



Sofia University "St. Kliment Ohridski"  
Faculty of Mathematics and Informatics  
Department of Mathematical Logic and Applications

MASTER THESIS

# **Satisfiability with Equivalences in Agreement**

*Krasimir Georgiev*

*faculty number 24691, Logic and Algorithms (Informatics)*

supervised by  
Prof. Tinko TINCHEV

Sofia  
September 2016



# Contents

<b>Abstract</b>	<b>ix</b>
<b>1 Preliminaries</b>	<b>1</b>
1.1 Syntax . . . . .	2
1.2 Semantics . . . . .	4
1.3 Games . . . . .	5
1.4 Types . . . . .	6
1.5 Scott normal form . . . . .	7
1.6 Complexity . . . . .	7
<b>2 Counter setups</b>	<b>9</b>
2.1 Bits . . . . .	9
2.2 Counters . . . . .	10
2.3 Vectors . . . . .	11
2.4 Permutations . . . . .	13
<b>3 Equivalence relations</b>	<b>15</b>
3.1 Two equivalence relations in agreement . . . . .	15
3.2 Many equivalence relations in agreement . . . . .	16
<b>4 Reductions</b>	<b>19</b>
4.1 Global agreement to refinement . . . . .	20
4.2 Local agreement to refinement . . . . .	23
4.3 Granularity . . . . .	27
<b>5 Monadic logics</b>	<b>31</b>
5.1 Cells . . . . .	31
5.2 Organs . . . . .	32
5.3 Satisfiability . . . . .	34
5.4 Hardness with a single equivalence . . . . .	35
5.5 Hardness with many equivalences in refinement . . . . .	41
<b>6 Two-variable logics</b>	<b>47</b>
6.1 Type realizability . . . . .	47
6.2 Type realizability with equivalences . . . . .	54
6.3 Cosmic spectrums . . . . .	58
6.4 Locally consistent cosmic spectrums . . . . .	61



# Glossary

$ A $ the cardinality of $A$ . 1	$v \prec w$ antilexicographically smaller. 2
$\wp A$ the powerset of $A$ . 1	$\mathbb{S}_n$ the set of permutations of $[1, n]$ . 2
$\wp^+ A$ the set of nonempty subsets of $A$ . 1	$\exp_a^e(x)$ tetration. 2
$\wp^\kappa A$ the set of subsets of $A$ of cardinality $\kappa$ . 1	$\Omega$ an alphabet. 2
$A \times B$ the cartesian product of $A$ and $B$ . 1	$w = w_1 w_2 \dots w_n$ a word. 2
$\text{dom } R$ the domain of $R$ . 1	$\Omega^*$ the set of words over $\Omega$ . 2
$\text{ran } R$ the range of $R$ . 1	$\Omega^+$ the set of nonempty words over $\Omega$ . 2
$R^{-1}$ the inverse of $R$ . 1	$\Omega^n$ the set of words of length $n$ over $\Omega$ . 2
$R \upharpoonright S$ the restriction of $R$ to $S$ . 1	$\mathbb{B}$ the bits. 2
$R[a]$ the $R$ -successors of $a$ . 1	$\mathbb{B}^+$ the bitstrings. 2
$S \circ R$ the composition of $S$ and $R$ . 1	$\ n\ $ the bitsize of $n$ . 2
$f : A \rightarrow B$ a total function from $A$ to $B$ . 1	$\bar{n}$ the binary encoding of $n$ . 2
$f : A \hookrightarrow B$ an injective function from $A$ into $B$ . 1	$\underline{b}$ the number encoded by $b$ . 2
$f : A \twoheadrightarrow B$ a surjective function from $A$ onto $B$ . 1	$N_t$ the largest $t$ -bit number. 2
$f : A \leftrightarrow B$ a bijective function between $A$ and $B$ . 1	$\mathbb{B}_t$ the $t$ -bit numbers. 2
$\text{id}_A$ the identity on $A$ . 1	$\Omega_{\mathcal{L}}$ the symbol alphabet. 2
$f : A \rightsquigarrow B$ a partial function from $A$ to $B$ . 1	$\mathcal{V}$ the variable symbols. 2
$f(a) \simeq b$ $f$ is defined at $a$ with value $b$ . 1	$\mathbf{x}$ the first variable symbol. 2
$f(a) \simeq \perp$ $f$ is not defined at $a$ . 1	$\mathbf{y}$ the second variable symbol. 2
$\text{ch}_S^A$ characteristic function. 1	$\mathbf{z}$ the third variable symbol. 2
$\ A\ $ the length of $A$ . 1	$\Sigma$ a predicate signature. 2
$\langle a, b, c \rangle$ a sequence. 1	$\mathbf{p}_i$ a predicate symbol. 2
$\varepsilon$ the empty sequence. 1	$\text{ar } \mathbf{p}_i$ the arity of $\mathbf{p}_i$ . 2
$A + B$ the concatenation of $A$ and $B$ . 1	$\mathcal{A}t[\Sigma]$ the atomic formulas over $\Sigma$ . 3
$A - B$ $A$ without the elements of $B$ . 1	$\mathcal{L}it[\Sigma]$ the literals over $\Sigma$ . 3
$\mathbb{N}$ the natural numbers. 1	$\mathcal{L}[\Sigma]$ the first-order formulas over $\Sigma$ . 3
$\mathbb{N}^+$ the positive natural numbers. 1	$\text{vars } \varphi$ the variables occurring $\varphi$ . 3
$[n, m]$ the discrete interval between $n$ and $m$ . 1	$\text{fvars } \varphi$ the variables freely occurring $\varphi$ . 3
$\log$ the base-2 logarithm. 2	$\mathcal{L}^v[\Sigma]$ the $v$ -variable first-order formulas over $\Sigma$ . 3
	$\text{qr } \varphi$ the quantifier rank of $\varphi$ . 3
	$\mathcal{L}_r[\Sigma]$ the $r$ -rank first-order formulas over $\Sigma$ . 3
	$\mathcal{L}_r^v[\Sigma]$ the $r$ -rank $v$ -variable first-order formulas over $\Sigma$ . 3

## Glossary

- $\mathfrak{A}$  a structure. 4
- $\varphi^{\mathfrak{A}}$  interpretation of  $\varphi$  in  $\mathfrak{A}$ . 4
- SAT- $\mathcal{K}$  the satisfiable sentences of  $\mathcal{K}$ . 4
- FIN-SAT- $\mathcal{K}$  the finitely satisfiable sentences of  $\mathcal{K}$ . 4
- $\varphi \equiv \psi$  logically equivalent formulas. 4
- $\mathfrak{A} \equiv \mathfrak{B}$  elementary equivalent structures. 4
- $\mathfrak{A} \equiv_r \mathfrak{B}$   $r$ -rank equivalent structures. 4
- $\mathfrak{A} \equiv^v \mathfrak{B}$   $v$ -variable equivalent structures. 4
- $\mathfrak{A} \equiv_r^v \mathfrak{B}$   $r$ -rank  $v$ -variable equivalent structures. 5
- $\mathfrak{p}$  parital isomorphism. 5
- $G_r(\mathfrak{A}, \mathfrak{B})$  the  $r$ -round Ehrenfeucht-Fraïssé game. 5
- $\Pi[\Sigma]$  the set of 1-types over  $\Sigma$ . 5
- $T[\Sigma]$  the set of 1-types over  $\Sigma$ . 5
- $\tau^{-1}$  the inverse of the type  $\tau$ . 6
- $\text{tp}_x \tau$  the  $x$ -type of  $\tau$ . 6
- $\text{tp}_y \tau$  the  $y$ -type of  $\tau$ . 6
- $\text{tp}^{\mathfrak{A}}[a]$  the 1-type of  $a$  in  $\mathfrak{A}$ . 6
- $\pi^{\mathfrak{A}}$  the interpretation of the 1-type  $\pi$  in  $\mathfrak{A}$ . 6
- $\text{tp}^{\mathfrak{A}}[a, b]$  the 2-type of  $(a, b)$  in  $\mathfrak{A}$ . 6
- $\tau^{\mathfrak{A}}$  the interpretation of the 2-type  $\tau$  in  $\mathfrak{A}$ . 6
- PTime complexity class. 7
- $A \leq_m^{\text{PTime}} B$   $A$  is polynomial-time reducible to  $B$ . 7
- $A =_m^{\text{PTime}} B$   $A$  and  $B$  are polynomial-time equivalent. 8
- $B$  a bit setup. 9
- $[u:\text{data}]^{\mathfrak{A}}$   $u$ -data at  $\mathfrak{A}$ . 9
- $[u:\text{eq}-d](x)$   $u$ -data at  $x$  is  $d$ . 9
- $[u:\text{eq}](x, y)$   $u$ -data equal at  $x$  and  $y$ . 9
- $[u:\text{eq}-01](x, y)$   $u$ -data at  $x$  and  $y$  is 0 and 1. 9
- $[u:\text{eq}-10](x, y)$   $u$ -data at  $x$  and  $y$  is 1 and 0. 9
- $C$  a counter setup. 10
- $[C:\text{data}]^{\mathfrak{A}}$  C-data at  $\mathfrak{A}$ . 10
- $[C:\text{eq}-d](x)$  C-data at  $x$  is  $d$ . 10
- $[C:\text{eq}](x, y)$  C-data equal at  $x$  and  $y$ . 10
- $[C:\text{less}](x, y)$  C-data at  $x$  less than C-data at  $y$ . 10
- $[C:\text{succ}](x, y)$  C-data at  $y$  succeeds C-data at  $x$ . 11
- $[C:\text{less}-d](x)$  C-data at  $x$  less than  $d$ . 11
- $[C:\text{betw}-d-e](x)$  C-data at  $x$  between  $d$  and  $e$ . 11
- $[C:\text{allbetw}-d-e]$  C-data between  $d$  and  $e$ . 11
- $[V(p):\text{data}]^{\mathfrak{A}} a$  the value of the  $p$ -th counter at  $a$ . 11
- $[V:\text{data}]^{\mathfrak{A}}$  the V-data at  $a$ . 11
- $[V:\text{eq}-v](x)$  the V-data at  $x$ . 11
- $[V(pq):\text{at}-i-\text{eq}](x)$  equal  $i$ -th bits at  $p$  and  $q$  at  $x$ . 12
- $[V(pq):\text{at}-i-\text{eq}-01](x)$  equal  $i$ -th bits at  $p$  and  $q$  are 0 and 1. 12
- $[V(pq):\text{at}-i-\text{eq}-10](x)$  equal  $i$ -th bits at  $p$  and  $q$  are 1 and 0. 12
- $[V(pq):\text{eq}](x)$  equal  $p$  and  $q$  V-data at  $x$ . 12
- $[V(pq):\text{less}](x)$  V-data at  $p$  less than at  $q$ . 12
- $[V(pq):\text{succ}](x)$  V-data at  $q$  succeeds the data at  $p$ . 12
- $[P:\text{alldiff}]$  P-data at different positions is different. 13
- $[P:\text{perm}]$  P-data is a permutation. 13
- $\mathcal{E}E$  the set of equivalence classes of  $E$ . 15
- $[e:\text{refl}]$   $e$  is reflexive. 15
- $[e:\text{symm}]$   $e$  is symmetric. 15
- $[e:\text{trans}]$   $e$  is transitive. 15
- $[e:\text{equiv}]$   $e$  is transitive. 15
- $[d, e:\text{refine}]$  refinement. 16
- $[d, e:\text{global}]$  global agreement. 16
- $[d, e:\text{local}]$  local agreement. 16
- $[e_1, e_2, \dots, e_e:\text{refine}]$  symbols in refinement. 17
- $[e_1, e_2, \dots, e_e:\text{global}]$  symbols in global agreement. 17
- $[e_1, e_2, \dots, e_e:\text{local}]$  symbols in local agreement. 17
- $\mathcal{L}_p^v e E_a$  logic notation. 19
- $[P:\text{alleg}]$  P-data equal everywhere. 20
- $[P:\text{globperm}]$  P-data is a global permutation. 20

- tion. 20
- $[L:eg-i](\mathbf{x}, \mathbf{y})$  global refinement induced by levels. 21
- gtr translation of global agreement to refinement. 21
- $[E:chperm]^{\mathfrak{A}}$  characteristic E-permutation in  $\mathfrak{A}$ . 23
- $[L:fixperm]$  fixed permutation condition. 24
- $[L:locperm]$  local agreement condition. 25
- $[L:el-i]$  local refinement induced by levels. 25
- ltr translation of local agreement to refinement. 26
- $g$  granularity. 27
- $G$  granularity color setup. 27
- $[I:d]$  finer equivalence granularity formula. 28
- grtr granularity translation. 28
- $[\Sigma:cell](\mathbf{x}, \mathbf{y})$   $\Sigma$ -cell formula. 31
- $\mathcal{O}$  organ-equivalence relation. 33
- $\mathcal{O}$  sub-organ-equivalence relation. 33
- $[D:Data]^{\mathfrak{A}}$  D-Data. 37
- $[D:Zero](\mathbf{x})$  zero D-Data at  $\mathbf{x}$ . 37
- $[D:Largest](\mathbf{x})$  maximum D-Data at  $\mathbf{x}$ . 38
- $\mathbf{m}_i$  message symbols. 46
- $\langle \Sigma, \bar{\mathbf{m}} \rangle$  classified signature. 46
- $T \subseteq T[\Sigma]$  type instance. 47
- $\Pi_T$  1-types over  $T$ . 47
- $\kappa$  king type. 47
- $K_T$  the king types over  $T$ . 47
- $W_T$  the worker types over  $T$ . 47
- $T[\pi]$  the neighbours of  $\pi$ . 47
- $T[\mathfrak{A}]$  the type instance of  $\mathfrak{A}$ . 47
- $\sigma$  star-type. 49
- $stp^{\mathfrak{A}}[a]$  the star-type of  $a$  in  $\mathfrak{A}$ . 49
- $\mathcal{S}$  certificate for a type instance. 50
- $T^g$  the galactic types of  $T$ . 52
- $T^c$  the cosmic types of  $T$ . 52
- $\nu$  noble type. 52
- $N_T$  the noble types over  $T$ . 52
- $P_T$  the peasant types over  $T$ . 52
- $\mathcal{G}^{\mathfrak{A}}$  the galaxies of  $\mathfrak{A}$ . 53
- $\mathcal{G}_N^{\mathfrak{A}}$  the noble galaxies of  $\mathfrak{A}$ . 53
- $\mathcal{G}_P^{\mathfrak{A}}$  the peasant galaxies of  $\mathfrak{A}$ . 53
- $tp^{\mathfrak{A}}[X]$  the 1-types realized in the galaxy  $X$ . 53
- $\varsigma$  cosmic spectrum. 56
- $Tp_x \varsigma$  the internal types of  $\varsigma$ . 57
- $Tp_y \varsigma$  the external types of  $\varsigma$ . 57
- $\pi^{-e}$  the reduct of  $\pi$  to  $\Sigma - \langle e \rangle$ . 57
- $\mathbf{in}$  the internal unary predicate symbol. 57
- $T^{\varsigma}$  spectral type instance of the cosmic spectrum  $\varsigma$ . 57





# Abstract

A sequence of equivalence relations  $E_1, E_2, \dots, E_n$  on  $A$  is in *refinement* if  $E_i \subseteq E_{i+1}$  for  $i \in [1, n-1]$ , that is if  $E_1 \subseteq E_2 \subseteq \dots \subseteq E_n$ . The sequence is in *global agreement* if there is some permutation  $\nu$  of  $[1, n]$  such that the sequence  $E_{\nu(1)}, E_{\nu(2)}, \dots, E_{\nu(n)}$  is in refinement. The sequence is in *local agreement* if for every  $a \in A$  there is some permutation  $\nu = \nu(a)$  of  $[1, n]$  such that  $E_{\nu(1)}[a] \subseteq E_{\nu(2)}[a] \subseteq \dots \subseteq E_{\nu(n)}[a]$ .

The topic of this work is to investigate questions about the algorithmic complexity of the satisfiability and finite satisfiability of logics featuring equivalence symbols at different levels of agreement. A summary of this work is as follows:

- In [Chapter 1](#) we introduce the notations and the tools that we will need further.
- In [Chapter 2](#) we define various *setups* — suites of appropriate formulas that allow us to model bounded discrete objects such as  $t$ -bit numbers or permutations of  $[1, n]$  — into logical structures.
- In [Chapter 3](#) we define the three agreement properties: local, global agreement and refinement and develop the theory of equivalence relations in local agreement sufficiently for our purposes. In particular, we prove [Theorem 3](#) that a sequence  $E = \langle E_1, E_2, \dots, E_n \rangle$  of equivalence relations on  $A$  is in local agreement iff the union  $\cup S$  of any nonempty subsequence  $S$  of  $E$  is an equivalence relation on  $A$ . This allows us to define the *level sequence* ([Definition 28](#)) of a sequence of equivalence relations in local agreement and to characterize it as a some kind of a “skeleton”, which combined with a permutation witnessing the local agreement at every element  $a \in A$  completely characterizes the original sequence  $E$  ([Lemma 2](#) and [Lemma 3](#)).
- In [Chapter 4](#) we provide deterministic polynomial-time reductions for the (finite) satisfiability problem featuring equivalence symbols in global and local agreement into the corresponding problem for equivalence symbols in refinement ([Proposition 1](#), [Proposition 2](#), [Proposition 3](#), [Proposition 4](#)). This allows us to concentrate on the case of refinement further.
- In [Chapter 5](#) we determine the computational complexity of the (finite) satisfiability problem for the first-order logic featuring only unary predicate symbols together with  $e$  equivalence symbols in agreement:  $\mathcal{L}_1 e E_{\text{refine}}$ ,  $\mathcal{L}_1 e E_{\text{global}}$  and  $\mathcal{L}_1 e E_{\text{local}}$ . We prove that these logics have the finite model property and that the (finite) satisfiability problem for any of them is  $N(e+1)\text{EXPTIME}$ -complete ([Proposition 5](#) and [Proposition 9](#)).

## *Abstract*

- In [Chapter 6](#) we determine the computational complexity of the (finite) satisfiability problem for the two-variable first-order logic featuring unary and binary predicate symbols together with  $e$  equivalence symbols in refinement,  $\mathcal{L}^2eE_{\text{refine}}$ . We prove that this logic has the finite model property and that its (finite) satisfiability problem is in NEXPTIME ([Corollary 5](#)).

As for future work in this area, we believe that the methods introduced in [Chapter 6](#) can be adapted to the two-variable first-order logic with counting quantifiers. Another direction for research is to check if the decidability of the satisfiability in corresponding modal logics is computationally simpler than the general two-variable case. Alternatively, it may be interesting to consider more relaxed notions than agreement, where two different equivalence classes may have common elements but only to some limited extent.

# 1 Preliminaries

The cardinal number  $|A|$  is the *cardinality* of the set  $A$ . The set  $\wp A$  is the *powerset* of  $A$ . The set  $\wp^+ A = \wp A \setminus \{\emptyset\}$  is the *set of nonempty subsets* of  $A$ . If  $\kappa$  is a cardinal number, the set  $\wp^\kappa A = \{S \in \wp A \mid |S| = \kappa\}$  is the  $\kappa$ -*powerset* of  $A$ . The *cartesian product* of  $A$  and  $B$  is  $A \times B$ . The sets  $A$  and  $B$  *properly intersect* if  $A \cap B \neq \emptyset$ ,  $A \setminus B \neq \emptyset$  and  $B \setminus A \neq \emptyset$ .

Let  $A$  and  $B$  be sets and let  $R \subseteq A \times B$  be a binary relation. The *domain* of  $R$  is  $\text{dom } R = A$  and its *range* is  $\text{ran } R = B$ . The *inverse*  $R^{-1} \subseteq B \times A$  of  $R$  is

$$R^{-1} = \{(b, a) \mid (a, b) \in R\}.$$

If  $A' \subseteq A$ , the *restriction*  $(R \upharpoonright A') \subseteq A' \times B$  of  $R$  to  $A'$  is

$$R \upharpoonright S = \{(a, b) \in R \mid a \in A'\}.$$

If  $a \in A$ , the  *$R$ -successors* of  $a$  are

$$R[a] = \{b \in B \mid (a, b) \in R\}.$$

If  $S \subseteq B \times C$  and  $R \subseteq A \times B$  are two binary relations, their *composition* is

$$S \circ R = \{(a, c) \in A \times C \mid (\exists b \in B) ((a, b) \in R \wedge (b, c) \in S)\}.$$

A *function*  $f : A \rightarrow B$  is formally just a functional relation  $f \subseteq A \times B$ . An *injective* function from  $A$  into  $B$  is denoted  $f : A \hookrightarrow B$ . A *surjective* function from  $A$  onto  $B$  is denoted  $f : A \twoheadrightarrow B$ . A *bijective* function between  $A$  and  $B$  is denoted  $f : A \leftrightarrow B$ . The *identity function* on  $A$  is  $\text{id}_A$ . A *partial function* from  $A$  to  $B$  is denoted  $f : A \rightsquigarrow B$ . If  $f : A \rightsquigarrow B$  is a partial function and  $a \in A$ , the notation  $f(a) \simeq b$  means that  $f$  is defined at  $a$  and its value is  $b$ ; the notation  $f(a) \simeq \perp$  means that  $f$  is not defined at  $a$ , where  $\perp$  is specially chosen to never be an element of  $B$ . If  $S \subseteq A$ , the *characteristic function*  $\text{ch}_S^A : A \rightarrow \{0, 1\}$  of  $S$  in  $A$  is defined by:

$$\text{ch}_S^A a = \begin{cases} 1 & \text{if } a \in S \\ 0 & \text{otherwise.} \end{cases}$$

The set of *natural numbers* is  $\mathbb{N} = \{0, 1, \dots\}$ . The set of *positive natural numbers* is  $\mathbb{N}^+ = \mathbb{N} \setminus \{0\}$ . If  $n, m \in \mathbb{N}$  are natural numbers, the *discrete interval*  $[n, m]$  between  $n$  and  $m$  is

$$[n, m] = \begin{cases} \{n, n+1, \dots, m\} & \text{if } n \leq m \\ \emptyset & \text{otherwise.} \end{cases}$$

## 1 Preliminaries

The function **log** is the *base-2 logarithm*.

An  $n$ -vector  $\mathbf{v} = (v_1, v_2, \dots, v_n) \in \mathbb{N}^n$  is an  $n$ -tuple of natural numbers. The  $n$ -vector  $\mathbf{v}$  is *antilexicographically smaller* than the  $n$ -vector  $\mathbf{w}$  (written  $\mathbf{v} \prec \mathbf{w}$ ) if there is a position  $p \in [1, n]$  such that  $v_p < w_p$  and  $v_q = w_q$  for all  $q \in [p + 1, n]$ . For instance  $(1, 1, 0) \prec (0, 0, 1)$ .

The set of  $n$ -permutations of  $[1, n]$  is  $\mathbb{S}_n$ . We think of an  $n$ -permutation  $\nu$  as an  $n$ -vector  $\nu = (\nu(1), \nu(2), \dots, \nu(n))$ .

A function  $f : \mathbb{N} \rightarrow \mathbb{N}$  is *polynomially bounded* if there is a polynomial  $p$  such that  $f(n) \leq p(n)$  for all  $n \in \mathbb{N}$ . The function  $f$  is *exponentially bounded* if there is a polynomial  $p$  such that  $f(n) \leq 2^{p(n)}$  for all  $n \in \mathbb{N}$ . We are going to use these terms implicitly with respect to quantities that depend on one another. For example, the cardinality of  $\mathbb{S}_n$  is exponentially bounded in  $n$ .

Define the *tetration* operation  $\exp_a^e(x)$  by  $\exp_a^0(x) = x$  and  $\exp_a^{e+1}(x) = a^{\exp_a^e(x)}$ , so  $\exp_a^e(x) = a^{a^{\dots^{a^x}}}$  is a tower of  $e$  exponentiations.

A *sequence* is formally just a function with domain an ordinal number. If  $A$  is a sequence, its *length*  $\|A\|$  is just the domain of  $A$ . An *element* of a sequence is an element from its range. The sequence consisting of the elements  $a$ ,  $b$  and  $c$  in that order is  $\langle a, b, c \rangle$ , or alternatively written using a word notation  $abc$ . The *empty sequence* is  $\varepsilon$ . A *finite sequence* is a sequence of finite length. If  $A$  and  $B$  are two sequences, their *concatenation* is  $A + B$ , and the sequence obtained from  $A$  by dropping all elements of  $B$  is  $A - B$ .

An *alphabet*  $\Omega$  is just a nonempty set. A *word*  $w = w_1 w_2 \dots w_n$  over  $\Omega$  is a finite sequence with elements from  $\Omega$ . The set of words over  $\Omega$  is  $\Omega^*$ . The set of nonempty words over  $\Omega$  is  $\Omega^+ = \Omega^* \setminus \{\varepsilon\}$ . If  $n \in \mathbb{N}$ , the set of words of length  $n$  over  $\Omega$  is  $\Omega^n$ . By abuse of notation, we identify the set of words of length  $n$  over  $\Omega$  with the  $n$ -ary cartesian power:  $\Omega^n = \underbrace{\Omega \times \Omega \times \dots \times \Omega}_n$ .

The set of *bits* is  $\mathbb{B} = \{0, 1\}$ . The set of *bitstrings* is  $\mathbb{B}^+$ . The bitstrings are read right-to-left, that is the bitstring  $b = 10$  has first character 0. If  $t < u \in \mathbb{N}^+$ , the  $t$ -bit bitstrings  $\mathbb{B}^t$  are embedded into the  $u$ -bit bitstrings  $\mathbb{B}^u$  by appending leading zeroes. If  $n \in \mathbb{N}$ , the *bitsize*  $\|n\|$  of  $n$  is:

$$\|n\| = \begin{cases} 1 & \text{if } n = 0 \\ \lfloor \log n \rfloor + 1 & \text{otherwise.} \end{cases}$$

If  $n \in \mathbb{N}$ , the *binary encoding* of  $n$  is  $\overline{n} \in \mathbb{B}^{\|n\|}$ . If  $b \in \mathbb{B}^t$ , the *number encoded by*  $b$  is  $\underline{b}$ . The *largest  $t$ -bit number* is  $N_t = 2^t - 1$ . The set of  *$t$ -bit numbers* is  $\mathbb{B}_t = [0, N_t]$ .

### 1.1 Syntax

The *symbol alphabet* for the first-order logic is

$$\Omega_{\mathcal{L}} = \{\neg, \wedge, \vee, \rightarrow, \leftrightarrow; \exists, \forall, =, (, , , )\}$$

The propositional connectives are listed in decreasing order of precedence. The *negation*  $\neg$  is unary; the *disjunction*  $\vee$ , *conjunction*  $\wedge$  and *equivalence*  $\leftrightarrow$  are left-associative; the *implication*  $\rightarrow$  is right-associative. The quantifiers bind as strong as the negation. We consider logics with *formal equality*  $=$ .

The sequence  $\mathcal{V} = \langle \mathbf{v}_1, \mathbf{v}_2, \dots \rangle$  is a countable sequence of distinct *variable symbols*. We pay special attention to  $\mathbf{x} = \mathbf{v}_1$ ,  $\mathbf{y} = \mathbf{v}_2$  and  $\mathbf{z} = \mathbf{v}_3$ , the *first*, *second* and *third* variable symbol, respectively.

A *predicate signature*  $\Sigma = \langle \mathbf{p}_1, \mathbf{p}_2, \dots, \mathbf{p}_s \rangle$  is a finite sequence of distinct *predicate symbols*  $\mathbf{p}_i$  together with their *arities*  $\text{ar } \mathbf{p}_i \in \mathbb{N}^+$ . A predicate signature is *unary* or *monadic* if all of its predicate symbols have arity 1. A predicate signature is *binary* if all of its predicate symbols have arity 1 or 2. For the purposes of this work we will not be considering constant and function symbols—constant symbols can be simulated by a fresh unary predicate symbol having the intended interpretation of being true at a unique element; presence of function symbols on the other hand leads quite easily to undecidable satisfiability problems. By convention  $\Omega_{\mathcal{L}}$ ,  $\mathcal{V}$  and  $\Sigma$  are disjoint.

Let  $\Sigma$  be a predicate signature. The set of *atomic formulas*  $\mathcal{At}[\Sigma] \subset (\Omega_{\mathcal{L}} \cup \mathcal{V} \cup \Sigma)^*$  over  $\Sigma$  is generated by the grammar:

$$\alpha ::= (x = y) \mid p(x_1, x_2, \dots, x_n)$$

for  $x, y \in \mathcal{V}$ ,  $p \in \Sigma$ ,  $n = \text{ar } p$  and  $x_1, x_2, \dots, x_n \in \mathcal{V}$ .

The set of *literals*  $\mathcal{Lit}[\Sigma] \subset (\Omega_{\mathcal{L}} \cup \mathcal{V} \cup \Sigma)^*$  over  $\Sigma$  is generated by the grammar:

$$\lambda ::= \alpha \mid (\neg \alpha).$$

The set of *first-order formulas*  $\mathcal{L}[\Sigma] \subset (\Omega_{\mathcal{L}} \cup \mathcal{V} \cup \Sigma)^*$  over  $\Sigma$  is generated by the grammar:

$$\varphi ::= \alpha \mid (\neg \varphi) \mid (\varphi \vee \varphi) \mid (\varphi \wedge \varphi) \mid (\varphi \rightarrow \varphi) \mid (\varphi \leftrightarrow \varphi) \mid (\exists x \varphi) \mid (\forall x \varphi)$$

for  $x \in \mathcal{V}$ .

The set of variables occurring in  $\varphi$  is  $\text{vars } \varphi \subset \mathcal{V}$ . The set of variables freely occurring in  $\varphi$  is  $\text{fvars } \varphi \subset \mathcal{V}$ . A formula  $\varphi$  is a *sentence* if  $\text{fvars } \varphi = \emptyset$ . For  $v \in \mathbb{N}$ , a formula  $\varphi$  is a *v-variable formula* if  $\text{vars } \varphi \subseteq \{\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_v\}$ . The set of *v-variable first-order formulas* over  $\Sigma$  is  $\mathcal{L}^v[\Sigma]$ .

If  $\varphi \in \mathcal{L}[\Sigma]$ , the *quantifier rank*  $\text{qr } \varphi \in \mathbb{N}$  of  $\varphi$  is defined as follows. If  $\varphi$  matches:

- $(x = y)$ , then  $\text{qr } \varphi = 0$
- $p(x_1, x_2, \dots, x_n)$ , then  $\text{qr } \varphi = 0$
- $(\neg \psi)$ , then  $\text{qr } \varphi = \text{qr } \psi$
- $\psi_1 \oplus \psi_2$  for  $\oplus \in \{\wedge, \vee, \rightarrow, \leftrightarrow\}$ , then  $\text{qr } \varphi = \max(\text{qr } \psi_1, \text{qr } \psi_2)$
- $(\exists x \psi)$  or  $(\forall x \psi)$ , then  $\text{qr } \varphi = 1 + \text{qr } \psi$

## 1 Preliminaries

An  $r$ -rank formula is a formula having quantifier rank  $r$ . The set of  $r$ -rank first-order formulas over  $\Sigma$  is  $\mathcal{L}_r[\Sigma]$ . The set of  $r$ -rank  $v$ -variable first-order formulas over  $\Sigma$  is  $\mathcal{L}_r^v[\Sigma]$ .

If  $\varphi$  is a formula and  $x_1, x_2, \dots, x_n \in \mathcal{V}$  are distinct variables, we use the notation  $\varphi(x_1, x_2, \dots, x_n)$ , a *focused formula*, to show that we are interested in the free occurrences of the variables  $x_i$  in  $\varphi$ . If  $\varphi(x_1, x_2, \dots, x_n)$  is a focused formula and  $y_1, y_2, \dots, y_n \in \mathcal{V}$ , then  $\varphi(y_1, y_2, \dots, y_n)$  denotes the formula  $\varphi$  where all free occurrences of  $x_i$  are replaced by  $y_i$ . The notation  $\varphi = \varphi(x_1, x_2, \dots, x_n)$  means that  $\text{fvars } \varphi \subseteq \{x_1, x_2, \dots, x_n\}$ .

