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Source: *The Journal of Symbolic Logic*, Vol. 64, No. 2 (Jun., 1999), pp. 747-760

Published by: [Association for Symbolic Logic](#)

Stable URL: <http://www.jstor.org/stable/2586497>

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## UNDECIDABLE RELATIVIZATIONS OF ALGEBRAS OF RELATIONS

SZABOLCS MIKULÁS AND MAARTEN MARX

**Abstract.** In this paper we show that relativized versions of relation set algebras and cylindric set algebras have undecidable equational theories if we include coordinatewise versions of the counting operations into the similarity type. We apply these results to the guarded fragment of first-order logic.

**§1. Introduction.** Relativized algebras of relations are extensively investigated in the literature, cf., e.g., [HMT, HMTAN, Ma82, Mo93, Né91]. In general, relativized versions of algebras of relations have a nicer behavior from the computational point of view than the original versions.

In this paper, we concentrate on (un)decidability. We show that if we include coordinatewise versions of the counting operations into the similarity type, then the expressive power is strong enough to interpret the tiling problem into the equational theories of relativized relation set algebras and cylindric-relativized set algebras of dimension (at least) three. Thus these equational theories must be undecidable.

Finally, in the last section, we apply these results to logic: the corresponding versions of the guarded fragment of first-order logic and of arrow logic are undecidable.

**Acknowledgments:** Thanks are due to Hajnal Andréka and an anonymous referee for careful reading and valuable suggestions. Special thanks are due to the members of the Group of Algebraic Logicians in London: Robin Hirsch, Ian Hodkinson and Mark Reynolds.

**1.1. Relativization.** Relativization of an algebra amounts to intersecting all its elements with a fixed set (usually an element of the algebra or a subset of the unit) and to defining the operations using this set as the unit of the new algebra.

It turned out that if we relativize (set) algebras of relations with arbitrary, symmetric and/or reflexive elements, then we get a class of algebras with nice algebraic properties. For instance, while relation (set) algebras and cylindric (set) algebras of dimension at least three have undecidable equational theories, the sets of equations valid in the above relativizations are decidable.

Traditionally, during relativization we keep the original similarity type — in the case of relation algebras: Booleans, composition, converse, identity. As a consequence, some operations that are definable in the original version are not available after relativization. An example is the global counting operations *once*

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Received October 25, 1996; revised August 8, 1997; revised December 16, 1997.  
Research supported by EPSRC No. GR/K54946 and GR/L82441.

and *twice* and their coordinatewise versions. The question of which operations of the clone of the original algebras can be included into the similarity type of the relativized versions such that the nice properties of the relativized algebras are preserved naturally arises.

Elsewhere, cf. [MMN], we showed that (some of) the nice properties are preserved even if we consider a similarity type including the global counting operations besides the usual operations. In particular, if we add the global counting operations as basic operations to relativized relation set algebras [MMN, Mi95] and to cylindric-relativized set algebras [Mi98] then we get classes of algebras with decidable equational theories. See also [AHN] for a general characterization of operations that can be included without the loss of decidability.

However, there are more definable operations in a relation set algebra that become undefinable after relativization. An example is the coordinatewise version of the counting operation *twice*, expressing that there are two different pairs with the same vertical (or horizontal) coordinate.

It is well known that cylindric algebras correspond to first-order logic, cf. [HMT]. After relativizing cylindric set algebras we cannot express that a certain relation is a function. Thus it is a natural approach to define such versions of cylindric-relativized set algebras that are able to express functionality. For instance, we may include the coordinatewise version of the operation *at most one*.

In this paper, we show that including (one of) the vertical and horizontal counting operations in the similarity type yields relativized relation set algebras with undecidable equational theory. The undecidability result for relativized relation set algebras will follow from (the proof of) a similar undecidability result for relativizations of algebras of relations with higher arity: cylindric-relativized set algebras of dimension (at least) three with a coordinatewise version of *at most one* have undecidable equational theory.

The idea of the undecidability proof is to interpret the tiling problem into the equational theories of our algebras. While interpreting the tiling problem into relation algebras is very intuitive, the interpretation into cylindric algebras is more involved. That is why we sketch the proof for relation algebras and work out the details for the cylindric case (from this the relation algebra case easily follows).

**1.2. Tiling.** We will interpret the undecidable tiling problem into the equational theories of algebras of relations. Recently [Ma97] showed how to interpret the tiling problem into the theory of some weakened, axiomatically defined versions of relation algebras. It turned out that his idea can be used in the representable case as well — we will use a “semantical” version of that argument. Another interesting application of the tiling problem for relation algebras is in [HH97]: representability is undecidable for finite relation algebras.

Let us recall what the tiling problem is. By a tile we mean a square with a color on each side. Tiling a grid amounts to covering the surface such that the colors of the adjacent tiles are matching (e.g., if a tile has color  $c$  on its right-hand side, then the tile on its right must have color  $c$  on its left-hand side). One version of the tiling problem is the following:

Given a finite set  $T$  of tiles, can  $T$  tile  $\omega \times \omega$ ?

This problem is undecidable (in fact, co-r.e. complete), cf. [Ro71]. Now we give a more formal definition.

**DEFINITION 1.1.** Let  $C$  be a set (of colors). By a *tile*  $t$  we mean a four-tuple of elements of  $C$ :  $t = (c_0, c_1, c_2, c_3) \in {}^4C$ . Given a tile  $t$ , we will denote  $c_0, c_1, c_2, c_3$  by  $\text{left}(t), \text{right}(t), \text{up}(t), \text{down}(t)$ , respectively.

Let  $T$  be a set of tiles. We say that  $T$  *tiles*  $\omega \times \omega$  if there is a function  $\tau : \omega \times \omega \rightarrow T$  such that, for every  $(n, m) \in \omega \times \omega$ ,

$$\begin{aligned} \text{right}(\tau(n, m)) &= \text{left}(\tau(n + 1, m)) \\ \text{up}(\tau(n, m)) &= \text{down}(\tau(n, m + 1)). \end{aligned}$$

**§2. Relativized relation algebras.** In this section we define an expansion of relativized relation set algebras with a coordinatewise counting operation. We sketch how to prove the undecidability of its equational theory by interpreting the tiling problem. A self-contained proof can be obtained by straightforward modification of the proof of the cylindric case, Theorem 3.3. While this section gives insight for interpreting the tiling problem, it is not necessary for understanding the latter sections.

