaneously a restraint on  $K_j$  for all  $j < i$ , but never on any  $K_j$  with  $j > i$ . Contrapositively, enumerating elements into  $X_i$  can force the enumeration of elements into  $X_j$  for  $j > i$ , but never forces enumeration into any  $X_j$  with  $j < i$ .

*Strategy for defining all the  $f_i$ :*

We have a single global strategy responsible for defining all the  $f_i$ . We begin by defining  $f_i(\{\infty_i\}) = \{\infty_{i-1}\}$  for all  $i$ , where  $\infty_i$  is the rightmost point of  $K_i$ . Similarly, we define  $f_i(\{-\infty_i\}) = \{-\infty_{i-1}\}$  for the leftmost points.



At stage  $s$ , we let  $B$  be the least block (by Gödel number) in any  $K_i - X_{i,s}$  with  $f_i(B)$  not yet defined. We choose a block  $C$  of  $K_{i-1} - X_{i-1,s}$  of the same order-type as  $B$  and positioned so as to maintain properties 3, 4 and 5, and define  $f_i(B) = C$ . Such a  $C$  can always be found because  $f_i$  has only been defined on finitely many of the blocks by this stage, and because  $A_i \subset A_{i-1}$ , and because of the nature of shuffle-sums.

We then let  $A$  be the least block (again by Gödel number) in any  $K_i - X_{i,s}$  with  $A$  not yet contained in  $f_{i+1}(C)$  for some  $C$  a block of  $K_{i+1} - X_{i+1,s}$ . Note that  $A$  may be contained in  $f_{i+1}(C)$  for some  $C \subseteq X_{i+1,s}$ . We choose a block  $B$  with  $A <_{K_i} B$  and such that no point  $x$  with  $A <_{K_i} x <_{K_i} B$  is contained in  $f_{i+1}(C)$  for any  $C$  a block of  $K_{i+1} - X_{i+1,s}$ . We choose a block  $C$  of  $K_{i+1} - X_{i+1,s}$  of order-type  $\zeta$  and positioned so as to maintain properties 3, 4 and 5, and define  $f_{i+1}(C) = A \cup \{x : A <_{K_i} x <_{K_i} B\} \cup B$ . Such a  $C$  can always be found because  $f_{i+1}$  has only been defined on finitely many blocks by this stage, and because of the nature of shuffle-sums.

*Strategy for ensuring property 6 for block  $B$ :*

For  $B$  a block of  $K_i$ , we wait until a stage  $s$  when either we see  $B \subseteq f_{i+1}(C)$  for some  $C \not\subseteq X_{i+1,s}$ , or we see  $B \subset X_{i,s}$ . In the former case, we restrain  $C$  from entering  $X_{i+1}$ . In the latter case, we do nothing. While we are waiting, we do not permit any lower priority strategy to act.

*Strategy for  $\trianglelefteq_e$  and  $X_j$ :*

This is much the same as in the anti-chain construction. We treat the restraints slightly differently, however. If there is some  $i \geq j$  and some  $B$  a block of  $K_i - X_{i,s}$  which some higher priority strategy has restrained from entering  $X_i$ , and  $g_{i,j}(B)$  is not yet defined, we do nothing and do not permit any lower priority strategy to act. Otherwise, consider the (finitely many) blocks  $g_{i,j}(B)$  for such blocks  $B$  with  $0_i <_{K_i} B$ . We let  $B_R$  be the leftmost such block, or  $B_R = \{\infty_j\}$  if the collection of such blocks is empty. Similarly, we consider  $g_{i,j}(B)$  for blocks  $B$  restrained by higher priority strategies with  $B <_{K_i} 0_i$  and let  $B_L$  be the rightmost such block or  $\{-\infty_j\}$ . This gives us our restraint  $(B_L, B_R)$ .

The strategy then proceeds as in the anti-chain construction, so we merely summarize. We choose arbitrary blocks  $C_L$  and  $C_R$  of  $K_j - X_{j,s}$  with  $B_L <_{K_j} C_L <_{K_j} 0_i <_{K_j} C_R <_{K_j} B_R$  and restrain them from entering  $X_j$ . We then search for a pair of points  $(a, b)$  from  $K_j - X_{j,s}$  satisfying the same properties as before. Having found such points, we enumerate the block containing  $a$  and all points between  $a$  and  $0_j$  into  $X_{j,s+1}$ .

Now we must take additional action to satisfy our promises and maintain property 2. For every block  $B$  of  $K_{j+1}$  such  $g_{j+1,j}$  is defined and we have just enumerated  $g_{j+1,j}(B)$  into  $X_j$ , we must enumerate  $B$  into  $X_{j+1}$ . Simultaneously, we must enumerate all points between  $B$  and  $0_{j+1}$  into  $X_{j+1}$ . Then, for every block  $B'$  of  $K_{j+2}$  such that  $g_{j+2,j+1}$  is defined and we have just enumerated  $g_{j+2,j+1}(B')$  into  $X_{j+1}$ , we must enumerate  $B'$  into  $X_{j+2}$ . Simultaneously, we must enumerate all points between  $B'$  and  $0_{j+2}$ , etc.

Note that this is a finite process: our restraints ensure that we will never need to enumerate  $\infty_i$  or  $-\infty_i$ , and since we only ever extend the definition of a single  $f_i$  at any given stage, there are only finitely many  $i$  such that  $f_i$  has been defined

on any point other than these. Thus this process will terminate. Once it does, we once more proceed as in the anti-chain construction: we choose new blocks  $C'_L$  and  $C'_R$  to restrain, being careful that this restraint prevents  $b$  from being enumerated into  $X_j$ , and then injure all lower priority strategies and end the action.