We will omit unnecessary brackets in formulas.

## 1.2 Semantics

If  $\Sigma$  is a predicate signature, a  $\Sigma$ -structure  $\mathfrak{A}$  consists of a nonempty set  $A$  (the *domain* of  $\mathfrak{A}$ ), together with a relation  $p^{\mathfrak{A}} \subseteq A^{\text{ar } p}$  (the *interpretation* of  $p$  in  $\mathfrak{A}$ ) for every predicate symbol  $p \in \Sigma$ . A structure is *finite* if its domain is finite. We omit the standard definitions of semantic notions. If  $\mathfrak{A}$  is a structure and  $B \subseteq A$  is a nonempty set of elements of  $\mathfrak{A}$ , the substructure of  $\mathfrak{A}$  induced by  $B$  is denoted by  $(\mathfrak{A} \upharpoonright B)$ . An *intended interpretation condition*  $\mathcal{A}$  for a predicate signature  $\Sigma$  is a class of  $\Sigma$ -structures. A *predicate signature with intended interpretation*  $\Sigma$  is a predicate signature together with an intended interpretation condition  $\mathcal{A}$ . The  $\Sigma$ -structure  $\mathfrak{A}$  is a model for the predicate signature  $\Sigma$  with intended interpretation  $\mathcal{A}$  if  $\mathfrak{A} \in \mathcal{A}$ . That is, when we speak about a predicate signature with intended interpretations, we are considering the logics strictly over the class of structures respecting the intended interpretation condition. The semantic concepts are relativized appropriately in this context. For example, if  $\Sigma = \langle e \rangle$  is a predicate signature consisting of the single binary predicate symbol  $e$ , having intended interpretation as an equivalence, then the  $\Sigma$ -formula  $\forall \mathbf{x} e(\mathbf{x}, \mathbf{x})$  is logically valid. From now on, we will use the term *predicate signature* as an abbreviation of a *predicate signature with possible intended interpretations*.

The predicate signature  $\Sigma'$  is an *enrichment* of the predicate signature  $\Sigma$  if  $\Sigma'$  contains all predicate symbols of  $\Sigma$  and respects their intended interpretation in  $\Sigma$ . A  $\Sigma'$ -structure  $\mathfrak{A}'$  is an enrichment of the  $\Sigma$ -structure  $\mathfrak{A}$  if they have the same domain and the same interpretation of the predicate symbols of  $\Sigma$ . The basic semantic significance of enrichment is that if  $\varphi(x_1, x_2, \dots, x_n)$  is a  $\Sigma$ -formula and  $a_1, a_2, \dots, a_n \in A$ , then  $\mathfrak{A} \models \varphi(a_1, a_2, \dots, a_n)$  iff  $\mathfrak{A}' \models \varphi(a_1, a_2, \dots, a_n)$ . If  $\mathfrak{A}'$  is an enrichment of  $\mathfrak{A}$  then  $\mathfrak{A}$  is a *reduct* of  $\mathfrak{A}'$ .

If  $\varphi = \varphi(x_1, x_2, \dots, x_n)$  is a focused formula, the interpretation of  $\varphi$  in  $\mathfrak{A}$  is

$$\varphi^{\mathfrak{A}} = \{(a_1, a_2, \dots, a_n) \in A^n \mid \mathfrak{A} \models \varphi(a_1, a_2, \dots, a_n)\}.$$

If  $\Sigma$  is a predicate signature and  $\varphi$  is a  $\Sigma$ -sentence, then  $\varphi$  is *satisfiable* if there is a  $\Sigma$ -structure that is a model for  $\varphi$ ;  $\varphi$  is *finitely satisfiable* if there is a *finite*  $\Sigma$ -structure that is a model for  $\varphi$ . If  $\mathcal{K} \subseteq \mathcal{L}[\Sigma]$  is a family of formulas over the predicate signature  $\Sigma$ , the set of *satisfiable sentences* is  $\text{SAT-}\mathcal{K} \subseteq \mathcal{K}$  and the set of *finitely satisfiable sentences* is  $\text{FIN-SAT-}\mathcal{K} \subseteq \mathcal{K}$ . The family  $\mathcal{K}$  has the *finite model property* if  $\text{SAT-}\mathcal{K} = \text{FIN-SAT-}\mathcal{K}$ .

By the Löwenheim-Skolem theorem, every satisfiable sentence  $\varphi$  has a finite or countable model, assuming the intended interpretation condition of the predicate signature is first-order-definable. In this work the intended interpretation conditions of the predicate signatures will always be first-order-definable formula and we will silently assume that all structures are either finite or countable.

Two  $\Sigma$ -sentences  $\varphi$  and  $\psi$  are *logically equivalent* (written  $\varphi \equiv \psi$ ) if they have the same models.

Two  $\Sigma$ -structures  $\mathfrak{A}$  and  $\mathfrak{B}$  are *elementary equivalent* (written  $\mathfrak{A} \equiv \mathfrak{B}$ ) if they satisfy the same first-order sentences. The structures  $\mathfrak{A}$  and  $\mathfrak{B}$  are  *$r$ -rank equivalent* (written  $\mathfrak{A} \equiv_r \mathfrak{B}$ ) if they satisfy the same  $r$ -rank first-order sentences. The structures  $\mathfrak{A}$  and  $\mathfrak{B}$  are  *$v$ -variable equivalent* (written  $\mathfrak{A} \equiv^v \mathfrak{B}$ ) if they satisfy the same  $v$ -variable first-order sentences. The structures  $\mathfrak{A}$  and  $\mathfrak{B}$  are  *$r$ -rank  $v$ -variable equivalent* (written  $\mathfrak{A} \equiv_r^v \mathfrak{B}$ ) if they satisfy the same  $r$ -rank  $v$ -variable first-order sentences.

## 1.3 Games

Logic games capture structure equivalence. Let  $\Sigma$  be a predicate signature and let  $\mathfrak{A}$  and  $\mathfrak{B}$  be  $\Sigma$ -structures. A *partial isomorphism*  $\mathfrak{p} : A \rightsquigarrow B$  from  $\mathfrak{A}$  to  $\mathfrak{B}$  is a partial mapping that is an isomorphism between the induced substructures  $(\mathfrak{A} \upharpoonright \text{dom } \mathfrak{p})$  and  $(\mathfrak{B} \upharpoonright \text{ran } \mathfrak{p})$ .

Let  $r \in \mathbb{N}^+$ . The  *$r$ -round Ehrenfeucht-Fraïssé game*  $G_r(\mathfrak{A}, \mathfrak{B})$  is a two-player game, played with a pair of pebbles, one for each structure. The two players are Spoiler and Duplicator. Initially the pebbles are off the structures. During each round, Spoiler picks a pebble and a structure and places it on some element in that structure. Duplicator responds by picking the other pebble and placing it on some element in the other structure. Thus during round  $i$  the players play a pair of elements  $a_i \mapsto b_i \in A \times B$ . Collect the sequences of played elements  $\bar{a} = \langle a_1, a_2, \dots, a_r \rangle$  and  $\bar{b} = \langle b_1, b_2, \dots, b_r \rangle$ . Duplicator wins the match if the relation  $\bar{a} \mapsto \bar{b} = \{a_1 \mapsto b_1, a_2 \mapsto b_2, \dots, a_r \mapsto b_r\} \subseteq A \times B$ , built from the pairs of elements in each round, is a partial isomorphism from  $\mathfrak{A}$  to  $\mathfrak{B}$ . Ehrenfeucht's theorem says that Duplicator has a winning strategy for  $G_r(\mathfrak{A}, \mathfrak{B})$  iff  $\mathfrak{A} \equiv_r \mathfrak{B}$ . Fraïssé's theorem gives a back-and-forth characterization of the winning strategy for Duplicator [1, ch. 2]:

**Theorem 1.** *Suppose that  $(\mathfrak{I}_0, \mathfrak{I}_1, \dots, \mathfrak{I}_r)$  is a sequence of nonempty sets of partial isomorphisms between  $\mathfrak{A}$  and  $\mathfrak{B}$  with the following properties:*

1. *For every  $i < r$ ,  $\mathfrak{p} \in \mathfrak{I}_i$  and  $a \in A$ , there is  $\mathfrak{q} \in \mathfrak{I}_{i+1}$  such that  $\mathfrak{p} \subseteq \mathfrak{q}$  and  $a \in \text{dom } \mathfrak{q}$ .*
2. *For every  $i < r$ ,  $\mathfrak{p} \in \mathfrak{I}_i$  and  $b \in B$ , there is  $\mathfrak{q} \in \mathfrak{I}_{i+1}$  such that  $\mathfrak{p} \subseteq \mathfrak{q}$  and  $b \in \text{ran } \mathfrak{q}$ .*

*Then  $\mathfrak{A} \equiv_r \mathfrak{B}$ .*

## 1.4 Types

Let  $\Sigma = \langle p_1, p_2, \dots, p_s \rangle$  be a predicate signature. A 1-type  $\pi$  over  $\Sigma$  is a maximal consistent set of literals featuring only the variable symbol<sup>1</sup>  $x$ . The set of 1-types over  $\Sigma$  is  $\Pi[\Sigma]$ . Note that consistency here is relativized by the intended interpretations of the predicate signature. For example if  $\Sigma$  contains the binary predicate symbol  $e$  with intended interpretation as an equivalence, then every 1-type over  $\Sigma$  includes the literal  $e(x, x)$ . Also note that the cardinality of a 1-type over  $\Sigma$  is polynomially bounded in the length  $s$  of  $\Sigma$  and the cardinality of  $\Pi[\Sigma]$  is exponentially bounded in  $s$ .

A 2-type  $\tau$  over  $\Sigma$  is a maximal consistent set of literals featuring only the variable symbols  $x$  and  $y$  and including the literal  $(x \neq y)$ . The set of 2-types over  $\Sigma$  is  $T[\Sigma]$ . Again, consistency is relativized by the intended interpretation of the predicate signature. For example, if  $\Sigma$  contains the binary predicate symbol  $e$  with intended interpretation as an equivalence, then if  $e(x, y) \in \tau$ , then  $e(y, x) \in \tau$ . Again, the cardinality of a 2-type over  $\Sigma$  is polynomially bounded in  $s$  and the cardinality of  $T[\Sigma]$  is exponentially bounded in  $s$ .

If  $\tau \in T[\Sigma]$ , the *inverse*  $\tau^{-1}$  of  $\tau$  is the 2-type obtained from  $\tau$  by swapping the variables  $x$  and  $y$  in every literal. The  *$x$ -type* of  $\tau$  is the 1-type  $\text{tp}_x \tau$  consisting of all the literals of  $\tau$  featuring only the variable symbol  $x$ . Similarly, the  *$y$ -type* of  $\tau$  is the 1-type  $\text{tp}_y \tau$  consisting of all the literals of  $\tau$  featuring only the variable symbol  $y$ , that is replaced by  $x$ . For instance we have the identity  $\text{tp}_x \tau^{-1} = \text{tp}_y \tau$ . We say that  $\tau$  *connects* the 1-types  $\text{tp}_x \tau$  and  $\text{tp}_y \tau$  and we refer to  $\text{tp}_x \tau$  and  $\text{tp}_y \tau$  as the *endpoints* of  $\tau$ . Two 2-types  $\tau, \tau'$  are *parallel* if  $\text{tp}_x \tau = \text{tp}_x \tau'$  and  $\text{tp}_y \tau = \text{tp}_y \tau'$ .

If  $\mathfrak{A}$  is a  $\Sigma$ -structure and  $a \in A$ , the 1-type of  $a$  in  $\mathfrak{A}$  is

$$\text{tp}^{\mathfrak{A}}[a] = \{\lambda(x) \in \text{Lit}[\Sigma] \mid \mathfrak{A} \models \lambda(a)\}.$$

If  $\text{tp}^{\mathfrak{A}}[a] = \pi$ , we say that the 1-type  $\pi$  is *realized* by  $a$  in  $\mathfrak{A}$ . The interpretation of the 1-type  $\pi$  in  $\mathfrak{A}$  is the set of elements realizing  $\pi$ :

$$\pi^{\mathfrak{A}} = \{a \in A \mid \text{tp}^{\mathfrak{A}}[a] = \pi\}.$$

If  $a \in A$  and  $b \in A \setminus \{a\}$ , the 2-type of  $(a, b)$  in  $\mathfrak{A}$  is

$$\text{tp}^{\mathfrak{A}}[a, b] = \{\lambda(x, y) \in \text{Lit}[\Sigma] \mid \mathfrak{A} \models \lambda(a, b)\}.$$

We do not define a 2-type in case  $a = b$ . If  $\text{tp}^{\mathfrak{A}}[a, b] = \tau$ , we say that the 2-type  $\tau$  is *realized* by  $(a, b)$  in  $\mathfrak{A}$ . The interpretation of the 2-type  $\tau$  in  $\mathfrak{A}$  is the set of pairs realizing  $\tau$ :

$$\tau^{\mathfrak{A}} = \{(a, b) \in A \times A \mid a \neq b \wedge \text{tp}^{\mathfrak{A}}[a, b] = \tau\}.$$

---

<sup>1</sup>this is different than the commonly used notion of type in model theory, where types are sets of general formulas, not just literals



## 1.5 Scott normal form

In two-variable logics, a common technique of reducing formula quantifier rank while preserving satisfiability is Skolemization [2]: Let  $\varphi$  be a  $\mathcal{L}^2$ -sentence. Consider a subformula  $\psi = \psi(y) = Qx\alpha(x, y)$  of  $\varphi$  that has the lowest possible nontrivial quantifier rank 1, where  $y \in \{\mathbf{x}, \mathbf{y}\}$  should not necessarily occur freely in  $\alpha$ ,  $x \in \{\mathbf{x}, \mathbf{y}\} \setminus \{y\}$  and  $Q \in \{\forall, \exists\}$ . Introduce a new unary predicate symbol  $\mathbf{u}_\psi$  with the intended interpretation  $\forall y(\mathbf{u}_\psi(y) \leftrightarrow Qx\alpha(x, y))$  and let  $\varphi'$  be the formula obtained from  $\varphi$  by replacing the subformula  $\psi$  by  $\mathbf{u}_\psi(y)$ . The original formula  $\varphi$  is equisatisfiable with  $\varphi_1 = \forall y(\mathbf{u}_\psi(y) \leftrightarrow Qx\alpha(x, y)) \wedge \varphi'$  in a strict sense, that is any model for  $\varphi$  can be  $\mathbf{u}_\psi$ -enriched into a model for  $\varphi_1$  and any model for  $\varphi_1$  is a model for  $\varphi$ . By repeating this process, we can bring the formula to a form where the quantifier rank is at most 2 [3, 2]:

**Theorem 2** (Scott). *There is a polynomial-time reduction  $\text{sctr} : \mathcal{L}^2 \rightarrow \mathcal{L}^2$  which reduces every sentence  $\varphi$  to a sentence  $\text{sctr } \varphi$  in Scott normal form:*

$$\forall \mathbf{x} \forall \mathbf{y} (\alpha_0(\mathbf{x}, \mathbf{y}) \vee \mathbf{x} = \mathbf{y}) \wedge \bigwedge_{1 \leq i \leq m} \forall \mathbf{x} \exists \mathbf{y} (\alpha_i(\mathbf{x}, \mathbf{y}) \wedge \mathbf{x} \neq \mathbf{y}),$$

where  $m \geq 1$ , the formulas  $\alpha_i$  are quantifier-free and use at most linearly many new unary predicate symbols. The sentences  $\varphi$  and  $\text{sctr } \varphi$  are satisfiable over the same domains of cardinality at least 2. Moreover the length  $\text{sctr } \varphi$  is linear in the length of  $\varphi$ .

## 1.6 Complexity

We denote the complexity classes  $\mathbf{P}\mathbf{T}\mathbf{IME} = \mathbf{TIME}[\text{poly}(n)] = \bigcup_{c \in \mathbb{N}^+} \mathbf{TIME}[n^c]$ ,  $\mathbf{NP}\mathbf{T}\mathbf{IME}$ ,  $\mathbf{PSPACE}$ ,  $\mathbf{EXPTIME}$  and  $\mathbf{NEXPTIME}$ . For  $e \in \mathbb{N}^+$ , the  $e$ -exponential deterministic and nondeterministic time classes are  $e\mathbf{EXPTIME} = \mathbf{TIME}[\exp_2^e(\text{poly}(n))]$  and  $\mathbf{NeEXPTIME}$ . The complexity class  $\mathbf{ELEMENTARY}$  is the union of the complexity classes  $e\mathbf{EXPTIME}$  for  $e \in \mathbb{N}^+$ .

The Grzegorzcyk hierarchy  $\mathcal{E}^i$  for  $i \in \mathbb{N}$  orders the primitive recursive functions by means of the power of recursion needed. The *basic functions* are the zero function  $\text{zero}(n) = 0$ , the successor function  $\text{succ}(n) = n + 1$  and the projection functions  $\text{proj}_i^u(n_1, n_2, \dots, n_u) = n_i$ . If  $u, v \in \mathbb{N}$ ,  $f : \mathbb{N}^u \rightarrow \mathbb{N}$  and  $g_1, g_2, \dots, g_u : \mathbb{N}^v \rightarrow \mathbb{N}$  are functions, their *superposition* is the function  $h : \mathbb{N}^v \rightarrow \mathbb{N}$  defined by  $h(\bar{n}) = f(g_1(\bar{n}), g_2(\bar{n}), \dots, g_u(\bar{n}))$  for  $\bar{n} \in \mathbb{N}^v$ . If  $u \in \mathbb{N}$ ,  $f : \mathbb{N}^u \rightarrow \mathbb{N}$  and  $g : \mathbb{N}^{u+2} \rightarrow \mathbb{N}$ , their *primitive recursion* is the function  $h : \mathbb{N}^{u+1} \rightarrow \mathbb{N}$  defined by:

$$\begin{aligned} h(\bar{n}, 0) &= f(\bar{n}) \\ h(\bar{n}, i + 1) &= g(\bar{n}, i, h(\bar{n}, i)) \end{aligned}$$

for  $\bar{n} \in \mathbb{N}^u$ . For  $i \in \mathbb{N}$ , define the function  $E_i$  by  $E_0(n) = n + 1$  and

$$E_{i+1}(n) = E_i^n(2) = \underbrace{E_i(E_i(\dots E_i(2)))}_n.$$

## 1 Preliminaries

For  $i \in \mathbb{N}$ , the  $i$ -th level of the Grzegorzcyk hierarchy  $\mathcal{E}^i$  as the least set of functions containing the basic functions, the functions  $E_k$  for  $k \in [0, i]$  and closed under superposition and *limited primitive recursion*, that is a primitive recursion  $h : \mathbb{N}^{u+1} \rightarrow \mathbb{N}$  of the functions  $f : \mathbb{N}^u \rightarrow \mathbb{N}$ ,  $g : \mathbb{N}^{u+2} \rightarrow \mathbb{N}$ ,  $f, g \in \mathcal{E}^i$ , such that there is a function  $b : \mathbb{N}^{u+1} \rightarrow \mathbb{N}$ ,  $b \in \mathcal{E}^i$  bounding  $h$ :  $h(\bar{n}) \leq b(\bar{n})$  for all  $n \in \mathbb{N}^{u+1}$ . A decision problem  $A \subseteq \Omega^*$  is in some level of the Grzegorzcyk hierarchy just in case its characteristic function occurs at that level. The primitive recursive functions are partitioned by the Grzegorzcyk hierarchy. The complexity class ELEMENTARY coincides with the third level of the Grzegorzcyk hierarchy  $\mathcal{E}^3$ .

If  $A \subseteq \Omega_1^*$  and  $B \subseteq \Omega_2^*$  are decision problems, the problem  $A$  is *polynomial-time reducible* to  $B$  (written  $A \leq_m^{\text{PTIME}} B$ ) if there is a polynomial-time algorithm  $f : \Omega_1^* \rightarrow \Omega_2^*$  such that  $a \in A$  iff  $f(a) \in B$ . Similar reductions where  $f$  might be in another complexity class are defined analogously. The decision problems  $A$  and  $B$  are *polynomial-time equivalent* (written  $A =_m^{\text{PTIME}} B$ ) if  $A \leq_m^{\text{PTIME}} B$  and  $B \leq_m^{\text{PTIME}} A$ . In the context of a decision problem, the *size* of an object is the number of bits required to represent it through some standard encoding.

A decision problem is *hard* for a complexity class if any decision problem of that complexity class is polynomial-time reducible to it. A decision problem is *complete* for a complexity class if it is hard for that class and contained in that class.

We will need the following standard domino tiling problem [4, p. 403]: A *domino system* is a triple  $D = (T, H, V)$ , where  $T = [1, k]$  is a finite set of *tiles* and  $H, V \subseteq T \times T$  are *horizontal* and *vertical matching relations*. A *tiling* of  $m \times m$  for a domino system  $D$  with *initial condition*  $c^0 = \langle t_1^0, t_2^0, \dots, t_n^0 \rangle$ , where  $n \leq m$ , is a mapping  $t : [1, m] \times [1, m] \rightarrow T$  such that:

- $(t(i, j), t(i + 1, j)) \in H$  for all  $i \in [1, m - 1]$  and  $j \in [1, m]$
- $(t(i, j), t(i, j + 1)) \in V$  for all  $i \in [1, m]$  and  $j \in [1, m - 1]$
- $t(i, 1) = t_i^0$  for all  $i \in [1, n]$ .

It is well-known [5, 6] that there exists a domino system  $D_0$  for which:

- the problem asking whether there exists a tiling of  $m \times m$  with initial condition  $c^0$  of length  $n$ , where  $m = n$ , is NP<sup>TIME</sup>-complete.
- the problem asking whether there exists a tiling of  $m \times m$  with initial condition  $c^0$  of length  $n$ , where  $m = 2^n$ , is NEXP<sup>TIME</sup>-complete.
- the problem asking whether there exists a tiling of  $m \times m$  with initial condition  $c^0$  of length  $n$ , where  $m = 2^{2^n}$ , is N2EXP<sup>TIME</sup>-complete.
- the argument extends to arbitrary exponential towers: the problem asking whether there exists a tiling of  $m \times m$  with initial condition  $c^0$  of length  $n$ , where  $m = \exp_2^e(n)$  is NeEXP<sup>TIME</sup>-complete.

## 2 Counter setups

In this chapter we develop formulas over unary predicate signatures allowing us to capture discrete objects such as bits, bounded integers, vectors and permutations. We employ these tools in the following chapters to obtain reductions and hardness bounds between the satisfiability problems for different classes of logics with built-in equivalence symbols. We call the formulas allowing us to encode an arbitrary bounded discrete structure of a particular type *setups*. The constructions have a strong computer science flavor in the sense that the structures are modelled as sequences of bits with additional constraints and the formulas are constructible in deterministic polynomial time.

### 2.1 Bits

A *bit setup*  $\mathbf{B} = \langle \mathbf{u} \rangle$  is a predicate signature consisting of a single unary predicate symbol  $\mathbf{u}$ .

**Definition 1.** Let  $\mathfrak{A}$  be a  $\mathbf{B}$ -structure. Define the function  $[\mathbf{u}:\text{data}]^{\mathfrak{A}} : A \rightarrow \mathbb{B}$  by:

$$[\mathbf{u}:\text{data}]^{\mathfrak{A}}a = \begin{cases} 1 & \text{if } \mathfrak{A} \models \mathbf{u}(a) \\ 0 & \text{otherwise.} \end{cases}$$

**Definition 2.** Let  $d \in \mathbb{B}$ . Define the quantifier-free  $\mathcal{L}^1[\mathbf{B}]$ -formula  $[\mathbf{u}:\text{eq-}d](\mathbf{x})$  by:

$$[\mathbf{u}:\text{eq-}d](\mathbf{x}) = \begin{cases} \mathbf{u}(\mathbf{x}) & \text{if } d = 1 \\ \neg \mathbf{u}(\mathbf{x}) & \text{otherwise.} \end{cases}$$

**Remark 1.** If  $\mathfrak{A}$  is a  $\mathbf{B}$ -structure,  $a \in A$  is an element and  $d \in \mathbb{B}$ , then  $\mathfrak{A} \models [\mathbf{u}:\text{eq-}d](a)$  iff  $[\mathbf{u}:\text{data}]^{\mathfrak{A}}a = d$ .

**Definition 3.** Define the quantifier-free  $\mathcal{L}^2[\mathbf{B}]$ -formulas  $[\mathbf{u}:\text{eq}](\mathbf{x}, \mathbf{y})$ ,  $[\mathbf{u}:\text{eq-01}](\mathbf{x}, \mathbf{y})$  and  $[\mathbf{u}:\text{eq-10}](\mathbf{x}, \mathbf{y})$  by:

$$\begin{aligned} [\mathbf{u}:\text{eq}](\mathbf{x}, \mathbf{y}) &= \mathbf{u}(\mathbf{x}) \leftrightarrow \mathbf{u}(\mathbf{y}) \\ [\mathbf{u}:\text{eq-01}](\mathbf{x}, \mathbf{y}) &= \neg \mathbf{u}(\mathbf{x}) \wedge \mathbf{u}(\mathbf{y}) \\ [\mathbf{u}:\text{eq-10}](\mathbf{x}, \mathbf{y}) &= \mathbf{u}(\mathbf{x}) \wedge \neg \mathbf{u}(\mathbf{y}). \end{aligned}$$

**Remark 2.** If  $\mathfrak{A}$  is a  $\mathbf{B}$ -structure and  $a, b \in A$ , then:

- $\mathfrak{A} \models [\mathbf{u}:\text{eq}](a, b)$  iff  $[\mathbf{u}:\text{data}]^{\mathfrak{A}}a = [\mathbf{u}:\text{data}]^{\mathfrak{A}}b$
- $\mathfrak{A} \models [\mathbf{u}:\text{eq-01}](a, b)$  iff  $[\mathbf{u}:\text{data}]^{\mathfrak{A}}a = 0$  and  $[\mathbf{u}:\text{data}]^{\mathfrak{A}}b = 1$
- $\mathfrak{A} \models [\mathbf{u}:\text{eq-10}](a, b)$  iff  $[\mathbf{u}:\text{data}]^{\mathfrak{A}}a = 1$  and  $[\mathbf{u}:\text{data}]^{\mathfrak{A}}b = 0$ .

## 2.2 Counters

A  $t$ -bit counter setup for  $t \in \mathbb{N}^+$  is a predicate signature  $\mathbf{C} = \langle \mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_t \rangle$  consisting of  $t$  distinct unary predicate symbols  $\mathbf{u}_i$ .

**Definition 4.** Let  $\mathfrak{A}$  be a  $\mathbf{C}$ -structure. Define the function  $[\mathbf{C}:\text{data}]^{\mathfrak{A}} : A \rightarrow \mathbb{B}_t$  by:

$$[\mathbf{C}:\text{data}]^{\mathfrak{A}} a = \sum_{1 \leq i \leq t} 2^{i-1} [\mathbf{u}_i:\text{data}]^{\mathfrak{A}} a.$$

**Definition 5.** Let  $d \in \mathbb{B}_t$  be a  $t$ -bit number. Define the quantifier-free  $\mathcal{L}^1[\mathbf{C}]$ -formula  $[\mathbf{C}:\text{eq}-d](\mathbf{x})$  by:

$$[\mathbf{C}:\text{eq}-d](\mathbf{x}) = \bigwedge_{1 \leq i \leq t} [\mathbf{u}_i:\text{eq}-\bar{d}_i](\mathbf{x}).$$

**Remark 3.** If  $\mathfrak{A}$  is a  $\mathbf{C}$ -structure,  $a \in A$  and  $d \in \mathbb{B}_t$ , then  $\mathfrak{A} \models [\mathbf{C}:\text{eq}-d](a)$  iff  $[\mathbf{C}:\text{data}]^{\mathfrak{A}} a = d$ .

If  $A$  is a nonempty set and  $\text{data} : A \rightarrow \mathbb{B}_t$  is any function, there is a  $\mathbf{C}$ -structure  $\mathfrak{A}$  over  $A$  such that  $[\mathbf{C}:\text{data}]^{\mathfrak{A}} = \text{data}$ .

**Definition 6.** Define the quantifier-free  $\mathcal{L}^2[\mathbf{C}]$ -formula  $[\mathbf{C}:\text{eq}](\mathbf{x}, \mathbf{y})$  by:

$$[\mathbf{C}:\text{eq}](\mathbf{x}, \mathbf{y}) = \bigwedge_{1 \leq i \leq t} [\mathbf{u}_i:\text{eq}](\mathbf{x}, \mathbf{y}).$$

**Remark 4.** If  $\mathfrak{A}$  is a  $\mathbf{C}$ -structure and  $a, b \in A$ , then  $\mathfrak{A} \models [\mathbf{C}:\text{eq}](a, b)$  iff  $[\mathbf{C}:\text{data}]^{\mathfrak{A}} a = [\mathbf{C}:\text{data}]^{\mathfrak{A}} b$ .

The bitstring  $a \in \mathbb{B}^t$  encodes a number less than the number encoded by the bitstring  $b \in \mathbb{B}^t$ , if they differ and at least position where they are different  $j \in [1, t]$  the bitstring  $a$  has value 0 and the bitstring  $b$  has value 1, that is, iff there is a position  $j \in [1, t]$  such that the following two conditions hold:

$$a_j = 0 \text{ and } b_j = 1 \quad (\text{Less1})$$

$$a_k = b_k \text{ for all } k \in [j+1, t]. \quad (\text{Less2})$$

**Definition 7.** Define the quantifier-free  $\mathcal{L}^2[\mathbf{C}]$ -formula  $[\mathbf{C}:\text{less}](\mathbf{x}, \mathbf{y})$  by:

$$[\mathbf{C}:\text{less}](\mathbf{x}, \mathbf{y}) = \bigvee_{1 \leq j \leq t} [\mathbf{u}_j:\text{eq}-01](\mathbf{x}, \mathbf{y}) \wedge \bigwedge_{j < k \leq t} [\mathbf{u}_k:\text{eq}](\mathbf{x}, \mathbf{y}).$$

**Remark 5.** If  $\mathfrak{A}$  is a  $\mathbf{C}$ -structure and  $a, b \in A$ , then  $\mathfrak{A} \models [\mathbf{C}:\text{less}](a, b)$  iff  $[\mathbf{C}:\text{data}]^{\mathfrak{A}} a < [\mathbf{C}:\text{data}]^{\mathfrak{A}} b$ .

The bitstring  $b \in \mathbb{B}^t$  encodes the successor of the number encoded by the bitstring  $a$  if there is a position  $j \in [1, t]$  such that the following four conditions hold:

$$a_j = 0 \text{ and } b_j = 1 \quad (\text{Succ1})$$

$$a_i = 1 \text{ for all } i \in [1, j-1] \quad (\text{Succ2})$$

$$b_i = 0 \text{ for all } i \in [1, j-1] \quad (\text{Succ3})$$

$$a_k = b_k \text{ for all } k \in [j+1, t]. \quad (\text{Succ4})$$

**Definition 8.** Define the quantifier-free  $\mathcal{L}^2[C]$ -formula  $[C:\text{succ}](x, y)$  by:

$$[C:\text{succ}](x, y) = \bigvee_{1 \leq j \leq t} [u_j:\text{eq-01}](x, y) \wedge \bigwedge_{1 \leq i < j} [u_i:\text{eq-10}](x, y) \wedge \bigwedge_{j < k \leq t} [u_k:\text{eq}](x, y).$$

**Remark 6.** If  $\mathfrak{A}$  is a C-structure and  $a, b \in A$ , then:

$$\mathfrak{A} \models [C:\text{succ}](a, b) \text{ iff } [C:\text{data}]^{\mathfrak{A}}b = 1 + [C:\text{data}]^{\mathfrak{A}}a.$$

**Definition 9.** Let  $d \in \mathbb{B}_t$ . Define the quantifier-free  $\mathcal{L}^1[C]$ -formula  $[C:\text{less-}d](x)$  by:

$$[C:\text{less-}d](x) = \bigvee_{1 \leq j \leq t} \neg u_j(x) \wedge \neg [u_j:\text{eq-}\bar{d}_j](x) \wedge \bigwedge_{j < k \leq t} [u_k:\text{eq-}\bar{d}_k](x).$$

**Remark 7.** If  $\mathfrak{A}$  is a C-structure,  $a \in A$  and  $d \in \mathbb{B}_t$ , then  $\mathfrak{A} \models [C:\text{less-}d](a)$  iff  $[C:\text{data}]^{\mathfrak{A}}a < d$ .