First we recall the definition of a (relativized) relation set algebra.

**DEFINITION 2.1.** By a *relation set algebra*, an  $\text{Rs}$ , we mean an algebra  $\mathcal{A} = (A, 0, 1, \cdot, -, ;, \smile, 1')$  such that  $A \subseteq \mathcal{P}(W)$  (the powerset of  $W$ ) for some set  $W = U \times U$ ,  $0 = \emptyset$ ,  $1 = W$ ,  $\cdot$  is intersection,  $-$  is complement w.r.t.  $W$ ,  $;$  is relation composition,  $\smile$  is relation converse, and  $1'$  is the identity relation on  $W$ . More formally, for all elements  $x, y \in A$ ,

$$\begin{aligned} x ; y &= \{(u, v) \in W : (u, w) \in x \text{ and } (w, v) \in y \text{ for some } w\} \\ x \smile &= \{(u, v) \in W : (v, u) \in x\} \\ 1' &= \{(u, v) \in W : u = v\}. \end{aligned}$$

We denote the class of relation set algebras by  $\text{Rs}$ . Given an  $\mathcal{A} \in \text{Rs}$ ,  $W$  and  $U$  as above we call  $W$  the *unit* of  $\mathcal{A}$  and  $U$  the *base* of  $\mathcal{A}$ .

The class  $\mathbf{RIRs}$  of *relativized relation set algebras* is defined by allowing any  $W \subseteq U \times U$  as unit in the definition of  $\text{Rs}$ .

The varieties generated by  $\text{Rs}$  and  $\mathbf{RIRs}$  are usually denoted by  $\text{RRA}$  and  $\text{SRIRRA}$ , respectively. It is easy to see that *relativizing* an  $\mathcal{A}' \in \text{Rs}$ , i.e., intersecting every element in  $\mathcal{A}'$  with some fixed element  $W \in \mathcal{A}'$ , yields an  $\mathcal{A} \in \mathbf{RIRs}$ . Conversely, every  $\mathcal{A} \in \mathbf{RIRs}$  can be obtained from an  $\mathcal{A}' \in \text{Rs}$  by relativization and taking subalgebras.

In relativized algebras, the behavior of the operators may be different than in the original version. For instance, composition is associative in  $\text{Rs}$ , while in  $\mathbf{RIRs}$  this does not hold in general (because some pairs may be missing from the unit).

The equational theory of  $\text{Rs}$  is undecidable [TG87], but that of  $\mathbf{RIRs}$  is decidable [Ma95]. This last fact stays true when we add all counting operations (see below) to  $\mathbf{RIRs}$  [Mi95].

In  $\text{Rs}$  we can term define the following operations:

$$\begin{aligned} D_0x &= \{(u, v) \in W : (u', v) \in x \text{ for some } u' \neq u\} \\ D_1x &= \{(u, v) \in W : (u, v') \in x \text{ for some } v' \neq v\} \\ Dx &= \{(u, v) \in W : (u', v') \in x \text{ for some } (u', v') \neq (u, v)\}, \end{aligned}$$

by setting  $D_0x = (-1') ; x$ ,  $D_1x = x ; (-1')$ , and  $Dx = (1 ; D_1x) + (D_0x ; 1)$ . On the other hand, this does not hold for **RIRs**; none of  $D$ ,  $D_1$  and  $D_0$  is definable in **RIRs**. For instance, let  $A = \{\emptyset, \{(0, 1)\}\}$ ,  $B = \{\emptyset, \{(0, 1), (2, 1)\}\}$  and  $\mathcal{A}, \mathcal{B}$  be in **RIRs** with universes  $A$  and  $B$ , respectively. Then  $\mathcal{A}$  and  $\mathcal{B}$  are isomorphic, but the intended meaning of  $D_0(1) = D_0(\{(0, 1)\})$  in  $\mathcal{A}$  is  $\emptyset$ , but  $D_0(1) = D_0(\{(0, 1), (2, 1)\}) = \{(0, 1), (2, 1)\}$  in  $\mathcal{B}$ .

These *difference* operators provide a limited ability to count: using them we can define the operators *at most once*,  $k^1$ , and the coordinatewise version *at most once in the  $i$ th coordinate*,  $k_i^1$ . In general these operations are defined as follows on an  $\mathcal{A}$  with unit  $W \subseteq {}^2U$ : for any  $x \in A$ ,

$$\begin{aligned}
 k^n x &= \begin{cases} 1 & \text{if } |x| \leq n \\ 0 & \text{otherwise} \end{cases} \\
 k_0^n x &= \{(u, v) \in W : \text{there exist at most } n \text{ distinct } w \in U \text{ such that } (w, v) \in x\} \\
 k_1^n x &= \{(u, v) \in W : \text{there exist at most } n \text{ distinct } w \in U \text{ such that } (u, w) \in x\}.
 \end{aligned}$$

We call the  $k^n$  ( $n \in \omega$ ) operators (*global*) *counting operations*, and the  $k_i^n$  ( $n \in \omega, i < 2$ ) *coordinatewise counting operations*. We note that, in an expanded **RIRs**, *at most one* is definable as  $k_i^1 x = -D_i(D_i x \cdot x)$  (with or without the index  $i$ ). As mentioned above, the expansion of **RIRs** with all global counting operations is decidable [Mi95], and has the finite base property [AHN], i.e., every non-valid equation fails in an algebra on a finite base. Here we show that adding only  $k_1^1$  (*at most one vertically*) destroys these properties.

**DEFINITION 2.2.** **RIRs**<sup>+</sup> denotes the class of all **RIRs** algebras expanded with an operation  $k_1^1$  as defined above.

**THEOREM 2.3.** 1. **RIRs**<sup>+</sup> *does not have the finite base property, i.e., there is a non-valid equation that is valid in every algebra with finite base.*

2. *The equational theory of **RIRs**<sup>+</sup> is undecidable.*

**SKETCH OF PROOF.** We prove the weaker 1 because it provides all the ingredients for the proof of 2 in a simple manner. We then only sketch the proof of 2, because below we provide a very similar proof for the more difficult case of  $\text{Cr}s_3^+$ , cf. Theorem 3.3, and a full proof for **RIRs**<sup>+</sup> is available in [Ma97].