*Full Construction:*

We arrange the various strategies into a standard priority construction, placing the global strategy responsible for defining the  $f_i$  as the highest priority strategy. Note that this highest strategy never injures lower priority strategies. All other strategies act and injure lower priority strategies at most once, and so this is finite injury.

*Verification:*

**Claim 11.1.** *The functions  $f_i$  satisfy the stated properties.*

*Proof.* That  $f_i$  is defined on all the blocks of  $K_i - X_i$  is immediate by the fact that the global strategy acts at every stage, and always chooses the Gödel least block not yet handled. Similarly, properties 3, 4 and 5 and properties 7 and 8 follow by the action of said strategy.

For property 2, note that we only enumerate into an  $X_i$  because of the action of the strategy for some  $\sqsubseteq_e$  and some  $X_j$ , and when we act for such a strategy, we explicitly ensure that we maintain this property.

Suppose that property 6 were not satisfied. Then some strategy for ensuring property 6 fails to ensure its requirement. Consider the highest priority strategy which fails, and let  $B$  a block of  $K_i - X_i$  be the block it was targeted for. Let  $s_0$  be a stage after which this strategy is never again injured. Then at every stage  $s > s_0$ , it must be that  $B$  is never contained in any  $f_{i+1}(C)$  for some  $C \not\subseteq X_{i+1,s}$ . For if there were such a  $C$ , the strategy would restrain it from entering  $X_{i+1}$ , and since the strategy is never injured, this  $C$  would witness property 6 for  $B$ , contrary to hypothesis.

So then after stage  $s_0$ , no lower priority strategy is ever permitted to act. Since the strategy is never again injured, no higher priority strategy will enumerate elements into any  $X_j$  at any stage after  $s_0$ . So for every block  $D$ , when the global strategy considers  $D$  after stage  $s_0$  and chooses a  $C$  and defines  $f_j(C) \supset D$ , that  $C$  will never be enumerated into  $X_j$ , and so the global strategy will never again consider this  $D$ . So eventually the global strategy will consider  $B$  and define such a  $C$ , contrary to hypothesis.  $\square$

**Claim 11.2.** *If the strategy for  $\sqsubseteq_e$  and  $X_j$  acts and is then never injured, then  $(\omega/E(X_j), \sqsubseteq_e)$  is not a linear order on  $E(X_j)$ .*

*Proof.* As in the anti-chain construction.  $\square$

Now, fix a c.e. relation  $\sqsubseteq$  and assume  $(\omega/E(X_j), \sqsubseteq)$  is a linear order on  $E(X_j)$ . Let  $(B_L, B_R)$  be the restraint on the strategy for  $\sqsubseteq$  and  $X_j$ . Define  $I_R = \{a \in K_j : X_j <_{K_j} a <_{K_j} B_R\}$  and  $I_L = \{a \in K_j : X_j <_{K_j} a <_{K_j} B_L\}$ .

**Claim 11.3.**  *$I_L$  and  $I_R$  both have order-type  $\sigma(A \cup \{\zeta\})$  in  $K_j$ .*

*Proof.* As in the anti-chain construction.  $\square$

**Claim 11.4.**  $\trianglelefteq$  places all elements of  $I_L$  on one side of  $X_j$  and all elements of  $I_R$  on the other.

*Proof.* As in the anti-chain construction.  $\square$

By replacing  $\trianglelefteq$  with  $\trianglelefteq^*$  if necessary, assume  $I_L \trianglelefteq X_j \trianglelefteq I_R$ .

**Claim 11.5.**  $I_L \cup X_j \cup I_R$  is an interval of  $(\omega/E(X_j), \trianglelefteq)$ .

*Proof.* As in the anti-chain construction.  $\square$

Now, fix  $a \in I_R$ , and let  $D$  be the block of  $K_j$  containing  $a$ , and let  $G$  be the block of  $(\omega/E(X_j), \trianglelefteq)$  containing  $a$ .

**Claim 11.6.** If  $D$  is finite,  $D = G$ . If  $D$  is infinite, then  $D \supseteq G$ .

*Proof.* As in Claim 9.2.1, ignoring the first half of the proof for infinite  $D$ .  $\square$

**Claim 11.7.**  $(\omega/E(X_j), \trianglelefteq) \not\cong (\omega/E(X_{j+1}), <_{K_{j+1}})$ .

*Proof.* Fix  $n \in A_j - A_{j+1}$ . In  $(\omega/E(X_j), \trianglelefteq)$ ,  $X$  is an accumulation point for blocks of size  $n$ . In  $(\omega/E(X_{j+1}), <_{K_{j+1}})$ , there are no blocks of size  $n$ .  $\square$

**Claim 11.8.**  $\trianglelefteq$  induces a well-defined linear ordering on the blocks of  $(I_R, <_{K_j})$  and  $(I_L, <_{K_j})$ , and it is the same as the ordering induced by  $<_{K_j}$ .

*Proof.* As in the anti-chain construction.  $\square$

**Claim 11.9.** There is a c.e. relation  $\hat{\trianglelefteq}$  such that  $(\omega/E(X_{j+1}), \hat{\trianglelefteq}) \cong (\omega/E(X_j), \trianglelefteq)$ .