**Definition 10.** Let  $d \leq e \in \mathbb{B}_t$ . Define the quantifier-free  $\mathcal{L}^1[C]$ -formula  $[C:\text{betw-}d\text{-}e](x)$  by:

$$[C:\text{betw-}d\text{-}e](x) = \neg [C:\text{less-}d](x) \wedge ([C:\text{less-}e](x) \vee [C:\text{eq-}e](x)).$$

**Remark 8.** If  $\mathfrak{A}$  is a C-structure,  $a \in A$  and  $d \leq e \in \mathbb{B}_t$ , then

$$\mathfrak{A} \models [C:\text{betw-}d\text{-}e](a) \text{ iff } d \leq [C:\text{data}]^{\mathfrak{A}}a \leq e.$$

**Definition 11.** Let  $d \leq e \in \mathbb{B}_t$ . Define the  $\mathcal{L}^1[C]$ -sentence  $[C:\text{allbetw-}d\text{-}e]$  by:

$$[C:\text{allbetw-}d\text{-}e] = \forall x [C:\text{betw-}d\text{-}e](x).$$

**Remark 9.** If  $\mathfrak{A}$  is a C-structure and  $d \leq e \in \mathbb{B}_t$ , then  $\mathfrak{A} \models [C:\text{betw-}d\text{-}e]$  iff  $d \leq [C:\text{data}]^{\mathfrak{A}}a \leq e$  for all  $a \in A$ .

## 2.3 Vectors

Let  $n, t \in \mathbb{N}^+$ . Recall the set of  $n$ -dimensional  $t$ -bit vectors is  $\mathbb{B}_t^n$ . An  $n$ -dimensional  $t$ -bit vector setup is a predicate signature  $V = \langle u_{11}, u_{12}, \dots, u_{nt} \rangle$  of  $(nt)$  distinct unary predicate symbols. The counter setup  $V(p)$  of  $V$  at position  $p \in [1, n]$  is  $V(p) = \langle u_{p1}, u_{p2}, \dots, u_{pt} \rangle$ .

**Definition 12.** Let  $\mathfrak{A}$  be a V-structure and  $a \in A$ . We refer to  $[V(p):\text{data}]^{\mathfrak{A}}a$  as the value of the  $p$ -th counter at  $a$ . Define the function  $[V:\text{data}]^{\mathfrak{A}} : A \rightarrow \mathbb{B}_t^n$  by:

$$[V:\text{data}]^{\mathfrak{A}}a = ([V(1):\text{data}]^{\mathfrak{A}}a, [V(2):\text{data}]^{\mathfrak{A}}a, \dots, [V(n):\text{data}]^{\mathfrak{A}}a).$$

**Definition 13.** Let  $v = (d_1, d_2, \dots, d_n) \in \mathbb{B}_t^n$  be an  $n$ -dimensional  $t$ -bit vector. Define the quantifier-free  $\mathcal{L}^1[V]$ -formula  $[V:\text{eq-}v](x)$  by:

$$[V:\text{eq-}v](x) = \bigwedge_{1 \leq p \leq n} [V(p):\text{eq-}d_p](x).$$

## 2 Counter setups

**Remark 10.** If  $\mathfrak{A}$  is a  $V$ -structure,  $a \in A$  and  $v \in \mathbb{B}_t^n$ , then  $\mathfrak{A} \models [V:\text{eq}-v](a)$  iff  $[V:\text{data}]^{\mathfrak{A}}a = v$ .

If  $\mathfrak{A}$  is a nonempty set and  $\text{data} : A \rightarrow \mathbb{B}_t^n$  is any function, then there is a  $V$ -structure  $\mathfrak{A}$  over  $A$  such that  $[V:\text{data}]^{\mathfrak{A}} = \text{data}$ .

**Definition 14.** Let  $p, q \in [1, n]$  and let  $i \in [1, t]$ . Define the quantifier-free  $\mathcal{L}^1[V]$ -formulas  $[V(pq):\text{at-}i\text{-eq}](\mathbf{x})$ ,  $[V(pq):\text{at-}i\text{-eq-01}](\mathbf{x})$  and  $[V(pq):\text{at-}i\text{-eq-10}](\mathbf{x})$  by:

$$\begin{aligned} [V(pq):\text{at-}i\text{-eq}](\mathbf{x}) &= \mathbf{u}_{pi}(\mathbf{x}) \leftrightarrow \mathbf{u}_{qi}(\mathbf{x}) \\ [V(pq):\text{at-}i\text{-eq-01}](\mathbf{x}) &= \neg \mathbf{u}_{pi}(\mathbf{x}) \wedge \mathbf{u}_{qi}(\mathbf{x}) \\ [V(pq):\text{at-}i\text{-eq-10}](\mathbf{x}) &= \mathbf{u}_{pi}(\mathbf{x}) \wedge \neg \mathbf{u}_{qi}(\mathbf{x}). \end{aligned}$$

**Remark 11.** If  $\mathfrak{A}$  is a  $V$ -structure and  $a \in A$ , then:

- $\mathfrak{A} \models [V(pq):\text{at-}i\text{-eq}](a)$  iff  $[\mathbf{u}_{pi}:\text{data}]^{\mathfrak{A}}a = [\mathbf{u}_{qi}:\text{data}]^{\mathfrak{A}}a$ , that is the values of the  $i$ -th bit at positions  $p$  and  $q$  at  $a$  are equal
- $\mathfrak{A} \models [V(pq):\text{at-}i\text{-eq-01}](a)$  iff  $[\mathbf{u}_{pi}:\text{data}]^{\mathfrak{A}}a = 0$  and  $[\mathbf{u}_{qi}:\text{data}]^{\mathfrak{A}}a = 1$ , that is the  $i$ -th bit at position  $p$  at  $a$  is 0 and the  $i$ -th bit at position  $q$  at  $a$  is 1
- $\mathfrak{A} \models [V(pq):\text{at-}i\text{-eq-10}](a)$  iff  $[\mathbf{u}_{pi}:\text{data}]^{\mathfrak{A}}a = 1$  and  $[\mathbf{u}_{qi}:\text{data}]^{\mathfrak{A}}a = 0$ , that is the  $i$ -th bit at position  $p$  at  $a$  is 1 and the  $i$ -th bit at position  $q$  at  $a$  is 0.

**Definition 15.** Let  $p, q \in [1, n]$ . Define the quantifier-free  $\mathcal{L}^1[V]$ -formula  $[V(pq):\text{eq}](\mathbf{x})$  by:

$$[V(pq):\text{eq}](\mathbf{x}) = \bigwedge_{1 \leq i \leq t} [V(pq):\text{at-}i\text{-eq}](\mathbf{x}).$$

**Remark 12.** If  $\mathfrak{A}$  is a  $V$ -structure and  $a \in A$ , then:

$$\mathfrak{A} \models [V(pq):\text{eq}](a) \text{ iff } [V(p):\text{data}]^{\mathfrak{A}}a = [V(q):\text{data}]^{\mathfrak{A}}a.$$

**Definition 16.** Let  $p, q \in [1, n]$ . Define the quantifier-free  $\mathcal{L}^1[V]$ -formula  $[V(pq):\text{less}](\mathbf{x})$  by:

$$[V(pq):\text{less}](\mathbf{x}) = \bigvee_{1 \leq j \leq t} [V(pq):\text{at-}j\text{-eq-01}](\mathbf{x}) \wedge \bigwedge_{j < k \leq t} [V(pq):\text{at-}k\text{-eq}](\mathbf{x}).$$

**Remark 13.** If  $\mathfrak{A}$  is a  $V$ -structure and  $a \in A$ , then:

$$\mathfrak{A} \models [V(pq):\text{less}](a) \text{ iff } [V(p):\text{data}]^{\mathfrak{A}}a < [V(q):\text{data}]^{\mathfrak{A}}a.$$

**Definition 17.** Let  $p, q \in [1, n]$ . Define the quantifier-free  $\mathcal{L}^1[V]$ -formula

$$\begin{aligned} [V(pq):\text{succ}](\mathbf{x}) &= \bigvee_{1 \leq j \leq t} \bigwedge_{1 \leq i < j} [V(pq):\text{at-}i\text{-eq-10}](\mathbf{x}) \wedge [V(pq):\text{at-}j\text{-eq-01}](\mathbf{x}) \wedge \\ &\quad \bigwedge_{j < k \leq t} [V(pq):\text{at-}k\text{-eq}](\mathbf{x}). \end{aligned}$$

**Remark 14.** If  $\mathfrak{A}$  is a  $V$ -structure and  $a \in A$ , then:

$$\mathfrak{A} \models [V(pq):\text{succ}](a) \text{ iff } [V(q):\text{data}]^{\mathfrak{A}}a = 1 + [V(p):\text{data}]^{\mathfrak{A}}a.$$

## 2.4 Permutations

Let  $n \in \mathbb{N}^+$ . An  $n$ -permutation setup  $P = \langle \mathbf{u}_{11}, \mathbf{u}_{12}, \dots, \mathbf{u}_{nt} \rangle$  is just an  $n$ -dimensional  $t$ -bit vector setup, where  $t = \|n\|$  is the bitsize of  $n$ . Recall that the set  $\mathbb{S}_n$  of all permutations of  $[1, n]$  is a subset of  $\mathbb{B}_t^n$ .

**Definition 18.** Define the quantifier-free  $\mathcal{L}^1[P]$ -sentence  $[P:\text{alldiff}]$  by:

$$[P:\text{alldiff}] = \forall \mathbf{x} \bigwedge_{1 \leq p < q \leq n} \neg [P(pq):\text{eq}](\mathbf{x}).$$

**Remark 15.** If  $\mathfrak{A}$  is a  $P$ -structure then  $\mathfrak{A} \models [P:\text{alldiff}]$  iff  $[P(p):\text{data}]^{\mathfrak{A}} a \neq [P(q):\text{data}]^{\mathfrak{A}} a$  for all  $a \in A$  and  $p \neq q \in [1, n]$ .

**Definition 19.** Define the quantifier-free  $\mathcal{L}^1[P]$ -sentence  $[P:\text{perm}]$  by:

$$[P:\text{perm}] = [P:\text{betw-1-n}] \wedge [P:\text{alldiff}].$$

**Remark 16.** If  $\mathfrak{A}$  is a  $P$ -structure then  $\mathfrak{A} \models [P:\text{perm}]$  iff  $[P:\text{data}]^{\mathfrak{A}} a \in \mathbb{S}_n$  for all  $a \in A$ .

If  $A$  is a nonempty set and  $\text{data} : A \rightarrow \mathbb{S}_n$  is any function, then there is a  $P$ -structure  $\mathfrak{A} \models [P:\text{perm}]$  over  $A$  such that  $[P:\text{data}]^{\mathfrak{A}} = \text{data}$ .





### 3 Equivalence relations

An *equivalence relation*  $E \subseteq A \times A$  on  $A$  is a relation that is reflexive, symmetric and transitive. The set of *equivalence classes* of  $E$  is  $\mathcal{E}E = \{E[a] \mid a \in A\}$ .

Let  $E = \langle e \rangle$  be a predicate signature consisting of a single binary predicate symbol  $e$ . Define the  $\mathcal{L}^2[E]$ -sentence  $[e:\text{refl}]$  by:

$$[e:\text{refl}] = \forall x e(x, x).$$

Define the  $\mathcal{L}^2[E]$ -sentence  $[e:\text{symm}]$  by:

$$[e:\text{symm}] = \forall x \forall y (e(x, y) \rightarrow e(y, x)).$$

Define the  $\mathcal{L}^3[E]$ -sentence  $[e:\text{trans}]$  by:

$$[e:\text{trans}] = \forall x \forall y \forall z (e(x, y) \wedge e(y, z) \rightarrow e(x, z)).$$

Define the  $\mathcal{L}^3[E]$ -sentence  $[e:\text{equiv}]$  by:

$$[e:\text{equiv}] = [e:\text{refl}] \wedge [e:\text{symm}] \wedge [e:\text{trans}].$$

Let  $\mathfrak{A}$  be an  $E$ -structure and let  $E = e^{\mathfrak{A}}$ . Then  $E$  is reflexive iff  $\mathfrak{A} \models [e:\text{refl}]$ ;  $E$  is symmetric iff  $\mathfrak{A} \models [e:\text{symm}]$ ;  $E$  is transitive iff  $\mathfrak{A} \models [e:\text{trans}]$ ;  $E$  is an equivalence on  $A$  iff  $\mathfrak{A} \models [e:\text{equiv}]$ . It can be shown that transitivity and equivalence cannot be defined in the two-variable fragment.

#### 3.1 Two equivalence relations in agreement

**Definition 20.** Let  $\langle D, E \rangle$  be a sequence of two equivalence relations on  $A$ . The relation  $D$  is *finer* than the relation  $E$  if every equivalence class of  $D$  is a subset of some equivalence class of  $E$ . Equivalently,  $D \subseteq E$ . Equivalently,

$$(\forall a \in A)(\forall b \in A) (D(a, b) \rightarrow E(a, b)).$$

If  $D$  is finer than  $E$ , then  $E$  is coarser than  $D$ . The sequence  $\langle D, E \rangle$  is a sequence of equivalence relations on  $A$  in *refinement* if  $D$  is finer  $E$ .

The sequence  $\langle D, E \rangle$  is a sequence of equivalence relations in *global agreement* if either  $D$  is finer than  $E$  or  $E$  is finer than  $D$ .

The sequence  $\langle D, E \rangle$  is a sequence of equivalence relations in *local agreement* if for every  $a \in A$ , either  $D[a] \subseteq E[a]$  or  $E[a] \subseteq D[a]$ . Equivalently, no two equivalence classes  $E[a]$  and  $D[b]$  properly intersect. Equivalently,

$$(\forall a \in A) ((\forall b \in A) (D(a, b) \rightarrow E(a, b)) \vee (\forall b \in A) (E(a, b) \rightarrow D(a, b))).$$

### 3 Equivalence relations

Let  $E = \langle \mathbf{d}, \mathbf{e} \rangle$  be a predicate signature consisting of the two binary predicate symbols  $\mathbf{d}$  and  $\mathbf{e}$ . Let  $\mathfrak{A}$  is an  $E$ -structure and suppose that  $\mathbf{d}$  and  $\mathbf{e}$  are interpreted in  $\mathfrak{A}$  as equivalence relations on  $A$ . Let  $D = \mathbf{d}^{\mathfrak{A}}$  and  $E = \mathbf{e}^{\mathfrak{A}}$  be the interpretations of the two symbols.

**Definition 21.** Define the  $\mathcal{L}^2[E]$ -sentence  $[\mathbf{d}, \mathbf{e}:\text{refine}]$  by:

$$[\mathbf{d}, \mathbf{e}:\text{refine}] = \forall x \forall y (\mathbf{d}(x, y) \rightarrow \mathbf{e}(x, y)).$$

Then  $\langle D, E \rangle$  is in refinement iff  $\mathfrak{A} \models [\mathbf{d}, \mathbf{e}:\text{refine}]$ .

**Definition 22.** Define the  $\mathcal{L}^2[E]$ -sentence  $[\mathbf{d}, \mathbf{e}:\text{global}]$  by:

$$[\mathbf{d}, \mathbf{e}:\text{global}] = [\mathbf{d}, \mathbf{e}:\text{refine}] \vee [\mathbf{e}, \mathbf{d}:\text{refine}].$$

Then  $\langle D, E \rangle$  is in global agreement iff  $\mathfrak{A} \models [\mathbf{d}, \mathbf{e}:\text{global}]$ .

**Definition 23.** Define the  $\mathcal{L}^2[E]$ -sentence  $[\mathbf{d}, \mathbf{e}:\text{local}]$  by:

$$[\mathbf{d}, \mathbf{e}:\text{local}] = \forall x (\forall y (\mathbf{d}(x, y) \rightarrow \mathbf{e}(x, y)) \vee \forall y (\mathbf{e}(x, y) \rightarrow \mathbf{d}(x, y))).$$

Then  $\langle D, E \rangle$  is in global agreement iff  $\mathfrak{A} \models [\mathbf{d}, \mathbf{e}:\text{local}]$ .

**Lemma 1.** If  $\langle D, E \rangle$  is a sequence two equivalence relations on  $A$ , then it is in local agreement iff  $L = D \cup E$  is an equivalence relation on  $A$ .

*Proof.* The union of two equivalence relations on  $A$  is a reflexive and symmetric relation.

First suppose that  $D$  and  $E$  are in local agreement. We claim that  $L$  is transitive. Let  $a, b, c \in A$  be such that  $(a, b) \in L$  and  $(b, c) \in L$ . Since  $D$  and  $E$  are in local agreement, without loss of generality  $D[b] \subseteq E[b]$ . Since  $(a, b) \in L$ , either  $a \in D[b] \subseteq E[b]$  or  $a \in E[b]$ . Similarly  $c \in E[b]$ . Therefore  $(a, c) \in E \subseteq L$ .

Next suppose that  $L$  is an equivalence relation, let  $b \in A$  and assume towards a contradiction that  $D[b] \not\subseteq E[b]$  and  $E[b] \not\subseteq D[b]$ . There is some  $a \in D[b] \setminus E[b]$  and  $c \in E[b] \setminus D[b]$ . Then  $(a, b) \in D \subseteq L$  and  $(b, c) \in E \subseteq L$ , hence  $(a, c) \in L$ . Without loss of generality  $(a, c) \in E$ . Since  $c \in E[b]$ , we have  $a \in E[b]$  — a contradiction.  $\square$

## 3.2 Many equivalence relations in agreement

Let  $e$  be a positive natural number.

**Definition 24.** Let  $\langle E_1, E_2, \dots, E_e \rangle$  be a sequence of equivalence relations on  $A$ .

The sequence is in refinement if  $E_1 \subseteq E_2 \subseteq \dots \subseteq E_e$ .

The sequence is in global agreement if the equivalence relations form a chain under inclusion, that is for all  $i, j \in [1, e]$ , either  $E_i \subseteq E_j$  or  $E_j \subseteq E_i$ . Equivalently, there is a (not necessarily unique) permutation  $\nu \in \mathbb{S}_e$  such that  $E_{\nu(1)} \subseteq E_{\nu(2)} \subseteq \dots \subseteq E_{\nu(e)}$ .

The sequence is in local agreement if for every element  $a \in A$  the equivalence classes  $E_1[a], E_2[a], \dots, E_e[a]$  form a chain under inclusion. Equivalently, no two equivalence classes  $E_i[a]$  and  $E_j[b]$  properly intersect.

### 3.2 Many equivalence relations in agreement

Let  $E = \langle e_1, e_2, \dots, e_e \rangle$  be a predicate signature consisting of  $e$  binary predicate symbols. Let  $\mathfrak{A}$  be an  $E$ -structure and suppose that the symbols  $e_i$  are interpreted as equivalence relations on  $A$ . Let  $E_i = e_i^{\mathfrak{A}}$  for  $i \in [1, e]$ .

**Definition 25.** Define the  $\mathcal{L}^2[E]$ -sentence  $[e_1, e_2, \dots, e_e:\text{refine}]$  by:

$$[e_1, e_2, \dots, e_e:\text{refine}] = \forall x \forall y \bigwedge_{1 \leq i < e} (e_i(x, y) \rightarrow e_{i+1}(x, y)).$$

Then  $\langle E_1, E_2, \dots, E_e \rangle$  is in refinement iff  $\mathfrak{A} \models [e_1, e_2, \dots, e_e:\text{refine}]$ . Note that this sentence is constructible in deterministic polynomial time from the sequence of equivalence symbols.

**Definition 26.** Define the  $\mathcal{L}^2[E]$ -sentence  $[e_1, e_2, \dots, e_e:\text{global}]$  by:

$$[e_1, e_2, \dots, e_e:\text{global}] = \bigvee_{\nu \in \mathbb{S}_e} [e_{\nu(1)}, e_{\nu(2)}, \dots, e_{\nu(e)}:\text{refine}].$$

Then  $\langle E_1, E_2, \dots, E_e \rangle$  is in global agreement iff  $\mathfrak{A} \models [e_1, e_2, \dots, e_e:\text{global}]$ . Note that the length of the formula  $[e_1, e_2, \dots, e_e:\text{global}]$  grows exponentially as  $e$  grows.

**Definition 27.** Define the  $\mathcal{L}^2[E]$ -sentence  $[e_1, e_2, \dots, e_e:\text{local}]$  by:

$$[e_1, e_2, \dots, e_e:\text{local}] = \forall x \bigvee_{\nu \in \mathbb{S}_e} \forall y \bigwedge_{1 \leq i < e} (e_{\nu(i)}(x, y) \rightarrow e_{\nu(i+1)}(x, y)).$$

Then  $\langle E_1, E_2, \dots, E_e \rangle$  is in local agreement iff  $\mathfrak{A} \models [e_1, e_2, \dots, e_e:\text{local}]$ . Note that the length of the formula  $[e_1, e_2, \dots, e_e:\text{local}]$  grows exponentially as  $e$  grows.

Let  $E = \langle E_1, E_2, \dots, E_e \rangle$  be a sequence of equivalence relations on  $A$ .

**Theorem 3.** The sequence  $E$  is in local agreement iff the union  $\cup S$  of any nonempty subsequence  $S \subseteq E$  is an equivalence relation on  $A$ .

*Proof.* First suppose that the equivalence relations  $E_i$  are in local agreement. We show that the union  $\cup S$  of arbitrary nonempty subsequence  $S = \{E_{i(1)}, E_{i(2)}, \dots, E_{i(s)}\}$ , where  $1 \leq i(1) < i(2) < \dots < i(s) \leq e$ , is an equivalence relation by induction on  $s$ , the length of  $S$ . If  $s = 1$  this claim is trivial. Suppose  $s > 1$ . By the induction hypothesis,  $D = \cup\{E_{i(1)}, E_{i(2)}, \dots, E_{i(s-1)}\}$  is an equivalence relation on  $A$ . We claim that  $D$  and  $E_{i(s)}$  are in local agreement. Indeed, let  $a \in A$  be arbitrary and consider  $D[a] = E_{i(1)}[a] \cup E_{i(2)}[a] \cup \dots \cup E_{i(s-1)}[a]$  and  $E_{i(s)}[a]$ . Since all equivalences  $E_k$  are in local agreement, either  $E_{i(s)}[a] \subseteq E_{i(j)}[a]$  for some  $j \in [1, s-1]$ , or  $E_{i(j)}[a] \subseteq E_{i(s)}[a]$  for all  $j \in [1, s-1]$ . In the first case  $E_{i(s)}[a] \subseteq D[a]$ ; in the second case  $D[a] \subseteq E_{i(s)}[a]$ . Thus  $D$  and  $E_{i(s)}$  are in local agreement. By Lemma 1,  $\cup S = D \cup E_{i(s)}$  is an equivalence relation on  $A$ .

Next suppose that the equivalences are not in local agreement. There is an element  $a \in A$  such that  $\{E_i[a] \mid i \in [1, e]\}$  is not a chain. There are  $i, j \in [1, e]$  such that  $E_i[a] \not\subseteq E_j[a]$  and  $E_j[a] \not\subseteq E_i[a]$ . Thus  $E_i$  and  $E_j$  are not in local agreement. By Lemma 1, the union  $E_i \cup E_j$  is not an equivalence relation on  $A$ .  $\square$

### 3 Equivalence relations

Suppose that the sequence  $E = \langle E_1, E_2, \dots, E_e \rangle$  is in local agreement.

**Definition 28.** An index set is an element  $I \in \wp^+[1, e]$ . Define  $(E \upharpoonright \cdot) : \wp^+[1, e] \rightarrow \wp^+E$  by:

$$(E \upharpoonright I) = \{E_i \mid i \in I\}.$$

That is,  $(E \upharpoonright I)$  just collects the equivalences having indices from  $I$ .

The level sequence  $L = \langle L_1, L_2, \dots, L_e \rangle$  of the sequence  $E$  is defined as follows. For  $k \in [1, e]$ :

$$L_k = \cap \left\{ \cup(E \upharpoonright I) \mid I \in \wp^k[1, e] \right\}.$$

**Remark 17.** All  $L_k$  are equivalence relations on  $A$ .

*Proof.* Let  $k \in [1, e]$  and let  $K \in \wp^k[1, e]$  be any  $k$ -index set. By [Theorem 3](#),  $\cup(E \upharpoonright K)$  is an equivalence relation on  $A$ . Since intersection of equivalence relations on  $A$  is again an equivalence relation on  $A$ , the level  $L_k = \cap \left\{ \cup(E \upharpoonright K) \mid K \in \wp^k[1, e] \right\}$  is an equivalence relation on  $A$ .  $\square$

**Lemma 2.** The level sequence  $L = \langle L_1, L_2, \dots, L_e \rangle$  is a sequence of equivalence relations on  $A$  in refinement.

*Proof.* Let  $i < j \in [1, e]$ . Let  $J \in \wp^j[1, e]$  be any  $j$ -index set. We claim that  $L_i \subseteq \cup(E \upharpoonright J)$ . Indeed, choose some  $i$ -index set  $I \subset J$ . By the definition of  $L_i$  we have  $L_i \subseteq \cup(E \upharpoonright I) \subseteq \cup(E \upharpoonright J)$ . Hence  $L_i \subseteq \cap \left\{ \cup(E \upharpoonright J) \mid J \in \wp^j[1, e] \right\} = L_j$ .  $\square$

Let  $a \in A$ . Since the sequence  $E = \langle E_1, E_2, \dots, E_e \rangle$  is in local agreement, there is a permutation  $\nu \in \mathbb{S}_e$  such that:

$$E_{\nu(1)}[a] \subseteq E_{\nu(2)}[a] \subseteq \dots \subseteq E_{\nu(e)}[a]. \quad (3.1)$$

**Lemma 3.** If  $\nu \in \mathbb{S}_e$  is a permutation satisfying [eq. \(3.1\)](#), then  $L_{\nu^{-1}(i)}[a] = E_i[a]$  for all  $i \in [1, e]$ .

*Proof.* Let  $k = \nu^{-1}(i)$ , so  $\nu(k) = i$ . We claim that  $L_k[a] = E_i[a]$ . First, consider the  $k$ -index set  $K = \{\nu(1), \nu(2), \dots, \nu(k)\}$ . By the definition of  $L_k$ , followed by [eq. \(3.1\)](#), we have  $L_k[a] \subseteq \cup(E \upharpoonright K)[a] = E_{\nu(k)}[a] = E_i[a]$ . Next, let  $K \subseteq \wp^k[1, e]$  be any  $k$ -index set. By the pigeonhole principle, there is some  $k' \geq k$  such that  $\nu(k') \in K$ . By [eq. \(3.1\)](#) we have:

$$E_i[a] = E_{\nu(k)}[a] \subseteq E_{\nu(k')}[a] \subseteq \cup(E \upharpoonright K)[a].$$

Hence  $E_i[a] \subseteq \cap \left\{ \cup(E \upharpoonright K)[a] \mid K \in \wp^k[1, e] \right\} = L_k[a]$ .  $\square$

## 4 Reductions

In this chapter we provide polynomial-time reductions from the case of equivalence symbols in global or local agreement to the case of equivalence symbols in refinement.

We restrict our attention to binary predicate signatures only consisting of unary and binary predicate symbols. To denote various logics with built-in equivalence symbols, we use the notation

$$\mathcal{L}_p^v e E_a$$

where:

- $\mathcal{L}$  is the *ground logic*
- $v$ , if given, bounds the number of variables
- $e$ , if given, bounds the number of built-in equivalence symbols
- $a \in \{\text{refine, global, local}\}$ , if given, gives the agreement condition between the built-in equivalence symbols
- $p$ , the *signature power*, specifies constraints on the signature:
  - if  $p = 0$ , the signature consists of only constantly many unary predicate symbols in addition to the built-in equivalence symbols
  - if  $p = 1$ , the signature consists of unboundedly many unary predicate symbols in addition to the built-in equivalence symbols
  - if  $p$  is not given, the signature consists of unboundedly many unary and binary predicate symbols in addition to the built-in equivalence symbols. This is the commonly investigated fragment with respect to satisfiability of the two-variable logics with or without counting quantifiers.

For example  $\mathcal{L}_1$  is the monadic first-order logic, featuring only unary predicate symbols.  $\mathcal{L}_0 1 E$  is the first-order logic of a single equivalence relation.  $\mathcal{L}^2 2 E$  is the two-variable logic, featuring unary, binary predicate symbols and two built-in equivalence symbols.  $\mathcal{L}_1^2 2 E_{\text{local}}$  is the two-variable logic, featuring unary predicate symbols and two built-in equivalence symbols in local agreement.  $\mathcal{L}_1 E_{\text{global}}$  is the monadic first-order logic featuring many equivalence symbols in global agreement.

When we working with a concrete logic, for example  $\mathcal{L}^2 2 E_{\text{local}}$ , we implicitly assume an appropriate generic predicate signature  $\Sigma$  for it. In this case, there are two built-in equivalence symbols  $d$  and  $e$  in  $\Sigma$  and in addition  $\Sigma$  contains arbitrary many unary

## 4 Reductions

and binary predicate symbols. The *intended interpretation* of the built-in equivalence symbols is fixed by an appropriate condition  $\theta$ . In this case:

$$\theta = [\mathbf{d}:\text{equiv}] \wedge [\mathbf{e}:\text{equiv}] \wedge [\mathbf{d}, \mathbf{e}:\text{local}].$$

Note that the interpretation condition might in general be a first-order formula outside the logic in interest, as in this case, since for instance  $[\mathbf{d}:\text{equiv}]$  uses the variables  $\mathbf{x}, \mathbf{y}$  and  $\mathbf{z}$  and the logic  $\mathcal{L}^2\mathbf{2E}_{\text{local}}$  is a two-variable logic. Recall that when talking about semantics, we include the intended interpretation condition in the definition of  $\Sigma$ -structures.

### 4.1 Global agreement to refinement

In this section we demonstrate how (finite) satisfiability in logics featuring built-in equivalence symbols in global agreement reduces to (finite) satisfiability in logics featuring built-in equivalence symbols in refinement. Our strategy is to encode the permutation of the built-in equivalence symbols in global agreement that turns them in refinement into a permutation setup.

Let  $\Sigma$  be a predicate signature for the logics  $\mathcal{LE}_{\text{global}}$  or  $\mathcal{LE}_{\text{refine}}$ . The  $e$  built-in equivalence symbols of  $\Sigma$  are  $\mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_e$ .