For 1 we propose the following infinity axiom ( $c_0^\partial x$  abbreviates  $-(1 ; -x)$ ):

$$\begin{aligned}
 (t_a) \quad & 1' \cdot -(1 ; f) \\
 (t_b) \quad & c_0^\partial [(f \cdot 1^\smile) ; 1^\smile] \\
 (t_c) \quad & c_0^\partial k_1^1 f^\smile.
 \end{aligned}$$

We show that  $t_a \cdot t_b \cdot t_c = 0$  is not valid, and that if  $t_a \cdot t_b \cdot t_c \neq 0$  in a **RIRs**<sup>+</sup> with unit  $W$ , then  $W$  must contain the graph of a non-total and surjective function.

Let  $\mathcal{A}$  be the full **RIRs**<sup>+</sup> with unit  $\omega \times \omega$  and let  $f$  be interpreted as the successor function. Then  $(0, 0) \in t_a$  and  $(f \cdot 1^\smile) ; 1^\smile$  and  $k_1^1 f^\smile$  contain every pair  $(k, 0)$  ( $k \in \omega$ ), as is easy to see. In  $\mathcal{A}$ , the term  $c_0^\partial R$  equals  $\{(x, y) : \text{for every } z \in \omega, (z, y) \in R\}$ , whence  $(0, 0) \in t_a \cdot t_b \cdot t_c$ .

To see that the term forces the base set to be infinite, let it be satisfied in a **RIRs**<sup>+</sup> with unit  $W \subseteq U \times U$ , at a pair  $(u_0, v_0)$ :  $(u_0, v_0) \in t_a \cdot t_b \cdot t_c$ . By  $t_a \neq 0$ , then  $u_0 = v_0$ . Let

$$K = \{u \in U : (u_0, u), (u, u_0) \in W\}.$$

We show that  $f^\sim$  (restricted to  $K$ ) is a non-total, surjective function from  $K$  to  $K$ . By  $(u_0, u_0) \in t_a$ ,  $f^\sim$  is not total on  $K$ . By  $t_b \neq 0$ ,  $f^\sim$  is surjective, because for every  $u \in K$ ,  $(u, u_0) \in (f \cdot 1^\sim); 1^\sim$ . Finally,  $f^\sim$  is a function on  $K$ , since  $(u_0, u_0) \in t_c$  implies that, for every  $u \in K$ ,  $(u, u_0) \in k_1^1 f^\sim$ . Hence  $K$  must be infinite. Thus we have shown 1.

The proof gives us two of the three crucial ingredients for our undecidability proof. The first is that using the fact that  $(u_0, u_0) \in W$  and, for all  $u_i \in K$ ,  $\{(u, u_0), (u_0, u)\} \subseteq W$ , we can by  $c_0^\partial$  ensure “locally” that certain relations hold at each  $(u, u_0)$ . The second is that using this ability we can say — with the help of  $k_1^1$  — that there exist functions from  $K$  to  $K$ . Finally, as we will see in the proof for  $\text{Cr}_3^+$ , the crucial point of our undecidability proof is that we can express that we have two total *commuting* functions. This is easily expressed using composition by (assuming we have  $t_b \neq 0$  and  $t_c \neq 0$  for two variables  $u$  and  $r$ )  $c_0^\partial[(r; u \cdot u; r); 1]$ .

Let  $T = \{\tau_i : i \in I\}$  be a set of tiles. We define the following terms:

$$\begin{aligned} (s_0) \quad & c_0^\partial[(r; u \cdot u; r); 1] \\ (s_1) \quad & c_0^\partial(k_1^1 r \cdot k_1^1 u) \\ (t_0) \quad & c_0^\partial \sum \{\tau_i : i \in I\} \cdot 1' \end{aligned}$$

and for every  $\tau_i \in T$ ,

$$\begin{aligned} (t_1^i) \quad & c_0^\partial(-\tau_i + \prod\{-\tau_j : i \neq j \in I\}) \\ (t_2^i) \quad & c_0^\partial(-\tau_i + [r; (\sum\{\tau_j : \text{right}(\tau_i) = \text{left}(\tau_j)\})]) \\ (t_3^i) \quad & c_0^\partial(-\tau_i + [u; (\sum\{\tau_j : \text{up}(\tau_i) = \text{down}(\tau_j)\})]) \end{aligned}$$

Let  $s_T$  be the term  $s_0 \cdot s_1 \cdot t_0 \cdot \prod\{t_j^i : i \in I, 1 \leq j \leq 3\}$ . Now the proof can easily be finished in the same way as with  $\text{Cr}_3^+$  in the proof of Theorem 3.3 by showing that  $s_T \neq 0$  if and only if  $T$  can tile  $\omega \times \omega$ . ←

**COROLLARY 2.4.** *The equational and universal theories of  $\text{RIRs}^+$  are r.e. complete.*

**SKETCH OF PROOF.** By Theorem 2.3, the complexity of these theories are at least r.e.

That these theories are r.e. can be proved by using pseudo-axiomatizations of these theories: one can define many-sorted structures and recursively axiomatize them in a suitable first-order language, whence there exist recursive enumerations of the valid equations and first-order formulas. See [HMT] 4.2.27–32 and [Né91] for how this method works in the case of  $\text{Cs}_\alpha$  (defined below). ←

Let us finish this section with an open problem:

Is the variety generated by  $\text{RIRs}^+$  finitely axiomatizable?

**§3. Cylindric algebras.** In this section we define strengthenings of cylindric-relativized set algebras by expanding the language with counting operations (both global and coordinatewise).

**DEFINITION 3.1.** 1. Let  $U$  be a set,  $\alpha$  be an ordinal, and  $W$  be a non-empty subset of  $\alpha$ -long sequences from  $U$ , i.e., let  $W \subseteq {}^\alpha U$ . We define

$$\mathcal{A} = (\mathcal{P}(W), 0, 1, \cdot, -, c_i, d_{ij})_{i, j < \alpha} \in \text{full Cr}_\alpha$$

if the following hold:  $0 = \emptyset$ ,  $1 = W$ ,  $\cdot$  is intersection,  $-$  is complement w.r.t.  $W$ , and for every  $x \subseteq W$  and  $i, j < \alpha$ ,

$$\begin{aligned} c_i x &= \{a \in W : \text{for some } b \in x \text{ and for every } j \neq i, a(j) = b(j)\} \\ d_{ij} &= \{a \in W : a(i) = a(j)\}. \end{aligned}$$

We define  $\text{Cr}_\alpha = \mathbf{S}$  full  $\text{Cr}_\alpha$ , i.e., we take subalgebras of the elements of the class full  $\text{Cr}_\alpha$ . We call  $\text{Cr}_\alpha$  the class of *cylindric-relativized set algebras of dimension  $\alpha$* .

