Rice sequences of relations

BY ANTONIO MONTALBÁN*

Department of Mathematics, University of Chicago, 5734 S. University Avenue, Chicago, IL 60637, USA

We propose a framework to study the computational complexity of definable relations on a structure. Many of the notions we discuss are old, but the viewpoint is new. We believe that all the pieces fit together smoothly under this new point of view. We also survey related results in the area. More concretely, we study the space of sequences of relations over a given structure. On this space, we develop notions of c.e.-ness, reducibility, join and jump. These notions are equivalent to other notions studied in other settings. We explain the equivalences and differences between these notions.

Keywords: structures; rice relations; jump

1. Introduction

The study of the complexity of definable relations over a given structure is a main theme in mathematical logic. In this study, we are interested in using computational ways of measuring the complexity of relations. The key notion of this study is the one of rice sequence of relations, where rice stands for relatively intrinsically computably enumerable. A rice relation on a structure $\mathcal{A}$ is one that is always computably enumerable relative to any given presentation of $\mathcal{A}$ (definition 3.1). Rather than looking at relations (i.e. subsets of $A^n$ for some $n$), we will look at sequences of relations that can be used, for instance, to code subsets of $A^{<\omega}$, and even subsets of $A^{<\omega} \times \mathbb{N}$. This idea of going beyond subsets of $A^n$ to develop a better theory of computability is not new, and it appears, for instance, in the work on hereditarily finite extensions or Moschovakis extensions that we will mention later. Once we have a notion of c.e.-ness (namely rice) on the space of sequences of relations over a fixed structure $\mathcal{A}$, we can define a notion of relative computability, of join and of jump. This notion of jump of a relation, or of a sequence of relations, can then be extended to the notion of the jump of a structure. Different notions of jump for structures have been developed in recent years by researchers in the computability groups of Novosibirsk and Sofia (see §§5 and 6), and by the present author.

In this study, we survey some of this recent work in the context of the study of sequences of relations. We believe that all the pieces fit together nicely under this new viewpoint, which is even slightly different from the one used by the present author in the past few years [1–3]. Much of the notation introduced in those

*Author for correspondence antonio@math.uchicago.edu

One contribution of 18 to a Theme Issue ‘The foundations of computation, physics and mentality: the Turing legacy.’
papers is revisited here. For instance, we remark that what used to be called a jump of \( A \) in Montalbán [1–3] is now called a structural jump of \( A \) defined in §6, and different from the jump of \( A \) as defined in §5.

The reason why we like the viewpoint developed here is that it is closer, in style, to the notions used by many of the people already working on computable structure theory, particularly in the West, which makes it more approachable. Of course, other researchers might disagree. This study also contains historical information explaining what the other known similar notions are, how they were developed and how they connect to the notions here.

The present author’s original motivation in this topic [1,2] was to study relations on a given structure \( A \) that contain all the structural \( \Sigma^n_c \) information about \( A \). In many cases, one can find a nice, small set of relations that, alone, give you everything you need to know about all other \( \Sigma^n_c \) relations. Finding such relations can, of course, be useful for other applications. We will talk about this in the last two sections of this study.

Most of the results in this study are not new, at least not in essence. This is except for the work in §7, where we study finite complete sets of rice relations. The work in that section was carried out during a visit to Sofia, Bulgaria, the week before CiE’11, by J. F. Knight, R. Miller, I. N. Soskov, A. Soskova, M. Soskova, S. VanDenDriessche and S. Vatev and the present author. (The author would like to thank them for allowing him to publish these results here.)

2. Background

We consider only relational languages, because functions can be coded as relations without changing the computational complexity of the objects we are interested in. Our languages are always computable. That is, they are countable and we can effectively list all their symbols and their arities. We will always use \( L \) to denote a language, where \( L = \{ P_0, P_1, \ldots \} \) is finite or infinite, and where \( P_i \) has arity \( p_i \). Because \( L \) is computable, the function \( i \mapsto p_i \) is computable. By an \( L \)-structure, we mean a tuple \( A = (A; P_0^A, P_1^A, \ldots) \), where \( P_i^A \subseteq A^{p_i} \) for all \( i \). We allow only countable structures, as we will not deal with larger structures in this study. By a copy of \( A \), or by a presentation of \( A \), we mean another structure \( B = (B; P_0^B, P_1^B, \ldots) \) that is isomorphic to \( A \) and where \( B \subseteq \mathbb{N} \). Because all our structures are countable, it does not hurt to assume that the domains are always subsets of \( \mathbb{N} \). However, the words ‘copy’ or ‘presentation’ emphasize that we are talking about this particular representation of \( A \), and not about the isomorphism type of \( A \).

Given a structure \( A \) with \( A \subseteq \mathbb{N} \), we let \( D(A) \) be the atomic diagram of \( A \). More concretely, let \( a_0, a_1, \ldots \) be constant symbols naming the elements of \( A \), where the number \( i \in \mathbb{N} \) is named by \( a_i \) (if \( i \not\in A \), then \( a_i \) does not name anybody). Let \( \varphi_0^{at}, \varphi_1^{at}, \ldots \) be an effective listing of all the atomic \( (L \cup \{a_0, a_1, \ldots \}) \) formulae. Finally, let \( D(A) \in 2^\omega \) be defined by

\[
D(A)(i) = \begin{cases} 
1, & \text{if } A \models \varphi_i^{at}, \\
0, & \text{if } A \not\models \varphi_i^{at}.
\end{cases}
\]

In particular, we let \( D(A)(i) = 0 \) if \( \varphi_i^{at} \) uses some constant \( a_j \) for which \( j \not\in A \). Notice that \( D(A) \) computes \( A \) by looking at the formulae \( a_i = a_i \).
When we say that a set \( X \) is c.e. (computable) in a structure \( A \), we mean that \( X \) is c.e. (computable) in \( D(A) \), which of course depends on the given presentation of \( A \). The spectrum of a structure \( A \) is

\[
Sp(A) = \{ x \in D : x \text{ computes a copy of } A \},
\]

where \( D \) is the set of Turing degrees. (The spectrum of \( A \) is often the set of degrees of all copies of \( A \). The two definitions are equivalent for non-trivial structures, as proved by Knight \cite{4}.)

All throughout we will use the letters \( A \), \( B \) and \( C \) to denote structures with domains \( A \), \( B \) and \( C \), and we will use the letters \( X \), \( Y \) and \( Z \) for sets of natural numbers. Unless we specify otherwise, \( A \) is always an \( L \)-structure where \( L \) is as mentioned earlier.

We will use \( \Sigma_n^{c} \) and \( \Pi_n^{c} \) to denote the set of computable infinitary \( \Sigma_n \) and \( \Pi_n \) formulae. These are first-order \( L \)-formulae in which we allow infinitary disjunctions and infinitary conjunctions so long as they are taken over a computable list of formulae, and so long as there are only finitely many different free variables over all the formulae in the list. When we count alternation of quantifiers, infinitary disjunctions count as \( \exists \) and infinitary conjunctions count as \( \forall \). See Ash & Knight \cite[ch. 7]{5} for more background on these formulae.

Given a tuple \( \bar{a} \) in \( A \), we let \( \Sigma_1\text{-}\text{tp}_{A}(\bar{a}) \), the \( \Sigma_1 \)-type of \( \bar{a} \) in \( A \), be the set of Gödel numbers of all \( \Sigma_1 \) formulae true about \( \bar{a} \) in \( A \).

We use \( P_{\text{fin}}(X) \) to denote the set of finite subsets of \( X \).

### 3. Rice relations

The following well-known notion is central to this study.

**Definition 3.1.** A relation \( R \subseteq A^n \) is rice (relatively intrinsically computably enumerable) if, for every copy \( (B, R^B) \) of \( (A, R) \), we have that \( R^B \) is c.e. in \( D(B) \).

Notice that the notion of being rice is independent of the presentation of \( A \), and depends only on its isomorphism type.

**Example 3.2.** Let \( A \) be a linear ordering. We say that \( x \) and \( y \) in \( A \) are adjacent, and write \( \text{Adj}(x, y) \), if there is no element in between them. The relation \( \neg \text{Adj}(\cdot, \cdot) \) is rice in \( A \).

We shall call a relation whose complement is rice as co-rice.

**Example 3.3.** Let \( G \) be a graph that consists of infinitely many disjoint cycles, one of each size \( n \) for \( n \geq 3 \). Let \( R \) be the set of vertices \( x \) in \( G \) such that \( x \) belongs to a cycle of size \( n \), for some \( n \in 0' \) (i.e. with \( \{n\}(n) \downarrow \)). Then, \( R \) is rice in \( G \).

The relations in the above-mentioned examples have quite a different feel to them. The former contain structural information, whereas the latter code ‘Turing-degree information’, namely \( 0' \). We will say more about this later.

The following theorem characterizes rice relations in purely syntactical terms, as opposed to the definition that refers to computations whose oracles are the diagrams of the copies of the given structure.
Theorem 3.4 (Ash et al. [6]; Chisholm [7]). Let $A$ be a structure, and $R \subseteq A^n$ a relation on it. The following are equivalent:

1. $R$ is rice.
2. $R$ is definable by a $\Sigma^c_1$ formula with parameters from $A$.

Recall that a $\Sigma^c_1$ formula is nothing more than an infinitary disjunction of a computable list of finitary $\Sigma^c_1 L$-formulae.

Once we have a notion of c.e.-ness among relations on $A$, we can develop a notion of computability.

Definition 3.5. Let $R$ and $Q$ be relations on $A$. We say that $R$ is relatively intrinsically computable in $Q$, and we write $R \leq^A_T Q$, if $R$ is both rice and co-rice in $(A, Q)$.

Historic remark 3.6. The notion of rice relation has appeared already in Ash et al. [6]—see also Ash & Knight [5, ch. 10]. The equivalent notion of $\Sigma$-definable relation on $\mathbb{HF}_A$ was used by Ershov as part of the study of admissibility over abstract structures, and is still used in Russia quite a bit. We will say more about $\Sigma$-definability in §4a. Moschovakis [8] defined an equivalent notion called a semi-search computable relation, which is also defined on an extended domain (of the sort of $\mathbb{HF}_A$), and appears often in the work of Soskov et al. The equivalence between these notions is due to Gordon [9].