Let  $\varphi$  be a  $\Sigma$ -sentence. The class of  $\mathcal{LE}_{\text{refine}}$ -structures satisfying  $\varphi$  coincides with the class of  $\mathcal{LE}_{\text{global}}$ -structures satisfying

$$\varphi \wedge [\mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_e:\text{refine}].$$

Hence:

$$(\text{FIN-})\text{SAT-}\mathcal{LE}_{\text{refine}} \leq_m^{\text{PTIME}} (\text{FIN-})\text{SAT-}\mathcal{LE}_{\text{global}}.$$

Since the formula  $[\mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_e:\text{refine}]$  is constructible in deterministic polynomial time from sequence of equivalence symbols:

$$(\text{FIN-})\text{SAT-}\mathcal{LE}_{\text{refine}} \leq_m^{\text{PTIME}} (\text{FIN-})\text{SAT-}\mathcal{LE}_{\text{global}}.$$

Consider the opposite direction. Let  $\mathbf{P} = \langle \mathbf{u}_{11}, \mathbf{u}_{12}, \dots, \mathbf{u}_{et} \rangle$  be an  $e$ -permutation setup (where  $t = \|e\|$ ).

**Definition 29.** Define the  $\mathcal{L}^2[\mathbf{P}]$ -sentence  $[\mathbf{P}:\text{alleq}]$  by:

$$[\mathbf{P}:\text{alleq}] = \forall \mathbf{x} \forall \mathbf{y} \bigwedge_{1 \leq i \leq e} [\mathbf{P}(i):\text{eq}](\mathbf{x}, \mathbf{y}).$$

Note that  $[\mathbf{P}:\text{alleq}]$  is constructible in deterministic polynomial time from  $\mathbf{P}$ .

**Remark 18.** If  $\mathfrak{A}$  is a  $\mathbf{P}$ -structure, then  $\mathfrak{A} \models [\mathbf{P}:\text{alleq}]$  iff  $[\mathbf{P}:\text{data}]^{\mathfrak{A}}a = [\mathbf{P}:\text{data}]^{\mathfrak{A}}b$  for all  $a, b \in A$ . If  $A$  is a nonempty set and  $\mathbf{v} \in \mathbb{B}_t^e$  is any  $e$ -dimensional  $t$ -vector, there is a  $\mathbf{P}$ -structure  $\mathfrak{A}$  over  $A$  such that  $\mathfrak{A} \models [\mathbf{P}:\text{alleq}]$  and  $[\mathbf{P}:\text{data}]^{\mathfrak{A}}a = \mathbf{v}$  for all  $a \in A$ .

**Definition 30.** Define the  $\mathcal{L}^2[\mathbf{P}]$ -sentence  $[\mathbf{P}:\text{globperm}]$  by:

$$[\mathbf{P}:\text{globperm}] = [\mathbf{P}:\text{perm}] \wedge [\mathbf{P}:\text{alleq}].$$

Note that  $[\mathbf{P}:\text{globperm}]$  is constructible in deterministic polynomial time from  $\mathbf{P}$ .

**Remark 19.** If  $\mathfrak{A}$  is a  $\mathbf{P}$ -structure then  $\mathfrak{A} \models [\mathbf{P}:\text{globperm}]$  iff there is a permutation  $\nu \in \mathbb{S}_e$  such that  $[\mathbf{P}:\text{data}]^{\mathfrak{A}}a = \nu$  for all  $a \in A$ . If  $A$  is a nonempty set and  $\nu \in \mathbb{S}_e$  is any permutation, there is a  $\mathbf{P}$ -structure  $\mathfrak{A}$  over  $A$  such that  $\mathfrak{A} \models [\mathbf{P}:\text{globperm}]$  and  $[\mathbf{P}:\text{data}]^{\mathfrak{A}}a = \nu$  for all  $a \in A$ .

Let  $\mathbf{L} = \langle l_1, l_2, \dots, l_e \rangle + \mathbf{P}$  be a predicate signature consisting of the binary predicate symbols  $l_k$  in addition to the symbols from  $\mathbf{P}$ .

**Definition 31.** For  $i \in [1, e]$ , define the quantifier-free  $\mathcal{L}^2[\mathbf{L}]$ -formula  $[\mathbf{L}:\text{eg-}i](\mathbf{x}, \mathbf{y})$  by:

$$[\mathbf{L}:\text{eg-}i](\mathbf{x}, \mathbf{y}) = \bigwedge_{1 \leq k \leq e} ([\mathbf{P}(k):\text{eq-}i](\mathbf{x}) \rightarrow l_k(\mathbf{x}, \mathbf{y})).$$

Note that  $[\mathbf{L}:\text{eg-}i](\mathbf{x}, \mathbf{y})$  is constructible in deterministic polynomial time given  $\mathbf{L}$  and  $i$ .

**Remark 20.** Let  $\mathfrak{A}$  be an  $\mathbf{L}$ -structure and suppose that  $\mathfrak{A} \models [\mathbf{P}:\text{globperm}]$  and that the binary symbols  $l_k$  are interpreted as equivalence relations on  $A$  in refinement. Recall that there is a permutation  $\nu \in \mathbb{S}_e$  such that  $[\mathbf{P}:\text{data}]^{\mathfrak{A}}a = \nu$  for all  $a \in A$ . Then for all  $i \in [1, e]$ :

$$[\mathbf{L}:\text{eg-}i]^{\mathfrak{A}} = l_{\nu^{-1}(i)}^{\mathfrak{A}}.$$

In particular,  $\langle [\mathbf{L}:\text{eg-}1]^{\mathfrak{A}}, [\mathbf{L}:\text{eg-}2]^{\mathfrak{A}}, \dots, [\mathbf{L}:\text{eg-}e]^{\mathfrak{A}} \rangle$  is a sequence of equivalence relations on  $A$  in global agreement.

*Proof.* Let  $k = \nu^{-1}(i)$ , so  $\nu(k) = i$  and  $[\mathbf{P}(k):\text{data}]^{\mathfrak{A}}a = i$ . Since  $\nu$  is a permutation, for every  $k' \in [1, e]$ :

$$\mathfrak{A} \models [\mathbf{P}(k'):\text{eq-}i](a) \text{ iff } [\mathbf{P}(k'):\text{data}]^{\mathfrak{A}}a = i \text{ iff } k' = k. \quad (4.1)$$

Let  $a, b \in A$ . First suppose that  $\mathfrak{A} \models [\mathbf{L}:\text{eg-}i](a, b)$ . By eq. (4.1) we must have that  $\mathfrak{A} \models [\mathbf{P}(k):\text{eq-}i](a)$ , hence  $\mathfrak{A} \models l_k(a, b)$ .

Now suppose that  $\mathfrak{A} \models \neg[\mathbf{L}:\text{eg-}i](a, b)$ . There is some  $k' \in [1, e]$  such that:

$$\mathfrak{A} \models \neg([\mathbf{P}(k'):\text{eq-}i](a) \rightarrow l_{k'}(a, b)) \equiv [\mathbf{P}(k'):\text{eq-}i](a) \wedge \neg l_{k'}(a, b).$$

By eq. (4.1) we have  $k' = k$ , hence  $\mathfrak{A} \models \neg l_k(a, b)$ . □

Let  $\mathbf{E} = \langle e_1, e_2, \dots, e_e \rangle$  be a predicate signature consisting of the binary predicate symbols  $e_i$ . Let  $\Sigma$  be a predicate signature enriching  $\mathbf{E}$  and not containing any symbols from  $\mathbf{L}$ . Let  $\Sigma' = \Sigma \cup \mathbf{L}$  and  $\mathbf{L}' = \Sigma' - \mathbf{E}$ .

#### 4 Reductions

**Definition 32.** Define the syntactic operation  $\text{gtr} : \mathcal{L}[\Sigma] \rightarrow \mathcal{L}[L']$  by:

$$\text{gtr } \varphi = \varphi' \wedge [\text{P:globperm}],$$

where  $\varphi'$  is obtained from  $\varphi$  by replacing all occurrences of a subformula of the form  $e_i(x, y)$  by the formula  $[\text{L:eg-}i](x, y)$ , where  $x$  and  $y$  are (not necessarily distinct) variables and  $i \in [1, e]$ . Note that the operation can be performed in deterministic polynomial time.

**Remark 21.** Let  $\varphi$  be a  $\Sigma$ -formula and let  $\mathfrak{A}$  be a  $\Sigma$ -structure. Suppose that  $\mathfrak{A} \models \varphi$  and that the symbols  $e_1, e_2, \dots, e_e$  are interpreted in  $\mathfrak{A}$  as equivalence relations on  $A$  in global agreement. Then there is a  $\Sigma'$ -enrichment  $\mathfrak{A}'$  of  $\mathfrak{A}$  such that  $\mathfrak{A}' \models \text{gtr } \varphi$  and that the symbols  $l_1, l_2, \dots, l_e$  are interpreted in  $\mathfrak{A}'$  as equivalence relations on  $A$  in refinement.

*Proof.* There is a permutation  $\nu \in \mathbb{S}_e$  such that  $e_{\nu(1)}^{\mathfrak{A}} \subseteq e_{\nu(2)}^{\mathfrak{A}} \subseteq \dots \subseteq e_{\nu(e)}^{\mathfrak{A}}$ . Consider an enrichment  $\mathfrak{A}'$  of  $\mathfrak{A}$  to a  $\Sigma'$ -structure where  $l_k^{\mathfrak{A}'} = e_{\nu(k)}^{\mathfrak{A}}$ , so the interpretations of  $l_k$  in  $\mathfrak{A}'$  are equivalence relations on  $A$  in refinement. We can interpret the unary predicate symbols from permutation setup  $P$  in  $\mathfrak{A}'$  so that  $\mathfrak{A}' \models [\text{P:globperm}]$  and  $[\text{P:data}]^{\mathfrak{A}'} a = \nu$  for all  $a \in A$ . By **Remark 20**, for every  $i \in [1, e]$ :

$$[\text{L:eg-}i]^{\mathfrak{A}'} = l_{\nu^{-1}(i)}^{\mathfrak{A}'} = e_{\nu(\nu^{-1}(i))}^{\mathfrak{A}'} = e_i^{\mathfrak{A}'} = e_i^{\mathfrak{A}}.$$

Hence  $\mathfrak{A}' \models \forall x \forall y (e_i(x, y) \leftrightarrow [\text{L:eg-}i](x, y))$ . Since  $\mathfrak{A}' \models \varphi$  we have  $\mathfrak{A}' \models \text{gtr } \varphi$ .  $\square$

**Remark 22.** Let  $\varphi$  be a  $\Sigma$ -formula and let  $\mathfrak{A}$  be an  $L'$ -structure. Suppose that  $\mathfrak{A} \models \text{gtr } \varphi$  and that the symbols  $l_1, l_2, \dots, l_e$  are interpreted in  $\mathfrak{A}$  as equivalence relations on  $A$  in refinement. Then there is a  $\Sigma'$ -enrichment  $\mathfrak{A}'$  of  $\mathfrak{A}$  such that  $\mathfrak{A}' \models \varphi$  and that the symbols  $e_1, e_2, \dots, e_e$  are interpreted as equivalence relations on  $A$  in global agreement in  $\mathfrak{A}'$ .

*Proof.* Consider an enrichment  $\mathfrak{A}'$  of  $\mathfrak{A}$  to a  $\Sigma'$ -structure where  $e_i^{\mathfrak{A}'} = [\text{L:eg-}i]^{\mathfrak{A}}$ . By **Remark 20**,  $\langle e_1^{\mathfrak{A}'}, e_2^{\mathfrak{A}'}, \dots, e_e^{\mathfrak{A}'} \rangle$  is a sequence of equivalence relations on  $A$  in global agreement. For every  $i \in [1, e]$  we have  $\mathfrak{A}' \models \forall x \forall y (e_i(x, y) \leftrightarrow [\text{L:eg-}i](x, y))$  by definition. Since  $\mathfrak{A}' \models \text{gtr } \varphi$  we have  $\mathfrak{A}' \models \varphi$ .  $\square$

The last two remarks show that a  $\mathcal{L}E_{\text{global}}$ -formula  $\varphi$  has essentially the same models as the  $\mathcal{L}E_{\text{refine}}$ -formula  $\text{gtr } \varphi$ , so we have shown:

**Proposition 1.** The logic  $\mathcal{L}E_{\text{global}}$  has the finite model property iff the logic  $\mathcal{L}E_{\text{refine}}$  has the finite model property. The corresponding satisfiability problems are polynomial-time equivalent:  $(\text{FIN-})\text{SAT-}\mathcal{L}E_{\text{global}} =_{\text{m}}^{\text{PTIME}} (\text{FIN-})\text{SAT-}\mathcal{L}E_{\text{refine}}$ .

Since the translation  $\text{gtr}$  is in deterministic polynomial time, we have shown:

**Proposition 2.** The logic  $\mathcal{L}E_{\text{global}}$  has the finite model property iff the logic  $\mathcal{L}E_{\text{refine}}$  has the finite model property. The corresponding satisfiability problems are polynomial-time equivalent:  $(\text{FIN-})\text{SAT-}\mathcal{L}E_{\text{global}} =_{\text{m}}^{\text{PTIME}} (\text{FIN-})\text{SAT-}\mathcal{L}E_{\text{refine}}$ .

The reduction is two-variable first-order and uses additional (et) unary predicate symbols for the permutation setup  $P$ , so it is also valid for the two-variable fragments  $\mathcal{L}_0^2 E_a$ ,  $\mathcal{L}_1^2 E_a$  and  $\mathcal{L}_1^2 E_a$  for  $a \in \{\text{global}, \text{refine}\}$  (but not for the fragment  $\mathcal{L}_0^2 E_a$ ).



## 4.2 Local agreement to refinement

In this section demonstrate how (finite) satisfiability in logics featuring built-in equivalence symbols in local agreement reduces to (finite) satisfiability in logics featuring built-in equivalence symbols in refinement. Our strategy is to start with the level equivalences which form a refinement, and to encode a permutation specifying the local chain structure for every element in the structure.

Let  $\Sigma$  be a predicate signature for the logics  $\mathcal{L}eE_{\text{local}}$  and  $\mathcal{L}eE_{\text{refine}}$ . The  $e$  built-in equivalence symbols of  $\Sigma$  are  $e_1, e_2, \dots, e_e$ .

Let  $\varphi$  be a  $\Sigma$ -sentence. The class of  $\mathcal{L}eE_{\text{refine}}$ -structures satisfying  $\varphi$  coincides with the class of  $\mathcal{L}eE_{\text{local}}$ -structures satisfying

$$\varphi \wedge [e_1, e_2, \dots, e_e : \text{refine}].$$

Hence:

$$(\text{FIN-})\text{SAT-}\mathcal{L}eE_{\text{refine}} \leq_m^{\text{PTIME}} (\text{FIN-})\text{SAT-}\mathcal{L}eE_{\text{local}}.$$

Since  $[e_1, e_2, \dots, e_e : \text{refine}]$  is constructible in deterministic polynomial time from the sequence of equivalence symbols, we have:

$$(\text{FIN-})\text{SAT-}\mathcal{L}E_{\text{refine}} \leq_m^{\text{PTIME}} (\text{FIN-})\text{SAT-}\mathcal{L}E_{\text{local}}.$$

Consider the opposite direction. Let  $E = \langle e_1, e_2, \dots, e_e \rangle$  be a predicate signature consisting of the binary predicate symbols  $e_i$  (later, we will need these to be not necessarily interpreted as equivalences, but for now we will interpret them as such). Let  $\mathfrak{A}$  be an  $E$ -structure and suppose that the symbols  $e_i$  are interpreted in  $\mathfrak{A}$  as equivalence relations on  $A$  in local agreement. Let  $E_i = e_i^{\mathfrak{A}}$  for  $i \in [1, e]$ . Recall that for every  $a \in A$  there is a permutation  $\nu \in \mathbb{S}_e$  satisfying [eq. \(3.1\)](#):

$$E_{\nu(1)}[a] \subseteq E_{\nu(2)}[a] \subseteq \dots \subseteq E_{\nu(e)}[a]. \quad (4.2)$$

**Definition 33.** The characteristic  $E$ -permutation of  $a$  in  $\mathfrak{A}$  is the antilexicographically smallest permutation  $\nu \in \mathbb{S}_e$  satisfying [eq. \(4.2\)](#). Define the function  $[E : \text{chperm}]^{\mathfrak{A}} : A \rightarrow \mathbb{S}_e$  so that  $[E : \text{chperm}]^{\mathfrak{A}} a$  is the characteristic  $E$ -permutation of  $a$  in  $\mathfrak{A}$ .

**Remark 23.** Let  $a \in A$ ,  $\nu = [E : \text{chperm}]^{\mathfrak{A}} a$  and  $i < j \in [1, e]$ . Suppose that  $E_{\nu(i)}[a] = E_{\nu(j)}[a]$ . Then  $\nu(i) < \nu(j)$ .

*Proof.* Suppose not. For some  $i < j \in [1, e]$  we have  $\nu(i) \geq \nu(j)$ . Since  $\nu$  is a permutation and  $i \neq j$ , we have  $\nu(i) > \nu(j)$ . Since  $E_{\nu(i)}[a] = E_{\nu(j)}[a]$ , by [eq. \(4.2\)](#) we have  $E_{\nu(k)} = E_{\nu(i)}$  for all  $k \in [i, j]$ . Consider the permutation  $\mu \in \mathbb{S}_e$  defined by:

$$\mu(k) = \begin{cases} \nu(j) & \text{if } k = i \\ \nu(i) & \text{if } k = j \\ \nu(k) & \text{otherwise.} \end{cases}$$

Clearly,  $\mu$  is a permutation satisfying [eq. \(4.2\)](#) that is antilexicographically smaller than  $\nu$  — a contradiction.  $\square$

#### 4 Reductions

**Remark 24.** Let  $a, b \in A$  and let  $\alpha = [\text{E:chperm}]^{\mathfrak{A}}a$  and  $\beta = [\text{E:chperm}]^{\mathfrak{A}}b$ . Let  $i \in [1, e]$  and suppose that  $(a, b) \in E_i$ . Then  $\alpha^{-1}(i) = \beta^{-1}(i)$ .

*Proof.* Suppose not, so  $\alpha^{-1}(i) \neq \beta^{-1}(i)$ . Let  $p = \alpha^{-1}(i)$  and  $q = \beta^{-1}(i)$ . Without loss of generality, suppose that  $p < q$ . Thus  $p$  is the position of  $i$  in the permutation  $\alpha$  and  $q > p$  is the position of  $i$  in the permutation  $\beta$ . By the pigeonhole principle, there is  $k \in [1, e]$  that occurs after  $i$  in  $\alpha$  and before  $j$  in  $\beta$ :  $p < \alpha^{-1}(k)$  and  $\beta^{-1}(k) < q$ . Since  $\beta$  is the characteristic E-permutation of  $b$  in  $\mathfrak{A}$ , by eq. (4.2) we have  $E_k[b] \subseteq E_i[b]$ . Since  $(a, b) \in E_i$ , we have  $E_k[b] \subseteq E_i[a]$ . Since  $E_k[b] \subseteq E_i[a]$  are equivalence classes,  $E_k[a] \subseteq E_i[a]$ . Since  $k$  occurs after  $i$  in  $\alpha$ , which is the characteristic E-permutation of  $a$  in  $\mathfrak{A}$ , by eq. (4.2) we have  $E_k[a] = E_i[a]$ . By Remark 23,  $i < k$ . By the contrapositive of Remark 23,  $E_k[b] = E_i[b]$  is impossible. Since  $k$  occurs before  $i$  in  $\beta$ , by eq. (4.2) we have  $E_k[b] \subset E_i[b]$ . Hence

$$E_k[b] \subset E_i[b] = E_i[a] = E_k[a]$$

— a contradiction — since the equivalence classes  $E_k[b]$  and  $E_k[a]$  are either equal or disjoint.  $\square$

Let  $L = \langle L_1, L_2, \dots, L_e \rangle$  be the levels of  $E = \langle E_1, E_2, \dots, E_e \rangle$ . Recall that by Lemma 2, the levels are equivalence relations on  $A$  in refinement.

**Remark 25.** Let  $a \in A$ ,  $\alpha = [\text{E:chperm}]^{\mathfrak{A}}a$  and let  $k \in [1, e]$ . Then  $L_k[a] = E_{\alpha(k)}[a]$ .

*Proof.* Since  $\alpha$  satisfies eq. (4.2), by Lemma 3:

$$L_k[a] = L_{\alpha^{-1}(\alpha(k))}[a] = E_{\alpha(k)}[a].$$

$\square$

**Remark 26.** Let  $a, b \in A$ ,  $\alpha = [\text{E:chperm}]^{\mathfrak{A}}a$ ,  $\beta = [\text{E:chperm}]^{\mathfrak{A}}b$  and  $k \in [1, e]$ . Suppose that  $(a, b) \in L_k$ . Then  $\alpha(k) = \beta(k)$ . That is, the elements connected at level  $k$  agree at position  $k$  in their characteristic permutations.

*Proof.* By Remark 25,  $L_k[a] = E_{\alpha(k)}[a]$ , thus  $(a, b) \in E_{\alpha(k)}$ . By Remark 23,

$$k = \alpha^{-1}(\alpha(k)) = \beta^{-1}(\alpha(k)).$$

Hence  $\beta(k) = \alpha(k)$ .  $\square$

Let  $P = \langle \mathbf{u}_{11}, \mathbf{u}_{12}, \dots, \mathbf{u}_{et} \rangle$  be an  $e$ -permutation setup. Let  $L = \langle \mathbf{l}_1, \mathbf{l}_2, \dots, \mathbf{l}_e \rangle + P$  be a predicate signature containing the binary predicate symbols  $\mathbf{l}_k$  (not necessarily interpreted as equivalence relations) together with the symbols from  $P$ .

**Definition 34.** Define the  $\mathcal{L}^2[L]$ -sentence  $[\text{L:fixperm}]$  by:

$$[\text{L:fixperm}] = \forall \mathbf{x} \forall \mathbf{y} \bigwedge_{1 \leq k \leq e} (\mathbf{l}_k(\mathbf{x}, \mathbf{y}) \rightarrow [P(k):\text{eq}](\mathbf{x}, \mathbf{y})).$$

Note that  $[\text{L:fixperm}]$  is constructible in deterministic polynomial time from  $L$ .

**Definition 35.** Define the  $\mathcal{L}^2[\mathbf{L}]$ -sentence  $[\mathbf{L}:\text{locperm}]$  by:

$$[\mathbf{L}:\text{locperm}] = [\mathbf{P}:\text{perm}] \wedge [\mathbf{L}:\text{fixperm}].$$

Note that  $[\mathbf{L}:\text{locperm}]$  is constructible in deterministic polynomial time from  $\mathbf{L}$ .

**Remark 27.** Let  $\mathfrak{A}$  be an  $\mathbf{L}$ -structure and suppose that  $\mathfrak{A} \models [\mathbf{L}:\text{locperm}]$ . Let  $a, b \in A$ ,  $k \in [1, e]$  and suppose that  $\mathfrak{A} \models \mathbf{l}_k(a, b)$ . Let  $\alpha = [\mathbf{P}:\text{data}]^{\mathfrak{A}}a$  and  $\beta = [\mathbf{P}:\text{data}]^{\mathfrak{A}}b$  be the  $e$ -permutations at  $a$  and  $b$ , encoded by the permutation setup  $\mathbf{P}$ . Then  $\alpha(k) = \beta(k)$ .

*Proof.* Since  $\mathfrak{A} \models [\mathbf{L}:\text{fixperm}]$  and  $\mathfrak{A} \models \mathbf{l}_k(a, b)$ , we have  $\mathfrak{A} \models [\mathbf{P}(k):\text{eq}](a, b)$ , which means  $\alpha(k) = \beta(k)$ .  $\square$

**Definition 36.** For  $i \in [1, e]$ , define the quantifier-free  $\mathcal{L}^2[\mathbf{L}]$ -formula  $[\mathbf{L}:\text{el-}i]$  by:

$$[\mathbf{L}:\text{el-}i](\mathbf{x}, \mathbf{y}) = \bigwedge_{1 \leq k \leq e} ([\mathbf{P}(k):\text{eq-}i](\mathbf{x}) \rightarrow \mathbf{l}_k(\mathbf{x}, \mathbf{y})).$$

Note that  $[\mathbf{L}:\text{el-}i](\mathbf{x}, \mathbf{y})$  is constructible in deterministic polynomial time from  $\mathbf{L}$  and  $i$ .

**Remark 28.** Let  $\mathfrak{A}$  be an  $\mathbf{L}$ -structure and suppose that  $\mathfrak{A} \models [\mathbf{L}:\text{locperm}]$  and that the binary symbols  $\mathbf{l}_k$  are interpreted in  $\mathfrak{A}$  as equivalence relations on  $A$  in refinement. Define  $\nu : A \rightarrow \mathbb{S}_e$  by  $\nu(a) = [\mathbf{P}:\text{data}]^{\mathfrak{A}}a$  for  $a \in A$ . Let  $a \in A$  be arbitrary. Then for all  $i \in [1, e]$ :

$$[\mathbf{L}:\text{el-}i]^{\mathfrak{A}}[a] = \mathbf{l}_{\nu(a)^{-1}(i)}^{\mathfrak{A}}[a].$$

*Proof.* Let  $E_i = [\mathbf{L}:\text{el-}i]^{\mathfrak{A}}$  and  $L_i = \mathbf{l}_i^{\mathfrak{A}}$  for every  $i \in [1, e]$ . Let  $i \in [1, e]$  be arbitrary. Let  $\alpha = \nu(a)$  and  $k = \alpha^{-1}(i)$ , so  $\alpha = [\mathbf{P}:\text{data}]^{\mathfrak{A}}a$  and  $\alpha(k) = i$ . We have to show that  $E_i[a] = L_k[a]$ . Since  $\alpha$  is a permutation, for every  $k' \in [1, e]$  we have:

$$\mathfrak{A} \models [\mathbf{P}(k'):\text{eq-}i](a) \text{ iff } \alpha(k') = i \text{ iff } k' = k. \quad (4.3)$$

First, suppose  $b \in E_i[a]$ . Then  $\mathfrak{A} \models [\mathbf{L}:\text{el-}i](a, b)$  and by eq. (4.3) we have  $\mathfrak{A} \models \mathbf{l}_k(a, b)$ , hence  $b \in L_k[a]$ .

Next, suppose  $b \notin E_i[a]$ . Then  $\mathfrak{A} \models \neg[\mathbf{L}:\text{el-}i](a, b)$ , so there is some  $k' \in [1, e]$  such that  $\mathfrak{A} \models \neg([\mathbf{P}(k'):\text{eq-}i](a) \rightarrow \mathbf{l}_{k'}(a, b)) \equiv [\mathbf{P}(k'):\text{eq-}i](a) \wedge \neg\mathbf{l}_{k'}(a, b)$ . By eq. (4.3) we have  $k' = k$ . Hence  $\mathfrak{A} \models \neg\mathbf{l}_k(a, b)$ , so  $b \notin L_k[a]$ .  $\square$

**Remark 29.** Let  $\mathfrak{A}$  and  $\nu$  be declared as in Remark 28. Then the sequence of interpretations  $\langle [\mathbf{L}:\text{el-}1]^{\mathfrak{A}}, [\mathbf{L}:\text{el-}2]^{\mathfrak{A}}, \dots, [\mathbf{L}:\text{el-}e]^{\mathfrak{A}} \rangle$  is a sequence of equivalence relations on  $A$  in local agreement.

*Proof.* Let  $E_i = [\mathbf{L}:\text{el-}i]^{\mathfrak{A}}$  and  $L_i = \mathbf{l}_i^{\mathfrak{A}}$  for every  $i \in [1, e]$ . Let  $i \in [1, e]$  be arbitrary. We check that  $E_i$  is reflexive, symmetric and transitive.

- For reflexivity, let  $a \in A$ . By Remark 28,  $E_i[a] = L_k[a]$  for  $k = \nu(a)^{-1}(i)$ . But  $L_k[a]$  is an equivalence class, hence  $a \in L_k[a]$ , so  $(a, a) \in E_i$ .

#### 4 Reductions

- For symmetry, let  $a, b \in A$  and  $(a, b) \in E_i$ . Let  $k = \nu(a)^{-1}(i)$  so that  $i = \nu(k)$ . By Remark 28,  $E_i[a] = L_k[a]$ . Thus  $\mathfrak{A} \models \mathbf{l}_k(a, b)$  and by Remark 27,  $i = \nu(a)(k) = \nu(b)(k)$ . By Remark 28:

$$E_i[b] = [\mathbf{L}:\mathbf{el}-i]^{\mathfrak{A}}[b] = \mathbf{l}_{\nu(b)^{-1}(i)}^{\mathfrak{A}}[b] = L_k[b] = L_k[a].$$

Since  $a \in L_k[a] = E_i[b]$ , we have  $(b, a) \in E_i$ .

- For transitivity, continue the argument for symmetry. Let  $c \in E_i[b]$ . Then  $c \in E_i[b] = L_k[a] = E_i[a]$ , thus  $(a, c) \in E_i$ .

By Remark 28, since the relations  $L_k$  are in refinement, we have that  $E_1, E_2, \dots, E_e$  are in local agreement.  $\square$

Let  $\mathbf{E} = \langle \mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_e \rangle$  be a predicate signature consisting of binary predicate symbols. Let  $\Sigma$  be a predicate signature enriching  $\mathbf{E}$  and not containing any symbols from  $\mathbf{L}$ . Let  $\Sigma' = \Sigma + \mathbf{L}$  and  $\mathbf{L}' = \Sigma' - \mathbf{E}$ .

**Definition 37.** Define the syntactic operation  $\mathbf{ltr} : \mathcal{L}[\Sigma] \rightarrow \mathcal{L}[\mathbf{L}']$  by:

$$\mathbf{ltr} \varphi = \varphi' \wedge [\mathbf{L}:\mathbf{locperm}],$$

where  $\varphi'$  is obtained from  $\varphi$  by replacing all occurrences of a subformula of the form  $\mathbf{e}_i(x, y)$  by the formula  $[\mathbf{L}:\mathbf{el}-i](x, y)$ , where  $x$  and  $y$  are (not necessarily distinct) variable symbols and  $i \in [1, e]$ . Note that this translation can be performed in deterministic polynomial time.

**Remark 30.** Let  $\varphi$  be a  $\Sigma$ -formula and let  $\mathfrak{A}$  be a  $\Sigma$ -structure. Suppose that  $\mathfrak{A} \models \varphi$  and that the symbols  $\mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_e$  are interpreted in  $\mathfrak{A}$  as equivalence relations on  $A$  in local agreement. Then there is a  $\Sigma'$ -enrichment  $\mathfrak{A}'$  of  $\mathfrak{A}$  such that  $\mathfrak{A}' \models \mathbf{ltr} \varphi$  and that the symbols  $\mathbf{l}_1, \mathbf{l}_2, \dots, \mathbf{l}_e$  are interpreted in  $\mathfrak{A}'$  as equivalence relations on  $A$  in refinement.