2. The class  $\text{Cs}_\alpha$  of *cylindric set algebras of dimension  $\alpha$*  is defined by requiring that the unit  $W$  be a Cartesian space on a base set  $U$  ( $W = {}^\alpha U$ ) in the definition of  $\text{Cr}_\alpha$ .

We note that the class  $\text{Cr}_\alpha$  is a variety, and the variety generated by  $\text{Cs}_\alpha$  is usually denoted by  $\text{RCA}_\alpha$ .

Let  $\mathcal{A}$  be an element of  $\text{Cr}_\alpha$ , and assume that  $W \subseteq {}^\alpha U$  is the unit of  $\mathcal{A}$ . The counting operations  $c^n$  ( $n \in \omega$ ) are defined in the following way: for every  $x \in \mathcal{A}$  and  $a \in W$ ,

$$a \in c^n x \iff |x| \geq n$$

or, equivalently

$$c^n x = \begin{cases} 1 & \text{if } |x| \geq n \\ 0 & \text{otherwise} \end{cases}$$

where  $|x|$  denotes the cardinality of  $x$ . Their coordinatewise versions  $c_i^n$  ( $i < \alpha, n \in \omega$ ) are defined as

$$a \in c_i^n x \iff \begin{aligned} &\text{there are at least } n \text{ different } b_1, \dots, b_n \in x \\ &\text{such that, for every } j \neq i \text{ and } 1 \leq k \leq n, a(j) = b_k(j). \end{aligned}$$

We note that  $c_i^1$  coincides with  $c_i$ . Similarly, we will usually drop the upper index 1 from  $c^1$ .

The presence of  $c_i^2$  enables us to express uniqueness in the  $i$ th coordinate:  $c_i^1!$ . More precisely, let

$$k_i^1 x = \{a \in W : \text{there is at most one } b \in x \text{ such that } b(j) = a(j) \text{ for every } j \neq i\}$$

in a set algebra with unit  $W$ . Then we can define  $k_i^1 x$  as  $-c_i^2 x$  and  $c_i^1! x$  as  $c_i x \cdot k_i^1 x$ . Thus we can express that certain relations are in fact functions, and this will be crucial in interpreting the tiling problem. Note also that the coordinatewise difference operator is definable by  $D_1 x = (c_1 x \cdot k_1^1 x \cdot -x) + -k_1^1 x$ .

The following defined operations in cylindric-relativized set algebras will be useful. Let  $i, j < \alpha$ . We define the *dual cylindrification*  $c_i^{\partial} x$  as  $-c_i - x$ , and the *substitution* as

$$s_j^i x = \begin{cases} c_i(d_{ij} \cdot x) & \text{if } i \neq j \\ x & \text{otherwise.} \end{cases}$$

The situation is very similar to the relational case. The class  $\text{Cs}_\alpha$  has undecidable equational theory whenever  $\alpha > 2$ , cf. [HMT] 4.2.18. Its relativized version  $\text{Cr}_\alpha$  and its expansion with the global counting operations have decidable equational theories, cf. [Né86, Né95] and [Mi98]. On the other hand, expansions with the coordinatewise counting operations are undecidable whenever  $\alpha > 2$ , by Theorem 3.3 below. However, in dimension 2, these expansions are decidable, Theorem 3.2.

The main results of this paper are the following two theorems. Their proofs are in the subsequent subsections.

	$Crs_\alpha$	$Crs_\alpha$ + global counting	$Crs_\alpha$ + coordinatewise counting	$Cs_\alpha$	$Cs_\alpha$ + coordinatewise counting
$\alpha = 2$	+ [Né86]	+ [Mi98]	+ Theorem 3.2	+ [HMT]	+ [GOR, Ma97]
$\alpha > 2$	+ [Né86]	+ [Mi98]	- Theorem 3.3	- [HMT]	- [HMT]

TABLE 1. (Un)decidability of the equational theories of classes of cylindric algebras.

**THEOREM 3.2.** *The equational theory of the expansion of  $Crs_2$  with the global and coordinatewise counting operations  $c^n, c_i^n$  ( $n \in \omega, i < 2$ )*

1. *is decidable, but*
2. *does not have the finite base property, i.e., there is a non-valid equation which is valid in every algebra with finite base.*

**THEOREM 3.3.** *Let  $\alpha \geq 3$ . The equational theory of the expansion of  $Crs_\alpha$  with the coordinatewise counting operations  $c_i^n$  ( $n \in \omega, i < \alpha$ ) is undecidable. In fact, the expansion  $Crs_3^+$  of  $Crs_3$  with a single operation  $k_1^1$  has an undecidable equational theory.*

We summarized these results in Table 1. We note that, similarly to the relation algebra case, the undecidable equational theories are in fact r.e. complete.

**3.1. Dimension 2.** Next we prove that expanding the language with counting operations in dimension 2 does not ruin decidability, though it enables us to express infinity.

**PROOF OF THEOREM 3.2.** 1: We will show how to decide the validity of an equation in expanded relativized algebras given a decision algorithm for validity of the same expansion of  $Cs_2$  (provided by [GOR] or [Ma97]). First let us note that an equation  $\rho = \sigma$  is valid iff  $c(\rho \oplus \sigma) = 1$  is not satisfiable (where  $\oplus$  is symmetric difference). Then it suffices to define a recursive translation  $t$  such that an equation  $e$  is satisfiable in an expanded relativized algebra iff  $t(e)$  is satisfiable in an expanded  $Cs_2$ . Let  $z$  be a new variable. We define a translation of terms as follows: for variable  $x$  and terms  $\sigma, \tau$ ,

$$\begin{aligned}
 t(x) &= x \cdot z \\
 t(1) &= 1 \cdot z \\
 t(d_{ij}) &= d_{ij} \cdot z \\
 t(\sigma \cdot \tau) &= t(\sigma) \cdot t(\tau) \cdot z \\
 t(-\sigma) &= -t(\sigma) \cdot z \\
 t(c_i \sigma) &= c_i t(\sigma) \cdot z \\
 t(c_i^n \sigma) &= c_i^n t(\sigma) \cdot z.
 \end{aligned}$$

Let  $e$  be  $\sigma = \tau$ . We define  $t(e)$  as  $t(\sigma) = t(\tau)$ .