(a) Sequences of relations

The space of relations on a structure $A$ is not rich enough to develop a good theory of computability because, for instance, it does not always have a universal rice relation. There are various approaches to solve this issue. One is to consider relations defined on extensions of the structure like the hereditarily finite extension (see §4a), or the Moschovakis extension [8]. Here, we take a different approach that is probably friendlier for the audience accustomed to the style of Ash & Knight’s book [5].

Definition 3.7. Let $RSeq(A)$ be the set of all sequences of relations $R = (R_0, R_1, \ldots)$, where $R_i \subseteq A^{r_i}$ and the arity function $i \mapsto r_i$ is computable.

We say that $R$ is rice in $A$ if, for every copy $(B, R^B)$ of $(A, R)$, we have that $R^B$ is uniformly c.e. in $D(B)$, that is, the set $\bigoplus_{i \in \omega} R^B_i = \{(i, \bar{b}) \subseteq \mathbb{N} \times B^{<\omega} : \bar{b} \in R^B_i\}$ is c.e. in $D(B)$.

Given $R$ and $Q \in RSeq(A)$, we say that $R$ is r.i. computable in $Q$, and write $R \leq^A_T Q$, if both $R$ and $\neg R$ are rice in $(A, Q)$, where $\neg R$ is the sequence of complements of the relations in $R$, and $(A, Q)$ is a new structure whose language is augmented with infinitely many new relations symbols $Q_i$, one for each $i \in \mathbb{N}$, interpreted in the obvious way according to $Q$.

Example 3.8. Let $V$ be a $\mathbb{Q}$-vector space. Then, $LD = (LD_2, LD_3, \ldots)$, given by $LD_i = \{(v_1, \ldots, v_i) \in V^i : v_1, \ldots, v_i$ are linearly dependent$, is rice in $V$.  

Phil. Trans. R. Soc. A (2012)
Example 3.9. Let $\mathcal{A}$ be a ring. Then, $R = (R_1, R_2, \ldots)$, given by $R_i = \{(a_0, \ldots, a_i) \in A^{i+1} : a_i x^i + \cdots + a_0 x + a_0 \text{ is a reducible polynomial}\}$, is rice in $\mathcal{A}$.

Remark 3.10. Note that we can represent not only subsets of $A^{<\omega}$ as sequences of relations, but also subsets of $A^{<\omega} \times \mathbb{N}$, for instance, by considering sequences $R = (R_{i,j} : i, j \in \mathbb{N})$ where $R_{i,j}$ has arity $i$. Furthermore, restricting ourselves to work just with subsets of $A^{<\omega} \times \mathbb{N}$ would be essentially equivalent to working with RSeq($\mathcal{A}$).

Historic remark 3.11. An equivalent notion of computability on subsets of $A^n \times \mathbb{N}^k$ for the structure $\mathcal{E} = (A; )$ on an empty language, has already been considered by Baleva [10] and Soskov [11].

(i) Information sequences

We can also use sequences of relations to code subsets of $\mathbb{N}$ in a natural way. We will allow ourselves to consider relations $R \subseteq A^r$, where $r = 0$. Recall that $A^0 = \{\langle \rangle\}$, where $\langle \rangle$ is the empty tuple, and hence either $R = \emptyset$ or $R = \{\langle \rangle\}$. In the former case, we say that $R = \perp$, and that $R = \top$ in the latter. (The reader who is uncomfortable with 0-ary relations can work with 1-ary relations $R$ instead, where either $R = \emptyset$ or $R = A$.)

Definition 3.12. If $R$ is a sequence of relations, all of arity 0, we say that $R$ is an information sequence. Given $X \subseteq \mathbb{N}$, let $X \in \text{RSeq}(\mathcal{A})$ be the information sequence $X = (X_0, X_1, \ldots)$ where

$$X_i = \begin{cases} \top, & \text{if } i \in X, \\ \perp, & \text{if } i \notin X. \end{cases}$$

We observe that $X$ is c.e. in an oracle $Z$ if and only if $X$ is c.e. in $Z$. Thus, $X$ is rice in $\mathcal{A}$ if and only if $X$ is c.e. in the diagrams of all the copies of $\mathcal{A}$. In particular, for every c.e. set $X$, $X$ is rice in $\mathcal{A}$. The set of all $X \subseteq \mathbb{N}$ such that $X$ is rice in $\mathcal{A}$, called the co-spectrum of $\mathcal{A}$ (see Soskov [11]), forms an ideal in the enumeration degrees. This ideal is characterized by a theorem of Knight (corollary 3.16) given later.

Also note that, for $X, Y \subseteq \mathbb{N}$, we have

$$X \leq_T Y \Rightarrow X \leq^A_T Y.$$ (ii) Join of sequences

We also have a least-upper-bound operation on RSeq($\mathcal{A}$).

Definition 3.13. Given $R = (R_0, R_1, \ldots)$ and $Q = (Q_0, Q_1, \ldots)$ in RSeq($\mathcal{A}$), let

$$R \oplus Q = (R_0, Q_0, R_1, Q_1, \ldots).$$

It is not hard to see that $R \oplus Q$ is the least upper bound of $R$ and $Q$ in the $\leq^A_T$-ordering.

We will sometimes abuse notation and write $R \oplus Q$, or $R_1 \oplus R_2$, even when $R, R_1, R_2$ are relations, rather than sequences of relations, interpreting a single relation $R$ by the sequence $(R, \emptyset, \emptyset, \emptyset, \ldots)$. 

Phil. Trans. R. Soc. A (2012)
(iii) The Ash–Knight–Manasse–Slaman–Chisholm theorem, revisited

This well-known theorem extends from relations to sequences of relations in a straightforward way. We include the proof here for completeness. The original proofs, which proved the result for r.i. $\Sigma^0_a$-relations, used forcing, but the rice case can be proved in a much simpler way. An interesting fact about this extended version is that it also extends two other well-known theorems, one of Knight’s and one of Selman’s. We will see how they follow as particular cases (corollaries 3.16 and 3.17).

**Theorem 3.14 (Ash et al. [6]; Chisholm [7]).** Let $\mathbf{R} = (R_0, R_1, \ldots)$ be a sequence of relations in $\mathbf{A}$. The following are equivalent:

(A1) $\mathbf{R}$ is rice.

(A2) There is a tuple $\bar{p} \in \mathbf{A}^{\omega}$ and a computable list $\phi_0, \phi_1, \ldots$ of $\Sigma^c_1$-formulae such that, for all $i \in \mathbb{N}$ and all $\bar{a} \in \mathbf{A}^c$ (where $r_i$ is the arity of $R_i$),

$$\bar{a} \in R_i \iff \mathbf{A} \models \phi_i(\bar{p}, \bar{a}).$$

**Proof.** It is easy to see that (A2) implies (A1) because deciding $\Sigma^c_1$ formulae about $\mathbf{A}$ is c.e. in $D(\mathbf{A})$. We prove the other direction. We will attempt to build a copy $\mathbf{B}$ of $\mathbf{A}$ where $R^B$ is not uniformly c.e. in $D(\mathbf{B})$. By (A1), this attempt is bound to fail, and we will use this failure to find the list of formulae $\phi_0, \phi_1, \ldots$ that we need.

Let $\mathbf{A}^*$ be the set of finite tuples from $\mathbf{A}$, all of whose entries are different. At stage $s$, we will define $\bar{p}_s \in \mathbf{A}^*$ such that $\bar{p}_{s-1} \subseteq \bar{p}_s$ (where inclusion here is as strings). At the end of stages, we will obtain $G = \bigcup_{s \in \mathbb{N}} \bar{p}_s : \mathbb{N} \to A$. Along the way, we will make sure that every element of $\mathbf{A}$ is in some $\bar{p}_s$, and hence that $G$ is a bijection between $\mathbb{N}$ and $\mathbf{A}$. We can then let $\mathbf{B}$ be the pull-back of $\mathbf{A}$ via $G$. That is, $\mathbf{B}$ has domain $\mathbb{N}$, and, if $P$ is a relation symbol of $\mathcal{L}$, $P^B(\bar{x})$ holds if and only if $P^A(G(\bar{x}))$ holds. By (A1), we know that, for some index $e$,

$$\bigoplus_{n \in \mathbb{N}} R^B_n = W^D(\mathbf{B}).$$

Given $\bar{q} \in \mathbf{A}^*$, we let $D(\bar{q})$ be the initial segment of $D(\mathbf{B})$ of length $|\bar{q}|$, which is determined by $\bar{q}$, assuming we have that $\bar{q} \subseteq G$. More formally, let $\{b_0, b_1, \ldots\}$ be a list of constant symbols where $b_j$ is interpreted as $i$ in $\mathbf{B}$, and let $\{\varphi_i^{at} : i \in \mathbb{N}\}$ be a list of all atomic $\mathcal{L} \cup \{b_0, \ldots\}$-sentences, and assume that $\varphi_i^{at}$ only uses constants $b_j$ for $j \leq i$. Given $\bar{q} = (q_0, \ldots, q_{k-1}) \in \mathbf{A}^*$, let $D(\bar{q}) \in 2^k$ be such that $D(\bar{q})(i) = 1$ if and only if $\mathbf{A} \models \varphi^{at}_i[b_j \mapsto q_j : j < k]$. This way we have that

$$D(\mathbf{B}) = \bigcup_{s \in \mathbb{N}} D(\bar{p}_s).$$

For $\sigma \in 2^{\omega}$, we let $W^S_e$ be the step $|\sigma|$ approximation to $W^S_e$ for any $S \supseteq \sigma$, noticing that $W^S_e$ cannot read the oracle $S$ beyond position $|\sigma|$ in less than $|\sigma|$ steps. So we have that $W^{D(\mathbf{B})}_e = \bigcup_{s \in \mathbb{N}} W^{D(\bar{p}_s)}_e$. We also notice that for $\sigma \in 2^k$ there is an atomic formula $\psi_\sigma$ such that $D(\bar{q}) = \sigma \iff \mathbf{A} \models \psi_\sigma(\bar{q})$.