*Proof.* Since the binary symbols  $\mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_e$  are interpreted as equivalence relations on  $A$  in local agreement in  $\mathfrak{A}$ , we may define the levels  $L_1, L_2, \dots, L_e \subseteq A \times A$  and the characteristic E-permutation mapping  $\nu = [\mathbf{E}:\mathbf{chperm}]^{\mathfrak{A}} : A \rightarrow \mathbb{S}_e$ . Consider an enrichment  $\mathfrak{A}'$  of  $\mathfrak{A}$  where  $\mathbf{l}_i^{\mathfrak{A}'} = L_i$ . By Lemma 2,  $L_i$  are equivalences on  $A$  in refinement. We interpret the unary symbols from the permutation setup  $\mathbf{P}$  so that  $[\mathbf{P}:\mathbf{data}]^{\mathfrak{A}'} a = \nu(a)$  for all  $a \in A$ . By Remark 26,  $\mathfrak{A}' \models [\mathbf{L}:\mathbf{fixperm}]$ . By Remark 28, followed by Lemma 3, for every  $i \in [1, e]$  and  $a \in A$  we have:

$$[\mathbf{L}:\mathbf{el}-i]^{\mathfrak{A}'}[a] = \mathbf{l}_{\nu(a)^{-1}(i)}^{\mathfrak{A}'}[a] = \mathbf{e}_{\nu(a)(\nu(a)^{-1}(i))}^{\mathfrak{A}'}[a] = \mathbf{e}_i^{\mathfrak{A}'}[a].$$

By Remark 29, the interpretations  $[\mathbf{L}:\mathbf{el}-i]^{\mathfrak{A}'}$  are equivalence relations. Since the interpretation of the formula  $[\mathbf{L}:\mathbf{el}-i]$  has the same classes as the interpretation of the symbol  $\mathbf{e}_i$ , we have  $\mathfrak{A}' \models \forall \mathbf{x} \forall \mathbf{y} (\mathbf{e}_i(\mathbf{x}, \mathbf{y}) \leftrightarrow [\mathbf{L}:\mathbf{el}-i](\mathbf{x}, \mathbf{y}))$ . Since  $\mathfrak{A}' \models \varphi$  we have  $\mathfrak{A}' \models \mathbf{ltr} \varphi$ .  $\square$

**Remark 31.** Let  $\varphi$  be a  $\Sigma$ -formula and let  $\mathfrak{A}$  be an  $L'$ -structure. Suppose that  $\mathfrak{A} \models \text{ltr } \varphi$  and that the symbols  $l_1, l_2, \dots, l_e$  are interpreted as equivalence relations on  $A$  in refinement in  $\mathfrak{A}$ . Then there is a  $\Sigma'$ -enrichment  $\mathfrak{A}'$  of  $\mathfrak{A}$  such that  $\mathfrak{A}' \models \varphi$  and that the binary symbols  $e_1, e_2, \dots, e_e$  are interpreted as equivalence relations on  $A$  in global agreement in  $\mathfrak{A}'$ .

*Proof.* Consider an enrichment  $\mathfrak{A}'$  of  $\mathfrak{A}$  to a  $\Sigma'$ -structure where  $e_i^{\mathfrak{A}'} = [L:e_l-i]^{\mathfrak{A}}$ . By **Remark 29**,  $e_i^{\mathfrak{A}'}$  are equivalence relations on  $A$  in local agreement. For every  $i \in [1, e]$  we have  $\mathfrak{A}' \models \forall x \forall y (e_i(x, y) \leftrightarrow [L:e_l-i](x, y))$  by definition. Since  $\mathfrak{A}' \models \text{ltr } \varphi$  we have  $\mathfrak{A}' \models \varphi$ .  $\square$

The last two remarks show that a  $\mathcal{L}eE_{\text{local}}$ -formula  $\varphi$  has essentially the same models as the  $\mathcal{L}eE_{\text{refine}}$ -formula  $\text{ltr } \varphi$ , so we have shown:

**Proposition 3.** The logic  $\mathcal{L}eE_{\text{local}}$  has the finite model property iff the logic  $\mathcal{L}eE_{\text{refine}}$  has the finite model property. The corresponding satisfiability problems are polynomial-time equivalent:  $(\text{FIN-})\text{SAT-}\mathcal{L}eE_{\text{local}} =_{\text{m}}^{\text{PTIME}} (\text{FIN-})\text{SAT-}\mathcal{L}eE_{\text{refine}}$ .

Since the translation  $\text{ltr}$  can be performed in deterministic polynomial time, we have:

**Proposition 4.** The logic  $\mathcal{L}E_{\text{local}}$  has the finite model property iff the logic  $\mathcal{L}E_{\text{refine}}$  has the finite model property. The corresponding satisfiability problems are polynomial-time equivalent:  $(\text{FIN-})\text{SAT-}\mathcal{L}E_{\text{local}} =_{\text{m}}^{\text{PTIME}} (\text{FIN-})\text{SAT-}\mathcal{L}E_{\text{refine}}$ .

The reduction is two-variable first-order and uses additional (*et*) unary predicate symbols for the permutation setup  $P$ , so it is also valid for the two-variable fragments  $\mathcal{L}_0^2 eE_a$ ,  $\mathcal{L}_1^2 eE_a$  and  $\mathcal{L}_1^2 E_a$  for  $a \in \{\text{local}, \text{refine}\}$ .

## 4.3 Granularity

In this section we demonstrate how to replace the finest equivalence from a sequence of equivalences in refinement with a counter setup. This works if the structures are *granular*, that is if the finest equivalence doesn't have many classes within a single bigger equivalence class.

**Definition 38.** Let  $\langle D, E \rangle$  be a sequence of two equivalence relations on  $A$  in refinement. Let  $g \in \mathbb{N}^+$ . The sequence is  $g$ -granular if every  $E$ -equivalence class includes at most  $g$   $D$ -equivalence classes.

**Definition 39.** Let  $g \in \mathbb{N}^+$  and let  $\langle D, E \rangle$  be  $g$ -granular. The function  $c : A \rightarrow [1, g]$  is a  $g$ -granular coloring for the sequence, if two  $E$ -equivalent elements have the same color iff they are  $D$ -equivalent. That is, for every  $(a, b) \in E$  we have  $c(a) = c(b)$  iff  $(a, b) \in D$ .

**Remark 32.** Let  $g \in \mathbb{N}^+$  and let  $\langle D, E \rangle$  be  $g$ -granular. Then there is a  $g$ -granular coloring for the sequence.

#### 4 Reductions

*Proof.* Let  $X$  be an  $E$ -class. Since  $D \subseteq E$  is  $g$ -granular, the set  $S = \{D[a] \mid a \in X\}$  has cardinality at most  $g$ . Let  $\iota : S \hookrightarrow [1, g]$  be any injective function. Define the color  $c$  on  $X$  as  $c(a) = \iota(D[a])$ .  $\square$

**Remark 33.** Let  $E \subseteq A \times A$  be an equivalence relation on  $A$ ,  $g \in \mathbb{N}^+$  and  $c : A \rightarrow [1, g]$ . Then there is an equivalence relation  $D \subseteq E$  on  $A$  such that  $\langle D, E \rangle$  is  $g$ -granular, having  $c$  as a  $g$ -granular coloring.

*Proof.* Take  $D = \{(a, b) \in E \mid c(a) = c(b)\}$ .  $\square$

**Definition 40.** Let  $g \in \mathbb{N}^+$  and let  $t = \|g\|$  be the bitsize of  $g$ . A  $g$ -color setup  $\mathbf{G} = \langle \mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_t \rangle$  is just a  $t$ -bit counter setup.

Let  $g \in \mathbb{N}^+$  and let  $\mathbf{G} = \langle \mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_t \rangle$  be a  $g$ -color setup. Let  $\Sigma$  be a predicate signature containing the binary symbols  $\mathbf{d}$  and  $\mathbf{e}$  and not containing any symbols from  $\mathbf{G}$ . Let  $\Sigma' = \Sigma + \mathbf{G}$  and  $\Gamma = \Sigma' - \{\mathbf{d}\}$ .

**Definition 41.** Define the quantifier-free  $\mathcal{L}^2[\Gamma]$ -formula  $[\Gamma:\mathbf{d}](\mathbf{x}, \mathbf{y})$  by:

$$[\Gamma:\mathbf{d}](\mathbf{x}, \mathbf{y}) = \mathbf{e}(\mathbf{x}, \mathbf{y}) \wedge [\mathbf{G}:\mathbf{eq}](\mathbf{x}, \mathbf{y}).$$

Note that  $[\Gamma:\mathbf{d}](\mathbf{x}, \mathbf{y})$  is constructible in deterministic polynomial time from  $\Sigma$ .

**Definition 42.** Define the syntactic operation  $\text{grtr} : \mathcal{L}[\Sigma] \rightarrow \mathcal{L}[\Gamma]$  by:

$$\text{grtr } \varphi = \varphi' \wedge [\mathbf{G}:\text{betw-1-}g],$$

where  $\varphi'$  is obtained from the formula  $\varphi$  by replacing all subformulas of the form  $\mathbf{d}(x, y)$  by  $[\Gamma:\mathbf{d}](x, y)$ , where  $x$  and  $y$  are (not necessarily distinct) variable symbols. Note that this translation can be performed in deterministic polynomial time.

**Lemma 4.** Let  $\mathfrak{A}$  be a  $\Sigma$ -structure and suppose that the sequence of symbols  $\langle \mathbf{d}, \mathbf{e} \rangle$  is interpreted in  $\mathfrak{A}$  as a  $g$ -granular sequence  $\langle D, E \rangle$ . Suppose that  $\mathfrak{A} \models \varphi$ . Then there is a  $\Sigma'$ -enrichment  $\mathfrak{A}'$  of  $\mathfrak{A}$  such that  $\mathfrak{A}' \models \text{grtr } \varphi$ .

*Proof.* By **Remark 32**, there exists a  $g$ -granular coloring  $c : A \rightarrow [1, g]$ . We interpret the unary symbols in  $\mathbf{G}$  so that  $[\mathbf{G}:\text{data}]^{\mathfrak{A}} = c$ . Since  $\mathfrak{A}'$  is an enrichment of  $\mathfrak{A}$ , we have  $\mathfrak{A}' \models \varphi$ . Let  $a, b \in A$ . Then  $\mathfrak{A}' \models [\Gamma:\mathbf{d}](a, b)$  is equivalent to:

$$\mathfrak{A}' \models \mathbf{e}(a, b) \text{ and } \mathfrak{A}' \models [\mathbf{G}:\mathbf{eq}](a, b),$$

which is equivalent to:

$$(a, b) \in E \text{ and } [\mathbf{G}:\text{data}]^{\mathfrak{A}'} a = [\mathbf{G}:\text{data}]^{\mathfrak{A}'} b,$$

which, since  $[\mathbf{G}:\text{data}]^{\mathfrak{A}'} = c$  is a  $g$ -granular coloring, is equivalent to:

$$(a, b) \in D.$$

Hence  $\mathfrak{A}' \models \forall \mathbf{x} \forall \mathbf{y} (\mathbf{d}(\mathbf{x}, \mathbf{y}) \leftrightarrow [\Gamma:\mathbf{d}](\mathbf{x}, \mathbf{y}))$  and since  $\mathfrak{A}' \models \varphi$ , we have  $\mathfrak{A}' \models \text{grtr } \varphi$ .  $\square$

**Lemma 5.** *Let  $\mathfrak{A}$  be a  $\Gamma$ -structure and suppose that the binary symbol  $e$  is interpreted in  $\mathfrak{A}$  as an equivalence relation on  $A$ . Suppose that  $\mathfrak{A} \models \text{grtr } \varphi$ . Then there is a  $\Sigma'$ -structure  $\mathfrak{A}'$  enriching  $\mathfrak{A}$  such that  $\mathfrak{A}' \models \varphi$  and the sequence of binary symbols  $\langle \mathbf{d}, \mathbf{e} \rangle$  is interpreted in  $\mathfrak{A}'$  as a  $g$ -granular sequence  $\langle D, E \rangle$ .*

*Proof.* Since  $\mathfrak{A} \models [\mathbf{G}:\text{betw-1-}g]$ , we have  $[\mathbf{G}:\text{data}]^{\mathfrak{A}}a \in [1, g]$  for all  $a \in A$ . Define  $c : A \rightarrow [1, g]$  by  $c(a) = [\mathbf{C}:\text{data}]^{\mathfrak{A}}a$ . By [Remark 32](#), we can find  $D \subseteq E$  such that the sequence  $\langle D, E \rangle$  is  $g$ -granular, having  $c$  as a  $g$ -granular coloring. Consider the  $\Sigma'$ -structure  $\mathfrak{A}'$ , where  $\mathbf{d}^{\mathfrak{A}'} = D$ . Since  $\mathfrak{A}'$  is an enrichment of  $\mathfrak{A} \models \text{grtr } \varphi$ , we have  $\mathfrak{A}' \models \text{grtr } \varphi$ . Let  $a, b \in A$ . Then  $\mathfrak{A}' \models [\Gamma:\mathbf{d}](a, b)$  is equivalent to:

$$\mathfrak{A}' \models e(a, b) \text{ and } \mathfrak{A}' \models [\mathbf{G}:\mathbf{eq}](a, b),$$

which is equivalent to:

$$(a, b) \in E \text{ and } c(a) = c(b),$$

which, since  $c$  is a  $g$ -granular coloring, is equivalent to:

$$(a, b) \in D.$$

Hence  $\mathfrak{A}' \models \forall \mathbf{x} \forall \mathbf{y} (e(\mathbf{x}, \mathbf{y}) \leftrightarrow [\Gamma:\mathbf{d}](\mathbf{x}, \mathbf{y}))$  and since  $\mathfrak{A}' \models \text{grtr } \varphi$ , we have  $\mathfrak{A}' \models \varphi$ .  $\square$





## 5 Monadic logics

In this chapter we investigate questions about (finite) satisfiability of first-order sentences featuring unary predicate symbols and built-in equivalence symbols in refinement. It is known that:

- The monadic first-order logic  $\mathcal{L}_1$  has the finite model property and its (finite) satisfiability problem is NEXPTIME-complete [7]
- The first-order logic of a single equivalence relation  $\mathcal{L}_01E$  has the finite model property and its (finite) satisfiability problem is PSPACE-complete [5]
- The first-order logic of two equivalence relations  $\mathcal{L}_02E$  lacks the finite model property and both the satisfiability and finite satisfiability problems are undecidable [8].

Our strategy is to extract small substructures of structures and analyse them using Ehrenfeucht-Fraïssé games. We prove that the logic  $\mathcal{L}_1eE_{\text{refine}}$  has the finite model property and its (finite) satisfiability problem is  $N(e+1)\text{EXPTIME}$ -complete.

Let  $U(u) = \langle \mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_u \rangle$  be an unary predicate signature consisting of the unary predicate symbols  $\mathbf{u}_i$ . Let  $E(e) = \langle \mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_e \rangle$  be a binary predicate signature consisting of the built-in equivalence symbols  $\mathbf{e}_j$  in refinement. Let  $\Sigma(u, e) = U(u) + E(e)$ , so  $\Sigma(u, e)$  is a generic predicate signature for the monadic first-order logic  $\mathcal{L}_1eE_{\text{refine}}$ .

### 5.1 Cells

Let  $u, e \in \mathbb{N}$ ,  $e \geq 1$  and  $\Sigma = \Sigma(u, e) = \langle \mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_u, \mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_e \rangle$  be a predicate signature. Abbreviate the finest equivalence symbol  $\mathbf{d} = \mathbf{e}_1$ .

**Definition 43.** Define the quantifier-free  $\mathcal{L}^2[\Sigma]$ -formula  $[\Sigma:\text{cell}](\mathbf{x}, \mathbf{y})$  by:

$$[\Sigma:\text{cell}](\mathbf{x}, \mathbf{y}) = \mathbf{d}(\mathbf{x}, \mathbf{y}) \wedge \bigwedge_{1 \leq i \leq u} (\mathbf{u}_i(\mathbf{x}) \leftrightarrow \mathbf{u}_i(\mathbf{y})).$$

Note that  $[\Sigma:\text{cell}](\mathbf{x}, \mathbf{y})$  can be constructed in deterministic polynomial time from  $\Sigma$ .

If  $\mathfrak{A}$  is a  $\Sigma$ -structure and  $D = \mathbf{d}^{\mathfrak{A}}$ , then the interpretation  $C = [\Sigma:\text{cell}]^{\mathfrak{A}} \subseteq A \times A$  is an equivalence relation on  $A$  that refines  $D$ . The cells of  $\mathfrak{A}$  are the equivalence classes of  $C$ . That is, a cell is a maximal set of  $D$ -equivalent elements satisfying the same  $\mathbf{u}$ -predicates.

**Remark 34.** Let  $\mathfrak{A}$  be a  $\Sigma$ -structure,  $r \in \mathbb{N}$ ,  $\bar{a} = a_1 a_2 \dots a_r \in A^r$ ,  $\bar{b} = b_1 b_2 \dots b_r \in A^r$  and  $a_i$  and  $b_i$  are in the same  $\mathfrak{A}$ -cell for all  $i \in [1, r]$ . Suppose that  $a_i = a_j$  iff  $b_i = b_j$  for all  $i, j \in [1, r]$ . Then  $\bar{a} \mapsto \bar{b}$  is a partial isomorphism.

*Proof.* Direct consequence of the fact that the cell equivalence relation refines the finest equivalence relation  $D$  and that the elements in the same cell satisfy the same  $\mathbf{u}$ -predicates. The equality condition ensures that the mapping is a bijection.  $\square$

**Lemma 6.** *Let  $\mathfrak{A}$  be a  $\Sigma$ -structure and  $r \in \mathbb{N}^+$ . There is  $\mathfrak{B} \subseteq \mathfrak{A}$  such that  $\mathfrak{B} \equiv_r \mathfrak{A}$  and every  $\mathfrak{B}$ -cell has cardinality at most  $r$ .*

*Proof.* Let  $C \subseteq A \times A$  be the  $\mathfrak{A}$ -cell equivalence relation. Execute the following process: for every  $\mathfrak{A}$ -cell, if it has cardinality less than  $r$ , select all elements from that cell; otherwise select  $r$  distinct elements from that cell. Let  $B \subseteq A$  be the set of selected elements and let  $\mathfrak{B} = \mathfrak{A} \upharpoonright B$ . By construction, every  $\mathfrak{B}$ -cell has cardinality at most  $r$ . We claim that  $\mathfrak{A} \equiv_r \mathfrak{B}$ . Let  $h = C \cap (A \times B)$  relates elements from  $A$  with elements from  $B$  in the same cell. Note that for all  $a \in A$ :

$$|h[a]| = \min(|C[a]|, r). \quad (5.1)$$

For  $i \in [0, r]$  let  $\mathfrak{I}_i$  be the set of partial isomorphisms from  $\mathfrak{A}$  to  $\mathfrak{B}$  that have length  $i$  and that are included in  $h$ . The set  $\mathfrak{I}_0$  is nonempty since it contains the empty partial isomorphism. We claim that the sequence  $\mathfrak{I}_0, \mathfrak{I}_1, \dots, \mathfrak{I}_r$  satisfies the back-and-forth conditions of [Theorem 1](#). Let  $i \in [0, r-1]$  and let

$$\mathfrak{p} = \bar{a} \mapsto \bar{b} = a_1 a_2 \dots a_i \mapsto b_1 b_2 \dots b_i \in \mathfrak{I}_i$$

be any partial isomorphism.

1. For the forth condition, let  $a \in A$ . We have to find some  $b \in B$  such that  $\bar{a}a \mapsto \bar{b}b \in \mathfrak{I}_{i+1}$ . If  $a = a_k$  for some  $k \in [1, i]$ , then  $b = b_k$  is appropriate.

Suppose that  $a \neq a_k$  for all  $k \in [1, i]$ . Let  $S \subseteq C[a]$  be the set of  $\bar{a}$ -elements in the same  $\mathfrak{A}$ -cell as  $a$ :

$$S = \{a_k \in C[a] \mid k \in [1, i]\}.$$

Note that  $|S| \leq r-1$  and  $|C[a]| \geq |S| + 1$ . By [eq. \(5.1\)](#),  $|h[a]| \geq |S| + 1$ . Hence there is an element  $b \in h[a]$  that is distinct from  $b_k$  for all  $k \in [1, i]$  and this  $b$  is appropriate.

2. For the back condition, let  $b \in B$ . We have to find some  $a \in A$  such that  $\bar{a}a \mapsto \bar{b}b \in \mathfrak{I}_{i+1}$ . If  $b = b_k$  for some  $k \in [1, i]$ , then  $a = a_k$  is appropriate.

Suppose that  $b \neq b_k$  for all  $k \in [1, i]$ . Since  $b \in h[b]$ ,  $a = b$  is appropriate.

By [Theorem 1](#),  $\mathfrak{A} \equiv_r \mathfrak{B}$ .  $\square$

## 5.2 Organs

Let  $u, e \in \mathbb{N}$ ,  $e \geq 2$  and  $\Sigma = \Sigma(u, e) = \langle \mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_u, \mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_e \rangle$  be a predicate signature. Abbreviate the finest two equivalence symbols  $\mathbf{d} = \mathbf{e}_1$  and  $\mathbf{e} = \mathbf{e}_2$ .

**Definition 44.** Let  $\mathfrak{A}$  be a  $\Sigma$ -structure and let  $D = \mathbf{d}^{\mathfrak{A}}$  and  $E = \mathbf{e}^{\mathfrak{A}}$ . Recall that the set of  $D$ -classes is  $\mathcal{E}D$ . Two  $D$ -classes  $X, Y \in \mathcal{E}D$  are organ-equivalent if they are included in the same  $E$ -class (equivalently  $X \times Y \subseteq E$ ), and the induced substructures  $(\mathfrak{A} \upharpoonright X)$  and  $(\mathfrak{A} \upharpoonright Y)$  are isomorphic. The organ-equivalence relation is  $\mathcal{O} \subseteq \mathcal{E}D \times \mathcal{E}D$ . Since  $D$  refines  $E$ , organ-equivalence is an equivalence relation on  $\mathcal{E}D$ . An organ is an organ-equivalence-class. That is, an organ is a maximal set of isomorphic  $D$ -classes, included in the same  $E$ -class.

For any two organ-equivalent  $D$ -classes  $(X, Y) \in \mathcal{O}$ , fix an isomorphism

$$\mathfrak{h}_{XY} : (\mathfrak{A} \upharpoonright X) \leftrightarrow (\mathfrak{A} \upharpoonright Y)$$

consistently, so that  $\mathfrak{h}_{XX} = \text{id}_X$ ,  $\mathfrak{h}_{YX} = \mathfrak{h}_{XY}^{-1}$  and if  $(Y, Z) \in \mathcal{O}$  then  $\mathfrak{h}_{XZ} = \mathfrak{h}_{YZ} \circ \mathfrak{h}_{XY}$ . Two elements  $a, b \in A$  are sub-organ-equivalent if  $(D[a], D[b]) \in \mathcal{O}$  and  $\mathfrak{h}_{D[a]D[b]}(a) = b$ . Since the isomorphisms  $\mathfrak{h}_{XY}$  are chosen consistently, sub-organ-equivalence  $\mathcal{O} \subseteq A \times A$  is an equivalence relation on  $A$  that refines  $E$ .

**Remark 35.** Let  $\mathfrak{A}$  be a  $\Sigma$ -structure,  $r \in \mathbb{N}$ ,  $\bar{a} = a_1 a_2 \dots a_r \in A^r$ ,  $\bar{b} = b_1 b_2 \dots b_r \in A^r$ ,  $a_i$  and  $b_i$  are sub-organ-equivalent for all  $i \in [1, r]$ . Suppose that  $\mathfrak{A} \models \mathbf{d}(a_i, a_j)$  iff  $\mathfrak{A} \models \mathbf{d}(b_i, b_j)$  for all  $i, j \in [1, r]$ . Then  $\bar{a} \mapsto \bar{b}$  is a partial isomorphism.

*Proof.* The condition about the finest equivalence symbol  $\mathbf{d}$  ensures that the interpretation of  $\mathbf{d}$  is preserved. Since sub-organ-equivalence relates isomorphic elements, the interpretation of the unary symbols and the formal equality is preserved. Since the sub-organ-equivalence  $\mathcal{O} \subseteq A \times A$  refines the second finest equivalence relation  $E$ , the interpretation of all remaining equivalence symbols  $\mathbf{e}_j$  is preserved.  $\square$

**Lemma 7.** Let  $\mathfrak{A}$  be a  $\Sigma$ -structure and  $r \in \mathbb{N}^+$ . There is  $\mathfrak{B} \subseteq \mathfrak{A}$  such that  $\mathfrak{B} \equiv_r \mathfrak{A}$  and every  $\mathfrak{B}$ -organ has cardinality at most  $r$ .

*Proof.* Let  $D = \mathbf{d}^{\mathfrak{A}}$ ,  $E = \mathbf{e}^{\mathfrak{A}}$  and let  $\mathcal{A} = \mathcal{E}D$  be the set of  $D$ -classes. Let  $\mathcal{O} \subseteq \mathcal{A} \times \mathcal{A}$  be the  $\mathfrak{A}$ -organ-equivalence relation on  $\mathcal{A}$ . Execute the following process: for every  $\mathfrak{A}$ -organ, if it has cardinality at most  $r$ , select all  $D$ -classes from that organ; otherwise select  $r$  distinct  $D$ -classes from that organ (note that these will be isomorphic). Let  $\mathcal{B} \subseteq \mathcal{A}$  be the set of selected  $D$ -classes. Let  $B = \cup \mathcal{B} \subseteq A$  be the set of elements in the selected classes and let  $\mathfrak{B} = (\mathfrak{A} \upharpoonright B)$ . By construction, every  $\mathfrak{B}$ -organ has cardinality at most  $r$ . We claim that  $\mathfrak{A} \equiv_r \mathfrak{B}$ . Let  $\mathcal{H} = \mathcal{O} \cap (\mathcal{A} \times \mathcal{B})$  relates the  $D$ -classes with the isomorphic  $D$ -classes from  $\mathcal{B}$  in the same organ. Let  $h$  relates the elements of  $A$  with their isomorphic elements from  $B$ . Note that for all elements  $a \in A$ :

$$|h[a]| = \min(|\mathcal{O}[D[a]]|, r). \quad (5.2)$$

For  $i \in [0, r]$  let  $\mathfrak{I}_i$  be the set of partial isomorphisms from  $\mathfrak{A}$  to  $\mathfrak{B}$  that have length  $i$  and that are included in  $h$ . The set  $\mathfrak{I}_0$  is nonempty since it contains the empty partial isomorphism. We claim that the sequence  $\mathfrak{I}_0, \mathfrak{I}_1, \dots, \mathfrak{I}_r$  satisfies the back-and-forth conditions of [Theorem 1](#). Let  $i \in [0, r-1]$  and let

$$\mathfrak{p} = \bar{a} \mapsto \bar{b} = a_1 a_2 \dots a_i \mapsto b_1 b_2 \dots b_i \in \mathfrak{I}$$

be any partial isomorphism.

1. For the forth condition, let  $a \in A$ . We have to find some  $b \in B$  such that  $\bar{a}a \mapsto \bar{b}b \in \mathcal{I}_{i+1}$ . If  $a \in D[a_k]$  for some  $k \in [1, i]$ , then  $b = \mathfrak{h}_{D[a_k]D[b_k]}(a)$  is appropriate.  
Suppose  $a \notin D[a_k]$  for all  $k \in [1, i]$ . Let  $\mathcal{S} \subseteq \mathcal{O}[D[a]]$  be the set of  $D$ -classes of  $\bar{a}$ -elements in the same  $\mathfrak{A}$ -organ as  $D[a]$ :

$$\mathcal{S} = \{D[a_k] \in \mathcal{O}[D[a]] \mid k \in [1, i]\}.$$

Note that  $|\mathcal{S}| \leq r - 1$  and  $|\mathcal{O}[D[a]]| \geq |\mathcal{S}| + 1$ . By [eq. \(5.2\)](#),  $|h[a]| \geq |\mathcal{S}| + 1$ . Hence there is some  $b \in h[a]$  such that  $b \notin D[b_k]$  for all  $k \in [1, i]$ . This  $b$  is appropriate.

2. For the back condition, let  $b \in B$ . We have to find some  $a \in A$  such that  $\bar{a}a \mapsto \bar{b}b \in \mathcal{I}$ . If  $b \in D[b_k]$  for some  $k \in [1, i]$ , then  $a = \mathfrak{h}_{D[b_k]D[a_k]}(b)$  is appropriate.  
Suppose that  $b \notin D[b_k]$  for all  $k \in [1, i]$ . Since  $b \in h[b]$ ,  $a = b$  is appropriate.

By [Theorem 1](#),  $\mathfrak{A} \equiv_r \mathfrak{B}$ . □

### 5.3 Satisfiability

In this section we will employ the results on cells and organs to bound the size of a small substructure of a general structure.

**Remark 36.** Let  $u, e \in \mathbb{N}$ ,  $e \geq 2$  and consider the predicate signature  $\Sigma = \Sigma(u, e) = \langle \mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_u, \mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_e \rangle$ . Abbreviate  $\mathbf{d} = \mathbf{e}_1$  and  $\mathbf{e} = \mathbf{e}_2$ . Let  $r \in \mathbb{N}^+$ . There is  $\mathfrak{B} \subseteq \mathfrak{A}$  such that  $\mathfrak{B} \equiv_r \mathfrak{A}$  and  $\langle \mathbf{d}^{\mathfrak{B}}, \mathbf{e}^{\mathfrak{B}} \rangle$  is  $g$ -granular for  $g = g(u, r) = r \cdot ((r + 1)^{2^u} - 1)$ . Furthermore, this  $\mathfrak{B}$  has the property that every  $\mathfrak{B}$ -cell has cardinality at most  $r$ .

*Proof.* By [Lemma 6](#), there is  $\mathfrak{B}' \subseteq \mathfrak{A}$  such that  $\mathfrak{B}' \equiv_r \mathfrak{A}$  and every  $\mathfrak{B}'$ -cell has cardinality at most  $r$ . By [Lemma 7](#), there is  $\mathfrak{B} \subseteq \mathfrak{B}'$  such that  $\mathfrak{B} \equiv_r \mathfrak{B}'$  and the  $\mathfrak{B}$ -organs have cardinality at most  $r$ . Let  $D = \mathbf{d}^{\mathfrak{B}}$  and  $E = \mathbf{e}^{\mathfrak{B}}$ . Since every  $D$ -class includes at most  $2^u$  cells and is nonempty and every cell has cardinality at most  $r$ , there are at most  $((r + 1)^{2^u} - 1)$  nonisomorphic  $D$ -classes in  $\mathfrak{B}$ . Since every  $E$ -class includes at most  $r$  isomorphic  $D$ -classes, we get that  $\langle D, E \rangle$  is  $g$ -granular. □

**Corollary 1.** Let  $u, e \in \mathbb{N}$ ,  $e \geq 2$  and consider  $\Sigma = \Sigma(u, e)$ . Let  $\varphi$  be a  $\mathcal{L}[\Sigma]$ -sentence having quantifier rank  $r$ . By [Lemma 4](#) and [Lemma 5](#) about granularity, the formula  $\varphi$  is essentially equisatisfiable with the formula  $\text{grtr } \varphi$ , which is a  $\Sigma(u + \|g(u, r)\|, e - 1)$ -sentence. Note that  $\|g(u, r)\|$  is exponentially bounded in the length  $\|\varphi\|$  of the formula. So we have a reduction:

$$(\text{FIN-})\text{SAT-}\mathcal{L}_1 e E_{\text{refine}} \leq_m^{\text{EXPTIME}} (\text{FIN-})\text{SAT-}\mathcal{L}_1 (e - 1) E_{\text{refine}}.$$

If  $u$  is a constant independent of  $\varphi$ , then  $\|g(u, r)\|$  is polynomially bounded in  $\|\varphi\|$ . So we have a reduction:

$$(\text{FIN-})\text{SAT-}\mathcal{L}_0 e E_{\text{refine}} \leq_m^{\text{PTIME}} (\text{FIN-})\text{SAT-}\mathcal{L}_1 (e - 1) E_{\text{refine}}.$$

**Remark 37.** Let  $u \in \mathbb{N}$  and consider  $\Sigma = \Sigma(u, 1) = \langle \mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_u, \mathbf{d} \rangle$ . Let  $r \in \mathbb{N}^+$ . There is  $\mathfrak{B} \subseteq \mathfrak{A}$  such that  $\mathfrak{A} \equiv_r \mathfrak{B}$  and  $|B| \leq g.r.2^u$  for  $g = g(u, r) = r((r+1)^{2^u} - 1)$ .