Let us assume that  $e$  is satisfied in a relativized  $\mathcal{A}$  with base  $U$  and unit  $W$ . Let  $\mathcal{B}$  be the full algebra with the Cartesian square unit  $U \times U$ . We evaluate the variables of  $e$  in  $\mathcal{B}$  as in  $\mathcal{A}$ , and let  $z$  have the value  $W$ . Then an easy induction shows that the value of a term  $\sigma$  in  $\mathcal{A}$  coincides with that of  $t(\sigma)$  in  $\mathcal{B}$ . From this follows that  $t(e)$  is satisfied in  $\mathcal{B}$ .

Now assume that  $t(e)$  is satisfied in an expanded  $\text{Cs}_2 \mathcal{A}$  under a certain evaluation. Let  $W$  be the value of  $z$ , and let  $\mathcal{B}$  be the relativization of  $\mathcal{A}$  by  $W$ , i.e.,  $B = \{a \cap W : a \in A\}$ . Then the above argument shows that  $\mathcal{B}$  satisfies  $e$ .

2: Let  $e$  be an equation of the form  $\rho = \sigma$ . Then  $e$  is satisfiable iff  $c(\rho \oplus \sigma) = 1$  is not valid. Thus it suffices to show that there is a satisfiable equation  $e$  such that satisfiability of  $e$  implies the infinity of the base.

Let us define the following terms:

$$\begin{aligned} \rho_0 &= c(d_{01} \cdot - c_1^1 f) \\ \rho_1 &= -c c_1^2 f \\ \rho_2 &= -c - (c_0(f \cdot c_1 d_{01})). \end{aligned}$$

The equation  $e$  is defined as  $\rho_0 \cdot \rho_1 \cdot \rho_2 = 1$ .

Let  $\mathcal{A}$  be the full algebra with unit  $\omega \times \omega$  and

$$f = \{(n + 1, n) : n \in \omega\}.$$

It is easy to check that  $e$  holds in  $\mathcal{A}$ .

Let  $\mathcal{A}$  be with unit  $W$  such that  $e$  holds in  $\mathcal{A}$ . Let  $K = \{x : (x, x) \in W\}$ . By  $\rho_1$ , for every  $x \in K$ , there is at most one  $y \in K$  such that  $(x, y) \in f$ ; let  $F(x) = y$  if such a  $y$  exists. Then  $F$  is a partial function  $F : K \rightarrow K$ . By  $\rho_0$ ,  $F$  is not total. By  $\rho_2$ ,  $F$  is onto. It follows that  $K$  is infinite. ⊣

**REMARK 3.4.** We note that the above idea can be used to prove that the *existential* theory of  $\text{Crs}_2$  does not have the finite base property. That is, there is a non-valid existential sentence that is valid in every finite  $\text{Crs}_2$ , cf. [Mi97] for details. Note that, on the other hand,  $\text{Crs}_\alpha$  ( $\alpha$  finite) has the finite base property for *universal* sentences, cf. [AHN].

**3.2. Dimensions higher than 2.** Now we turn to proving Theorem 3.3.

Let  $T = \{\tau_i : i \in I\}$  be a given finite set of tiles. Let us recall that for a given tile  $\tau_i \in T$  we denote its colors by  $\text{left}(\tau_i)$ ,  $\text{right}(\tau_i)$ ,  $\text{up}(\tau_i)$ , and  $\text{down}(\tau_i)$ . For every  $\tau_i \in T$ , let  $\tau_i$  be a variable, and let  $r$  and  $u$  be variables as well.

The idea of the undecidability proof is that we can “code up” the tiling of  $\omega \times \omega$  into an equation. We will map  $\omega \times \omega$  onto  $\omega$  and evaluate the  $\tau_i$ ’s on sequences of the form  $(n, 0, 0, \dots)$  ( $n \in \omega$ ). Using two variables  $r$  and  $u$  we will define right- and up-successors. These will be commuting total functions, and we will make sure that the evaluation of the  $\tau_i$ ’s is in correspondence with these successor functions so that adjacent colors match.

**PROOF OF THEOREM 3.3.** We prove the theorem for the expansion of  $\text{Crs}_3$  by  $k_1^1$  (that is definable by  $c_1^2$ ). Let us denote this expansion by  $\text{Crs}_3^+$ . Obvious modifications in the proof yield the same result for higher dimensions and larger similarity types.

We define (a kind of) composition of two elements  $x$  and  $y$  as

$$x ; y = c_2(c_0(d_{02} \cdot c_2 y) \cdot c_1(d_{12} \cdot c_2 x)) = c_2(s_2^0 c_2 y \cdot s_2^1 c_2 x),$$

cf. [HMT] 5.3.7. The idea of the above definition is to consider  $x$  and  $y$  as binary relations, and using an extra coordinate, to express their composition, cf. Remark 3.7 after the proof.