Phil. Trans. R. Soc. A (2012)
Now that we have got the background notation out of the way, here is the construction. Let \( \tilde{p}_0 \) be the empty sequence. At stage \( s + 1 = 2e \), we try to force \( \bigoplus_{n \in \mathbb{N}} R_n^B \neq W_e^{D(B)} \) as follows. Ask if there exist \( n \in \mathbb{N}, \bar{j} = (j_1, \ldots, j_n) \in \mathbb{N}^n \) and \( \bar{q} \supseteq \tilde{p}_s \), such that \( (n, \bar{j}) \in W_e^{D(\tilde{q})} \) but \( \mathcal{A} \not\models R_n(q_j) \) (where \( q_j = (q_{j_1}, \ldots, q_{j_n}) \)). If so, let \( \tilde{p}_{s+1} \) be such \( \bar{q} \), and otherwise let \( \tilde{p}_{s+1} = \tilde{p}_s \). Notice that in the former case we have succeeded in making \( \bigoplus_{n \in \mathbb{N}} R_n^B \neq W_e^{D(B)} \) because we are forcing \( (n, \bar{j}) \in W_e^{D(B)} \) and \( b_j \not\in R_n^B \). At stage \( s + 1 = 2e + 1 \), we take care of making \( G \) onto: if the \( e \)-th element of \( \mathcal{A} \) is not already in \( \tilde{p}_s \), add it to the range of \( \tilde{p}_{s+1} \); otherwise let \( \tilde{p}_{e+1} = \tilde{p}_s \).

Because we are assuming (A1), for some \( e \) we do get \( \bigoplus_{n \in \mathbb{N}} R_n^B = W_e^{D(B)} \). Thus, at stage \( s + 1 = 2e \), there were no \( n, \bar{j} \) and \( \bar{q} \) as we wanted, as otherwise we would have acted. Let \( \tilde{p} = \tilde{p}_s \). We now claim that, for all \( n \in \mathbb{N} \) and all \( \bar{a} \in A^n \), we have that

\[
\mathcal{A} \models R_n(\bar{a}) \text{ if and only if for some } \bar{q} \in A^*, \text{ with } \bar{q} \supseteq \tilde{p} \text{ and with } \bar{q}(j_1, \ldots, j_n) = \bar{a} \text{ for some } j_1, \ldots, j_n < |\bar{q}|, \text{ we have that } (n, (j_1, \ldots, j_n)) \in W_e^{D(\bar{q})}.
\]

Note that this can be written as the disjunction over all \( \sigma \in 2^{<\omega} \) and all \( \bar{j} \) with \( (n, \bar{j}) \in W_*^e \), of the formulae that say that there exists \( \bar{y} \in A^{<\omega} \) such that, if we let \( \bar{q} = p\bar{y} \), we get \( \bar{q} \in A^*, \bar{q}(\bar{j}) = \bar{a} \) and \( D(\bar{q}) = \sigma \). So, the claim gives us a \( \Sigma_1^n \) definition \( \phi_n(\bar{x}) \) of \( R_n^A \), with parameters \( \bar{p} \) and which is uniform on \( n \). To prove the claim, notice that the left-to-right direction follows from \( \bigoplus_{n \in \mathbb{N}} R_n^B = W_e^{D(B)} \) by taking \( \bar{q} \) to be a long enough segment of \( G \). For the other direction, notice that if such \( \bar{j} \) and \( \bar{q} \) existed, but \( \mathcal{A} \not\models R_n(\bar{a}) \), we would have chosen them and acted at step \( s + 1 \). Contradicting the fact that we did not act. \( \blacksquare \)

For the next corollaries, we recall the definition of enumeration reducibility.

**Definition 3.15.** A set \( X \subseteq \mathbb{N} \) is \( \text{e-reducible to } Y \subseteq \mathbb{N} \) if there exists a c.e. set \( \Phi \subseteq \mathbb{N} \times \mathcal{P}_{\text{fin}}(\mathbb{N}) \) (called an enumeration operator) such that, for all \( n \in \mathbb{N}, n \in X \) if and only if there exists \( D \in \mathcal{P}_{\text{fin}}(\mathbb{N}) \) such that \( (n, D) \in \Phi \) and \( D \subseteq Y \).

**Corollary 3.16 (Knight; see Ash & Knight [5, theorem 10.17]).** Let \( X \subseteq \mathbb{N} \). The following are equivalent:

(B1) \( X \) is c.e. in every copy of \( \mathcal{A} \).

(B2) \( X \) is e-reducible to \( \Sigma_1^1\text{-tp}_A(\bar{p}) \) for some \( \bar{p} \in A^{<\omega} \).

**Proof.** It is not hard to show that (B2) implies (B1) using that all \( \Sigma_1 \) types are c.e. in every copy of \( \mathcal{A} \). We prove the other direction.

As we mentioned earlier, \( X \) is c.e. in every copy of \( \mathcal{A} \) if and only if \( X \) is rice in \( \mathcal{A} \). So, we have that (A1), and hence (A2), of theorem 3.14 hold for \( \mathcal{R} = X \). Let \( \{n : n \in \mathbb{N}\} \) be a computable sequence of \( \mathcal{L} \)-sentences with parameters \( \bar{p} \) witnessing (A2). Each \( \phi_n \) is of the form \( \bigvee_{j \in \mathbb{N}} \exists \bar{y} \phi^n_{i_{n,j}}(\bar{p}, \bar{y}) \), where \( \phi^n_{i} \) is the \( i \)-th \( \Sigma_1 \) \( \mathcal{L} \)-formula.

Let \( \Phi = \{(n, (i_{n,j})) : n, j \in \mathbb{N}\} \), so that \( n \in \Phi^{\Sigma_1^1\text{-tp}_A(\bar{p})} \) if and only if, for some \( j \in \mathbb{N}, i_{n,j} \in \Sigma_1^1\text{-tp}_A(\bar{p}) \), which happens if and only if \( \phi_n \) holds. So, \( X = \Phi^{\Sigma_1^1\text{-tp}_A(\bar{p})} \). \( \blacksquare \)
Corollary 3.17 (Selman [12]). Let $X, Y \subseteq \mathbb{N}$. The following are equivalent:

- (C1) Every enumeration of $Y$ computes an enumeration of $X$.
- (C2) $X$ is $e$-reducible to $Y$.

(By enumeration of $Y$, we mean a function $f : \mathbb{N} \to \mathbb{N}$ with range $Y$.)

Proof. It is not hard to show that (C2) implies (C1). We prove the other direction. Assume $Y$ is infinite; otherwise both statements are trivially equivalent to $X$ being c.e. Consider a language with constants $c_0, c_1, \ldots$ and a binary relation $Q$. Let $A$ be the structure with domain $\mathbb{N}$, where $c_i$ is interpreted as $2i$, and no constants are assigned to the odd numbers, and where $Q$ is a bijection between the odd numbers and the set $\{c_i : i \in Y\}$.

Now, it is clear that every presentation of $A$ computes an enumeration of the set $Y$. Hence, (C1) implies that $X$ is c.e. in every presentation of $A$, and thus that $X$ is rice in $A$. So, we have that (B1), and hence (B2), of the previous corollary hold, that is, that $X$ is $e$-reducible to $\Sigma_1$-tp($\vec{p}$) for some $\vec{p} \in A^{<\omega}$. Now, every $\Sigma_1$-type in $A$ is $e$-reducible to the set $Y$: it is not hard to show, using disjunctive normal forms in a standard way, that every $\Sigma_1$ formula about $A$ is equivalent to a finite disjunction of formulæ of the form $\exists x \ Q(x, c_i)$ (which holds if and only if $i \in Y$). So we have that $X$ is $e$-reducible to $Y$. ■

(b) The jump of a sequence of relations

So far, on $R\text{Seq}(A)$ we have defined a notion of c.e.-ness, of computability and of join. Now, as the central notion of this study, we define a notion of jump. We start by defining the universal rice sequence of relations.

Let $\phi_0^\Sigma, \phi_1^\Sigma, \ldots$ be an effective listing of all $\Sigma_i^c$ $\mathcal{L}$-formulae, where $\phi_i^\Sigma$ has arity $k_i$.

Definition 3.18. Let $K^A = (K^A_0, K^A_1, \ldots)$ be defined by

$$K^A_i = \{ \vec{a} \in A^{k_i} : A \models \phi_i^\Sigma(\vec{a}) \}. $$

$K^A$ is nothing more than the $\Sigma_i^c$-diagram of $A$.

It should be clear that $K^A$ is rice.

Observation 3.19. $K^A$ is universal among rice sequences of relations in $A$ in the following sense. If $Q$ is rice, there is $\vec{p} \in A^{<\omega}$ and a computable $f : \mathbb{N} \to \mathbb{N}$ such that

$$\forall i \in \mathbb{N} \forall \vec{a} \in A^{q_i} (\vec{a} \in Q_i \iff (\vec{p}, \vec{a}) \in K^A_{f(i)}), $$

where $q_i$ is the arity of $Q_i$, and the arity of $K^A_{f(i)}$ is $|\vec{p}| + q_i$. To prove this, we use the extended Ash–Knight–Manasse–Slaman–Chisholm theorem 3.14: just let $\vec{p}$ and $\{\phi_i : i \in \mathbb{N}\}$ be as given by the theorem, and let $f$ be the computable function such that $\phi_i$ is $\phi_{f(i)}^\Sigma$.

Definition 3.20. Given $Q \in R\text{Seq}(A)$, let $(A, Q)$ be the structure $A$ augmented with infinitely many new relations interpreting $Q_i$ for $i \in \mathbb{N}$. Let the jump of $Q$ in $A$ be $K^{(A,Q)}$. We denote it by $Q'$. 

Phil. Trans. R. Soc. A (2012)
We can also define $Q''$ as $K^{(A,Q')}$, etc.

**Remark 3.21.** Let us use $\emptyset_A$ to denote the sequence of empty (unary) relations $(\emptyset, \emptyset, \ldots) \in RSeq(A)$. Let us emphasize the difference between $\emptyset'_A$ and $0'$. The former is $K^A$ as in definition 3.18 where the relations in the sequence have all possible arities, each arity appearing infinitely often. The latter is the information sequence coding $0'$; so it consists of only 0-ary relations and contains no structural information about $A$. We have that $0' \leq^A A \emptyset''_A$ always holds just because $0'$ is rice. However, in most cases, $\emptyset'_A$ has structural information about $A$ that $0'$ alone does not. The last two sections of this paper are dedicated to studying this structural information.