*Proof.* Let  $\Sigma' = \Sigma + \langle \mathbf{e} \rangle$  be an enrichment of  $\Sigma$  with the built-in equivalence symbols  $\mathbf{e}$ . Consider an enrichment  $\mathfrak{A}'$  of  $\mathfrak{A}$  to a  $\Sigma'$ -structure, where  $\mathbf{e}^{\mathfrak{A}'} = A \times A$  is interpreted as the full relation on  $A$ . Then  $\langle \mathbf{d}^{\mathfrak{A}'}, \mathbf{e}^{\mathfrak{A}'} \rangle$  is a sequence of equivalence relations on  $A$  in refinement. By Remark 36, there is  $\mathfrak{B}' \subseteq \mathfrak{A}'$  such that  $\mathfrak{B}' \equiv_r \mathfrak{A}'$  and  $\langle \mathbf{d}^{\mathfrak{B}'}, \mathbf{e}^{\mathfrak{B}'} \rangle$  is  $g$ -granular. Consider the reduct  $\mathfrak{B}$  of  $\mathfrak{B}'$  to a  $\Sigma$ -structure. Let  $D = \mathbf{d}^{\mathfrak{B}}$  and  $E = \mathbf{e}^{\mathfrak{B}}$ . Since every  $\mathfrak{B}$ -cell has cardinality at most  $r$  and every  $D$ -class includes at most  $2^u$  cells, we have that every  $D$ -class has cardinality at most  $r.2^u$ . Since  $\mathbf{e}$  was interpreted in  $\mathfrak{A}$  as the full relation, it is also interpreted in  $\mathfrak{B}$  as the full relation, so there is a single  $E$ -class—the whole domain  $B$ . Since the sequence  $\langle D, E \rangle$  is  $g$ -granular, there are at most  $g$   $D$ -classes, so  $|B| \leq g.r.2^u$ .  $\square$

**Corollary 2.** The logic  $\mathcal{L}_1 1E$  has the finite model property and its (finite) satisfiability problem is in  $\text{N2EXPTIME}$ .

Combining Corollary 2 with Corollary 1, we get by induction on  $e$ :

**Proposition 5.** For  $e \in \mathbb{N}^+$ , the logic  $\mathcal{L}_1 eE_{\text{refine}}$  has the finite model property and its (finite) satisfiability problem is in  $\text{N}(e+1)\text{EXPTIME}$ .

By Proposition 1 and Proposition 3, the same holds for  $\mathcal{L}_1 eE_{\text{global}}$  and  $\mathcal{L}_1 eE_{\text{local}}$ .

**Proposition 6.** The logic  $\mathcal{L}_1 E_{\text{refine}}$  has the finite model property and its (finite) satisfiability problem is in the forth level of the Grzegorzczk hierarchy  $\mathcal{E}^4$ .

By Proposition 2 and Proposition 4, the same holds for  $\mathcal{L}_1 E_{\text{global}}$  and  $\mathcal{L}_1 E_{\text{local}}$ .

**Proposition 7.** For  $e \geq 2$ , the logic  $\mathcal{L}_0 eE_{\text{refine}}$  has the finite model property and its (finite) satisfiability problem is in  $\text{NeEXPTIME}$ .

By Proposition 1 and Proposition 3, the same holds for  $\mathcal{L}_0 eE_{\text{global}}$  and  $\mathcal{L}_0 eE_{\text{local}}$ .

## 5.4 Hardness with a single equivalence

In this section we show that the (finite) satisfiability of monadic first-order logic with a single equivalence symbol  $\mathcal{L}_1 1E$  is  $\text{N2EXPTIME}$ -hard by reducing the doubly exponential tiling problem to such satisfiability. Our strategy is to employ a counter setup of  $u$  unary predicate symbols to encode the exponentially many positions of a binary encoding of a doubly exponentially bounded quantity, encoding the coordinates of a cell of the doubly exponential tiling square.

Consider the counter setup  $C(u) = \langle \mathbf{u}_1, \mathbf{u}_2, \dots, \mathbf{u}_u \rangle$  for  $u \in \mathbb{N}^+$ . Recall that the intention of a counter setup is to encode an arbitrary exponentially bounded value at every element of a structure. Let  $D(u) = C(u) + \langle \mathbf{d} \rangle$  be a predicate signature enriching  $C(u)$  with the built-in equivalence symbol  $\mathbf{d}$ . We will define a system where every  $\mathbf{d}$ -equivalence class includes exponentially many cells. These cells will correspond to the exponentially many positions of the binary encoding of a doubly exponential value for

the  $\mathbf{d}$ -class. The bit values at each cell position will be encoded by the cardinality of that cell: bit value 0 if the cardinality of the cell is 1 and bit value 1 if the cardinality is greater than 1. This will allow us to encode a doubly exponential value at each  $\mathbf{d}$ -class. Call the data  $[C:\text{data}]^{\mathfrak{A}}a$ , encoded by the counter setup at  $a$  the *position* of  $a$ .

Let  $\mathfrak{A}$  be a  $D = D(u)$ -structure.

**Definition 45.** Define the quantifier-free  $\mathcal{L}^2[D]$ -formula  $[D:\text{pos-eq}](x, y)$  by:

$$[D:\text{pos-eq}](x, y) = [C:\text{eq}](x, y).$$

Note that  $[D:\text{pos-eq}](x, y)$  is constructible in deterministic polynomial time from  $D$ .

**Remark 38.**  $\mathfrak{A} \models [D:\text{pos-eq}](a, b)$  iff  $a$  and  $b$  are at the same positions (in possibly distinct  $\mathbf{d}$ -classes):  $[C:\text{data}]^{\mathfrak{A}}a = [C:\text{data}]^{\mathfrak{A}}b$ .

**Definition 46.** Define the quantifier-rank-1  $\mathcal{L}^2[D]$ -formula  $[D:\text{bit-0}](x)$  by:

$$[D:\text{bit-0}](x) = \forall y (\mathbf{d}(y, x) \wedge [D:\text{pos-eq}](y, x) \rightarrow y = x).$$

Note that  $[D:\text{bit-0}](x)$  is constructible in deterministic polynomial time from  $D$ .

**Remark 39.**  $\mathfrak{A} \models [D:\text{bit-0}](a)$  iff the cell of  $a$  has cardinality 1.

**Definition 47.** Define the quantifier-rank-1  $\mathcal{L}^2[D]$ -formula  $[D:\text{bit-1}](x)$  by:

$$[D:\text{bit-1}](x) = \exists y (\mathbf{d}(y, x) \wedge [D:\text{pos-eq}](y, x) \wedge y \neq x).$$

Note that  $[D:\text{bit-1}](x)$  is constructible in deterministic polynomial time from  $D$ .

**Remark 40.**  $\mathfrak{A} \models [D:\text{bit-1}](a)$  iff the cell of  $a$  has cardinality greater than 1.

**Definition 48.** Define the quantifier-free  $\mathcal{L}^2[D]$ -formula  $[D:\text{pos-zero}](x)$  by:

$$[D:\text{pos-zero}](x) = \bigwedge_{1 \leq i \leq u} \neg \mathbf{u}_i(x).$$

Note that  $[D:\text{pos-zero}](x)$  is constructible in deterministic polynomial time from  $D$ .

**Remark 41.**  $\mathfrak{A} \models [D:\text{pos-zero}](a)$  iff the position of  $a$  is 0.

**Definition 49.** Define the quantifier-free  $\mathcal{L}^2[D]$ -formula  $[D:\text{pos-largest}](x)$  by:

$$[D:\text{pos-largest}](x) = \bigwedge_{1 \leq i \leq u} \mathbf{u}_i(x).$$

Note that  $[D:\text{pos-zero}](x)$  is constructible in deterministic polynomial time from  $D$ .

**Remark 42.**  $\mathfrak{A} \models [D:\text{pos-largest}](a)$  iff the position of  $a$  is the largest  $u$ -bit number  $N_u$ .

**Definition 50.** Define the quantifier-free  $\mathcal{L}^2[D]$ -formula  $[D:\text{pos-less}](x, y)$  by:

$$[D:\text{pos-less}](x, y) = d(x, y) \wedge [C:\text{less}](x, y).$$

Note that  $[D:\text{pos-less}](x, y)$  is constructible in deterministic polynomial time from  $D$ .

**Remark 43.**  $\mathfrak{A} \models [D:\text{pos-less}](a, b)$  iff  $a$  and  $b$  are in the same  $d$ -class and the position of  $a$  is less than the position of  $b$ .

**Definition 51.** Define the quantifier-free  $\mathcal{L}^2[D]$ -formula  $[D:\text{pos-succ}](x, y)$  by:

$$[D:\text{pos-succ}](x, y) = d(x, y) \wedge [C:\text{succ}](x, y).$$

Note that  $[D:\text{pos-succ}](x, y)$  is constructible in deterministic polynomial time from  $D$ .

**Remark 44.**  $\mathfrak{A} \models [D:\text{pos-succ}](a, b)$  iff  $a$  and  $b$  are in the same  $d$ -class and the position of  $b$  is the successor of the position of  $a$ .

**Definition 52.** Define the closed  $\mathcal{L}^2[D]$ -sentence  $[D:\text{pos-full}]$  by:

$$\begin{aligned} [D:\text{pos-full}] = & \forall x \exists y \left( d(y, x) \wedge [D:\text{pos-zero}](y) \right) \wedge \\ & \forall x \left( \neg [D:\text{pos-largest}](x) \rightarrow \exists y [D:\text{pos-succ}](x, y) \right). \end{aligned}$$

Note that  $[D:\text{pos-full}]$  is constructible in deterministic polynomial time from  $D$ .

The first part of this formula asserts that every  $d$ -class has an element at position 0. The second part asserts that if  $a$  is an element at position  $p$ , that is not the largest possible, there exists an element  $b$  in the same  $d$ -class at position  $p+1$ . Therefore in any model of  $[D:\text{pos-full}]$ , every  $d$ -class has  $2^u$  cells. For example, in particular, every  $d$ -class has cardinality at least  $2^u$ . For the rest of the section, suppose that  $\mathfrak{A} \models [D:\text{pos-full}]$ .

**Definition 53.** For every  $u$ -bit number  $p \in \mathbb{B}_u$ , define the  $\mathcal{L}^2[D]$ -formula  $[D:\text{pos-}p](x)$  recursively by:

$$[D:\text{pos-0}](x) = [D:\text{pos-zero}](x)$$

and for  $p \in [0, N_u - 1]$ :

$$[D:\text{pos-}(p+1)](x) = \exists y \left( [D:\text{pos-}p](y) \wedge [D:\text{pos-succ}](y, x) \right).$$

In this case, for the formula to be a two-variable formula, the formula  $[D:\text{pos-}p](y)$  is obtained from  $[D:\text{pos-}p](x)$  by swapping all occurrences (not only the unbounded ones) of the variables<sup>1</sup>  $x$  and  $y$ . Note that  $[D:\text{pos-}p](x)$  is constructible in deterministic polynomial time from  $D$  and  $p$ .

**Remark 45.**  $\mathfrak{A} \models [D:\text{pos-}p](a)$  iff  $p$  is the position of  $a$ .

<sup>1</sup>this is reminiscent to the process of defining a standard translation of modal logic to the two-variable first-order fragment

**Definition 54.** Let  $\mathfrak{A}$  be a  $D$ -structure. Let  $D = \mathbf{d}^{\mathfrak{A}}$ . Define the function  $[\mathbf{D:Data}]^{\mathfrak{A}} : \mathcal{E}D \rightarrow \mathbb{B}^{2^u}$ , assigning a  $2^u$ -bit bitstring to any  $D$ -class  $X$  by:

$$[\mathbf{D:Data}]_p^{\mathfrak{A}} X = \begin{cases} 1 & \text{if } [\mathbf{C:data}]^{\mathfrak{A}}(a) = (p-1) \text{ implies } \mathfrak{A} \models [\mathbf{D:bit-1}](a) \text{ for all } a \in X \\ 0 & \text{otherwise} \end{cases}$$

for  $p \in [1, 2^u]$ .

**Definition 55.** Define the quantifier-rank-1  $\mathcal{L}^2[D]$ -formula  $[\mathbf{D:Zero}](\mathbf{x})$  by:

$$[\mathbf{D:Zero}](\mathbf{x}) = \forall \mathbf{y} \left( \mathbf{d}(\mathbf{y}, \mathbf{x}) \rightarrow [\mathbf{D:bit-0}](\mathbf{y}) \right).$$

Note that  $[\mathbf{D:Zero}](\mathbf{x})$  is constructible in deterministic polynomial time from  $D$ .

**Remark 46.**  $\mathfrak{A} \models [\mathbf{D:Zero}](a)$  iff the data at the class of  $a$  encodes 0:  $[\mathbf{D:Data}]^{\mathfrak{A}} D[a] = 0$ .

**Definition 56.** Define the quantifier-rank-1  $\mathcal{L}^2[D]$ -formula  $[\mathbf{D:Largest}](\mathbf{x})$  by:

$$[\mathbf{D:Largest}](\mathbf{x}) = \forall \mathbf{y} \left( \mathbf{d}(\mathbf{y}, \mathbf{x}) \rightarrow [\mathbf{D:bit-1}](\mathbf{y}) \right).$$

Note that  $[\mathbf{D:Largest}](\mathbf{x})$  is constructible in deterministic polynomial time from  $D$ .

**Remark 47.**  $\mathfrak{A} \models [\mathbf{D:Largest}](a)$  iff the data at the  $D$ -class of  $a$  encodes the largest  $2^u$ -bit number:  $[\mathbf{D:Data}]^{\mathfrak{A}} D[a] = N_{2^u}$ .

**Definition 57.** Let  $M \in \mathbb{B}_{2^u}$  be a  $t$ -bit number (where  $t \leq 2^u$ ). Define the  $\mathcal{L}^2[D]$ -formula  $[\mathbf{D:Eq-M}](\mathbf{x})$  by:

$$\begin{aligned} [\mathbf{D:Eq-M}](\mathbf{x}) = & \forall \mathbf{y} \left( \mathbf{d}(\mathbf{y}, \mathbf{x}) \rightarrow \bigwedge_{0 \leq p < t} \left( [\mathbf{D:pos-p}](\mathbf{y}) \rightarrow [\mathbf{D:bit-}(\overline{M}_{p+1})](\mathbf{y}) \right) \wedge \right. \\ & \left. \forall \mathbf{x} \left( [\mathbf{D:pos-(t-1)}](\mathbf{y}) \wedge [\mathbf{D:pos-less}](\mathbf{y}, \mathbf{x}) \rightarrow [\mathbf{D:bit-0}](\mathbf{x}) \right) \right). \end{aligned}$$

Note that  $[\mathbf{D:Eq-M}](\mathbf{x})$  is constructible in deterministic polynomial time from  $D$  and  $M$ .

The first part of this formula asserts that the bits at the first  $t$  positions of the  $\mathbf{d}$ -class of  $\mathbf{x}$  encode the number  $M$ . The second part asserts that all the remaining bits at larger positions are zeroes. Note that the length of this formula is polynomially bounded in  $t$ , the bitsize of  $M$ . We have  $\mathfrak{A} \models [\mathbf{D:Eq-M}](a)$  iff the data at the  $D$ -class of  $a$  encodes  $M$ :  $[\mathbf{D:Data}]^{\mathfrak{A}} D[a] = M$ .

**Definition 58.** Define the  $\mathcal{L}^6[D]$ -formula  $[\mathbf{D:Less}](\mathbf{x}, \mathbf{y})$  by:

$$\begin{aligned} [\mathbf{D:Less}](\mathbf{x}, \mathbf{y}) = & \exists \mathbf{x}' \exists \mathbf{y}' \left( \mathbf{d}(\mathbf{x}', \mathbf{x}) \wedge \mathbf{d}(\mathbf{y}', \mathbf{y}) \wedge \right. \\ & \left( [\mathbf{D:pos-eq}](\mathbf{x}', \mathbf{y}') \wedge [\mathbf{D:bit-0}](\mathbf{x}') \wedge [\mathbf{D:bit-1}](\mathbf{y}') \right) \wedge \tag{Less1} \\ & \forall \mathbf{x}'' \left( [\mathbf{D:pos-less}](\mathbf{x}', \mathbf{x}'') \rightarrow \exists \mathbf{y}'' \left( \mathbf{d}(\mathbf{y}'', \mathbf{y}') \wedge \right. \right. \\ & \left. \left. [\mathbf{D:pos-eq}](\mathbf{y}'', \mathbf{x}'') \wedge ([\mathbf{D:bit-0}](\mathbf{y}'') \leftrightarrow [\mathbf{D:bit-0}](\mathbf{x}'')) \right) \right) \Big). \tag{Less2} \end{aligned}$$



#### 5.4 Hardness with a single equivalence

Note that  $[D:\text{Less}](x, y)$  is constructible in deterministic polynomial time from  $D$ .

Then  $\mathfrak{A} \models [D:\text{Less}](a, b)$  iff  $[D:\text{Data}]^{\mathfrak{A}} D[a] < [D:\text{Data}]^{\mathfrak{A}} D[b]$ . By rearrangement and reusing variables, this can be also written using just three variables (but not using just two variables). Indeed,  $[D:\text{Less}](x, y)$  is logically equivalent to:

$$\begin{aligned} \exists z \Big( & d(z, x) \wedge \exists x \Big( x = z \wedge \exists z \Big( d(z, y) \wedge \exists y \Big( y = z \wedge \\ & ([D:\text{pos-eq}](x, y) \wedge [D:\text{bit-0}](x) \wedge [D:\text{bit-1}](y)) \wedge \end{aligned} \quad (\text{Less1})$$

$$\begin{aligned} \forall z \Big( & [D:\text{pos-less}](x, z) \rightarrow \exists x \Big( x = z \wedge \exists z \Big( d(z, y) \wedge \exists y \Big( y = z \wedge \\ & [D:\text{pos-eq}](y, x) \wedge ([D:\text{bit-0}](y) \leftrightarrow [D:\text{bit-0}](x)) \Big) \Big) \Big) \Big). \end{aligned} \quad (\text{Less2})$$

**Definition 59.** Define the  $\mathcal{L}^6[D]$ -formula  $[D:\text{Succ}](x, y)$  by:

$$\begin{aligned} [D:\text{Succ}](x, y) = & \exists x' \exists y' \Big( d(x', x) \wedge d(y', y) \wedge \\ & ([D:\text{pos-eq}](x', y') \wedge [D:\text{bit-0}](x') \wedge [D:\text{bit-1}](y')) \wedge \end{aligned} \quad (\text{Succ1})$$

$$\forall x'' \Big( [D:\text{pos-less}](x'', x') \rightarrow [D:\text{bit-1}](x'') \Big) \wedge \quad (\text{Succ2})$$

$$\forall y'' \Big( [D:\text{pos-less}](y'', y') \rightarrow [D:\text{bit-0}](y'') \Big) \wedge \quad (\text{Succ3})$$

$$\forall x'' \Big( [D:\text{pos-less}](x', x'') \rightarrow \exists y'' \Big( d(y'', y') \wedge \end{aligned}$$

$$[D:\text{pos-eq}](y'', x'') \wedge ([D:\text{bit-0}](y'') \leftrightarrow [D:\text{bit-0}](x'')) \Big) \Big). \quad (\text{Succ4})$$

Note that  $[D:\text{Succ}](x, y)$  is constructible in deterministic polynomial time from  $D$ . By rearrangement and reusing variables, this can be also written using just three variables (but not using just two variables).

**Remark 48.**  $\mathfrak{A} \models [D:\text{Succ}](a, b)$  iff  $[D:\text{Data}]^{\mathfrak{A}} D[b] = 1 + [D:\text{Data}]^{\mathfrak{A}} D[a]$ .

**Definition 60.** Define the  $\mathcal{L}^3[D]$ -sentence  $[D:\text{Full}]$  by:

$$[D:\text{Full}] = \exists x [D:\text{Zero}](x) \wedge \forall x \Big( \neg [D:\text{Largest}](x) \rightarrow \exists y [D:\text{Succ}](x, y) \Big).$$

Note that this sentence is constructible in deterministic polynomial time from  $D$ .

**Remark 49.** If  $\mathfrak{A}$  satisfies  $[D:\text{Full}]$  then  $\mathfrak{A}$  contains a  $\mathbf{d}$ -class of encoding any possible data: for every  $M \in [0, N_{2^u}]$ , there is a  $\mathbf{d}$ -class  $X$  such that  $[D:\text{Data}]^{\mathfrak{A}} X = M$ .

**Definition 61.** Define the  $\mathcal{L}^4[D]$ -formula  $[D:\text{Eq}](x, y)$  by:

$$[D:\text{Eq}](x, y) = \forall x' \forall y' \left( d(x', x) \wedge d(y', y) \wedge [D:\text{pos-eq}](x', y') \rightarrow ([D:\text{bit-0}](x') \leftrightarrow [D:\text{bit-0}](y')) \right).$$

Note that  $[D:\text{Eq}](x, y)$  is constructible in deterministic polynomial time from  $D$ . By rearrangement and reusing variables, this can be also written using just three variables (but not using just two variables).

**Remark 50.**  $\mathfrak{A} \models [D:\text{Eq}](x, y)$  iff  $[D:\text{Data}]^{\mathfrak{A}} D[a] = [D:\text{Data}]^{\mathfrak{A}} D[b]$ .

**Definition 62.** Define the  $\mathcal{L}^4[D]$ -sentence  $[D:\text{Alldiff}]$  by:

$$[D:\text{Alldiff}] = \forall x \forall y \left( \neg d(x, y) \rightarrow \exists x' \exists y' \left( d(x', x) \wedge d(y', y) \wedge [D:\text{pos-eq}](x', y') \wedge \neg ([D:\text{bit-0}](x') \leftrightarrow [D:\text{bit-0}](y')) \right) \right).$$

Note that  $[D:\text{Alldiff}]$  is constructible in deterministic polynomial time from  $D$ . By rearrangement and reusing variables, this can be also written using just three variables (but not using just two variables).

**Remark 51.** If  $\mathfrak{A}$  satisfies  $[D:\text{Alldiff}]$  then all  $D$ -classes in  $\mathfrak{A}$  encode different data.

Recall from [Section 1.6](#) that an instance of the *doubly exponential tiling problem* is an initial condition  $c^0 = \langle t_1^0, t_2^0, \dots, t_n^0 \rangle \subseteq T = [1, k]$  of tiles from the domino system  $D_0 = (T, H, V)$ , where  $H, V \subseteq T \times T$  are the horizontal and vertical matching relations. We need to define a predicate signature capable enough to express a doubly exponential grid of tiles. Consider the predicate signature

$$D = \langle \mathbf{u}_1^H, \mathbf{u}_2^H, \dots, \mathbf{u}_n^H; \mathbf{u}_1^V, \mathbf{u}_2^V, \dots, \mathbf{u}_n^V; \mathbf{u}_1^T, \mathbf{u}_2^T, \dots, \mathbf{u}_k^T; \mathbf{d} \rangle.$$

It has the following relevant subsignatures:

- $D^H = \langle \mathbf{u}_1^H, \mathbf{u}_2^H, \dots, \mathbf{u}_n^H, \mathbf{d} \rangle$  encodes the horizontal index of a tile
- $D^V = \langle \mathbf{u}_1^V, \mathbf{u}_2^V, \dots, \mathbf{u}_n^V, \mathbf{d} \rangle$  encodes the vertical index of a tile
- $D^{HV} = \langle \mathbf{u}_1^H, \mathbf{u}_2^H, \dots, \mathbf{u}_n^H, \mathbf{u}_1^V, \mathbf{u}_2^V, \dots, \mathbf{u}_n^V, \mathbf{d} \rangle$  encodes the combined horizontal and vertical index of a tile; we need this to define the full grid
- $D^T = \langle \mathbf{u}_1^T, \mathbf{u}_2^T, \dots, \mathbf{u}_k^T \rangle$  encodes the type of a tile.

Let  $\mathfrak{A}$  be a  $D$ -structure satisfying  $[D^{HV}:\text{pos-full}]$  and let  $D = \mathbf{d}^{\mathfrak{A}}$ . The sentence

$$[D^{HV}:\text{Full}] \wedge [D^{HV}:\text{Alldiff}] \tag{5.3}$$

### 5.5 Hardness with many equivalences in refinement

asserts that the  $D$ -classes form a doubly exponential grid. The sentence

$$\forall \mathbf{x} \left( \bigvee_{1 \leq i \leq k} \left( \mathbf{u}_i^T(\mathbf{x}) \wedge \bigwedge_{j \in [1, k] \setminus \{i\}} \neg \mathbf{u}_j^T(\mathbf{x}) \right) \right) \quad (5.4)$$

asserts that every element has a unique type. The sentence

$$\forall \mathbf{x} \forall \mathbf{y} \left( \mathbf{d}(\mathbf{x}, \mathbf{y}) \rightarrow \bigwedge_{1 \leq i \leq k} (\mathbf{u}_i^T(\mathbf{x}) \leftrightarrow \mathbf{u}_i^T(\mathbf{y})) \right) \quad (5.5)$$

asserts that all elements in a  $D$ -class have the same type—the type of the tile corresponding to that  $D$ -class. For  $j \in [1, n]$ , the sentence

$$\forall \mathbf{x} \left( [\mathbf{D}^H : \mathbf{Eq} \cdot (j - 1)](\mathbf{x}) \wedge [\mathbf{D}^V : \mathbf{Zero}](\mathbf{x}) \rightarrow \mathbf{u}_{t_j^0}^T(\mathbf{x}) \right) \quad (5.6)$$

encodes the initial segment in the first row of the square. The sentence

$$\forall \mathbf{x} \forall \mathbf{y} \left( [\mathbf{D}^H : \mathbf{Succ}](\mathbf{x}, \mathbf{y}) \wedge [\mathbf{D}^V : \mathbf{Eq}](\mathbf{x}, \mathbf{y}) \rightarrow \bigvee_{(i, j) \in H} \mathbf{u}_i^T(\mathbf{x}) \wedge \mathbf{u}_j^T(\mathbf{y}) \right) \quad (5.7)$$

encodes the horizontal matching condition. The sentence

$$\forall \mathbf{x} \forall \mathbf{y} \left( [\mathbf{D}^V : \mathbf{Succ}](\mathbf{x}, \mathbf{y}) \wedge [\mathbf{D}^H : \mathbf{Eq}](\mathbf{x}, \mathbf{y}) \rightarrow \bigvee_{(i, j) \in V} \mathbf{u}_i^T(\mathbf{x}) \wedge \mathbf{u}_j^T(\mathbf{y}) \right) \quad (5.8)$$

encodes the vertical matching condition.

Combining  $[\mathbf{D}^{HV} : \mathbf{pos-full}]$  with the formulas 5.3–5.8, which are constructible in deterministic polynomial time, we may encode an instance of the doubly exponential tiling problem as a (finite) satisfiability of a formula, so we have:

**Proposition 8.** *The (finite) satisfiability problem for the monadic first-order logic with a single equivalence symbol  $\mathcal{L}_1 1\mathbf{E}$  is  $\mathbf{N2EXPTime}$ -hard. More precisely, even the three-variable fragment  $\mathcal{L}_1^3 1\mathbf{E}$  has this property.*

## 5.5 Hardness with many equivalences in refinement

The argument from the previous section can be iterated to yield the hardness of the (finite) satisfiability of the monadic first-order logic with several built-in equivalence symbols in refinement  $\mathcal{L}_1 e\mathbf{E}_{\text{refine}}$ . Our strategy is to encode  $(e+1)$ -exponential numbers at every equivalence class of the coarsest relation by thinking of the  $e$ -exponential numbers at the classes of the second-to-coarsest relation as bit positions.

For  $e \in \mathbb{N}^+$ , consider the predicate signature  $\mathbf{E}(e) = \langle \mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_e \rangle$  consisting of the built-in equivalence symbols  $\mathbf{e}_i$  in refinement. Abbreviate the *coarsest* equivalence symbol  $\mathbf{d} = \mathbf{e}_e$ .

**Definition 63.** Let  $e \in \mathbb{N}^+$ . An  $e$ -exponential setup is a uniform effective deterministic polynomial time process for creating the following data structure. For every  $u \in \mathbb{N}^+$ , there is a predicate signature  $D(e, u)$  having length polynomial in  $u$ , consisting of unary predicate symbols and containing  $E(e)$ . The following data is effectively defined:

E1 There is a  $\mathcal{L}^3[D(e, u)]$ -sentence  $[D(e, u):\text{pos-full}]$  that is constructible in deterministic polynomial time from  $D(e, u)$ .

E2 If  $\mathfrak{A}$  is a  $D(e, u)$ -structure,  $\mathfrak{A} \models [D(e, u):\text{pos-full}]$  and  $D = \mathbf{d}^{\mathfrak{A}}$ , then there is a function  $[D(e, u):\text{Data}]^{\mathfrak{A}} : \mathcal{E}D \rightarrow \mathbb{B}^{\exp_2^e(u)}$  that assigns an  $e$ -exponential bitstring to every  $D$ -class.

E3 There is a  $\mathcal{L}^3[D(e, u)]$ -formula  $[D(e, u):\text{Eq}](\mathbf{x}, \mathbf{y})$  that is constructible in deterministic polynomial time from  $D(e, u)$ , such that for all  $a, b \in A$ :

$$\mathfrak{A} \models [D(e, u):\text{Eq}](a, b) \text{ iff } \underline{[D(e, u):\text{Data}]^{\mathfrak{A}} D[a]} = \underline{[D(e, u):\text{Data}]^{\mathfrak{A}} D[b]}.$$

E4 There is a  $\mathcal{L}^3[D(e, u)]$ -formula  $[D(e, u):\text{Zero}](\mathbf{x})$  that is constructible in deterministic polynomial time from  $D(e, u)$ , such that for all  $a \in A$ :

$$\mathfrak{A} \models [D(e, u):\text{Zero}](a) \text{ iff } \underline{[D(e, u):\text{Data}]^{\mathfrak{A}} D[a]} = 0.$$

E5 There is a  $\mathcal{L}^3[D(e, u)]$ -formula  $[D(e, u):\text{Largest}](\mathbf{x})$  that is constructible in deterministic polynomial time from  $D(e, u)$ , such that for all  $a \in A$ :

$$\mathfrak{A} \models [D(e, u):\text{Largest}](a) \text{ iff } \underline{[D(e, u):\text{Data}]^{\mathfrak{A}} D[a]} = N_{\exp_2^e(u)} = \exp_2^{e+1}(u) - 1.$$

E6 There is a  $\mathcal{L}^3[D(e, u)]$ -formula  $[D(e, u):\text{Less}](\mathbf{x}, \mathbf{y})$  that is constructible in deterministic polynomial time from  $D(e, u)$ , such that for all  $a, b \in A$ :

$$\mathfrak{A} \models [D(e, u):\text{Less}](a, b) \text{ iff } \underline{[D(e, u):\text{Data}]^{\mathfrak{A}} D[a]} < \underline{[D(e, u):\text{Data}]^{\mathfrak{A}} D[b]}.$$

E7 There is a  $\mathcal{L}^3[D(e, u)]$ -formula  $[D(e, u):\text{Succ}](\mathbf{x}, \mathbf{y})$  that is constructible in deterministic polynomial time from  $D(e, u)$ , such that for all  $a, b \in A$ :

$$\mathfrak{A} \models [D(e, u):\text{Succ}](a, b) \text{ iff } \underline{[D(e, u):\text{Data}]^{\mathfrak{A}} D[b]} = \underline{[D(e, u):\text{Data}]^{\mathfrak{A}} D[a]} + 1.$$

E8 For every  $\exp_2^e(u)$ -bit number  $M$ , there is a  $\mathcal{L}^3[D(e, u)]$ -formula  $[D(e, u):\text{Eq-M}](\mathbf{x})$ , that is constructible in deterministic polynomial time from  $D(e, u)$ , such that for all  $a \in A$ :

$$\mathfrak{A} \models [D(e, u):\text{Eq-M}](a) \text{ iff } \underline{[D(e, u):\text{Data}]^{\mathfrak{A}} D[a]} = M.$$

The previous section defines a 1-exponential setup. Suppose that we have an  $e$ -exponential setup having predicate signature  $D = D(e, u)$ . Analogously to the previous section, we will describe an  $(e + 1)$ -exponential setup  $D' = D(e + 1, u) = D + \langle e \rangle$  which

### 5.5 Hardness with many equivalences in refinement

is based on  $D$ , where  $e = e_{e+1}$  is the new coarsest built-in equivalence symbol in  $D'$ . Define the following formulas:

$$\begin{aligned}
[D':\text{pos-eq}](x, y) &= [D:\text{Eq}](x, y) \\
[D':\text{bit-0}](x) &= \forall y (e(y, x) \wedge [D':\text{pos-eq}](y, x) \rightarrow d(y, x)) \\
[D':\text{bit-1}](x) &= \exists y (e(y, x) \wedge [D':\text{pos-eq}](y, x) \wedge \neg d(y, x)) \\
[D':\text{pos-zero}](x) &= [D:\text{Zero}](x) \\
[D':\text{pos-largest}](x) &= [D:\text{Largest}](x) \\
[D':\text{pos-less}](x, y) &= e(x, y) \wedge [D:\text{Less}](x, y) \\
[D':\text{pos-succ}](x, y) &= e(x, y) \wedge [D:\text{Succ}](x, y) \\
[D':\text{pos-full}] &= \forall x \exists y (e(y, x) \wedge [D':\text{pos-zero}](y)) \wedge \\
&\quad \forall x (\neg [D':\text{pos-largest}](x) \rightarrow \exists y [D':\text{pos-succ}](x, y)) \\
[D':\text{pos-0}](x) &= [D':\text{pos-zero}](x) \\
[D':\text{pos-}(p+1)](x) &= \exists y ([D':\text{pos-}p](y) \wedge [D':\text{pos-succ}](y, x)) \\
&\quad \text{for } p \in [0, N_{\exp_2^e(u)} - 1].
\end{aligned} \tag{E1}$$

Let  $\mathfrak{A}$  be a  $D'$ -structure,  $\mathfrak{A} \models [D':\text{pos-full}]$  and let  $E = e^{\mathfrak{A}}$ . Define the function  $[D':\text{Data}]^{\mathfrak{A}} : \mathcal{E}E \rightarrow \mathbb{B}^{\exp_2^{e+1}(u)}$  assigning a  $\exp_2^{e+1}(u)$ -bit bitstring to any  $E$ -class  $X$  by:

$$[D':\text{Data}]_p^{\mathfrak{A}} X = \begin{cases} 1 & \text{if } \mathfrak{A} \models [D':\text{pos-}(p-1)](a) \text{ implies } \mathfrak{A} \models [D':\text{bit-1}](a) \text{ for all } a \in X \\ 0 & \text{otherwise} \end{cases} \tag{E2}$$

for  $p \in [1, \exp_2^{e+1}(u)]$ .