*Proof.* Let  $C_L$  and  $C_R$  be such that  $B_L \subseteq f_{j+1}(C_L)$  and  $B_R \subseteq f_{j+1}(C_R)$ . Define

$$O_{j+1} = \{a : a <_{K_{j+1}} B_L\} \cup B_L \cup B_R \cup \{a : B_R <_{K_{j+1}} a\},$$

and

$$O_j = \{a : a <_{K_j} g_{j+1,j}(B_L)\} \cup g_{j+1,j}(B_L) \cup g_{j+1,j}(B_R) \cup \{a : g_{j+1,j}(B_R) <_{K_j} a\}.$$

Note that these are computable sets, and either these are both infinite, or  $(B_L, B_R) = (\{-\infty_j\}, \{\infty_j\})$ , in which case they both have size 2. In either case, fix  $h : O_{j+1} \rightarrow O_j$  a computable bijection.

For every block  $B$  of  $K_{j+1} - O_{j+1}$  with  $f_{j+1}(B)$  defined, fix  $h_B$  a computable bijection between  $B$  and  $f_{j+1}(B)$ . Now, we define  $\hat{\trianglelefteq}$  by pulling back along these bijections. Specifically:

- (1) If  $a, b \in O_{j+1}$ , when we see  $h(a) \trianglelefteq h(b)$  we enumerate  $a \hat{\trianglelefteq} b$ ;
- (2) If  $a, b \in K_{j+1} - O_{j+1}$ ,  $a$  and  $b$  are in different blocks and  $a <_{K_{j+1}} b$ , we enumerate  $a \hat{\trianglelefteq} b$ ;
- (3) If  $a, b \in B$  a block of  $K_{j+1} - O_{j+1}$ , when we see  $h_B(a) \trianglelefteq h_B(b)$  we enumerate  $a \hat{\trianglelefteq} b$ ;
- (4) If  $a \in K_{j+1} - O_{j+1}$  and  $b \in O_{j+1}$ , when we see  $0_j \trianglelefteq h(b)$  we enumerate  $a \hat{\trianglelefteq} b$ , and when we see  $h(b) \trianglelefteq 0_j$  we enumerate  $b \hat{\trianglelefteq} a$ ;
- (5) If  $a, b \in X_{j+1}$ , we enumerate  $a \hat{\trianglelefteq} b$  and  $b \hat{\trianglelefteq} a$ .

**Claim 11.9.1.**  $\hat{\trianglelefteq}$  is well-defined on  $\omega/E(X_{j+1})$ .

*Proof.* Suppose  $a_0, a_1 \in X_{j+1}$  and  $b \in K_{j+1}$ . We must show that  $a_0 \hat{\trianglelefteq} b \iff a_1 \hat{\trianglelefteq} b$ , and  $b \hat{\trianglelefteq} a_0 \iff b \hat{\trianglelefteq} a_1$ .

If  $b \in X_{j+1}$ , this is by case 5 of the definition.

If  $b \in O_{j+1}$ , this is by case 4.

If  $b \in K_{j+1} - X_{j+1} - O_{j+1}$ , then  $b$  cannot be in the same block as either  $a_0$  or  $a_1$ . So case 2 applies, and  $a_0 \hat{\trianglelefteq} b \iff a_0 <_{K_{j+1}} b$  and  $a_1 \hat{\trianglelefteq} b \iff a_1 <_{K_{j+1}} b$ . Since  $X_{j+1}$  is an interval of  $K_{j+1}$ , this follows.  $\square$

**Claim 11.9.2.**  $(\omega/E(X_{j+1}), \hat{\trianglelefteq})$  is antisymmetric.

*Proof.* Given  $a, b \in K_{j+1}$  distinct and not both in  $X_{j+1}$ , we must show that precisely one of  $a \hat{\trianglelefteq} b$  or  $b \hat{\trianglelefteq} a$  holds.

If  $a, b \in O_{j+1}$ , then this is by case 1 and the fact that  $\trianglelefteq$  is a linear order on  $\omega/E(X_j)$  (and  $O_j$  is disjoint from  $X_j$ ).

If  $a, b \in K_{j+1} - O_{j+1}$  are in different blocks, then case 2 applies, and this is by the fact that  $<_{K_{j+1}}$  is a linear order.

If  $a, b \in K_{j+1} - O_{j+1}$  are in the same block  $B$ , then  $B$  is disjoint from  $X_{j+1}$ , and  $f_{j+1}(B)$  is disjoint from  $X_j$ . Then this is by case 3 and the fact that  $\trianglelefteq$  is a linear order on  $\omega/E(X_j)$ .

If  $a \in K_{j+1}$  and  $b \in O_{j+1}$ , then case 4 applies, and this is by the fact that  $\trianglelefteq$  is a linear order on  $\omega/E(X_j)$ .  $\square$

**Claim 11.9.3.**  $(\omega/E(X_{j+1}), \hat{\trianglelefteq})$  is a linear order.

*Proof.* It remains to show that  $\hat{\trianglelefteq}$  is transitive. Suppose  $a \hat{\trianglelefteq} b$  and  $b \hat{\trianglelefteq} c$ . We must show that  $a \hat{\trianglelefteq} c$ . What follows is an exhaustive case analysis.

If  $b \in O_{j+1}$ , then by case 4, it cannot be that both  $a, c \in K_{j+1} - O_{j+1}$ . If both  $a, c \in O_{j+1}$ , then this is by case 1 and the fact that  $\trianglelefteq$  is transitive.