**Example 3.22.** Let $A$ be a linear ordering. Then

$$\emptyset'_A \equiv^A_T \text{Adj}(\cdot, \cdot) \oplus 0'.$$

This proof is given in Montalbán [2, theorem 2.1] using different notation.

**Example 3.23.** Let $V$ be a $\mathbb{Q}$-vector space. Then

$$\emptyset^{(n)}_V \equiv^V_T \text{LD} \oplus 0^{(n)}.$$

This is because we can use $\text{LD}$ to compute an isomorphism between $V$ and the standard computable presentation of $\mathbb{Q}^d$, where $d = \dim_\mathbb{Q}(V)$, and then we can use $0^{(n)}$ to decide $\Sigma^c_n$-relations on $\mathbb{Q}^d$.

(i) **Diagonalization**

We now prove that, on the space of sequences of relations, the jump is actually a jump in the sense that is strictly increasing.

**Theorem 3.24 (Vatev [13]; Stukachev).** For every $Q \in RSeq(A)$, $Q \leq^A T Q'$.

**Proof** (Montalbán). It is easy to see that $Q \leq^A T Q'$ because the $\Sigma^c_1$ diagram of $(A, Q)$ clearly computes the atomic diagram of $(A, Q)$. We now show that $Q'$ is not r.i. computable in $Q$. It is enough to show that $K^A$ is not r.i. computable in $A$ for any given $A$.

We start by re-indexing $K^A$ so that the arity of each relation is reflected in the index. Let $K^A_{ij}(\bar{x}) \equiv \varphi^{\Sigma^c_i}_{ij}(\bar{x})$ where $\varphi^{\Sigma^c_i}_{ij}$ is the $i$th $\Sigma^c_i$ formula with arity $j$. Suppose, towards a contradiction, that $K^A$ is co-rice. For each $e, j \in \mathbb{N}$, let

$$R_{e,j}(\bar{x}) = \begin{cases} K^A_{\{e\}(e,j),2j}(\bar{x}, \bar{x}), & \text{if } \{e\}(e,j) \downarrow, \\ \emptyset, & \text{otherwise,} \end{cases}$$
Rice sequences of relations

where \{e\} is the \emph{e}th Turing functional. Note that, under the assumption that \(K^A\) is co-rice, \(R\) is rice. By the universality of \(K^A\) (observation 3.19), there is an \(n \in \mathbb{N}\), an \(\bar{a} \in A^n\), and an index \(k\) for a total computable function \(\{k\}\) such that

\[
R_{e,j}(\bar{x}) \iff K^A_{\{k\}(e,j),n+j}(\bar{a}, \bar{x}).
\]

We then get the following contradiction:

\[
R_{k,n}(\bar{a}) \iff K^A_{\{k\}(k,n),n+n}(\bar{a}, \bar{a}) \iff \neg R_{k,n}(\bar{a}).
\]

Historic remark 3.25. The proof given earlier is new, although it is clearly similar to the standard proof of the incomputability of the Halting problem. Theorem 3.24 had been previously proved for a different, yet equivalent, notion of jump (notion J2; see below) by Vatev [13]. Vatev’s proof, restated in our terms, goes by showing that if \(B\) is a generic copy of \(A\), then \(K^B\) has degree \(D(B)'\) (which, of course, is not computable in \(D(B)\)), and hence \(K^A\) is not r.i. computable in \(A\). Stukachev (A. I. Stukachev 2011, personal communication) has another proof that has not been translated into English yet.

4. Superstructures

We mentioned in §1 that the notion of rice sequences of relations is equivalent to other notions that were known many decades ago. In this section, we briefly sketch two of these other notions: the study of \(\Sigma\)-definable subsets of the hereditarily finite superstructures, and the study of semi-search computable subsets of the Moschovakis superstructure.

The reader can skip this section without affecting the understanding of the rest of the paper.

(a) The hereditarily finite superstructure

As we mentioned earlier, another approach to the study of rice relations is using \(\Sigma\)-definability on admissible structures. We will not use admissible structures in general but just the hereditarily finite extension of an abstract structure \(A\), which we define subsequently. We will see how this is essentially equivalent to studying rice sequences of relations. For more background, see Barwise’s book [14, ch. II] or Stukachev’s survey paper [15].

Definition 4.1. Let \(P_{\text{fin}}(X)\) denote the collection of finite subsets of \(X\). Given a set \(A\), we define:

1. \(HF_A(0) = \emptyset\).
2. \(HF_A(n+1) = P_{\text{fin}}(A \cup HF_A(n))\) and
3. \(HF_A = \bigcup_{n \in \mathbb{N}} HF_A(n)\).

Now, given an \(L\)-structure \(A\), we define the \(L \cup \{\epsilon, D\}\)-structure \(HF_A\) whose domain has two sorts, \(A\) and \(HF_A\), and where the symbols of \(L\) are interpreted in the \(A\)-sort as in \(A\), ‘\(\epsilon\)’ is interpreted in the obvious way, and \(D\) is a unary relation coding the atomic diagram of \(A\), as we explain later.

Phil. Trans. R. Soc. A (2012)
A quantifier of the form $\forall x \in y \ldots$ and $\exists x \in y \ldots$ is called a bounded quantifier. A $\Sigma$-formula is one that is built out of atomic and negation of atomic formulae using disjunction, conjunction, bounded quantifiers and existential unbounded quantifiers. A subset of $\mathbb{HF}_A$ is $\Delta$-definable if it and its complement are $\Sigma$-definable.

Clearly, on $\mathbb{HF}_A$, we have the usual pairing function $\langle x, y \rangle = \{\{x\}, \{x, y\}\}$, and, of course, we can also encode $n$-tuples, strings, etc. Notice, also, that $\mathbb{HF}_A$ includes the finite ordinals (denoted by $\mathbb{n}$, where $0 = \emptyset$ and $\mathbb{n} + 1 = \{\mathbb{n}\} \cup \mathbb{n}$). We use $\omega$ to denote the $\Delta$-definable set of finite ordinals of $\mathbb{HF}_A$. Well-known arguments in admissibility theory show that every c.e. subset of $\omega$ is $\Sigma$-definable in $\mathbb{HF}_A$, and every computable function is $\Delta$-definable (see, for instance, Barwise [14, theorem II.2.3]).

We let $D(A)$ be the satisfaction relation for atomic formulae, that is, $D(A) = \{\langle i, \bar{a} \rangle : A \models \varphi^a_i(\bar{a}) \subseteq \mathbb{HF}_A$, where $\{\varphi^a_0, \varphi^a_1, \ldots\}$ is an effective enumeration of all the atomic formulae of $A$. Notice that, if the language of $A$ is finite, this is a finite list. So, when the language of $A$ is finite, $D(A)$ is $\Delta$-definable in $\mathbb{HF}_A$, without using $D(A)$ of course, and hence it does not need to be added to the definition of $\mathbb{HF}_A$.

Now, given any $R \in \text{RSeq}(A)$, we can encode it by

$$h(R) = \{\langle n, \bar{a} \rangle : n \in \mathbb{N}, \bar{a} \in R_n \subseteq \mathbb{HF}_A.$$

Another set we will use is the satisfaction relation for $\Sigma_1$ formulae, that is,

$$hK(A) = \{\langle i, \bar{a} \rangle : \mathbb{HF}_A \models \varphi_i^\Sigma(\bar{a}) \subseteq \mathbb{HF}_A,$$

where $\{\varphi_i^\Sigma_0, \varphi_i^\Sigma_1, \ldots\}$ is an enumeration of all the $\Sigma_1$ formulae of $\mathbb{HF}_A$. Using recursion on the size of the formulae, it is not hard to prove that $hK(A)$ is $\Sigma$-definable in $\mathbb{HF}_A$.

**Theorem 4.2.** Let $R \in \text{RSeq}(A)$. The following are equivalent:

1. $R$ is Rice in $A$.
2. $h(R)$ is $\Sigma$-definable in $\mathbb{HF}_A$ with parameters.

**Historic remark 4.3.** This theorem is credited to Vaïtsenavichyus [16] in Stukachev [15] and appears in some form in Beljaev & Taïclin [17].

**Sketch of the proof.** We start by proving that $h(K^A)$ is $\Sigma$-definable in $\mathbb{HF}_A$, where $K^A$ is as in definition 3.18. Let $hK_0$ be the satisfaction relation for finitary $\Sigma_1$ formulae in $A$, that is,

$$hK_0(A) = \{\langle i, \bar{a} \rangle : A \models \varphi_i^\Sigma(\bar{a}) \subseteq \mathbb{HF}_A,$$

where $\{\varphi_i^\Sigma_0, \varphi_i^\Sigma_1, \ldots\}$ is an enumeration of all the $\Sigma_1$ formulae of $A$. As with $hK(A)$, it is not hard to prove that $hK_0(A)$ is $\Sigma$-definable in $\mathbb{HF}_A$. Each $\Sigma_i^\mathbb{HF}_A$ formula is a disjunction over some c.e. set $W_e$ of formulae $\varphi_i^\Sigma$ for $i \in W_e$. Using the $\Sigma$-definitions of $\{(e, n) \in \mathbb{N}^2 : n \in W_e\}$ and of $hK_0(A)$, we get a $\Sigma$-definition of $h(K^A)$.

Assume now that $R$ is Rice. Thus, there is $\bar{p} \in A^{<\omega}$ and a computable function $f : \mathbb{N} \to \mathbb{N}$ such that, for all $i \in \mathbb{N}$ and all $\bar{a} \in A^{<\omega}$, $R_i(\bar{a})$ holds in $A$ if and only if

*Phil. Trans. R. Soc. A (2012)*
It is not hard to show that, for every copy \( B \), we define \( A \). This gives a \( S \) with parameters \( \bar{a} \) in \( HF \) of different variable symbols. Every \( t \in HF_x \) is essentially a term, and we write \( t(\bar{x}) \) to show the variables that appear in \( t \). Observe that \( HF_A = \{ t(\bar{a}) : t(\bar{a}) \in HF_X, \bar{a} \in A^{[\bar{a}]} \} \). Let \( \{ t_i : i \in \mathbb{N} \} \) be an effective enumeration of \( HF_X \cup X \), and let \( q_i \) be the number of different variables in \( t_i \). Now, given \( Q \subseteq HF_A \), we define

\[
s(Q) = (Q_0, Q_1, \ldots) \in RSeq(A) \quad \text{where} \quad Q_i = \{ \bar{a} \in A^{q_i} : t_i(\bar{a}) \in Q \}.
\]

With a bit of effort, one can show that the relation \( \{ (a, n, \bar{a}) : a \in A, n \in \mathbb{N}, \bar{a} \in A^{q_n} \& a = t_n(\bar{a}) \} \) is \( \Delta \)-definable in \( HF_A \). This can be used to prove the following theorem.