Define the following formulas:

$$[D':\text{Eq}](x, y) = \forall x' \forall y' (e(x', x) \wedge e(y', y) \wedge \quad (\text{E3})$$

$$[D':\text{pos-eq}](x', y') \rightarrow ([D':\text{bit-0}](x') \leftrightarrow [D':\text{bit-0}](y'))$$

$$[D':\text{Zero}](x) = \forall y (e(y, x) \rightarrow [D':\text{bit-0}](y)) \quad (\text{E4})$$

$$[D':\text{Largest}](x) = \forall y (e(y, x) \rightarrow [1:\text{bit-D'}](y)) \quad (\text{E5})$$

$$[D':\text{Less}](x, y) = \exists x' \exists y' (e(x', x) \wedge e(y', y) \wedge \quad (\text{E6})$$

$$([D':\text{pos-eq}](x', y') \wedge [D':\text{bit-0}](x') \wedge [D':\text{bit-1}](y')) \wedge$$

$$\forall x'' ([D':\text{pos-less}](x', x'') \rightarrow \exists y'' (e(y'', y') \wedge$$

$$[D':\text{pos-eq}](y'', x'') \wedge ([D':\text{bit-0}](y'') \leftrightarrow [D':\text{bit-0}](x''))))$$

$$[D':\text{Succ}](x, y) = \exists x' \exists y' (e(x', x) \wedge e(y', y) \wedge \quad (\text{E7})$$

$$([D':\text{pos-eq}](x', y') \wedge [D':\text{bit-0}](x') \wedge [D':\text{bit-1}](y')) \wedge$$

$$\forall x'' ([D':\text{pos-less}](x'', x') \rightarrow [D':\text{bit-1}](x'')) \wedge$$

$$\forall y'' ([D':\text{pos-less}](y'', y') \rightarrow [D':\text{bit-0}](y'')) \wedge$$

$$\forall x'' ([D':\text{pos-less}](x', x'') \rightarrow \exists y'' (e(y'', y') \wedge$$

$$[D':\text{pos-eq}](y'', x'') \wedge ([D':\text{bit-0}](y'') \leftrightarrow [D':\text{bit-0}](x''))))$$

If  $M \in \mathbb{B}_{\exp_2^{e+1}(u)}$  is an  $\exp_2^{e+1}(u)$ -bit number, let  $t = \|M\|$  and define the formula:

$$[D':\text{Eq-M}](x) = \forall y \left( e(y, x) \rightarrow \bigwedge_{0 \leq p < t} ([D':\text{pos-p}](y) \rightarrow [D':\text{bit-}\overline{M}_{p+1}](y)) \wedge \quad (\text{E8})$$

$$\forall x ([D':\text{pos-(t-1)}](y) \wedge [D':\text{pos-less}](y, x) \rightarrow [D':\text{bit-0}](x)) \right).$$

This completes the definition of the  $(e+1)$ -exponential setup.

We can encode an instance of the  $(e+1)$ -exponential tiling problem into a (finite) satisfiability D-formula completely analogously to the previous section. Thus we have:

**Proposition 9.** *The (finite) satisfiability problem for the monadic first-order logic with  $e$  equivalence symbols in refinement  $\mathcal{L}_1 e\text{E}_{\text{refine}}$  is  $N(e+1)\text{EXPTIME}$ -hard. Even the three-variable fragment  $\mathcal{L}_1^3 e\text{E}_{\text{refine}}$  has this property.*

## 5.5 Hardness with many equivalences in refinement

By *Proposition 1* and *Proposition 3*, the same holds for  $\mathcal{L}_1^{(3)}eE_{\text{global}}$  and  $\mathcal{L}_1^{(3)}eE_{\text{local}}$ .

**Proposition 10.** *The (finite) satisfiability problem for the monadic first-order logic with many equivalence symbols in refinement  $\mathcal{L}_1E_{\text{refine}}$  is ELEMENTARY-hard. Even the three-variable fragment  $\mathcal{L}_1^3E_{\text{refine}}$  has this property.*

By *Proposition 2* and *Proposition 4*, the same holds for  $\mathcal{L}_1^{(3)}E_{\text{global}}$  and  $\mathcal{L}_1^{(3)}E_{\text{local}}$ .





## 6 Two-variable logics

In this chapter we investigate questions about the complexity of satisfiability and finite satisfiability of the two-variable first-order logic  $\mathcal{L}^2$  with built-in equivalence symbols in refinement. Recall that for this logic we are only interested in predicate signatures restricted to only unary and binary predicate symbols and the formal equality.

The base case for  $\mathcal{L}^2$  and the general case of several *unrelated* built-in equivalence symbols have been studied. The following is known:

- The two-variable first-order logic  $\mathcal{L}^2$  has the finite model property [9] and its (finite) satisfiability problem is NEXPTIME-complete [10].
- The two-variable first-order logic with a single built-in equivalence symbol  $\mathcal{L}^2\text{1E}$  has the finite model property and its (finite) satisfiability problem is NEXPTIME-complete [11].
- The two-variable first-order logic with two *unrelated* built-in equivalence symbols  $\mathcal{L}^2\text{2E}$  lacks the finite model property and both its satisfiability and finite satisfiability problems are N2EXPTIME-complete [12].
- The satisfiability and finite satisfiability problems for the two-variable first-order logic with  $e$  built-in equivalence symbols  $\mathcal{L}^2e\text{E}$  are both undecidable for  $e \geq 3$  [13].

In this chapter we prove that the logic  $\mathcal{L}^2e\text{E}_{\text{refine}}$  has the finite model property and its (finite) satisfiability problem is in NEXPTIME for every  $e \geq 0$ . We do this by defining an auxiliary problem — the *type realizability* problem — which is formulated at the level of abstraction of 2-types as opposed to the level of abstraction of formulas; this proves more flexible for implementing our approach: we look at the different classes of the coarsest equivalence symbol in a model, we transform them into instances of the simpler problem featuring one less equivalence symbols and we include enough additional information to allow us to reconstruct a big model from the traces of its galaxies.

### 6.1 Type realizability

Recall from [Section 1.5](#) about normal forms that every  $\mathcal{L}^2$ -sentence  $\varphi$  can be reduced in deterministic polynomial time to a sentence  $\text{sctr } \varphi$  in Scott normal form:

$$\forall x \forall y (\alpha_0(x, y) \vee x = y) \wedge \bigwedge_{1 \leq i \leq m} \forall x \exists y (\alpha_i(x, y) \wedge x \neq y),$$

where  $m \geq 1$ , all the formulas  $\alpha_i$  are quantifier-free and use at most linearly many new unary predicate symbols. The semantic connection between  $\varphi$  and  $\text{sctr } \varphi$  is that they

## 6 Two-variable logics

are essentially equisatisfiable. More precisely, every model for  $\varphi$  of cardinality at least 2 can be enriched to a model for  $\text{sctr } \varphi$  and also every model of  $\text{sctr } \varphi$  (which by  $m \geq 1$  must have cardinality at least 2) is a model for  $\varphi$ . We refer to  $\alpha_0$  as the *universal part* of the formula  $\text{sctr } \varphi$  and to  $\alpha_i$  for  $i \in [1, m]$  as the *existential parts* of  $\text{sctr } \varphi$ .

For any formula  $\text{sctr } \varphi$  in Scott normal form, we may replace its existential parts by fresh binary predicate symbols: for  $i \in [1, m]$  let  $\mathbf{m}_i$  be a fresh binary predicate symbol with intended interpretation  $\forall \mathbf{x} \forall \mathbf{y} (\mathbf{m}_i(\mathbf{x}, \mathbf{y}) \leftrightarrow \alpha_i(\mathbf{x}, \mathbf{y}))$ . Since this is a universal sentence, it can be added to the universal part  $\alpha_0$ . The symbols  $\mathbf{m}_i$  are the *message symbols*. Hence  $\text{sctr } \varphi$  can be transformed in deterministic polynomial time to the form:

$$\forall \mathbf{x} \forall \mathbf{y} (\alpha(\mathbf{x}, \mathbf{y}) \vee \mathbf{x} = \mathbf{y}) \wedge \bigwedge_{1 \leq i \leq m} \forall \mathbf{x} \exists \mathbf{y} (\mathbf{m}_i(\mathbf{x}, \mathbf{y}) \wedge \mathbf{x} \neq \mathbf{y}), \quad (6.1)$$

where the universal part  $\alpha$  is quantifier-free and over an extended signature. For convenience, we make the existential parts part of the signature, so we can focus only on the universal part. The following term is similar to the one defined in [14]:

**Definition 64.** A classified signature  $\langle \Sigma, \bar{\mathbf{m}} \rangle$  for the two-variable first-order logic  $\mathcal{L}^2$  is a predicate signature  $\Sigma$  together with a nonempty sequence  $\bar{\mathbf{m}} = \mathbf{m}_1 \mathbf{m}_2 \dots \mathbf{m}_m$  of distinct binary predicate symbols from  $\Sigma$  having intended interpretation

$$\bigwedge_{1 \leq i \leq m} \forall \mathbf{x} \exists \mathbf{y} (\mathbf{m}_i(\mathbf{x}, \mathbf{y}) \wedge \mathbf{x} \neq \mathbf{y}). \quad (6.2)$$

That is, a classified signature *automatically includes* the existential parts, so  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ -structures *automatically satisfy* the the existential parts:

**Definition 65.** A structure  $\mathfrak{A}$  for the classified signature  $\langle \Sigma, \bar{\mathbf{m}} \rangle$  is a structure for the predicate signature  $\Sigma$  that satisfies the intended interpretation *eq. (6.2)* of the message symbols. Note that  $\mathfrak{A}$  must have cardinality at least 2 by  $m \geq 1$ .

**Definition 66.** The (finite) classified satisfiability problem for two-variable first-order logic is: given a classified signature  $\langle \Sigma, \bar{\mathbf{m}} \rangle$  and a quantifier-free  $\mathcal{L}^2[\Sigma]$ -formula  $\alpha(\mathbf{x}, \mathbf{y})$ , is there a (finite)  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ -structure  $\mathfrak{A}$  satisfying *eq. (6.1)*. Note that since  $\mathfrak{A}$  is a  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ -structure, it must also satisfy *eq. (6.2)* and must have cardinality at least 2. Denote the classified satisfiability problem by CL-SAT- $\mathcal{L}^2$  and its finite version by FIN-CL-SAT- $\mathcal{L}^2$ .

**Remark 52.** The problem of (finite) satisfiability reduces in nondeterministic polynomial time to the problem of (finite) classified satisfiability:

$$(\text{FIN-})\text{SAT-}\mathcal{L}^2 \leq_{\text{m}}^{\text{NPTIME}} (\text{FIN-})\text{CL-SAT-}\mathcal{L}^2.$$

*Proof.* Note that (finite) satisfiability in the class of models of cardinality 1 is trivially decidable in nondeterministic polynomial time — just guess the atomic 1-type (whose size is polynomially bounded in the size of the predicate signature) of the unique element of the structure and check (in deterministic polynomial time) that it satisfies the original formula.

Scott normal form shows that (finite) satisfiability in the class of models of cardinality at least 2 reduces in deterministic polynomial time to (finite) classified satisfiability. Hence the following nondeterministic polynomial time procedure reduces an instance  $(\Sigma, \varphi)$  of the (finite) satisfiability problem to an instance  $(\langle \Sigma', \bar{\mathbf{m}} \rangle, \alpha)$  of the (finite) classified satisfiability problem: Guess if  $\varphi$  will be satisfiable in the class of models of cardinality 1 or not. If you guessed so, extend  $\Sigma$  to  $\Sigma'$  by adding a single message symbol  $\mathbf{m}_1$  and let  $\alpha = (\mathbf{x} = \mathbf{x})$  be a fixed predicate tautology. If you guessed otherwise, transform  $\varphi$  into the form eq. (6.1) and let  $\alpha$  be the universal part of that normal form.  $\square$

A *type instance*  $\mathbf{T} \subseteq \mathbf{T}[\Sigma]$  over the classified signature  $\langle \Sigma, \bar{\mathbf{m}} \rangle$  is a nonempty set of 2-types that is closed under inversion. The set of 1-types included in the type instance  $\mathbf{T}$  is  $\Pi_{\mathbf{T}} = \{\text{tp}_{\mathbf{x}} \tau \mid \tau \in \mathbf{T}\}$ . Two 1-types  $\pi, \pi' \in \Pi_{\mathbf{T}}$  are *connectable* if some  $\tau \in \mathbf{T}$  connects them. Connectability is symmetric, however it is not necessarily neither transitive nor reflexive. A 1-type  $\kappa$  is a *king type* if it is not connectable with itself; the set of king types over  $\mathbf{T}$  is  $\mathbf{K}_{\mathbf{T}}$ . A 1-type  $\pi$  that is not a king type is a *worker type*; the set of worker types is  $\mathbf{W}_{\mathbf{T}}$ . So we have  $\Pi_{\mathbf{T}} = \mathbf{K}_{\mathbf{T}} \cup \mathbf{W}_{\mathbf{T}}$ .

If  $\pi \in \Pi_{\mathbf{T}}$ , the *neighbours*  $\mathbf{T}[\pi] \subseteq \Pi_{\mathbf{T}}$  of  $\pi$  are defined by:

$$\mathbf{T}[\pi] = \begin{cases} \Pi_{\mathbf{T}} & \text{if } \pi \in \mathbf{W}_{\mathbf{T}} \text{ is a worker type} \\ \Pi_{\mathbf{T}} \setminus \{\pi\} & \text{otherwise, that is if } \pi \in \mathbf{K}_{\mathbf{T}} \text{ is a king type.} \end{cases}$$

Note that  $\pi \in \mathbf{T}[\pi]$  iff  $\pi \in \mathbf{W}_{\mathbf{T}}$  is a worker type.

If  $\mathfrak{A}$  is a  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ -structure, the *type instance* of  $\mathfrak{A}$  is:

$$\mathbf{T}[\mathfrak{A}] = \left\{ \text{tp}^{\mathfrak{A}}[a, b] \mid a \in A, b \in A \setminus \{a\} \right\}.$$

That is  $\mathbf{T} = \mathbf{T}[\mathfrak{A}]$  is the set of 2-types realized in  $\mathfrak{A}$ . Note that this is indeed a type instance over  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ :  $\mathbf{T}[\mathfrak{A}]$  is nonempty since  $\mathfrak{A}$  has cardinality at least 2 and  $\mathbf{T}[\mathfrak{A}]$  is closed under inversion by construction. If  $\mathbf{T}$  is the type instance of  $\mathfrak{A}$ , then  $\mathfrak{A}$  is a *model* for  $\mathbf{T}$ . An element realizing a king type is a *king element*. An element realizing a worker type is a *worker element*.

**Definition 67.** The (finite) type realizability problem for  $\mathcal{L}^2$  is the following: given a classified signature  $\langle \Sigma, \bar{\mathbf{m}} \rangle$  and a type instance  $\mathbf{T}$  over  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ , is there a (finite) model for  $\mathbf{T}$ . Denote the type realizability problem by TP-REALIZ- $\mathcal{L}^2$  and its finite version by FIN-TP-REALIZ- $\mathcal{L}^2$ .

**Remark 53.** Let  $\langle \Sigma, \bar{\mathbf{m}} \rangle$  be a classified signature and let  $\alpha(\mathbf{x}, \mathbf{y})$  be a quantifier-free  $\mathcal{L}^2[\Sigma]$ -formula. Let  $\mathbf{T}^{\alpha} \subseteq \mathbf{T}[\Sigma]$  be the set of those 2-types that are consistent with  $\alpha(\mathbf{x}, \mathbf{y})$  and the intended interpretation for classified signatures eq. (6.2). Then a  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ -structure  $\mathfrak{A}$  is a classified model for  $\alpha(\mathbf{x}, \mathbf{y})$  iff  $\mathbf{T}[\mathfrak{A}] \subseteq \mathbf{T}^{\alpha}$ .

Recall that the number of possible 1-types or 2-types over  $\Sigma$  is exponentially bounded in the cardinality of  $\Sigma$  and that the size of a 1-type or a 2-type over  $\Sigma$  is polynomially

## 6 Two-variable logics

bounded in the cardinality of  $\Sigma$ . Hence the (finite) classified satisfiability problem reduces to the (finite) type realizability problem in nondeterministic exponential time:

$$(\text{FIN-})\text{CL-SAT-}\mathcal{L}^2 \leq_m^{\text{NEXP TIME}} (\text{FIN-})\text{TP-REALIZ-}\mathcal{L}^2.$$

**Lemma 8** (Model Characterization). *Let  $\mathfrak{A}$  be a model for  $T$ . Then:*

1. *If  $\tau \in T$  then some  $a \in A$  and  $b \in A \setminus \{a\}$  have  $\text{tp}^{\mathfrak{A}}[a, b] = \tau$ .  
If  $a \in A$  and  $b \in A \setminus \{a\}$ , then  $\text{tp}^{\mathfrak{A}}[a, b] = \tau$  for some  $\tau \in T$ .  
Equivalently  $T = \left\{ \text{tp}^{\mathfrak{A}}[a, b] \mid a \in A, b \in A \setminus \{a\} \right\}$ .*
2. *If  $\pi \in \Pi_T$  then some  $a \in A$  has  $\text{tp}^{\mathfrak{A}}[a] = \pi$ .  
If  $a \in A$  then  $\text{tp}^{\mathfrak{A}}[a] = \pi$  for some  $\pi \in \Pi_T$ .  
Equivalently  $\Pi_T = \left\{ \text{tp}^{\mathfrak{A}}[a] \mid a \in A \right\}$ .*
3. *Let  $\kappa \in \Pi_T$ . Then  $\kappa \in K_T$  iff a unique  $a \in A$  has  $\text{tp}^{\mathfrak{A}}[a] = \kappa$ .*
4. *Let  $\pi \in \Pi_T$ . Then  $\pi \in W_T$  iff for every  $a \in A$  such that  $\text{tp}^{\mathfrak{A}}[a] = \pi$  there is some  $b \in A \setminus \{a\}$  having  $\text{tp}^{\mathfrak{A}}[b] = \pi$ .*
5. *Let  $a \in A$  and let  $\pi = \text{tp}^{\mathfrak{A}}[a]$ .  
If  $\pi' \in T[\pi]$  then some  $b \in A \setminus \{a\}$  has  $\text{tp}^{\mathfrak{A}}[b] = \pi'$ .  
If  $b \in A \setminus \{a\}$  then  $\text{tp}^{\mathfrak{A}}[b] = \pi'$  for some  $\pi' \in T[\pi]$ .*

We will be applying this lemma implicitly.

*Proof.* 1. By definition  $T = T[\mathfrak{A}] = \left\{ \text{tp}^{\mathfrak{A}}[a, b] \mid a \in A, b \in A \setminus \{a\} \right\}$ .

2. If  $\pi \in \Pi_T$  then some  $\tau \in T$  has  $\text{tp}_x \tau = \pi$ , so some  $a \in A$  and  $b \in A \setminus \{a\}$  has  $\text{tp}^{\mathfrak{A}}[a, b] = \tau$ , so  $\text{tp}^{\mathfrak{A}}[a] = \pi$ .

If  $a \in A$ , then note that  $\mathfrak{A}$  has cardinality at least 2 and let  $b \in A \setminus \{a\}$  be any other element. Then  $\text{tp}^{\mathfrak{A}}[a, b] = \tau \in T$ , so  $\pi = \text{tp}^{\mathfrak{A}}[a] = \text{tp}_x \tau \in \Pi_T$ .

3. First let  $\kappa \in K_T$ , so some  $a \in A$  has  $\text{tp}^{\mathfrak{A}}[a] = \kappa$ . Suppose towards a contradiction that some  $b \in A \setminus \{a\}$  has  $\text{tp}^{\mathfrak{A}}[b] = \kappa$ . Then  $\tau = \text{tp}^{\mathfrak{A}}[a, b] \in T$  connects  $\kappa$  with itself — a contradiction.

Next suppose that  $\pi \in \Pi_T \setminus K_T = W_T$ , so some  $\tau \in T$  connects  $\kappa$  with itself. Then some  $a \in A$  and  $b \in A \setminus \{a\}$  have  $\text{tp}^{\mathfrak{A}}[a, b] = \tau$ , so  $\text{tp}^{\mathfrak{A}}[a] = \text{tp}^{\mathfrak{A}}[b] = \pi$ , so there is not a unique  $a \in A$  having  $\text{tp}^{\mathfrak{A}}[a] = \pi$ .

4. First suppose that  $\pi \in W_T$  and that  $a \in A$  has  $\text{tp}^{\mathfrak{A}}[a] = \pi$ . Since  $\pi \notin K_T$ , such  $a$  is not unique, so there is some  $b \in A \setminus \{a\}$  having  $\text{tp}^{\mathfrak{A}}[b] = \pi$ .

Next suppose that  $\pi \in \Pi_T$  and that for every  $a \in A$  such that  $\text{tp}^{\mathfrak{A}}[a] = \pi$  there is some  $b \in A \setminus \{a\}$  having  $\text{tp}^{\mathfrak{A}}[b] = \pi$ . Since  $\pi \in \Pi_T$ , some  $a \in A$  has  $\text{tp}^{\mathfrak{A}}[a] = \pi$ , so some  $b \in A \setminus \{a\}$  has  $\text{tp}^{\mathfrak{A}}[b] = \pi$ , so there is not a unique  $a \in A$  having  $\text{tp}^{\mathfrak{A}}[a] = \pi$ , so  $\pi \notin K_T$ , so  $\pi \in W_T$ .

5. Let  $a \in A$  and  $\pi = \text{tp}^{\mathfrak{A}}[a]$ .

First let  $\pi' \in T[\pi]$ . If  $\pi' \neq \pi$ , then some  $b \in A$  has  $\text{tp}^{\mathfrak{A}}[b] = \pi'$ , so  $b \in A \setminus \{a\}$ . If  $\pi' = \pi$ , then  $\pi \in W_T$  is a worker type, so some  $b \in A \setminus \{a\}$  has  $\text{tp}^{\mathfrak{A}}[b] = \pi = \pi'$ .

Next suppose that some  $b \in A \setminus \{a\}$  has  $\text{tp}^{\mathfrak{A}}[b] = \pi'$ . If  $\pi' \neq \pi$ , then  $\pi' \in T[\pi]$ . If  $\pi' = \pi$ , then  $\pi$  must be a worker type, so  $\pi' \in T[\pi] = \Pi_T$ .

□

**Definition 68.** Let  $T$  be a type instance over  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ . A star-type  $\sigma \subseteq T$  over  $T$  is a nonempty set of 2-types satisfying the following conditions:

( $\sigma x$ ) If  $\tau, \tau' \in \sigma$ , then  $\text{tp}_x \tau = \text{tp}_x \tau'$ . Denote  $\text{tp}_x \tau$  for any  $\tau \in \sigma$  by  $\pi = \text{tp}_x \sigma$ .

( $\sigma \pi y$ ) If  $\pi' \in T[\pi]$ , then some  $\tau \in \sigma$  has  $\text{tp}_y \tau = \pi'$ .

( $\sigma \kappa y$ ) If  $\kappa' \in T[\pi] \cap K_T$  and if  $\tau, \tau' \in \sigma$  have  $\text{tp}_y \tau = \text{tp}_y \tau' = \kappa'$ , then  $\tau = \tau'$ .

( $\sigma \mathbf{m}$ ) If  $\mathbf{m} \in \bar{\mathbf{m}}$ , then some  $\tau \in \sigma$  has  $\mathbf{m}(x, y) \in \tau$ .

A star-type  $\sigma$  is a *king star-type* if  $\text{tp}_x \sigma$  is a king type. Otherwise the star-type is a *worker star-type*. Note that the size of a star-type is linear with respect to the size of the type instance.

**Remark 54.** If  $\sigma$  is a star-type over  $T$ , then:

( $\sigma \kappa y'$ ) If  $\kappa' \in T[\pi] \cap K_T$ , then a unique  $\tau \in \sigma$  has  $\text{tp}_y \tau = \kappa$ .

*Proof.* By ( $\sigma \pi y$ ), some  $\tau \in \sigma$  has  $\text{tp}_y \tau = \kappa$ . By ( $\sigma \kappa y$ ), such  $\tau$  is unique. □

**Definition 69.** Let  $\mathfrak{A}$  be a model for  $T$  and let  $a \in A$ . The star-type  $\text{stp}^{\mathfrak{A}}[a]$  of  $a$  is defined by:

$$\text{stp}^{\mathfrak{A}}[a] = \left\{ \text{tp}^{\mathfrak{A}}[a, b] \mid b \in A \setminus \{a\} \right\}.$$

**Remark 55.** Indeed  $\sigma = \text{stp}^{\mathfrak{A}}[a]$  is a star-type over  $T$  in the sense of Definition 68.

*Proof.* The set  $\sigma$  is nonempty since  $\mathfrak{A}$  has cardinality at least 2. We check the conditions for a star-type  $\sigma$  over  $T$ :

( $\sigma x$ ) If  $\tau, \tau' \in \sigma$ , then  $\tau = \text{tp}^{\mathfrak{A}}[a, b]$  and  $\tau' = \text{tp}^{\mathfrak{A}}[a, b']$  for some  $b, b' \in A \setminus \{a\}$ . Then  $\text{tp}_x \tau = \text{tp}_x \tau' = \text{tp}^{\mathfrak{A}}[a]$ .

Let  $\pi = \text{tp}_x \sigma = \text{tp}^{\mathfrak{A}}[a]$ .

( $\sigma \pi y$ ) If  $\pi' \in T[\pi]$ , then some  $b \in A \setminus \{a\}$  has  $\text{tp}^{\mathfrak{A}}[b] = \pi'$ , so  $\tau = \text{tp}^{\mathfrak{A}}[a, b] \in \sigma$  has  $\text{tp}_y \tau = \pi'$ .

( $\sigma \kappa y$ ) If  $\kappa' \in T[\pi] \cap K_T$ , then  $\kappa' \neq \pi$ . Suppose towards a contradiction that some  $\tau \neq \tau' \in \sigma$  have  $\text{tp}_y \tau = \text{tp}_y \tau' = \kappa'$ . Then  $\tau = \text{tp}^{\mathfrak{A}}[a, b]$  and  $\tau' = \text{tp}^{\mathfrak{A}}[a, b']$  for some  $b \neq b' \in A \setminus \{a\}$ . Then  $\text{tp}^{\mathfrak{A}}[b] = \text{tp}^{\mathfrak{A}}[b'] = \kappa'$  — a contradiction.

( $\sigma\mathbf{m}$ ) Let  $\mathbf{m} \in \bar{\mathbf{m}}$ . Since  $\mathfrak{A}$  is a  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ -structure, some  $b \in A \setminus \{a\}$  has  $\mathbf{m}(x, y) \in \text{tp}^{\mathfrak{A}}[a, b] \in \sigma$ .

□

**Definition 70.** Let  $T$  be a type instance over  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ . A certificate  $\mathcal{S}$  for  $T$  is a nonempty set of star-types over  $T$  satisfying the following conditions:

( $\mathcal{S}\tau$ ) If  $\tau \in T$ , then some  $\sigma \in \mathcal{S}$  has  $\tau \in \sigma$ , that is there is a star-type containing each 2-type.

( $\mathcal{S}\kappa$ ) If  $\kappa \in K_T$  and if  $\sigma, \sigma' \in \mathcal{S}$  have  $\text{tp}_x \sigma = \text{tp}_x \sigma' = \kappa$ , then  $\sigma = \sigma'$ .

**Remark 56.** Let  $\mathcal{S}$  be a certificate over  $T$ . Then:

( $\mathcal{S}\pi$ ) If  $\pi \in \Pi_T$ , then some  $\sigma \in \mathcal{S}$  has  $\text{tp}_x \sigma = \pi$ .

( $\mathcal{S}\kappa'$ ) If  $\kappa \in K_T$ , then a unique  $\sigma \in \mathcal{S}$  has  $\text{tp}_x \sigma = \pi$ .

*Proof.* ( $\mathcal{S}\pi$ ) If  $\pi \in \Pi_T$ , then some  $\tau \in T$  has  $\text{tp}_x \tau = \pi$ , so by ( $\mathcal{S}\tau$ ) some  $\sigma \in \mathcal{S}$  has  $\tau \in \sigma$ , so  $\text{tp}_x \sigma = \text{tp}_x \tau = \pi$ .

( $\mathcal{S}\kappa'$ ) If  $\kappa \in K_T$ , then by ( $\mathcal{S}\pi$ ) some  $\sigma \in \mathcal{S}$  has  $\text{tp}_x \sigma = \kappa$ . By ( $\mathcal{S}\kappa$ ), such  $\sigma$  is unique.

□

Note that the size of a certificate may be exponential with respect to the size of the type instance. However, we may extract polynomial certificates:

**Lemma 9** (Certificate extraction). Let  $\mathfrak{A}$  be a model for the type instance  $T$ . For each 2-type  $\tau \in T$ , let  $a_\tau \in A$  and  $b_\tau \in A \setminus \{a_\tau\}$  have  $\text{tp}^{\mathfrak{A}}[a_\tau, b_\tau] = \tau$ . Let

$$\mathcal{S} = \left\{ \text{stp}^{\mathfrak{A}}[a_\tau] \mid \tau \in T \right\}.$$

Then  $\mathcal{S}$  is a certificate for  $T$ . Note that the size of  $\mathcal{S}$  is polynomially bounded with respect to the size of  $T$ .