If  $a \in K_{j+1} - O_{j+1}$  and  $b, c \in O_{j+1}$ , then by case 1 we see that  $h(b) \trianglelefteq h(c)$ , while by case 4 we see that  $0_j \trianglelefteq h(b)$ . Since  $\trianglelefteq$  is transitive, we have that  $0_j \trianglelefteq h(c)$ , and so by case 4 again we have  $a \hat{\trianglelefteq} c$ .

If  $a, b \in O_{j+1}$  and  $c \in K_{j+1} - O_{j+1}$ , the reasoning is symmetric to the above.

If  $b \in K_{j+1} - O_{j+1}$  and  $a, c \in O_{j+1}$ , then by case 4 we have that  $h(a) \trianglelefteq 0_j$  and  $0_j \trianglelefteq h(c)$ , so by transitivity of  $\trianglelefteq$  we have  $h(a) \trianglelefteq h(c)$ , and so by case 1 we have  $a \hat{\trianglelefteq} c$ .

If  $a, b \in K_{j+1} - O_{j+1}$  and  $c \in O_{j+1}$ , then by two applications of case 1 we see that  $a \hat{\trianglelefteq} c$ .

If  $a \in O_{j+1}$  and  $b, c \in K_{j+1} - O_{j+1}$ , the reasoning is symmetric to the above.

If  $a, b, c \in K_{j+1} - O_{j+1}$ , and  $a$  and  $c$  are in the same block, then by case 2 and antisymmetry, either  $b$  is in the same block or  $a, b, c \in X_{j+1}$ . The former case follows by case 3 and the transitivity of  $\trianglelefteq$ , while the latter case follows by case 5.

If  $a, b, c \in K_{j+1} - O_{j+1}$ ,  $a, b \in X_{j+1}$  and  $c \notin X_{j+1}$ , then by case 2 the block of  $c$  is to the right of the block of  $b$ , so  $c$  is to the right of  $X_{j+1}$ . By case 2,  $a \hat{\trianglelefteq} b$ .

If  $a, b, c \in K_{j+1} - O_{j+1}$ ,  $b, c \in X_{j+1}$  and  $a \notin X_{j+1}$ , the reasoning is symmetric to the above.

If  $a, b, c \in K_{j+1} - O_{j+1}$ ,  $a$  and  $c$  are in different blocks, and no more than one of  $a, b$  or  $c$  is in  $X_{j+1}$ , then by case 2 the block of  $a$  is to the left of the block of  $b$ , and the block of  $b$  is to the left of the block of  $c$ , so the block of  $a$  is to the left of the block of  $c$ , and so  $a \hat{\trianglelefteq} c$  by case 2.

If  $a, c \in X_{j+1}$ , then  $a \hat{\trianglelefteq} c$  by case 5.  $\square$

Now it remains only to show that  $(\omega/E(X_{j+1}), \hat{\leq}) \cong (\omega/E(X_j), \leq)$ . We define the isomorphism  $g$  as follows:

- $g(X_{j+1}) = X_j$ ;
- For  $x \in O_{j+1}$ ,  $g(x) = h(x)$ ;
- For  $x \in B$  a block of  $K_{j+1} - O_{j+1} - X_{j+1}$ ,  $g(x) = h_B(x)$ .

By property 6 of  $f_{j+1}$  and our definitions of  $h$  and the various  $h_B$ , this map is a bijection. It remains to show that for  $a, b \in \omega/E(X_{j+1})$ , we have  $a \hat{\leq} b \iff g(a) \leq g(b)$ .

If  $a, b \in B$  a block of  $K_{j+1} - O_{j+1} - X_{j+1}$ , this is by definition.

If  $a, b \in O_{j+1}$ , this is again by definition.

If  $a = X_{j+1}$  and  $b \in O_{j+1}$ , this is again by definition.

If  $a \in K_{j+1} - O_{j+1} - X_{j+1}$  and  $b \in O_{j+1}$ , this is by the fact that  $K_{j+1} - O_{j+1}$  is an interval in  $(\omega/E(X_j), \leq)$ .

If  $a \in B_0$  and  $b \in B_1$  are distinct blocks of  $K_{j+1} - O_{j+1} - X_{j+1}$ , then using the fact that  $\leq$  induces the same ordering on the blocks of  $I_L \cup I_R \supseteq K_j - O_j - X_j$  as  $<_{K_j}$  does:

$$\begin{aligned} a \hat{\leq} b &\Rightarrow a <_{K_{j+1}} b \\ &\Rightarrow f_{j+1}(a) <_{K_j} f_{j+1}(b) \\ &\Rightarrow f_{j+1}(a) \leq f_{j+1}(b) \\ &\Rightarrow h_{B_0}(a) \leq h_{B_1}(b) \\ &\Rightarrow g(a) \leq g(b). \end{aligned}$$

By antisymmetry, this suffices.  $\square$

It follows that  $E(X_j) \leq_{lo} E(X_{j+1})$ , while  $(\omega/E(X_{j+1}), <_{K_{j+1}})$  witnesses that  $E(X_j) \not\equiv_{lo} E(X_{j+1})$ . This completes the proof.  $\square$

#### 4. THE PARTIAL ORDER $\leq_{lo}$ ON EQUIVALENCE RELATIONS $E(X_1, \dots, X_n)$

In this section we study basic properties of the partial order  $\leq_{lo}$  restricted to the following set:

$$\mathcal{P}_n = \{E(X_1, \dots, X_n) \mid X_1, \dots, X_n \text{ are c.e. sets}\}.$$