**Theorem 4.4.** Given \( Q \subseteq HF_A \), the following are equivalent:

1. \( s(Q) \) is \( \Sigma \)-definable in \( HF_A \) with parameters.
2. \( Q \) is \( \Sigma \)-definable in \( HF_A \) with parameters.

**Proof.** Assume \( s(Q) \) is \( \Sigma \)-definable in \( HF_A \). Then, \( h(s(Q)) \) is \( \Sigma \)-definable. Now, \( a \in Q \) if and only if there exist \( n \in \mathbb{N} \) and \( \bar{a} \in A^{q_n} \) such that \( a = t_n(\bar{a}) \) and \( (n, \bar{a}) \in h(s(Q)) \). This gives a \( \Sigma \)-definition of \( Q \) from the one of \( h(s(Q)) \).

Suppose now that \( Q \) is \( \Sigma \)-definable. As in the proof of the previous theorem, it is not hard to show that, for every copy \( B \) of \( A \), \( s(Q)^B \) is c.e. in \( D(B) \). ■

(b) **The Moschovakis enrichment**

The Moschovakis extension \( A^* \) of a structure \( A \) is not too far from \( HF_A \).

**Definition 4.5 (Moschovakis [8]).** Let \( 0 \) be a new constant symbol. Given a set \( A \), we define \( A^0 = A \cup \{ 0 \} \), and we let \( A^* \) be the closure of \( A^0 \) under a pairing operation \( x, y \mapsto (x, y) \).

Moschovakis [8] then defines a class of partial multi-valued functions from \( (A^*)^n \) to \( A^* \) which he calls search computable functions. This class is defined as the least class closed under certain primitive operations, much in the style of Kleene’s definition of primitive recursive and partial recursive functions, where, instead of Kleene’s least-element operator \( \mu \), we have a multi-valued search operator \( v \). A subset of \( A^* \) is search computable if its characteristic function is, and it is semi-search computable if it has a definition of the form \( \exists y \ (f(x, y) = 1) \), where \( f \) is search computable.

The definition of search computable allows us to add a list of new primitive functions to our starting list (so long as they are given in an effective list, with computable arities), obtaining a sort of relativized version of search computability.

*Phil. Trans. R. Soc. A* (2012)
If we have a structure $\mathcal{A}$, we would add to the list of primitive functions the characteristic functions of the relations in $\mathcal{A}$ to obtain a notion of partial, multi-valued, search computable function in $\mathcal{A}$.

Much in the same way as we did for $\mathcal{HF}_{\mathcal{A}}$ earlier, we have a natural way of encoding sequences $R \in \text{RSeq}(\mathcal{A})$ by subsets of $\mathcal{A}^*$, and vice versa. Perhaps even more directly, one can go from subsets of $\mathcal{A}^*$ to subsets of $\mathcal{HF}_{\mathcal{A}}$ and back. Gordon [9] proved that the notions of search computable in $\mathcal{A}$ and semi-search computable in $\mathcal{A}$ for subsets of $\mathcal{A}^*$ coincide with the notions of $\Delta$-definable and $\Sigma$-definable for subsets of $\mathcal{HF}_{\mathcal{A}}$. And hence, when you add parameters, they also coincide with the notions of r.i. computable and rice for sequences of relations in $\text{RSeq}(\mathcal{A})$.

5. The jump of a structure

In this section, we look at the jump as a map from abstract structures to abstract structures, rather than from $\text{RSeq}(\mathcal{A})$ to $\text{RSeq}(\mathcal{A})$.

**Definition 5.1.** Given an $\mathcal{L}$-structure $\mathcal{A}$, we let $$\mathcal{A}' = (\mathcal{A}, K^\mathcal{A}),$$
where $K^\mathcal{A}$ is as in definition 3.18, and $\mathcal{A}'$ is now an $\mathcal{L}'$-structure, where $\mathcal{L}' = \mathcal{L} \cup \{K_i : i \in \mathbb{N}\}$.

Notice that the isomorphism type of $\mathcal{A}'$ does not depend on the presentation of $\mathcal{A}$. However it does depend, in a non-essential way, on the Gödel numbering of the $\Sigma^c_1$ $\mathcal{L}$-formulae, in the same way as the Turing jump of a set depends on the numbering of the partial computable functions. Also notice that the extended language $\mathcal{L}'$ is still a computable relational language. $\mathcal{L}'$ is now infinite, even if $\mathcal{L}$ was finite, and this can be viewed as a disadvantage of this definition. That is the price to pay if we want $\mathcal{A}$ and $\mathcal{A}'$ to have the same domain.

We note that the above-mentioned definition also works for uncountable structures. However, we will still assume that all our structures are countable throughout this paper.

**Historic remark 5.2.** The jump of structures has been independently defined various times in the last few years. We have four different definitions of maps from abstract structures to abstract structures that we call jump. All these definitions are equivalent up to $\Sigma$-equivalence (see definition 5.5).

(J1) The first appearance in print of such a definition for all countable abstract structures is due to Baleva [10], as part of her PhD thesis under the supervision of Ivan Soskov. That definition uses, as the domain for the jump of $\mathcal{A}$, the Moschovakis extension $(A \times \mathbb{N})^*$ of $A \times \mathbb{N}$ (see §4b). Baleva’s jump of $\mathcal{A}$ adds to $(A \times \mathbb{N})^*$ a universal $\Sigma^c_1$ set, very similar to the set $h(K^\mathcal{A})$ mentioned in §4a. Baleva sets up her definition in the semi-lattice of countable structures over a fixed domain ordered by SC-reducibility. This reducibility is essentially $\leq^E_T$ as defined in definition 3.7, where $E$ is the countable structure on the empty language, and all other structures are viewed as having the same domain as $E$.
(J2) Soskova and co-workers [18,19] worked with another map from structures to structures, which they did not call the jump of the structure until later papers. There, the domain of $A'$ is the Moschovakis extension $A^*$ of $A$, and the added relation is one that codes (the negation of) the forcing relation on $\Pi_1$ formulae, which is essentially \( \{ (\bar{p}, e, x) \in A^* \times \mathbb{N}^2 : \exists \bar{q} \in A^* (\bar{q} \supseteq \bar{p} \land x \in W_{e}^{\phi(\bar{q})}) \} \) following the notation of the proof of theorem 3.14.

(J3) Stukachev [20,21], who was working on the semi-lattice of structures of any size below an arbitrary cardinal, ordered under $\Sigma$-reducibility, provided a new definition of the jump of a structure in that setting. Stukachev was the first one to work with uncountable structures of any size. For him, the domain of $A'$ is $\mathbb{H}F_A$, and the added relation is the satisfaction relation for $\Sigma_1$-formulae, namely $hK(A)$. The importance of the role of $\Sigma$-reducibility in this context was previously shown by Stukachev [22,23].

Another independent definition of the jump is due to Puzarenko [24]. However, he defines only the jump of an admissible structure, and does not deal with structures in general. The definition is almost the same as that of Stukachev when one considers the jump of the admissible structure $\mathbb{H}F_A$; although they only realized this afterwards. Puzarenko’s definition generalized an earlier definition of jump by Morozov [25] that works only for recursively listed admissible structures, which are the admissible structures when there is a $\Sigma$-definable bijection between the whole domain and the class of ordinals.

(J4) Montalbán [2], independently of all this previous work, introduced yet another definition. The original definition in Montalbán [2] is not completely equivalent to the above-mentioned definitions; it is what we call the structural jump in §6. In that definition, the domain of the jump of a structure $A$ is the same as the domain of $A$, and the language is extended with finitely or infinitely many new relations that, altogether, form a complete set of $\Pi_1^c$-relations.

(a) Comparing structures

Working with structures as objects, we need to have a way of comparing the computational complexity of different structures. There is more than one way to do this. A measurement that is widely accepted is to say that a structure is more complicated than another if it is harder to compute, in the sense that it takes smarter oracles to produce a presentation of it. This reduction is more commonly used implicitly than explicitly as in the following definition.

**Definition 5.3.** Given two structures $A$ and $B$, we say that $A$ is Muchnik reducible to $B$, and write $A \leq_w B$, if

\[ \forall X \subseteq \mathbb{N}, \quad X \text{ computes a copy of } B \Rightarrow X \text{ computes a copy of } A, \]

or equivalently, if $\text{Sp}(B) \subseteq \text{Sp}(A)$. The ‘$w$’ stands for ‘weak’, where the strong reduction is the Medvedev reduction that asks for a uniform way of computing a copy of $A$ from a copy of $B$.

This reduction defines a pre-ordering on the class of all countable structures, and hence an equivalence, $\equiv_w$, as usual.
In some cases, this equivalence may not be appropriate, as it does not look too deeply into the model-theoretical aspects of a structure. For example, any two computable structures are equivalent under $\equiv_w$, even if the structures are model-theoretically very different. The following reduction is nothing more than an effective version of the notion of interpretability used in model theory.

**Definition 5.4.** Let $\mathcal{A}$ be an $\mathcal{L}$-structure, and $\mathcal{B}$ be any structure, where $\mathcal{L} = \{P_0, P_1, \ldots\}$ and $P_i$ has arity $p_i$.

We say that $\mathcal{A}$ is **effectively interpretable** in $\mathcal{B}$, and write $\mathcal{A} \leq_I \mathcal{B}$, if, for some $n \in \mathbb{N}$, in $\mathcal{B}$, there is a r.e. subset $D \subseteq B^n$, a r.i. computable subset $\eta \subseteq B^n \times B^n$ which is an equivalence relation on $D$, and a r.i. computable sequence of sets $R_i \subseteq B^{n-p_i}$, closed under the equivalence $\eta$ within $D$, such that

$$(A; P_0^A, P_1^A, \ldots) \cong (D/\eta; R_0, R_1, \ldots).$$

The sets $R_i$ do not need to be subsets of $D^{p_i}$, and when we refer to the structure $(D/\eta; R_0, R_1, \ldots)$ we, of course, mean $(D/\eta; (R_0 \cap D^{p_0})/\eta, (R_1 \cap D^{p_1})/\eta, \ldots)$.