Consider the set of terms below. Their intuitive meaning is as follows. For a given sequence  $(n, 0, 0)$ ,  $s_0$  guarantees that there are  $m, l$  such that  $m$  is the right-successor of  $n$ ,  $l$  is the up-successor of  $n$  and the up-successor of  $m$  and the right-successor of  $l$  coincide. The uniqueness of the up- and right-successors is guaranteed by  $s_1$ . The role of  $t_0$  and  $t_1^i$  is to evaluate the  $\tau_i$ 's on the diagonal  $d_{12}$  in a disjoint way. Finally,  $t_2^i$  and  $t_3^i$  ensure that the successor functions and the evaluation of the tiles make the colors of adjacent tiles match. We define

$$\begin{aligned} (s_0) & \quad c_0^\partial [([(r \cdot d_{02}); (u \cdot d_{02})] \cdot [(u \cdot d_{02}); (r \cdot d_{02})]); d_{12}] \\ (s_1) & \quad c_0^\partial s_0^1 s_0^2 (k_1^1 r \cdot k_1^1 u) \\ (t_0) & \quad c_0^\partial (\sum \{\tau_i : i \in I\}) \cdot d_{01} \cdot d_{12} \end{aligned}$$

and for every  $\tau_i \in T$ ,

$$\begin{aligned} (t_1^i) & \quad c_0^\partial (-\tau_i + \prod \{-\tau_j : i \neq j \in I\}) \\ (t_2^i) & \quad c_0^\partial (-\tau_i + [(r \cdot d_{02}); (\sum \{\tau_j : \text{right}(\tau_j) = \text{left}(\tau_i)\} \cdot d_{12})]) \\ (t_3^i) & \quad c_0^\partial (-\tau_i + [(u \cdot d_{02}); (\sum \{\tau_j : \text{up}(\tau_j) = \text{down}(\tau_i)\} \cdot d_{12})]). \end{aligned}$$

Let  $s_T$  be the term  $s_0 \cdot s_1 \cdot t_0 \cdot \prod \{t_j^i : i \in I, 1 \leq j \leq 3\}$ . We will show that the equation  $s_T = 0$  is valid in  $\text{CrS}_3^+$  if and only if  $T$  cannot tile  $\omega \times \omega$ , yielding the undecidability of the validity problem of equations. Note that the equation  $s_T = 0$  is not valid in  $\text{CrS}_3^+$  iff there is an  $\mathcal{A} \in \text{CrS}_3^+$  and a sequence  $(a, b, c)$  in the unit of  $\mathcal{A}$  which is in the value  $(s_T)^\mathcal{A}$  of the term  $s_T$  in  $\mathcal{A}$ . (If no confusion is likely we will omit the superscript  $\mathcal{A}$ .)

First assume that  $T$  tiles  $\omega \times \omega$ . We have to show that  $s_T$  is satisfiable in an  $\mathcal{A} \in \text{CrS}_3^+$ , i.e., that there is a sequence  $(x, y, z)$  in the unit  $W$  of  $\mathcal{A}$  which is in the value of the term  $s_T$  in  $\mathcal{A}$ . Let  $\mathcal{A}$  be the full  $\text{Cs}_3$  with unit  $W = {}^3\omega$  expanded with  $k_1^1$ . Let  $f : \omega \times \omega \rightarrow \omega$  be a bijection such that  $f(0, 0) = 0$ . Let every  $\tau_i \in T$  be evaluated according to the given tiling of  $\omega \times \omega$ :  $(x, 0, 0) \in \tau_i$  iff there are  $n, m \in \omega$  such that  $f(n, m) = x$  and  $\tau_i$  tiles  $(n, m)$ . We evaluate  $u$  and  $r$  as follows. For every  $(x, y, z) \in W$ , we let  $(x, y, z) \in r$  iff  $x = z$  and there are  $n, m \in \omega$  such that  $f(n, m) = x$  and  $f(n + 1, m) = y$ . Since every  $(n, m)$  has a unique right-successor  $(n + 1, m)$ , for a given  $(x, 0, 0)$  there is a unique  $y$  such that  $(x, y, x) \in r$ . We define  $u$  similarly. We claim that  $(0, 0, 0) \in s_T$ .

The term  $t_0$  is satisfied at  $(0, 0, 0)$ , since  $(0, 0, 0) \in d_{01} \cdot d_{12}$  and, by the surjectivity of  $f$ , for every  $x \in \omega$ ,  $(x, 0, 0) \in \tau_i$  for some  $i \in I$ .

We show that  $(0, 0, 0) \in s_0$ . Indeed, let  $x \in \omega$  be arbitrary, and assume that  $x = f(n, m)$  for some  $n, m \in \omega$ . Further, let  $f(n + 1, m) = y$ ,  $f(n, m + 1) = z$  and  $f(n + 1, m + 1) = v$ . Then  $(x, y, x) \in r \cdot d_{02}$ ,  $(y, v, y) \in u \cdot d_{02}$ ,  $(x, z, x) \in u \cdot d_{02}$  and  $(z, v, z) \in r \cdot d_{02}$  by the definition of  $r$  and  $u$ . By unfolding the definition of composition, we get that  $(x, v, 0) \in [(r \cdot d_{02}); (u \cdot d_{02})] \cdot [(u \cdot d_{02}); (r \cdot d_{02})]$ . Since  $(v, 0, 0) \in d_{12}$ , we have  $(x, 0, 0) \in ([ (r \cdot d_{02}); (u \cdot d_{02}) ] \cdot [ (u \cdot d_{02}); (r \cdot d_{02}) ]) ; d_{12}$ .

Next we check  $s_1$ . Again let  $x, y, z$  be as in the previous paragraph. By the injectivity of  $f$ ,  $y$  is the unique element of  $\omega$  such that  $(x, y, x) \in r$ . Thus  $(x, x, x) \in k_1^1 r$ , and similarly  $(x, x, x) \in k_1^1 u$ . Hence  $(x, 0, 0) \in s_0^1 s_0^2 (k_1^1 r \cdot k_1^1 u)$ .

Since in the given tiling of  $\omega \times \omega$  every  $(n, m) \in {}^2\omega$  is covered by a unique tile,  $t_1^i$  holds at  $(0, 0, 0)$  for every  $i \in I$ . So far we have seen that, for every  $x \in \omega$ ,  $(x, 0, 0) \in \tau_i$  for a unique  $i \in I$ .

Finally, we check  $t_2^i$  — the proof of  $t_3^i$  is completely analogous. Let  $(x, 0, 0) \in \tau_i$ ,  $x = f(n, m)$ ,  $y = f(n + 1, m)$  and  $(y, 0, 0) \in \tau_j$ . Then  $\text{right}(\tau_i) = \text{left}(\tau_j)$ , by the evaluation of  $\tau_i$  and  $\tau_j$ . Since  $(x, y, x) \in r$ , we get that  $(x, 0, 0) \in (r \cdot d_{02}) ; (\tau_j \cdot d_{12})$ .

To prove the other direction, let us assume that  $s_T$  is satisfied in an  $\mathcal{A} \in \text{CrS}_3^+$ . We will show that  $T$  can tile  $\omega \times \omega$ .