It is easy to see that if  $E(X_1, \dots, X_n)$  realizes a linear order then the sets  $X_1, \dots, X_n$  are pairwise computably separable, that is, for each  $i \neq j$  there exists a computable set  $R_{i,j}$  such that  $X_i \subseteq R_{i,j}$  and  $R_{i,j} \cap X_j = \emptyset$ . An easy proposition is the following:

**Proposition 12.** Let  $E(X_1, \dots, X_n) \in \mathcal{P}_n$  such that the sets  $X_1, \dots, X_n$  are pairwise computably separable. The following are equivalent:

- (1)  $E(X_1, \dots, X_n)$  realizes a linear order.
- (2) Each  $E(X_1), \dots, E(X_n)$  realizes a linear order.
- (3) The disjoint sum  $E(X_1) \oplus \dots \oplus E(X_n)$  realizes a linear order (note that this sum is an equivalence relation on  $\omega \times \omega$ ).

*Proof.* (1)  $\rightarrow$  (2). Let  $\mathcal{L}$  be an  $E(X_1, \dots, X_n)$ -linear order  $(\omega/E(X_1, \dots, X_n); \leq)$ . By finite intersection, there is a computable set  $R_i \supseteq X_i$  such that  $R_i$  is disjoint from every  $X_j$  for  $j \neq i$ . We define a new c.e. relation by restricting to  $\leq$  on  $R_i$  and placing all the points of  $\omega \setminus R_i$  to the right of  $R_i$  in their natural ordering. That is, we define  $\hat{\leq}$  as follows: for  $a, b \in R_i$ ,  $a \hat{\leq} b \iff a \leq b$ ; for  $a, b \notin R_i$ ,  $a \leq b \iff a \leq b$ ; for  $a \in R_i$  and  $b \notin R_i$ ,  $a \hat{\leq} b$  and  $\neg(b \hat{\leq} a)$ . Clearly this is a linear order on  $\omega/E(X_i)$ .

(2)  $\rightarrow$  (3). Let  $\preceq_i$  be a linear order realized by  $E(X_i)$ ,  $i = 1, \dots, n$ . Then if we define

$$(i, a) \preceq (j, b) \iff [(i < j) \vee (i = j \wedge a \preceq_i b)],$$

this realizes a linear order on  $E(X_i) \oplus \dots \oplus E(X_n)$ .

(3)  $\rightarrow$  (1). Consider  $R_i = \bigcap_{j \neq i} R_{i,j}$  and assume that these partition  $\omega$ . Then the map  $(i, a) \mapsto a$  is a bijection between  $R_1 \oplus \dots \oplus R_n$  and  $\omega$  which induces a bijection between the quotient sets  $R_1 \oplus \dots \oplus R_n / E(X_1) \oplus \dots \oplus E(X_n)$  and  $\omega / E(X_1, \dots, X_n)$ . By taking the linear order on  $E(X_1) \oplus \dots \oplus E(X_n)$ , restricting and pushing forward, we obtain a linear order on  $E(X_1, \dots, X_n)$ .  $\square$

As mentioned previously, an equivalence relation  $E(X_1, \dots, X_n)$  realises only linear orders with computable copies. We now show that this can fail for an equivalence relation of the form  $E(X_1, X_2, \dots)$ .

**Definition 13.** An infinite linear order is called  $\eta$ -like if every block it contains is finite.

For an  $\eta$ -like linear order  $\mathcal{L}$ , define

$$\text{blocks}(\mathcal{L}) = \{n : n \text{ is the size of a block of } \mathcal{L}\}$$

Note that  $\text{blocks}(\mathcal{L})$  necessarily omits 0.

**Theorem 14** (Lerman [8]). *There is a non-empty  $\Delta_3^0$ -set  $Z \subseteq \omega \setminus \{0\}$  with  $Z \neq \text{blocks}(\mathcal{L})$  for every computable linear order  $\mathcal{L}$ .*

**Theorem 15.** *For every non-empty  $\Sigma_3^0$ -set  $Z \subseteq \omega \setminus \{0\}$ , there is a uniformly c.e. sequence  $(X_i)_{i \in \omega}$  such that  $E(X_1, X_2, \dots)$  realises an  $\eta$ -like linear order  $\mathcal{L}$  with  $\text{blocks}(\mathcal{L}) = Z$ .*

*Proof.* We simultaneously construct  $(X_i)_{i \in \omega}$  and  $\mathcal{L}$ . Nonuniformly fix some  $k \in Z$ . Fix a quantifier-free formula  $\varphi(n, x, s)$  such that  $n \in Z \iff \exists x \exists^\infty s \varphi(n, x, s)$ . We will describe a strategy which, given  $n, x \in \omega$ , constructs  $k \cdot \mathbb{Q} + n$  when  $\exists^\infty s \varphi(n, x, s)$ , and constructs  $k \cdot \mathbb{Q} + k$  when  $\neg \exists^\infty s \varphi(n, x, s)$ .  $\mathcal{L}$  will be formed by simply concatenating the results of all of these strategies. Note that as described, we will necessarily have  $Z = \text{blocks}(\mathcal{L})$ .