Being $\equiv_I$ is a very strong notion of equivalence, which reflects both effective and model-theoretical aspects of the structure. However, in some cases, the restriction of $D$ to being a subset of $B^n$ can be too strong. We already argued that, when studying ricer relations, one needs to go beyond the study of subsets $D \subseteq B^n$. The following notion fixes this problem.

**Definition 5.5.** Consider structures $\mathcal{A}$ and $\mathcal{B}$ as mentioned already. We say that $\mathcal{A}$ is **$\Sigma$-reducible** to $\mathcal{B}$ if there is an effective interpretation of $\mathcal{A}$ in $\mathcal{B}$ as in the previous definition, but allowing $D$ to be a r.e subset of $A^{<\omega} \times \mathbb{N}$, and $\eta$ and $R$ to be r.i. computable relations on $A^{<\omega} \times \mathbb{N}$, of course viewed as elements of $\text{RSeq}(\mathcal{A})$.

**Observation 5.6.** Consider structures $\mathcal{A}$ and $\mathcal{B}$ as above. Then

$A \leq \mathcal{B} \iff \mathcal{A} \leq_I \mathcal{B}$.

**Theorem 5.7.** For any structures $\mathcal{A}$ and $\mathcal{B}$,

1. $A \leq_I \mathcal{B}$ implies $A \leq \mathcal{B}$, and
2. $A \leq \mathcal{B}$ implies $A \leq_w \mathcal{B}$.

None of the implications above reverses.

**Proof.** None of the implications is hard to prove. To see that the first implication does not reverse consider $\mathcal{A} = (\omega; \text{Adj})$, and $\mathcal{B} = \mathcal{E} = (B; \epsilon)$ the countable infinite structure over the empty language. Then, $A \leq \mathcal{E}$ because $\mathcal{A}$ can be effectively interpreted in arithmetic, and hence $A$ is $\leq \mathcal{E}$ because the only r.e subsets of $B^n$ in $\mathcal{E}$ are either finite or co-finite.

There are various proofs that $A \leq_w \mathcal{B}$ does not imply $A \leq \mathcal{B}$; see, for instance, Stukachev [22] and Kalimullin [26,27]. For one such example: let $\mathcal{A}$ be the structure coding the family of the graphs of all computable functions, i.e. it is a family of sets of pairs, each set being the graph of a computable function. Let $\mathcal{B}$ be the family of all c.e. sets. Then, it is proved in Kalimullin & Puzarenko [27] that $A \leq_w \mathcal{B}$ but $A \not\leq \mathcal{B}$. ■
Historic remark 5.8. The notion of $\Sigma$-reducibility between abstract structures was introduced independently by Khisamiev [28] and Stukachev [22], and it is based on the notion of $\Sigma$-definability of a structure inside an admissible set by Ershov. Stukachev [22,23] and Puzarenko and co-workers [24,27] showed the importance of this reducibility and compared it with various other reducibilities between structures (including $\leq_w$). The definitions of earlier studies [22,28] used, of course, the notions of $\Sigma$-definability rather than rice. The equivalence with the definition given here follows from theorems 4.2 and 4.4.

(b) The three main theorems about the jump

We now state the three main results about the jump of structures.

(i) The first jump inversion theorem

This theorem is a generalization of the Friedberg jump inversion theorem to the semi-lattice of structures under $\leq_S$-reducibility.

Theorem 5.9. For every structure $A$ which codes $0'$ (i.e. $0'$ is r.i. computable in $A$), there is a structure $C$ such that $C \equiv_S A$.

Historic remark 5.10. For the case of Muchnik equivalence, this theorem was proved independently in two occasions. One is due to Goncharov et al. [29, lemma 5.5 for $\alpha = 2$]. They do not state their result in terms of the jump of a structure, and they prove only the theorem for graphs, but any degree spectrum can be realized as the degree spectrum of a graph. They prove inversion, not only for a single jump, but also for the $\alpha$th jump, for every $\alpha < \omega^C_1$. They proved this result as a tool to get other results about $\Delta^0_\alpha$ categoricity and intrinsic $\Sigma^0_\alpha$ relations. Their $\alpha$-jump inversion theorem was used on other occasions, for instance by Greenberg et al. [30] to build a structure whose spectrum is exactly the non-hyperarithmetic degrees.

The other proof of theorem 5.9 for $\equiv_w$ is due to Soskova and co-workers [18,19]. Her construction is quite different and uses Marker extensions. The inspiration to use a Marker extension in this context came from Goncharov & Khusainov [31]. Furthermore, she proved a relativized version of the theorem, where the relativization is to structures. That is, she proved that if $A \geq_w B'$, then there is a structure $C \geq_w B$ such that $A \equiv_w C'$.

Stukachev [15,21] then proved this theorem for the stronger notion of $\Sigma$-equivalence, as in the statement of the above-mentioned theorem, and for structures of arbitrary cardinality. Stukachev used the same structure that Soskova used, although the proof that it works for $\Sigma$-equivalence is completely different and more model theoretical.

(ii) The second jump inversion theorem

This second jump inversion theorem is not a generalization of the usual jump inversion theorem to a more general class of degrees, but a generalization in the sense that, given $X \subseteq \mathbb{N}$, it gives $Y \subseteq \mathbb{N}$ with $Y' \equiv_T X$ and some extra properties.

Theorem 5.11. If $X$ computes a copy of $A'$, then there is a set $Y$, with $Y' \equiv_T X$, which computes a copy of $A$. Equivalently, this says that

$$\text{Sp}(A') = \{ y' : y \in \text{Sp}(A) \}.$$
This theorem is proved by showing that any copy of \( A' \) can compute a one-generic copy \( B \) of \( A \), and that, for such a copy, \( D(B)' \leq_T D(A') \).

The equivalent formulation in the second sentence of the theorem can be viewed as a correctness statement: it reaffirms that our definition of the jump is an analogue of the usual definition of the Turing jump on sets of numbers.

**Corollary 5.12 (Montalbán [2, theorem 3.5]).** The following are equivalent:

1. \( A \) has the low property: if \( X' \equiv_T Y' \) and \( X \) computes a copy of \( A \), then so does \( Y \).
2. \( A \) admits strong jump inversion: if \( X' \) computes a copy of \( A' \), then \( X \) computes a copy of \( A \).

**Historic remark 5.13.** Theorem 5.11 was first introduced by Soskov at a talk during the LC’02 in Münster, Germany; a full proof then appeared in Soskova & Soskov [19]. That proof just shows the existence of a structure \( B \) with \( \text{Sp}(B) = \{ y' : y \in \text{Sp}(A) \} \); this structure \( B \) was only later called the jump of \( A \), and it is notion \( J2 \) (see above). Theorem 5.11 was first stated in print in Baleva [10, theorem 5], but the proof there is not complete (lemma 4 is not correct).

Another proof of the theorem then appeared independently in Montalbán [2]. Both proofs are essentially the same, although the great differences in the underlying setting make them look quite different.

(iii) **The fixed point theorem**

The third theorem says that the jump operation on structures does not always jump.

**Theorem 5.14 (Puzarenko [32], Montalbán [33]).** There is a structure \( A \) such that \( A \equiv \omega \).

**Historic remark 5.15.** Puzarenko’s and Montalbán’s proofs were found independently. Montalbán uses the existence of \( 0^\sharp \), and is a paragraph long, once the definition of \( 0^\sharp \) is understood. Puzarenko’s proof works inside \( ZFC \), but is much more complicated. Both proofs work by building an ill-founded \( \omega \)-model \( A \) of \( V=L \) where, for some ordinal \( \alpha \) of the model, \((L_\alpha)^A \cong A\).

More surprising than the theorem itself is the complexity necessary for its proof.

**Theorem 5.16 (Montalbán [33]).** Higher order arithmetic cannot prove that there exists a structure \( A \) with \( A \equiv \omega \) (i.e. \( \text{Sp}(A) = \text{Sp}(A') \)). Higher order arithmetic refers to the union of \( n \)-th-order arithmetic for all \( n \in \mathbb{N} \).

One of the main steps to prove this theorem is to show that if \( A \equiv \omega \), then the co-spectrum of \( A \) (i.e. \( \{ X \subseteq \mathbb{N} : X \text{ is rice in } A \} \)) is the second-order part of an \( \omega \)-model of full second-order arithmetic. Generalizing this to higher orders, the author proves that the \( \omega \)-jump of any presentation of \( A \) computes a countably coded \( \omega \)-model of higher order arithmetic.

Puzarenko’s proof of theorem 5.14 uses \( KP \) plus \( \omega_1^{CK} + 1 \) iterations of the power-set axiom. So there is still a gap as to what is actually needed to prove the fixed point theorem.
6. The structural jump

The present author’s original definition of the jump of a structure [2], which is different from the one we give here, uses a complete set of $\Pi_{S}^{c}$-relations. Complete sets of $\Pi_{S}^{c}$-relations or, by taking complements, of rice relations provide the link between the formal definition of the jump of a relation and its applications on concrete natural structures.

(a) Complete sets of rice relations

The author’s original definition [2, definition 1.1] is given as part (2) of lemma 6.3. The following definition is equivalent.

**Definition 6.1.** A sequence of relations $R$ is *structurally rice complete* if it is rice and

$$\varnothing^{\prime}_{A} \equiv^{A}_{T} R \oplus 0^{\prime}.$$  

More generally, $R$ is *structurally $\Sigma_{n}^{c}$ ($\Pi_{n}^{c}$) complete* if it is $\Sigma_{n}^{c}$ ($\Pi_{n}^{c}$) and

$$\varnothing^{(n)}_{A} \equiv^{A}_{T} R \oplus 0^{(n)}.$$  

In Montalbán [2, definition 1.1], instead of saying that $R$ is structurally rice complete, we said that $R$ is a complete set of rice relations. The new notation is more accurate, but, as an abuse of notation, we will still use the old notation sometimes. The word ‘structurally’ reflects that $R$ is complete in the sense that it has all the structural information of $\varnothing^{\prime}_{A}$, but it may need to borrow other information from $0^{\prime}$ to be actually equivalent to $\varnothing^{\prime}_{A}$. In addition, it is important that $R$ is a sequence and not just a set, because the $\equiv^{A}_{T}$-equivalence asks for uniform reductions between sequences.