Let  $W$  be the unit and  $U$  be the base of  $\mathcal{A}$ , and let  $(k, l, m) \in W$  be in the value of  $s_T$ . Let us fix such a  $k$  and denote it by 0. By  $t_0$ ,  $(0, l, m) \in d_{01} \cdot d_{12}$ , i.e.,  $k = l = m = 0$ . We define

$$K = \{x \in U : (x, 0, 0) \in W\}.$$

Let  $x \in K$  be arbitrary. Then  $(x, 0, 0) \in \tau_i$  for some  $i \in I$ , by  $t_0$ . By  $t_2^i$ ,  $(x, 0, 0) \in (r \cdot d_{02}) ; (\sum\{\tau_j : \text{right}(\tau_i) = \text{left}(\tau_j)\} \cdot d_{12})$ . Unfolding the definition of composition, we get that there is a  $y \in U$  such that  $(y, 0, 0) \in \sum\{\tau_j : \text{right}(\tau_i) = \text{left}(\tau_j)\}$  and  $(x, y, x) \in r$ . On the other hand, by  $s_1$ , there is at most one  $y$  such that  $(x, y, x) \in r$ . Thus we can define a function  $\text{Right} : K \rightarrow K$  by letting  $\text{Right}(x)$  be the unique  $y$  for which  $(x, y, x) \in r$  and  $(y, 0, 0) \in W$ . Similarly we define  $\text{Up} : \text{Up}(x) = z$  iff  $z$  is the unique element of  $K$  such that  $(x, z, x) \in u$ . We are ready to formulate the following lemma.

LEMMA 3.5. *Right and Up are commuting functions on K, i.e.,  $\text{Right}, \text{Up} : K \rightarrow K$  and, for every  $x \in K$ ,  $\text{Right}(\text{Up}(x)) = \text{Up}(\text{Right}(x))$ .*

PROOF. Let  $x \in K$  be arbitrary. By  $s_0$ ,

$$(x, 0, 0) \in ((r \cdot d_{02}) ; (u \cdot d_{02})) \cdot ((u \cdot d_{02}) ; (r \cdot d_{02})) ; d_{12}.$$

Then we have  $y, z, v \in U$  such that  $(x, y, x) \in r$ ,  $(y, v, y) \in u$ ,  $(x, z, x) \in u$  and  $(z, v, z) \in r$ . The argument we used above the lemma ensures that  $y, z, v \in K$ , i.e.,  $y = \text{Right}(x)$ ,  $v = \text{Up}(y)$ ,  $z = \text{Up}(x)$  and  $v = \text{Right}(z)$ . Hence  $\text{Up}(\text{Right}(x)) = \text{Right}(\text{Up}(x))$ . ⊢

We define a tiling  $\tau$  of  $\omega \times \omega$  as follows: for every  $(n, m) \in \omega \times \omega$  and  $i \in I$ , let

$$\tau(n, m) = \tau_i \iff (\text{Right}^n \text{Up}^m(0), 0, 0) \in \tau_i,$$

where  $\text{Right}^0(0) = \text{Up}^0(0) = 0$ ,  $\text{Right}^{k+1} \text{Up}^l(0) = \text{Right}(\text{Right}^k \text{Up}^l(0))$  and  $\text{Right}^k \text{Up}^{l+1}(0) = \text{Right}^k \text{Up}^l(\text{Up}(0))$  for every  $k, l \in \omega$ .

LEMMA 3.6. *The function  $\tau$  defined above is a tiling of  $\omega \times \omega$ .*

PROOF. Let  $(n, m) \in \omega \times \omega$  be arbitrary and  $x = \text{Right}^n \text{Up}^m(0)$ . Since  $\text{Right}$  and  $\text{Up}$  are functions with range  $K$ , there exists, by  $t_0$ , a  $\tau_i \in T$  such that  $(x, 0, 0) \in \tau_i$ , and by  $t_1^i$  such a  $\tau_i$  must be unique. Hence,  $\tau$  is indeed a function with domain  $\omega \times \omega$  and with range  $T$ .

It remains to check that adjacent tiles have matching colors. Let  $(n, m) \in \omega \times \omega$  be arbitrary. Let  $\tau(n, m) = \tau_i$  and  $x = \text{Right}^n \text{Up}^m(0)$ . Then  $(x, 0, 0) \in \tau_i$ .

Let  $\tau(n + 1, m) = \tau_j$ , i.e.,  $(\text{Right}(x), 0, 0) \in \tau_j$ . Recall that  $\text{Right}(x)$  is the unique element of  $U$  such that  $(x, \text{Right}(x), x) \in r$ . Then by  $t_2^i$ ,  $\text{right}(\tau_i) = \text{left}(\tau_j)$ .

To prove that  $\text{up}(\tau(n, m)) = \text{down}(\tau(n, m + 1))$  one needs the following:

$$\text{Up}(\text{Right}^n \text{Up}^m(0)) = \text{Right}^n \text{Up}^{m+1}(0).$$

This can be proved by an easy induction using Lemma 3.5. Then, using  $t_3^i$  instead of  $t_2^i$ , the above argument gives the desired result.  $\dashv$

This finishes the proof of Theorem 3.3.  $\dashv$

**REMARK 3.7.** From the above proof we can see that any subclass of  $\text{Cr}_\alpha^+$  which contains an expanded full  $\text{Cs}_\alpha$  with a countable base set has an undecidable equational theory. Similar remark applies to the  $\text{RIRs}^+$  case.

We note that the above definition of composition works properly (i.e., according to the intuition) only in algebras with Cartesian space units. More precisely, if we consider the relation-algebraic reduct of a cylindric set algebra of dimension three, it turns out to be a relation set algebra, cf. [HMT] 5.3.16. On the other hand, there is a  $\text{Cr}_3$  such that its relation-algebraic reduct is not in the class  $\text{RIRs}$  (for instance, consider a  $\text{Cr}_3$  with a unit  $W = \{(a, c, c), (a, b, b), (b, c, c)\}$ ). That is why we could not prove the above theorem by reducing it to the relation algebra case.