Our strategy begins by choosing points  $y_0, \dots, y_{n-1}$  and indices  $i_0, \dots, i_{n-1}$ , which it lays claim to. It also lays claim to an infinite subset of the domain  $\omega$  to work with; all future points placed by this strategy will be drawn from this subset, and we will be certain to place every point in the subset. We order the points  $y_0 \triangleleft y_1 \triangleleft \dots \triangleleft y_{n-1}$  and immediately enumerate  $y_j$  into  $X_{i_j}$  for  $j < n$ . We then place  $k - 1$  points to the immediate right of each  $y_j$ . We begin building a copy of  $k \cdot \mathbb{Q}$  to the immediate left of each  $y_j$ . We then proceed in stages:

At stage  $s$ , if  $\varphi(n, x, s)$  holds, for every  $j < n - 1$  we enumerate into  $X_{i_j, s+1}$  every point  $z$  between  $y_j$  and  $y_{j+1}$ . For  $y_{n-1}$ , we enumerate into  $X_{i_{n-1}, s+1}$  the  $k - 1$  points to the immediate right of  $X_{i_{n-1}, s}$ . Thus the  $n$  points  $[y_0] \triangleleft [y_1] \triangleleft \dots \triangleleft [y_{n-1}]$  are currently adjacent. We then add a new set of  $k - 1$  points to the immediate right  $X_{i_j, s+1}$  for each  $j$ . Also, for each  $j > 0$ , we start building a new copy of  $k \cdot \mathbb{Q}$  to the immediate left of  $y_j$ ; the copy of  $k \cdot \mathbb{Q}$  to the immediate left of  $y_0$  was unaffected by this process, and we continue building it at this stage.

At stage  $s$ , if  $\varphi(n, x, s)$  does not hold, we simply continue constructing the copies of  $k \cdot \mathbb{Q}$ .

Note that if there are infinitely many  $s$  with  $\varphi(n, x, s)$  holding, then every point placed between  $y_j$  and  $y_{j+1}$  will be enumerated into  $X_{i_j}$ , and all the points placed to the right of  $y_{n-1}$  will be enumerated into  $X_{i_{n-1}}$ . So after identifying equivalent points, we have constructed a copy of  $k \cdot \mathbb{Q} + n$ , as desired.

If instead there are only finitely many  $s$  with  $\varphi(n, x, s)$  holding, then eventually  $k - 1$  points are placed to the immediate right of each  $y_j$  and those points are never enumerated into  $X_{i_j}$  (or any other  $X_i$ ). Simultaneously, a copy of  $k \cdot \mathbb{Q}$  is begun to the immediate left of each  $y_j$  and the points in that copy are never enumerated into any  $X_i$ . So after identifying equivalent points, we have constructed a copy of  $(k \cdot \mathbb{Q} + k) \cdot n \cong k \cdot \mathbb{Q} + k$ , as desired.  $\square$

**Corollary 16.** There is a uniformly c.e. sequence  $(X_i)_{i \in \omega}$  such that  $E(X_1, X_2, \dots)$  realises a linear order with no computable copy.

Now we give a full description of linearly ordered sets realized by certain equivalence relations from the class  $\mathcal{P}_n$ .

**Definition 17.** An equivalence relation  $E(X_1, \dots, X_n)$  is *n-simple* if there is a computable partition  $\omega = R_1 \sqcup \dots \sqcup R_n$  such that for each  $i$ ,  $X_i \subseteq R_i$  and  $X_i$  is simple inside  $R_i$ —that is,  $X_i$  intersects every infinite c.e. subset of  $R_i$ .

**Lemma 18.** If  $E(X_1, \dots, X_n)$  is *n-simple*, then the choice of partition is unique mod finite: for every computable partition  $\omega = S_1 \sqcup \dots \sqcup S_n$  with  $X_i \subseteq S_i$ ,  $S_i$  is determined up to a finite difference.

*Proof.* Let  $\omega = R_1 \sqcup \dots \sqcup R_n$  be a partition witnessing *n-simplicity*, and  $\omega = S_1 \sqcup \dots \sqcup S_n$  be any other partition with  $X_i \subseteq S_i$ . If there is some  $i$  with  $R_i \Delta S_i$  infinite, then there is some  $j$  with  $R_j \setminus S_j$  infinite. But then this is an infinite computable subset of  $R_j$  disjoint from  $X_j$ , contrary to hypothesis.  $\square$

Using results from [5] mentioned in the introduction we can fully characterise the order-types of linear orders realized over *n-simple* equivalence relations. For this we give the following definition:

**Definition 19.** Call an order-type *basic* if it is isomorphic to either  $\omega + i$  or  $i + \omega^*$  or  $\omega + 1 + \omega^*$ . Call an order type  $(n, s)$ -*basic* if it is isomorphic to the sum  $\mathcal{L}_1 + \dots + \mathcal{L}_n$  of  $n$  basic linear orders of which at least  $s$  have the order type  $\omega + 1 + \omega^*$ .

**Theorem 20.** Let  $E(X_1, \dots, X_n)$  be an *n-simple* equivalence relation that realises a linear order. There exists an  $s \leq n$  such that a linear order  $\mathcal{L}$  is realized over  $E(X_1, \dots, X_n)$  if and only if  $\mathcal{L}$  is  $(n, s)$ -*basic*.

*Proof.* Given a linear order  $\mathcal{L}$  realized over  $E(X_1, \dots, X_n)$ , partition  $\omega$  into  $R_1 \sqcup \dots \sqcup R_n$  with  $X_i \subseteq R_i$  and the  $R_i$  convex under  $\mathcal{L}$ 's ordering. Then  $\mathcal{L} = \mathcal{L}_{\sigma(1)} + \dots + \mathcal{L}_{\sigma(n)}$ , where each  $\mathcal{L}_i$  is realized over  $R_i/E(X_i)$ , for some permutation  $\sigma$  of  $\{1, \dots, n\}$ . Since  $X_i$  is simple inside  $R_i$ , from the results in [5] as mentioned in the introduction,  $\mathcal{L}_i$  is basic. The number  $s$  is the number of  $i$  such that the only linear order realized over  $R_i/E(X_i)$  has the order type  $\omega + 1 + \omega^*$  (since  $R_i$  is unique up to finite difference, this does not depend on the choice of partition).  $\square$

## 5. THE PARTIAL ORDER $\leq_{lo}$ HAS A MAXIMAL ELEMENT

In this section we show that  $\leq_{lo}$  has a maximal element.