**Example 6.2.** From examples 3.22 and 3.23, we get that $\neg$Adj alone and $LD$ are structurally rice complete for linear orderings and vector spaces, respectively. More examples are given in §7.

The following lemma shows how having a simple complete set of rice relations on a structure $A$ can be very useful: first because it gives a simple characterization of all the r.i. $\Sigma_{2}^{n}$ relations in $A$, and second because it can be used to build copies of $A$.

**Lemma 6.3.** Let $R$ be a finite or infinite $\Sigma_{n}^{c}$ sequence of relations on $A$. The following are equivalent:

1. $R$ is structurally $\Sigma_{n}^{c}$ complete.
2. Every $\Sigma_{n+1}^{c}$ formula $\psi(\bar{x})$ about $A$ is equivalent to a $0^{(n)}$-computable disjunction of finitary $\Sigma_{1}$ formulae about $(A, R)$, and this equivalent disjunction can be found uniformly in $\psi$.
3. If $X \geq^{T} 0^{(n)}$ computes a copy of $(A, R)$, then there exists $Y$ with $Y^{(n)} \equiv^{T} X$ that computes a copy of $A$, and, furthermore, $X$ computes an isomorphism between $A$ and its copy.

*Phil. Trans. R. Soc. A* (2012)
Sketch of the proof. That (2) implies (1) follows from the fact that both $\varnothing_A^{(n)}$ and $\neg \varnothing_A^{(n)}$ are $\Sigma^c_{n+1}$-definable. To prove that (1) implies (2), one needs to use, first, that every $\Sigma^c_{n+1}$ formula about $\mathcal{A}$ is equivalent to a $\Sigma^c_1$ formula about $\mathcal{A}^{(n)} = (\mathcal{A}, \varnothing_A^{(n)})$, and, second, that $\varnothing_A^{(n)}$ is both $\Sigma^c_1$- and $\Pi^c_1$-definable in $(\mathcal{A}, R, 0^{(n)})$, to get that every $\Sigma^c_{n+1}$ formula is equivalent to a $\Sigma^c_1$ formula about $(\mathcal{A}, R, 0^{(n)})$. Such a $\Sigma^c_1$ formula is equivalent to a $0^{(n)}$-computable disjunction of finitary $\Sigma_1$ formulae about $(\mathcal{A}, R)$.

That (1) implies (3) follows from theorem 5.11 iterated $n$ times.

Let us now assume that (3). To show that (1) holds, we need to show that, for every copy $\mathcal{B}$ of $\mathcal{A}$, $R^\mathcal{B} \oplus 0^{(n)}$ computes $\varnothing_B^{(n)}$. Let $X$ compute $(\mathcal{B}, R^\mathcal{B}, 0^{(n)})$. By (3), there exists $Y$, with $Y^{(n)} \equiv_T X$, which computes a copy $\mathcal{C}$ of $\mathcal{B}$ and $X$ computes the isomorphism. Then, $X$ computes $\varnothing_C^{(n)}$, and, through the isomorphism, it computes $\varnothing_B^{(n)}$. ■

The following particular case of the previous lemma was independently proved by Frolov.

**Corollary 6.4 (Frolov [34, theorem 6]).** If $\mathcal{A}$ is a linear ordering and $(\mathcal{A}, \text{Adj})$ has a $0'$-computable copy, then $\mathcal{A}$ has a low copy.

It is not always the case that there is a nice complete set of rice relations. Conditions for when this is the case, under a certain interpretation of ‘nice’, are given in Montalbán [1]. There, the author studies sequences of $\Pi^c_n$ formulae that define complete sets of $\Pi_n$ relations for all the structures inside a class $\mathbb{K}$, and that, furthermore, are complete relative to any oracle. It is proved in Montalbán [1] that such a set of formulæ exists if and only if the number of $n$-back-and-forth types of tuples in structures in $\mathbb{K}$ is countable, and some mild effectiveness conditions hold on these types.

(b) The author’s original definition of jump

The definition given in this paper is better than the one in Montalbán [2] in the sense that it matches the other definitions of jump. However, the definition from Montalbán [2] has the advantage that it is more practical, and aesthetic, when looking at particular examples of jumps.

**Definition 6.5.** A structural jump of $\mathcal{A}$ is a structure of the form $(\mathcal{A}, R)$ where $R \in \text{RSeq}(\mathcal{A})$ is structurally rice complete.

Notice that $\mathcal{A}'$, as defined in definition 5.1, is a structural jump of $\mathcal{A}$, and that the only essential difference between $\mathcal{A}'$ and any other structural jump $\hat{\mathcal{A}}$ of $\mathcal{A}$ is that $\mathcal{A}'$ codes the information sequence $\theta'$ while $\hat{\mathcal{A}}$ might not. This difference is not structural; it just involves information unrelated to the structure $\mathcal{A}$.

The following examples show how simple the structural jump of a structure can be. More examples are given in the next section.

**Example 6.6.** If $\mathcal{A}$ is a linear ordering, then $(\mathcal{A}, \text{Adj})$ is a structural jump of $\mathcal{A}$. If $\mathcal{A}$ is a $\mathbb{Q}$-vector space, $(\mathcal{A}, \text{LD})$ is a structural jump of $\mathcal{A}$. If $\mathcal{A}$ is a Boolean algebra, $(\mathcal{A}, \text{atom})$ is a structural jump of $\mathcal{A}$, and $(\mathcal{A}, \text{atom, inf, atomless})$ is a structural double-jump of $\mathcal{A}$.
7. Finite complete sets of rice relations

In this section, we look at the following question: for which structures, and \( n \in \mathbb{N} \), is there a finite structurally \( \Sigma^c_2 \) complete set of relations? We do not have a general answer for this question, but we have some interesting examples.

(a) Linear orderings

As we have said a few times already, for linear orderings we have a finite complete set of rice relations, namely the singleton \( \{ \neg \text{Adj} \} \), and a proof of this can be found in Montalbán [2]. Linear orderings also enjoy a nice structural double jump. The following is a complete set of \( \Pi^c_2 \) relations for linear orderings with endpoints:

1. \( \text{Adj}(x, y) \).
2. \( \text{limleft}(x) \); where \( \text{limleft}(x) \) holds if \( x \) is a limit from the left, that is, if \( \exists y < x \land \forall y < x \exists z (y < z < x) \).
3. \( \text{limright}(x) \); where \( \text{limright}(x) \) holds if \( x \) is a limit from the right, that is, if \( \exists y > x \land \forall y > x \exists z (x < z < y) \).
4. \( D_n(x, y) \) for \( n \geq 1 \); where \( D_n(x, y) \) holds if there is no string of \( n + 1 \) adjacent elements somewhere between \( x \) and \( y \), that is, if \( x < y \land \neg \exists z_0, \ldots, z_n (x \leq z_0 < \cdots < z_n \leq y \land \bigwedge_{i<n} \text{Adj}(z_i, z_{i+1})) \).

That these form a complete set of \( \Pi^c_2 \) relations follows from the work of Frolov [34, theorem 7], who proved that part (3) of lemma 6.3 holds for these relations. In the case when the linear ordering has no endpoints, the situation is not much different; we just need to consider extra relations \( D_{n, +\infty}(x) \) and \( D_{n, -\infty}(x) \), which are like \( D_n(\cdot, \cdot) \) but look at the end and initial segments, \( (x, +\infty) \) and \( (-\infty, x) \), respectively.

This is a nice set of relations, but it is not finite.

Theorem 7.1 (J. F. Knight, R. Miller, A. Montalbán, I. N. Soskov, A. Soskova, M. Soskova, S. VanDenDriessche & S. Vatev 2011, unpublished data). There is a finite complete set of \( \Pi^c_2 \) relations for linear orderings with endpoints. These relations are:

\[
\begin{align*}
\text{Adj}(x, y), \\
\text{limleft}(x), \\
\text{limright}(x), \text{ and } \\
P(x, y, z, w) \equiv \bigwedge_{n \in \mathbb{N}} (\text{Succ}^n(z) = w \rightarrow D_{n+1}(x, y)), \text{ where } \text{Succ}^n(z) = w \text{ is a shorthand for } \exists z_0, \ldots, z_n (z = z_0 < z_1 < \cdots < z_n = w \land \bigwedge_{i<n} \text{Adj}(z_i, z_{i+1})).
\end{align*}
\]

The theorem also holds for linear orderings without endpoints, although one needs to consider a couple of added relations.

Proof. Let \( A \) be a presentation of linear orderings with endpoints. We need to show that the relations \( D_n \) are uniformly computable in the relations above. Fix \( n \). If \( n = 1 \), then \( D_1(x, y) \equiv P(x, y, x, x) \). Suppose now that \( n > 1 \), and consider \( x, y \in A \). Suppose that, recursively, we know whether or not \( D_n(x, y) \) holds, and we want to check if \( D_{n+1}(x, y) \) holds. If \( D_n(x, y) \) holds, then we know that \( D_{n+1}(x, y) \) holds too. Suppose now that \( \neg D_n(x, y) \) holds. Then, we can search for \( z, w \) such that \( \text{Succ}^n(z) = w \) and we have that \( P(x, y, z, w) \iff D_{n+1}(x, y) \). \( \blacksquare \)
(b) Boolean algebras

Harris & Montalbán [35] proved that, for all \( n \in \mathbb{N} \), there is a finite structurally \( \Pi_n^c \)-complete set of relations. They describe a recursive procedure to build these sets of relations, but the construction is too involved to give here. Up to Boolean combination, and for the cases \( n = 1 \leq 4 \), relations that are structurally \( \Pi_n^c \) complete for Boolean algebras were considered by Downey & Jockusch [36] for \( n = 1 \), Thurber [37] for \( n = 2 \), and Knight & Stob [38] for \( n = 3, 4 \). They did not mention their completeness, but they proved that (3) of lemma 6.3 holds. Moreover, they showed that Boolean algebras have the low_\text{I} property by showing that they admit strong fourth jump inversion (see corollary 5.12).