**§4. Logical applications.** In [MMN] and [Mi95] we raised the question of how to find computationally well-behaved versions of well-investigated logics. The following strategy proved to be fruitful: (1) weakening the logic by widening the class of models such that this version of the logic has nice properties and (2) strengthening the weakened version by (re-)introducing connectives without losing the nice properties.

For instance, we may consider *relativized versions of first-order logic*, where we restrict the set of available evaluations of the variables to an arbitrary non-empty subset of all possible valuations. This logic corresponds to cylindric-relativized set algebras,  $\text{Cr}_s$ , and is decidable [Né95] even if we expand the signature by the graded modalities [Mi98]. Applying the results of the previous sections shows a limit of the strategy described above: adding the counting quantifiers (the coordinatewise versions of the graded modalities) yields undecidable relativized logics.

There is also another route towards decidability in first-order logic and that is to consider only certain syntactic fragments, but keep the standard semantics. As van Benthem observed [vB96] the distinction between these two routes is relative. It is easy to translate the formulas from the weakened first-order logics to formulas inside the decidable, so called *Guarded Fragment*. What Theorem 3.3 then implies is that any expansion of the Guarded Fragment with some operation sufficient to express that a relation behaves as a partial function must be undecidable. We will now briefly review the connection between (relativized) cylindric set algebras and first-order logic, and show how to obtain the mentioned result on the Guarded Fragment.

Let  $L_n^r$  denote the *restricted version of the  $n$ -variable fragment of first-order logic with equality*: the language does not contain function symbols or constants, all variables occurring in a formula are from the set  $\{v_0, \dots, v_{n-1}\}$ , and the atomic formulas are of the form  $R(v_0, v_1, \dots, v_{n-1})$  or  $v_i = v_j$ . So we only have  $n$ -ary predicate symbols, and the variables always occur in the same order. The cylindric-algebraic terms and the  $L_n^r$  formulas are just syntactic variants, by the following

(bijective) translation:

$$\begin{aligned} x^t &= X(v_0, v_1, \dots, v_{n-1}) \\ (-\tau)^t &= \neg\tau^t \\ (\tau \cdot \sigma)^t &= \tau^t \wedge \sigma^t \\ \mathbf{d}_{ij} &= v_i = v_j \\ (\mathbf{c}_i\tau)^t &= \exists v_i\tau^t, \end{aligned}$$

where  $X$  is a predicate symbol (different for different variables). In fact  $(\cdot)^t$  is truth-preserving, namely

$$\begin{aligned} \text{Cs}_n \models \tau = \sigma &\iff \models \sigma^t \leftrightarrow \tau^t \\ \models \varphi &\iff \text{Cs}_n \models (\varphi^t)^{-1} = 1 \end{aligned}$$

where  $(\cdot)^{-1}$  denotes the inverse of  $(\cdot)^t$ . Let  $(\cdot)^{t'}$  be the same as  $(\cdot)^t$ , except for

$$(\mathbf{c}_i\tau)^{t'} = \exists v_i(V(v_0, \dots, v_{n-1}) \wedge \tau^t),$$

where  $V$  is a new fixed predicate symbol. Then (cf. [vB96] Corollary 9.14)

$$\text{Crs}_n \models \sigma = \tau \iff \models V(v_0, \dots, v_{n-1}) \rightarrow (\sigma^t \leftrightarrow \tau^t).$$

The interesting thing about the range of  $(\cdot)^{t'}$  is that every occurrence of a quantifier occurs relativized by  $V(v_0, \dots, v_{n-1})$  (this predicate corresponds to the available evaluations in a relativized model). These formulas all belong to the *Guarded Fragment*, defined as follows. We expand (the  $n$ -variable fragment of) first-order logic (with equality but without function symbols or constants) with polyadic quantifiers  $\exists \vec{v}$  ( $\vec{v}$  a vector of variables). A formula of this language is called *guarded* if it is generated from atoms using the Booleans and “guarded quantification”

$$\exists \vec{v}(G\vec{v}\vec{x} \wedge \varphi(\vec{v}\vec{x})),$$

where  $G$  is a predicate symbol, and the variables occurring in  $\vec{v}$  and  $\vec{x}$  may occur in any order and with any multiplicity in both  $G$  and  $\varphi$ , though they are the only variables which occur there free. All these formulas together form the *Guarded Fragment*.

The *Guarded Fragment* is decidable [vB96], thus it is a decidable extension of  $\text{Cs}_n$ , by the effective translation  $(\cdot)^{t'}$ . Note that the translation even goes into the *Guarded Fragment* of restricted first-order logic  $L'_n$ .

No truth preserving translation of the term  $k_1^1\tau$  can go to the *Guarded Fragment*, otherwise we could decide  $\text{Crs}_3^+$ , which we cannot by Theorem 3.3. Thus if we expand the *Guarded Fragment* with an operation  $[\text{func}]_1$ , with meaning

$$\begin{aligned} \mathcal{M} \models [\text{func}]_1\varphi [a] &\text{ iff there exists at most one } d \in M \text{ such that} \\ &\mathcal{M} \models \varphi [a(a(1) \mapsto d)], \end{aligned}$$

then that expansion is undecidable, because we could interpret  $\text{Crs}_3^+$  in it, using the above  $(\cdot)^{t'}$  which now translates  $k_1^1\tau$  to  $[\text{func}]_1\tau^{t'}$ . This even holds if we restrict the application of  $[\text{func}]_1$  to predicate symbols only, because in the given encoding of the tiling problem we only applied  $k_1^1$  to variables. Moreover, this also holds for the restriction of the *Guarded Fragment* to three variables, and not containing the polyadic quantifiers  $\exists \vec{v}$ , since these are not needed in the translation of  $\text{Crs}_3^+$ .

On the other hand,  $\text{Cr}_s$  expanded with all the global counting (or graded) modalities is decidable [Mi95], and even has the finite base property [AHN]. The translation of these operators does not arrive in the guarded fragment. It seems likely that the Guarded Fragment can be expanded in this direction as well, without loss of decidability.

We note that in two dimensions the situation is better: the expansion of  $L_2^+$  with all the counting quantifiers is decidable ([GOR] and [Ma97]), but does not have the finite base property, by Theorem 3.2.

Finally, we note that, in a similar fashion, the undecidability result for relation algebras yields undecidability of (relativized) arrow logic (cf. [MMP]) if we expand the signature with coordinatewise counting quantifiers.

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