**Lemma 21.** If  $E$  realises both  $(\omega, <)$  and  $(\mathbb{Q}, <)$ , then  $E$  is computable.

*Proof.* Since  $\omega$  is discrete, every equivalence class in  $E$  is computable. Of course, it remains to show that they are uniformly so, but fix  $\leq_0$  such that  $(\omega/E, \leq_0)$  realizes  $(\omega, <)$ , and nonuniformly fix a computable index for  $[e]$ , the equivalence class of the  $\leq_0$ -leftmost point. Fix  $\leq_1$  such that  $(\omega/E, \leq_1)$  realizes  $(\mathbb{Q}, <)$ . We must show that we can co-enumerate  $E$ .

Given  $a, b \in \omega$  without loss of generality we may assume that  $a \leq_1 b \leq_1 e$ . If  $(a, b) \notin E$ , then the  $\leq_1$ -interval  $([a], [b])$  contains infinitely many equivalence classes. Of course, the  $\leq_1$ -interval  $([e], \infty)$  does as well. Thus we will eventually locate points  $c, d, f \in \omega$  with  $a \leq_1 c \leq_1 d \leq_1 b \leq_1 e \leq_1 f$ ,  $c \leq_0 f \leq_0 d$  and  $f \notin [e]$ .

Note that such a triple  $(c, d, f)$  proves that  $(a, b) \notin E$ , for since equivalence classes must be convex in both  $\leq_0$  and  $\leq_1$ , if  $aEb$ , then  $aEcEdEb$ , and thus  $fEd$ , and thus  $fEe$ , which would be a contradiction. So upon finding such a triple, we may enumerate  $(a, b) \notin E$ .  $\square$

As a corollary of this lemma one gets the following result:

**Theorem 22.** *There is a  $\leq_{lo}$ -degree containing precisely the computable equivalence relations, and this degree is maximal.*

*Proof.* Necessarily a computable equivalence relation realizes every computable linear order and only the computable linear orders. Thus all computable equivalence relations share the same  $\leq_{lo}$ -degree. Denote this degree by  $\mathbf{c}$ . Then for any  $E \geq_{lo} \mathbf{c}$ ,  $E$  must realize all computable linear orders, and in particular must realize both  $(\omega, <)$  and  $(\mathbb{Q}, <)$ . It follows that  $E$  is computable, and so  $E \in \mathbf{c}$ .  $\square$

**Corollary 23.** The set of all  $lo$ -degrees is not an upper semi-lattice.

*Proof.* Let  $E$  be a computable equivalence relation. Let  $E'$  be a c.e. equivalence relation that realises a linear order with no computable copy. The existence of such equivalence relations was originally shown by Feiner [2], but an alternate proof is given in Section 4. From the above, no equivalence relation  $F$  exists such that  $E \leq_{lo} F$  and  $E' \leq_{lo} F$ .  $\square$

Note that Lemma 21 could be extended by replacing  $(\omega, <)$  by any linear order of Hausdorff rank 1 (a finite sum of  $\omega, \omega^*$  and  $n \in \omega$ ), and by replacing  $(\mathbb{Q}, <)$  by any linear order with only finitely many adjacencies. However, we will now show that the lemma fails if we try to extend to Hausdorff rank 2.

A *transversal* of an equivalence relation is a c.e. set  $X \subseteq \omega$  such that  $X$  contains precisely one point from every equivalence class. It is not hard to see that a c.e. equivalence relation has a transversal if and only if it is computable.

We now prove the following result:

**Theorem 24.** *There is a noncomputable c.e. equivalence relation  $E$  that realizes both  $(\omega^2, <)$  and  $(\mathbb{Q}, <)$ .*

*Proof.* Let  $\omega^{[i]} = \{\langle i, n \rangle : n \in \omega\}$ . On each  $\omega^{[i]}$  we define an equivalence  $E_i$  and relations  $\leq_1^i, \leq_2^i$  that respect  $E_i$  such that  $(\omega^{[i]}/E_i, \leq_1^i) \cong (\omega, \leq)$  and  $(\omega^{[i]}/E_i, \leq_2^i) \cong (\mathbb{Q}, \leq)$ . Then we let  $E$  be the disjoint union of  $E_i$ 's and define  $\leq_k$ , for  $k = 1, 2$ , as follows: if  $a \in \omega^{[i]}$  and  $b \in \omega^{[j]}$  then

$$a \leq_k b \iff i < j \text{ or } i = j \text{ and } a \leq_k^i b.$$

In this case we will have  $(\omega/E, \leq_1) \cong (\omega^2, \leq)$  and  $(\omega/E, \leq_2) \cong (\mathbb{Q}, \leq)$ .



Consider the requirements

$$R_i : \text{the range of } \varphi_i \text{ is not a transversal of } E.$$

Each  $R_i$  will work inside  $\omega^{[i]}$  and will not interfere with the other requirements. Each requirement will act at most once and is never injured. If  $R_i$  never acts then  $E_i$  will be the identity relation on  $\omega^{[i]}$ . Otherwise,  $E_i$  will have the form  $E(X)$  for some finite  $X \subseteq \omega^{[i]}$ .