(c) Vector spaces

As we mentioned before, \( LD \) is structurally rice complete for \( \mathbb{Q} \)-vector spaces. This is again a very nice sequence of relations that is not finite.

**Theorem 7.2** (J. F. Knight, R. Miller, A. Montalbán, I. N. Soskov, A. Soskova, M. Soskova, S. VanDenDriessche & S. Vatev 2011, unpublished data). Let \( \mathcal{V} \) be the infinite dimensional countable \( \mathbb{Q} \)-vector space. There is no finite complete set of rice relations in \( \mathcal{V} \).

**Sketch of the proof.** The proof has two parts. First, we give a different, more hands on, proof that \( LD \) is structurally rice complete. A proof that lets us observe that every rice relation \( R(x) \) is \( \leq_T^\mathcal{V} \)-reducible to \( 0' \) and finitely many instances of \( LD \). Let \( n \) be the arity of \( R \) and let \( (v_1, \ldots, v_n) \in \mathcal{V}^n \). Then, using \( (LD_2, \ldots, LD_n) \) we can find out all the linear dependencies among the vectors \( v_1, \ldots, v_n \). So we can find a linearly independent subset of \( v_1, \ldots, v_n \) which generates the rest, and then we can search for the equations witnessing these dependencies. Let us now assume that the \( v_i \)'s are all linearly independent, as otherwise we can reduce the problem to a smaller set. By standard arguments using disjunctive normal forms, one can show that every finitary \( \Sigma_1 \) formula about \( v_1, \ldots, v_n \) can be effectively decided by solving systems of linear equations and inequations, and hence \( 0' \) can then decide infinitary \( \Sigma_1^c \) formulae about \( v_1, \ldots, v_n \) in a uniform way.

Second, we show that no finite sequence \( (LD_2, \ldots, LD_{n-1}) \) can \( \leq_T^\mathcal{V} \)-compute the whole sequence \( LD \). We build a copy \( \mathcal{A} \) of \( \mathcal{V} \) where \( (LD_2, \ldots, LD_{n-1}) \) is computable, but \( LD \) is not. We will define a computable subspace \( W \) of \( \mathbb{Q}^{\omega} \) and then let \( A \) be the quotient \( \mathbb{Q}^{\omega}/W \). Let \( b_0, b_1, \ldots \) be the standard basis of \( \mathbb{Q}^{\omega} \). To make sure \( LD_n \) is not computable, we will let \( LD_n(b_{kn}, \ldots, b_{(n+1)-1}) \) hold in \( A \) if and only if \( k \in 0' \). Given \( s \in \mathbb{N} \), let \( A_s \) be the set of all \( v \in \mathbb{Q}^{\omega} \) which are linear combinations of \( b_0, \ldots, b_s \), using coefficients among the first \( s \) rational numbers. At stage \( s \) of the construction, if we see that \( k \) enters \( 0' \) we enumerate a non-trivial linear combination of \( b_{kn}, \ldots, b_{(n+1)-1} \) to \( W \) without adding to \( W \) any vector of \( A_s \) that was not in \( W \) already, and without adding any new dependence between any set of vectors of \( A_s \) of size less than \( n \). Proving that this can be done requires a little linear algebra, and proving that \( W \) and \( LD_2, \ldots, LD_{n-1} \) end up being computable is a rather standard argument (for a fully spelled out argument of a similar kind, see Downey et al. [39]).

Relativizing this proof to \( 0' \), we get a \( 0' \)-computable copy of \( \mathcal{V} \), where \( (LD_2, \ldots, LD_{n-1}) \oplus 0' \) is \( 0' \)-computable, but \( LD \) computes \( 0'' \). Thus \( LD \) is not r.i. computable in \( (LD_2, \ldots, LD_{n-1}) \oplus 0' \).

*Phil. Trans. R. Soc. A* (2012)
Finally, if $R_1, \ldots, R_m$ were structurally rice complete, then by the first part of the argument we would have that finitely many of the $LD_i$ would also be rice complete, but the second part shows that this is not the case.

(d) Equivalence structures

An equivalence structure is a structure with a binary relation $E$ which is an equivalence relation. For equivalence structures, the following is a complete set of rice relations:

(1) $F_k(x)$ for $k \in \mathbb{N}$, where $F_k(x)$ holds if there are $\geq k$ elements equivalent to $x$, and

(2) the information sequence $G$ (called the character of $E$), where $G = \{(n,k) \in \mathbb{N}^2 : \text{there are } \geq n \text{ equivalence classes with } \geq k \text{ elements}\}$.

Fix an equivalence structure $A$, and a rice relation $R$ of arity $n$. We will show how we can uniformly compute $R^A$ using $F^A$, $G^A$ and $0'$. Let $(v_1, \ldots, v_n) \in A^n$. Using $(F_2, \ldots, F_n)$, find which of the $v_i$s are equivalent to which. Let us assume that they are all non-equivalent, as otherwise we can reduce the problem to a maximal subset of non-equivalent $v_i$s. Given $k \in \mathbb{N}$, let $F_k(\bar{x}) = \bigwedge_{i=1}^{n} F_k(x_i)$.

A standard argument shows that every finitary $\Sigma_1$ formula about $v_1, \ldots, v_n$ is equivalent to a disjunction of formulae of the form $F_k(\bar{v})$ in conjunction with some formulae of the form $'\exists (m,k) \in G$. So, using $G$, we can effectively transform every $\Sigma_1^e$ formula into a disjunction of formulae $F_k(\bar{v})$ for $k$ in some computable set $C \subseteq \mathbb{N}^n$. Define the following ordering on $\mathbb{N}^n$: $\bar{k} \preceq \bar{l}$ if for all $i = 1, \ldots, n$, $k_i \leq l_i$. Note that if $\bar{k} \preceq \bar{l}$, then $F_k(\bar{v}) \lor F_l(\bar{v}) \equiv F_k(\bar{v})$. It is not hard to show (by induction on $n$) that $(\mathbb{N}^n, \preceq)$ is a well-quasi ordering, that is, for every sequence $\{\bar{k}_i : i \in \mathbb{N}\}$, there is $i < j$ with $\bar{k}_i \preceq \bar{k}_j$. Well-quasi orderings have the property that for every set $C \subseteq \mathbb{N}^n$ there is a finite subset $C_0 \subseteq C$ such that every element of $C$ is $\preceq$-above some element of $C_0$. It follows that $\bigvee_{\bar{k} \in C} F_k(\bar{v}) \equiv \bigvee_{\bar{k} \in C_0} F_k(\bar{v})$. Let us note that $0'$ is necessary to find $C_0$ from $C$. So, we have shown that every $\Sigma_1^e$ formula can be re-written, with the help of $0'$ and $G$, as a finite disjunction of the form $\bigvee_{\bar{k} \in C_0} F_k(\bar{v})$.

**Theorem 7.3 (J. F. Knight, R. Miller, A. Montalbán, I. N. Soskov, A. Soskova, M. Soskova, S. VanDenDriessche & S. Vatev 2011, unpublished data).** Let $A$ be an equivalence structure that has one equivalence class of each finite size. There is no finite complete set of rice relations in $A$.

**Sketch of the proof.** First, observe that every rice relation $R(\bar{x})$ is $\leq^A_T$-reducible to $0'$ and finitely many instances of $F$, noting that $G$ is computable in this case.

Second, we show that no finite sequence $(F_2, \ldots, F_{n-1})$ can $\leq^A_T$-compute the whole sequence $F$. We build a copy $B$ of $A$ where $(F_2, \ldots, F_{n-1})$ are computable, but $F$ is not. Suppose $n$ is even; if not take $n+1$ as $n$. Start by building a structure with equivalence classes of all even sizes and all sizes less than $n$; we will build the odd size classes beyond $n$ by stages. Let $b_k$ be a fixed element in a class of size $2k + n$. If $k$ enters $0'$, we will make $b_k$’s equivalence class bigger, so asking whether $F_{2k+n+1}(b_k)$ holds will tell us if $k \in 0'$. At each stage, build one new odd size equivalence class. If $k$ enters $0'$ add elements to $b_k$’s equivalence class.
class to make it have some large odd size not considered yet, and also make a
new equivalence class of size $2k + n$. Notice that the value of $F_i$ for $i < n$ is never
changed during the construction, and hence these relations are all computable.

Relativize this proof to $0'$ to obtain a $0'$-computable copy of $A$ where $(F_2, \ldots, F_{n-1}) \oplus 0'$ is $0'$-computable but $F$ computes $0''$.

Finally, if there was a finite complete set of rice relations, we would get that a
finite set of the $F_i$s would also make a complete set, but we just proved that this
cannot be the case. ■

The author was partially supported by NSF grant no. DMS-0901169 and the Packard Fellowship.
The author thanks Asher Kach for helpful comments throughout the paper.

References

2 Montalbán, A. 2009 Notes on the jump of a structure. In Mathematical Theory and
3 Montalbán, A. In press. Coding and definability in computable structures. Notes from a course
at Notre Dame University. NDJFL.
5 Ash, C. J. & Knight, J. 2000 Computable structures and the hyperarithmetic hierarchy.
7 Chisholm, J. 1990 Effective model theory vs. recursive model theory. J. Symbol. Logic 55,
427–464.
9 Gordon, C. E. 1970 Comparisons between some generalizations of recursion theory. Compositio
(doi:10.1007/s00153-004-0245-z)
Inform. 96, 45–68.
(doi:10.1002/mlq.19710170139)
13 Vatev, S. 2011 Conservative extensions of abstract structures. In CiE (eds B. Löwe, D.
Normann, I. N. Soskow & A. A. Soskova), pp. 300–309. Lecture Notes in Computer Science,
vol. 6735. Berlin, Germany: Springer.
14 Barwise, J. 1975 Admissible sets and structures: an approach to definability theory, perspectives
in mathematical logic. Berlin, Germany: Springer.
15 Stukachev, A. I. 2008 Effective model theory via the $\Sigma$-definability approach. In Proc. Effective
17 Beljaev, V. Ja. & Taicolin, M. A. 1979 Elementary properties of existentially closed systems.
Uspekhi Mat. Nauk 34, 39–94.
Notes in Computer Science, no. 4497, pp. 716–726. Berlin, Germany: Springer.
19 Soskow, A. A. & Soskow, I. N. 2009 A jump inversion theorem for the degree spectra. J. Logic