Let  $(\omega, \leq_\omega)$  and  $(\omega, \leq_{\mathbb{Q}})$  be some fixed computable presentations of  $(\omega, \leq)$  and  $(\mathbb{Q}, \leq)$ , respectively. At stage  $s$  we define  $E_i^s$  and  $\leq_k^{i,s}$ , for  $k = 1, 2$ , on some finite subset  $D_i^s \subseteq \omega^{[i]}$  such that  $(D_i^s/E_i^s, \leq_1^{i,s}) \cong (\{0, \dots, s\}, \leq_\omega)$  and  $(D_i^s/E_i^s, \leq_2^{i,s}) \cong (\{0, \dots, s\}, \leq_{\mathbb{Q}})$ . In the end of the construction we will have  $E_i = \bigcup_s E_i^s$  and  $\leq_k^i = \bigcup_s \leq_k^{i,s}$ .

At stage 0 we let all  $D_i^0$ ,  $E_i^0$  and  $\leq_k^{i,0}$  be empty sets. At stage  $s+1$  we consider all  $i \leq s+1$  and for each  $R_i$  check if there are  $x, y \leq s+1$  such that  $\varphi_i^{s+1}(x) \downarrow = \langle i, 0 \rangle$  and  $\varphi_i^{s+1}(y) \downarrow = \langle i, 1 \rangle$ . If no such  $x, y$  exist or if  $R_i$  has already acted, then we extend  $D_i^s$ ,  $E_i^s$ ,  $\leq_k^{i,s}$  to  $D_i^{s+1}$ ,  $E_i^{s+1}$ ,  $\leq_k^{i,s+1}$  in such a way that  $(D_i^{s+1}/E_i^{s+1}, \leq_1^{i,s+1}) \cong (\{0, \dots, s+1\}, \leq_\omega)$  and  $(D_i^{s+1}/E_i^{s+1}, \leq_2^{i,s+1}) \cong (\{0, \dots, s+1\}, \leq_{\mathbb{Q}})$ . While doing so we also make sure that if  $E_i^s$  was the identity relation on  $D_i^s$ , then  $E_i^{s+1}$  is the identity on  $D_i^{s+1}$ . Similarly, if  $E_i^s$  had the form of  $E(X)$  for some finite  $X$  on domain  $D_i^s$ , then  $E_i^{s+1}$  also has the same form  $E(X)$  but on a larger domain  $D_i^{s+1}$ .

If we find such  $x, y$  and  $R_i$  has not acted yet, then we collapse all elements of  $D_i^s = \{0, \dots, s\}$  into one equivalence class so that  $E_i^t$  at all later stages  $t \geq s$  will have the form  $E(D_i^s)$ . After that again extend  $D_i^s$ ,  $E_i^s$ ,  $\leq_k^{i,s}$  to  $D_i^{s+1}$ ,  $E_i^{s+1}$ ,  $\leq_k^{i,s+1}$  in such a way that  $(D_i^{s+1}/E_i^{s+1}, \leq_1^{i,s+1}) \cong (\{0, \dots, s+1\}, \leq_\omega)$  and  $(D_i^{s+1}/E_i^{s+1}, \leq_2^{i,s+1}) \cong (\{0, \dots, s+1\}, \leq_{\mathbb{Q}})$ .

This completes the construction. It is not hard to see that  $E$  and  $\leq_k$ , for  $k = 1, 2$ , are c.e. relations. Moreover, each requirement  $R_i$  is satisfied, which implies that  $E$  is not computable.  $\square$

Much more needs to be done in the study of properties of  $lo$ -degrees. For instance, we do not know if there exist infinitely many maximal elements among the  $lo$ -degrees. We do not know if the set of  $lo$ -degrees is dense upward, that is, if it is true that for every non-maximal  $lo$ -degree  $x$  there exists a non-maximal  $lo$ -degree  $y$  such that  $x <_{lo} y$ .

## REFERENCES

- [1] S. Coskey, J. D. Hamkins, R. Miller. The hierarchy of equivalence relations on the natural numbers under computable reducibility. *Computability* 1(1):15–38 (2012).
- [2] L. Feiner. Orderings and Boolean algebras not isomorphic to recursive ones. PhD thesis. MIT. 1967.
- [3] E. Fokina, S. D. Friedman. On  $\Sigma_1^1$  equivalence relations over the natural numbers. *Math. Log.* Q. 58 (2012), no. 1–2, 113–124.
- [4] S. Gao, P. Gerdes. Computably enumerable equivalence relations. *Studia Logica* 67: 27–59, 2001.
- [5] A. Gavruskin, B. Khossainov, F. Stephan. Reducibilities among equivalence relations induced by recursively enumerable structures. *CDMTCS Research Report Series*, CDMTCS-449, 2014.
- [6] A. Gavryushkin, S. Jain, B. Khossainov, F. Stephan. Graphs realized by r.e. equivalence relations. *Ann. Pure Appl. Logic* 165(7-8): 1263-1290, 2014.

- [7] C. Jockusch. Semirecursive sets and positive reducibility. *Transactions of the American Mathematical Society*, 131:420–436, 1968.
- [8] M. Lerman. On recursive linear orders. *Logic Year 1979-80, Lecture Notes in Mathematics*: 132-142, 1981.