*Proof.* Since  $T$  is nonempty,  $\mathcal{S}$  is nonempty. We check the conditions for  $\mathcal{S}$  to be a certificate for  $T$ :

( $\mathcal{S}\tau$ ) If  $\tau \in T$ , then  $\tau = \text{tp}^{\mathfrak{A}}[a_\tau, b_\tau] \in \text{stp}^{\mathfrak{A}}[a_\tau] \in \mathcal{S}$ .

( $\mathcal{S}\kappa$ ) Let  $\kappa \in K_T$  and let  $\sigma, \sigma' \in \mathcal{S}$  have  $\text{tp}_x \sigma = \text{tp}_x \sigma' = \kappa$ . Then  $\sigma = \text{stp}^{\mathfrak{A}}[a_\tau]$  and  $\sigma' = \text{stp}^{\mathfrak{A}}[a_{\tau'}]$  for some  $\tau, \tau' \in T$ . Then  $\text{tp}_x \tau = \text{tp}_x \tau' = \kappa$ . Then  $\text{tp}^{\mathfrak{A}}[a_\tau] = \text{tp}_x \kappa = \text{tp}^{\mathfrak{A}}[a_{\tau'}]$ . Since  $\kappa$  is a king type,  $a_\tau = a_{\tau'}$ , so  $\sigma = \sigma'$ .

□

**Theorem 4** (Certificate expansion). Let  $\mathcal{S}$  be a certificate for the type instance  $T$  over the classified signature  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ . Then  $T$  has a finite model. More precisely, let  $t \geq |T|$  be a parameter. Then  $T$  has a finite model in which each worker type is realized at least  $t$  times.

*Proof.* We adapt the standard strategy<sup>1</sup> used in the proof of the finite model property for the logic  $\mathcal{L}^2$ , as presented in [2]. We build a model  $\mathfrak{A}$  for  $T$  as follows. The domain  $A$  of  $\mathfrak{A}$  is the union of the following disjoint sets of elements:

- The singleton set  $A^\sigma = \{a^\sigma\}$  for every king star-type  $\sigma \in \mathcal{S}$ ,  $\text{tp}_x \sigma \in K_T$ . The elements  $a^\sigma$  are the *kings*.
- The three disjoint copies of  $t$  elements  $A^\sigma = A_0^\sigma \cup A_1^\sigma \cup A_2^\sigma$  for every worker star-type  $\sigma \in \mathcal{S}$ ,  $\text{tp}_x \sigma \in W_T$ , where  $A_i^\sigma = \{a_{i1}^\sigma, a_{i2}^\sigma, \dots, a_{it}^\sigma\}$  for  $i \in \{0, 1, 2\}$ . The elements  $a_{ij}^\sigma$  are the *workers*.

Let  $\sigma : A \rightarrow \mathcal{S}$  denote the intended star-type of the elements:  $\sigma(a) = \sigma$  on  $A^\sigma$ . Let  $\pi : A \rightarrow \Pi_T$  denote the intended 1-type of the elements:  $\pi(a) = \text{tp}_x(\sigma(a))$ . We consistently assign 2-types between distinct elements on stages.

**Realization of kings** We first assign 2-types consistently between the kings and any other element. Let  $a \in A$  be any king, so  $a = a^{\sigma'}$  for some king star-type  $\sigma' \in \mathcal{S}$ . Let  $\kappa' = \pi(a) = \text{tp}_x \sigma' \in K_T$  be the intended (king) type of  $a$ . Let  $b \in A \setminus \{a\}$  be any other element and let  $\sigma = \sigma(b)$  and  $\pi = \pi(b) = \text{tp}_x \sigma$  be its intended star-type and 1-type, respectively. Since  $A$  contains a unique element for each king star-type,  $\sigma \neq \sigma'$ . By  $(\mathcal{S}\kappa)$ ,  $\pi \neq \kappa'$ , so  $\kappa' \in T[\pi] \cap K_T$ . By  $(\sigma\kappa y')$ , a unique  $\tau \in \sigma$  has  $\text{tp}_y \tau = \kappa'$ . We assign  $\text{tp}^{\mathfrak{A}}[b, a] = \tau$ . We must check that these assignments are consistent.

First, these assignments are symmetric over the kings. Suppose that  $b$  is a king, so  $\pi = \kappa$  is a king type. Since  $\kappa' \neq \kappa$ ,  $\kappa \in T[\kappa'] \cap K_T$ . By  $(\sigma\kappa y')$ , a unique  $\tau' \in \sigma'$  has  $\text{tp}_y \tau' = \kappa$  and we would want to assign  $\text{tp}^{\mathfrak{A}}[a, b] = \tau'$ . We claim that  $\tau' = \tau^{-1}$ . Indeed, by  $(\mathcal{S}\tau)$ ,  $\tau^{-1} \in \sigma''$  for some  $\sigma'' \in \mathcal{S}$ . Then  $\text{tp}_x \sigma'' = \text{tp}_x(\tau^{-1}) = \kappa$ , so by  $(\mathcal{S}\kappa)$ ,  $\sigma'' = \sigma$ . Then  $\tau^{-1} \in \sigma$  has  $\text{tp}_y \tau^{-1} = \kappa$ , so  $\tau^{-1} = \tau'$ .

Next, these assignments cover  $\sigma'$ . Let  $\tau' \in \sigma'$  be any. Then by  $(\mathcal{S}\tau)$ , some  $\sigma \in \mathcal{S}$  has  $\tau = \tau'^{-1} \in \sigma$ . If  $\sigma = \sigma'$ , then  $\text{tp}_y \tau' = \text{tp}_x \tau = \text{tp}_x \sigma = \kappa$ , so  $\tau'$  would connect  $\kappa$  with itself — a contradiction. So  $\sigma \neq \sigma'$ . By  $(\mathcal{S}\kappa)$ ,  $\pi \neq \kappa$ , so  $\kappa \in T[\pi]$ . Then by  $(\sigma\kappa y')$ ,  $\tau \in \sigma$  is the unique having  $\text{tp}_y \tau = \kappa$ . Since  $\mathfrak{A}$  contains some element for each star-type, some  $b \in A \setminus \{a\}$  has  $\sigma(b) = \sigma$ , so we had assigned  $\text{tp}^{\mathfrak{A}}[b, a] = \tau$ .

**Realization of workers** Next we consistently assign 2-types between workers. Let  $a \in A$  be any worker and let  $\sigma = \sigma(a)$  and  $\pi = \pi(a)$  be its intended star-type and 1-type, respectively. Then  $a = a_{ij}^\sigma$  for some  $i \in \{0, 1, 2\}$  and  $j \in [1, t]$ . Let  $i' = (i + 1 \bmod 3) \in \{0, 1, 2\}$  be the index of *the next copy* of the workers. Let  $\tau \in \sigma$  be any 2-type.

First suppose that  $\text{tp}_y \tau = \kappa' \in K_T$  is a king type. By  $(\mathcal{S}\kappa')$ , let  $\sigma' \in \mathcal{S}$  be the unique star-type having  $\text{tp}_x \sigma' = \kappa'$  and let  $b = a^{\sigma'}$  be the unique king having  $\pi(b) = \kappa'$ . Since  $\kappa' \neq \pi$ ,  $\kappa' \in T[\pi]$  and by  $(\sigma\kappa y')$ ,  $\tau \in \sigma$  is the unique having  $\text{tp}_y \tau = \kappa'$ . So we had already assigned  $\text{tp}^{\mathfrak{A}}[a, b] = \tau$  during the realization of kings.

<sup>1</sup>with the slight difference that our approach doesn't need a *court*, since the information about it is implicit in the certificate

Next suppose that  $\text{tp}_{\mathbf{y}}\tau = \pi' \in W_T$  is a worker type. Let  $U = \{\eta \in \sigma \mid \text{tp}_{\mathbf{y}}\eta = \pi'\}$  be the set of all 2-types from  $\sigma$  parallel to  $\tau$ . We simultaneously find distinct elements  $b_\eta$  that are distinct from  $a$  for the assignments  $\text{tp}^{\mathfrak{A}}[a, b_\eta] = \eta$ . By  $(\mathcal{S}\tau)$ , for each  $\eta \in U$  there is some star-type  $\sigma'_\eta \in \mathcal{S}$  such that  $\eta^{-1} \in \sigma'_\eta$ . Note that  $\text{tp}_{\mathbf{x}}\sigma'_\eta = \pi'$  is a worker type. Since  $U \subseteq T$  we have  $|U| \leq t$ , so there are enough distinct workers from the next copy  $b_\eta \in A_{i'}^{\sigma'_\eta}$  for the assignments  $\text{tp}^{\mathfrak{A}}[a, b_\eta] = \eta$ . These assignments do not clash with each other, since they are made between *consecutive copies* of worker elements.

**Completion** Suppose that  $a \neq b \in A$  are any two distinct elements such that  $\text{tp}^{\mathfrak{A}}[a, b]$  has not yet been assigned. Then both  $\pi(a)$  and  $\pi(b)$  are worker types, so  $\pi(b) \in T[\pi(a)] = \Pi_T$ . By  $(\sigma\pi\mathbf{y})$ , some  $\tau \in \sigma(a)$  has  $\text{tp}_{\mathbf{y}}\tau = \pi(b)$ , so we may assign  $\text{tp}^{\mathfrak{A}}[a, b] = \tau$ . Note that this may extend the actual star-type of  $a$  and  $b$ , but this is appropriate.

The structure  $\mathfrak{A}$  is a  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ -structure by  $(\sigma\mathbf{m})$  and is a model for  $T$  by  $(\mathcal{S}\tau)$ .  $\square$

**Proposition 11.** *The type realizability problem for  $\mathcal{L}^2$  coincides with the finite type realizability problem and is in NPTIME.*

*Proof.* Let  $T$  be a type instance for the classified signature  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ . Guess a polynomial certificate for  $T$ . By Lemma 9 and Theorem 4, such a certificate exists iff  $T$  has a model. The general version coincides with the finite version since the model constructed in Theorem 4 is finite.  $\square$

**Corollary 3** ([10]). *The logic  $\mathcal{L}^2$  has the finite model property and its (finite) satisfiability problem is in NEXPTIME.*

## 6.2 Type realizability with equivalences

In this section we consider the logic  $\mathcal{L}^2 e E_{\text{refine}}$  featuring  $e \geq 1$  equivalence symbols  $e_1, e_2, \dots, e_e$  in refinement. By convention let  $e_0$  be the formal equality, so that  $\mathcal{L}^2 0 E_{\text{refine}}$  means  $\mathcal{L}^2$ . Abbreviate the coarsest equivalence symbol  $e = e_e$ .

The following reductions carry over from the previous section:

$$\begin{aligned} (\text{FIN-})\text{SAT-}\mathcal{L}^2 e E_{\text{refine}} &\leq_{\text{m}}^{\text{NPTIME}} (\text{FIN-})\text{CL-SAT-}\mathcal{L}^2 e E_{\text{refine}} \\ (\text{FIN-})\text{CL-SAT-}\mathcal{L}^2 e E_{\text{refine}} &\leq_{\text{m}}^{\text{NEXPTIME}} (\text{FIN-})\text{TP-REALIZ-}\mathcal{L}^2 e E_{\text{refine}}. \end{aligned}$$

We proceed to define new terms. The terminology is based on [14].

Let  $\langle \Sigma, \bar{\mathbf{m}} \rangle$  be a predicate signature over  $\mathcal{L}^2 e E_{\text{refine}}$ . A 2-type  $\tau \in T[\Sigma]$  is a *galactic type* if  $e(\mathbf{x}, \mathbf{y}) \in \tau$ . Otherwise, that is if  $(\neg e(\mathbf{x}, \mathbf{y})) \in \tau$ , the 2-type  $\tau$  is a *cosmic type*. Let  $T$  be a type instance over  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ . The sets of galactic and cosmic types in  $T$  are  $T^g$  and  $T^c$ , respectively. Two 1-types  $\pi, \pi' \in \Pi_T$  are *cosmically connectable* if some cosmic  $\tau \in T^c$  connects them. A 1-type  $\nu$  is a *noble type* if it is not cosmically connectable with itself; the set of noble types over  $T$  is  $N_T$ . A 1-type  $\pi$  that is not a noble type is a *peasant type*; the set of peasant types is  $P_T$ . So we have  $\Pi_T = N_T \cup P_T$ ,  $K_T \subseteq N_T$  and  $P_T \subseteq W_T$ .



We think of the  $\mathbf{e}$ -classes in a  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ -structure as *galaxies*; of the whole structure as the *cosmos*; of the galactic 2-types as characterizing the interactions in the interior of the galaxies and of cosmic 2-types characterize the interactions between different galaxies.

Let  $\mathfrak{A}$  be a model for  $\mathbf{T}$ . An element realizing a noble type is a *noble element*. An element realizing a peasant type is a *peasant element*. We denote the galaxies of  $\mathfrak{A}$  by  $\mathcal{G}^{\mathfrak{A}} = \mathcal{E}^{\mathfrak{A}}$ . A galaxy  $X \in \mathcal{G}^{\mathfrak{A}}$  is a *noble galaxy* if it contains a noble element. Otherwise, that is if every  $a \in X$  is a peasant, the galaxy  $X$  is a *peasant galaxy*. The sets of noble and peasant galaxies are  $\mathcal{G}_N^{\mathfrak{A}}$  and  $\mathcal{G}_P^{\mathfrak{A}}$ , respectively. So we have  $\mathcal{G}^{\mathfrak{A}} = \mathcal{G}_N^{\mathfrak{A}} \cup \mathcal{G}_P^{\mathfrak{A}}$ . If  $X \in \mathcal{G}^{\mathfrak{A}}$  is a galaxy, denote  $\text{tp}^{\mathfrak{A}}[X] = \{ \text{tp}^{\mathfrak{A}}[a] \mid a \in X \}$  to be the set of 1-types realized by elements of  $X$ .

**Lemma 10** (Galaxy characterization). *Let  $\mathfrak{A}$  be a model for  $\mathbf{T}$ . Then:*

1. *If  $\pi \in \Pi_{\mathbf{T}}$  then some  $X \in \mathcal{G}^{\mathfrak{A}}$  has  $\pi \in \text{tp}^{\mathfrak{A}}[X]$ .  
If  $X \in \mathcal{G}^{\mathfrak{A}}$  then  $\text{tp}^{\mathfrak{A}}[X] \subseteq \Pi_{\mathbf{T}}$ , or equivalently every  $\pi \in \text{tp}^{\mathfrak{A}}[X]$  has  $\pi \in \Pi_{\mathbf{T}}$ .*
2. *Let  $X \in \mathcal{G}^{\mathfrak{A}}$ . Then  $X \in \mathcal{G}_N^{\mathfrak{A}}$  iff  $\text{tp}^{\mathfrak{A}}[X] \cap N_{\mathbf{T}} \neq \emptyset$ , or equivalently iff some  $\nu \in \text{tp}^{\mathfrak{A}}[X]$  has  $\nu \in N_{\mathbf{T}}$ .*
3. *Let  $X \in \mathcal{G}^{\mathfrak{A}}$ . Then  $X \in \mathcal{G}_P^{\mathfrak{A}}$  iff  $\text{tp}^{\mathfrak{A}}[X] \subseteq P_{\mathbf{T}}$ , or equivalently iff every  $\pi \in \text{tp}^{\mathfrak{A}}[X]$  has  $\pi \in P_{\mathbf{T}}$ .*
4. *Let  $\nu \in \Pi_{\mathbf{T}}$ . Then  $\nu \in N_{\mathbf{T}}$  iff a unique  $X \in \mathcal{G}^{\mathfrak{A}}$  has  $\nu \in \text{tp}^{\mathfrak{A}}[X]$ .*
5. *Let  $\pi \in \Pi_{\mathbf{T}}$ . Then  $\pi \in P_{\mathbf{T}}$  iff for every  $X \in \mathcal{G}^{\mathfrak{A}}$  such that  $\pi \in \text{tp}^{\mathfrak{A}}[X]$  there is some  $Y \in \mathcal{G}^{\mathfrak{A}} \setminus \{X\}$  having  $\pi \in \text{tp}^{\mathfrak{A}}[Y]$ .*

*We will be applying this lemma implicitly.*

*Proof.* 1. If  $\pi \in \Pi_{\mathbf{T}}$ , then some  $a \in A$  has  $\text{tp}^{\mathfrak{A}}[a] = \pi$ , so  $X = \mathbf{e}^{\mathfrak{A}}[a] \in \mathcal{G}^{\mathfrak{A}}$  has  $\pi \in \text{tp}^{\mathfrak{A}}[X]$ . If some  $X \in \mathcal{G}^{\mathfrak{A}}$  has  $\pi \in \text{tp}^{\mathfrak{A}}[X]$ , then some  $a \in X$  has  $\text{tp}^{\mathfrak{A}}[a] = \pi$ , so  $\pi \in \Pi_{\mathbf{T}}$ .

2. This follows by the definition of noble galaxy.

3. This follows by the definition of peasant galaxy.

4. If  $\nu \in N_{\mathbf{T}}$ , then some  $X \in \mathcal{G}^{\mathfrak{A}}$  has  $\nu \in \text{tp}^{\mathfrak{A}}[X]$ , so some  $a \in X$  has  $\text{tp}^{\mathfrak{A}}[a] = \nu$ . Suppose towards a contradiction that some other  $Y \in \mathcal{G}^{\mathfrak{A}} \setminus \{X\}$  has  $\nu \in \text{tp}^{\mathfrak{A}}[Y]$ , so some  $b \in Y$  has  $\text{tp}^{\mathfrak{A}}[b] = \nu$ . Then  $\tau = \text{tp}^{\mathfrak{A}}[a, b] \in \mathbf{T}$  is a cosmic type connecting  $\nu$  with itself — a contradiction.

Next suppose that  $\pi \in \Pi_{\mathbf{T}} \setminus N_{\mathbf{T}} = P_{\mathbf{T}}$ , so some cosmic  $\tau \in \mathbf{T}$  connects  $\pi$  with itself. Then some  $a \in A$  and  $b \in A \setminus \{a\}$  have  $\text{tp}^{\mathfrak{A}}[a, b] = \tau$ . Let  $X = \mathbf{e}^{\mathfrak{A}}[a] \in \mathcal{G}^{\mathfrak{A}}$  and  $Y = \mathbf{e}^{\mathfrak{A}}[b] \in \mathcal{G}^{\mathfrak{A}}$ . Since  $\tau$  is cosmic,  $X \neq Y$ . So we have that  $\pi \in \text{tp}^{\mathfrak{A}}[X]$  and  $\pi \in \text{tp}^{\mathfrak{A}}[Y]$  is realized in at least 2 galaxies.

## 6 Two-variable logics

5. First suppose that  $\pi \in P_T$  and that  $X \in \mathcal{G}^{\mathfrak{A}}$  has  $\pi \in \text{tp}^{\mathfrak{A}}[X]$ . Since  $\pi \notin N_T$ ,  $X$  is not unique, so there must be some other  $Y \in \mathcal{G}^{\mathfrak{A}} \setminus \{X\}$  such that  $\pi \in \text{tp}^{\mathfrak{A}}[Y]$ .

Next let  $\pi \in \Pi_T$  and suppose that for every  $X \in \mathcal{G}^{\mathfrak{A}}$  such that  $\pi \in \text{tp}^{\mathfrak{A}}[X]$  there is some  $Y \in \mathcal{G}^{\mathfrak{A}} \setminus \{X\}$  having  $\pi \in \text{tp}^{\mathfrak{A}}[Y]$ . Since  $\pi \in \Pi_T$ , some  $X \in \mathcal{G}^{\mathfrak{A}}$  has  $\pi \in \text{tp}^{\mathfrak{A}}[X]$ . Then some  $Y \in \mathcal{G}^{\mathfrak{A}} \setminus \{X\}$  has  $\pi \in \text{tp}^{\mathfrak{A}}[Y]$ , so  $\pi \notin N_T$ , so  $\pi \in P_T$ .  $\square$

Note that a noble galaxy might contain a peasant element. We will define a class of models — the *nobly distinguished* models — where this doesn't happen. For this we first define *peasantly united* models.

**Definition 71.** *The model  $\mathfrak{A}$  for  $T$  is peasantly united if whenever  $\pi \in \Pi_T$  is a peasant type that is realized in some peasant galaxy:  $\pi \in \text{tp}^{\mathfrak{A}}[X]$  for some  $X \in \mathcal{G}_P^{\mathfrak{A}}$ , then  $\pi$  is also realized in some other peasant galaxy:  $\pi \in \text{tp}^{\mathfrak{A}}[Y]$  for some  $Y \in \mathcal{G}_P^{\mathfrak{A}} \setminus \{X\}$ .*

**Lemma 11** (Peasant unitedness). *If the type instance  $T$  has a (finite) model, then it has a (finite) peasantly united model.*

*Proof.* Suppose that  $\mathfrak{A}$  is a (finite) model for  $T$ . We copy its peasant galaxies. We describe the (finite) model  $\mathfrak{A}'$  by describing its galaxies  $\mathcal{G}^{\mathfrak{A}'}$ . The noble galaxies  $\mathcal{G}_N^{\mathfrak{A}'}$  of  $\mathfrak{A}'$  coincide with the noble galaxies  $\mathcal{G}_N^{\mathfrak{A}}$  of  $\mathfrak{A}$ . The peasant galaxies  $\mathcal{G}_P^{\mathfrak{A}'}$  of  $\mathfrak{A}'$  consist of two copies  $X_1, X_2$  of each peasant galaxy  $X \in \mathcal{G}_P^{\mathfrak{A}}$  of  $\mathfrak{A}$ . This naturally induces the 1-type of every  $a \in A'$  and the 2-type between distinct elements that do not come from the two copies of the same peasant galaxy. Already at this point, the partial structure  $\mathfrak{A}'$  satisfies the existential parts eq. (6.2), so it is a *partial*  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ -structure. We proceed to complete  $\mathfrak{A}'$ . Let  $X \in \mathcal{G}_P^{\mathfrak{A}}$  be any peasant  $\mathfrak{A}$ -galaxy and let  $a_1 \in X_1$  and  $b_2 \in X_2$  be any elements from the different copies of  $X$  in  $\mathfrak{A}'$ . Note that  $a, b \in X$  and let  $\pi = \text{tp}^{\mathfrak{A}'}[a] = \text{tp}^{\mathfrak{A}}[a]$ . Since  $X$  is a peasant galaxy,  $\pi$  must be a peasant type, so some  $Y \in \mathcal{G}^{\mathfrak{A}} \setminus \{X\}$  has  $\pi \in \text{tp}^{\mathfrak{A}}[Y]$ , so some  $a' \in Y$  has  $\text{tp}^{\mathfrak{A}}[a'] = \pi$ . Then  $\tau = \text{tp}^{\mathfrak{A}}[a', b]$  is cosmic and the assignment  $\text{tp}^{\mathfrak{A}'}[a_1, b_2] = \text{tp}^{\mathfrak{A}}[a', b]$  is appropriate. The model  $\mathfrak{A}'$  is peasantly united by construction: any peasant type that is realized in a peasant galaxy  $X_i$  is also realized in the peasant galaxy  $X_{3-i}$ .  $\square$

**Definition 72.** *The model  $\mathfrak{A}$  for  $T$  is nobly distinguished if every noble galaxy contains only noble elements. That is if  $X \in \mathcal{G}_N^{\mathfrak{A}}$ , then  $\text{tp}^{\mathfrak{A}}[X] \subseteq N_T$ .*

**Definition 73.** *The (finite) nobly distinguished type realizability problem for the logic  $\mathcal{L}^2\text{eE}_{\text{refine}}$  is the following: given a classified signature  $\langle \Sigma, \bar{\mathbf{m}} \rangle$  and a type instance  $T$  over  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ , is there a (finite) nobly distinguished model for  $T$ . Denote the nobly distinguished type realizability problem by ND-TP-REALIZ- $\mathcal{L}^2\text{eE}_{\text{refine}}$  and its finite version by FIN-ND-TP-REALIZ- $\mathcal{L}^2\text{eE}_{\text{refine}}$ .*

Let  $T$  be a type instance over  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ . For every noble type  $\nu \in N_T$ , let  $\mathbf{p}^\nu$  be a new unary predicate symbol. Let  $\Sigma' = \Sigma + \langle \mathbf{p}^\nu \mid \nu \in N_T \rangle$  be an enrichment of  $\Sigma$  featuring these new symbols. Consider the following sets of literals over  $\Sigma'$ :

$$\mathbf{p}_\nu(x) = \{\mathbf{p}^\nu(x)\} \cup \left\{ \neg \mathbf{p}^{\nu'}(x) \mid \nu' \in N_T \setminus \{\nu\} \right\}.$$

## 6.2 Type realizability with equivalences

Let  $\perp$  be a special element and define the special set of literals:

$$\mathbf{p}_\perp(\mathbf{x}) = \{\neg \mathbf{p}^\nu(\mathbf{x}) \mid \nu \in N_T\}.$$

If  $\pi \in \Pi_T$  is a 1-type and  $\rho \in N_T \cup \{\perp\}$ , let  $\pi_\rho$  be the following 1-type over  $\Sigma'$ :

$$\pi_\rho = \pi \cup \mathbf{p}_\rho(\mathbf{x}).$$

We refer to  $\pi_\rho$  as the  $\rho$ -copy of  $\pi$ . If  $\tau \in T$  and  $\rho, \rho' \in N_T \cup \{\perp\}$ , let  $\tau_{\rho\rho'}$  be the following 2-type over  $\Sigma'$ :

$$\tau_{\rho\rho'} = \tau \cup \mathbf{p}_\rho(\mathbf{x}) \cup \mathbf{p}_{\rho'}(\mathbf{y}).$$

So we have  $\text{tp}_{\mathbf{x}}(\tau_{\rho\rho'}) = (\text{tp}_{\mathbf{x}}\tau)_\rho$  and  $\text{tp}_{\mathbf{y}}(\tau_{\rho\rho'}) = (\text{tp}_{\mathbf{y}}\tau)_{\rho'}$ . Define the set  $T'$  of 2-types over  $\langle \Sigma', \bar{\mathbf{m}} \rangle$  as follows:

$$T' = \{\tau_{\rho\rho'} \mid \tau \in T, \rho, \rho' \in N_T \cup \{\perp\}\}.$$

Note that  $T'$  is constructible in deterministic polynomial time from  $T$ .

**Definition 74.** A promotion for the type instance  $T$  over  $\langle \Sigma, \bar{\mathbf{m}} \rangle$  is a type instance  $T_\bullet \subseteq T'$  over  $\langle \Sigma', \bar{\mathbf{m}} \rangle$  such that for every  $\tau \in T$  there are some  $\rho, \rho' \in N_T \cup \{\perp\}$  such that  $\tau_{\rho\rho'} \in T_\bullet$ .

**Lemma 12** (Noble distinguishability). *The type instance  $T$  has a (finite) model iff there is some promotion  $T_\bullet$  for  $T$  that has a (finite) nobly distinguished model.*

*Proof.* First, suppose that  $\mathfrak{A}$  is (finite) a model for  $T$ . By [Lemma 11](#), without loss of generality assume that  $\mathfrak{A}$  is peasantly united. We define a promotion  $T_\bullet$  for  $T$  and a  $\Sigma'$ -enrichment  $\mathfrak{A}'$  that is a nobly distinguished model for  $T_\bullet$ . For every noble galaxy  $X \in \mathcal{G}_N^{\mathfrak{A}}$  choose any noble type  $\nu \in \text{tp}^{\mathfrak{A}}[X]$  realized in it and define  $X = X_\nu$ . Define the enrichment  $\mathfrak{A}'$  as follows: for every  $a \in A$ :

1. If  $a \in X_\nu$  is an element of some noble galaxy, then let  $\text{tp}^{\mathfrak{A}'}[a] = \text{tp}^{\mathfrak{A}}[a]_\nu$ .
2. Otherwise, if  $a \in X$  is an element of a peasant galaxy, then let  $\text{tp}^{\mathfrak{A}'}[a] = \text{tp}^{\mathfrak{A}}[a]_\perp$ .

Note that we have the following characterization of this construction: for every  $X \in \mathcal{G}^{\mathfrak{A}'}$ :

1. If  $\nu \in N_T$  and  $\pi_\nu \in \text{tp}^{\mathfrak{A}'}[X]$  for some  $\pi \in \Pi_T$ , then  $\nu \in \text{tp}^{\mathfrak{A}}[X]$ .  
Indeed, if  $\pi_\nu \in \text{tp}^{\mathfrak{A}'}[X]$  then some  $a \in X$  has  $\text{tp}^{\mathfrak{A}'}[a] = \pi_\nu$ , so by construction  $X = X_\nu$ , so  $\nu \in X$ .
2. If  $\pi \in \Pi_T$  and  $\pi_\perp \in \text{tp}^{\mathfrak{A}'}[X]$ , then  $X \in \mathcal{G}_P^{\mathfrak{A}}$  is a peasant galaxy and  $\pi \in \text{tp}^{\mathfrak{A}}[X]$  is a peasant type.

Indeed, if  $\pi_\perp \in \text{tp}^{\mathfrak{A}'}[X]$  then some  $a \in X$  has  $\text{tp}^{\mathfrak{A}'}[a] = \pi_\perp$ , so by construction  $X \in \mathcal{G}_P^{\mathfrak{A}}$  and  $\text{tp}^{\mathfrak{A}'}[a] = \text{tp}^{\mathfrak{A}}[a]_\perp$ , so  $\pi = \text{tp}^{\mathfrak{A}}[a] \in \text{tp}^{\mathfrak{A}}[X]$  is a peasant type.

Let  $T_\bullet = T[\mathfrak{A}']$  be the type instance of  $\mathfrak{A}'$ . By construction  $T_\bullet \subseteq T'$ . If  $\tau \in T$ , then some  $a \in A$  and  $b \in A \setminus \{a\}$  have  $\text{tp}^{\mathfrak{A}}[a, b] = \tau$ . Let  $\text{tp}^{\mathfrak{A}'}[a] = \text{tp}^{\mathfrak{A}}[a]_\rho$  and  $\text{tp}^{\mathfrak{A}'}[b] = \text{tp}^{\mathfrak{A}}[b]_{\rho'}$ , so  $\tau_{\rho\rho'} = \text{tp}^{\mathfrak{A}'}[a, b] \in T_\bullet$ . So  $T_\bullet$  is a promotion of  $T$ .

We claim that  $\pi' \in \Pi_{T_\bullet}$  is a noble type iff  $\pi' = \pi_\nu$  for some  $\pi \in \Pi_T$  and  $\nu \in N_T$ , or equivalently:

$$N_{T_\bullet} = \{\pi_\nu \in \Pi_{T_\bullet} \mid \pi \in \Pi_T, \nu \in N_T\}.$$

First, suppose that  $\pi_\nu \in \Pi_{T_\bullet}$  for some  $\pi \in \Pi_T$  and  $\nu \in N_T$ . Let  $X \in \mathcal{G}^{\mathfrak{A}'}$  be such that  $\pi_\nu \in \text{tp}^{\mathfrak{A}'}[X]$ . Suppose towards a contradiction that  $\pi_\nu \in P_{T_\bullet}$  is a peasant type. Then there is some  $Y \in \mathcal{G}^{\mathfrak{A}'} \setminus \{X\}$  such that  $\pi_\nu \in \text{tp}^{\mathfrak{A}'}[Y]$ . Then by construction  $\nu \in \text{tp}^{\mathfrak{A}}[X]$  and  $\nu \in \text{tp}^{\mathfrak{A}}[Y]$  — a contradiction.

Next, suppose that  $\pi_\perp \in \Pi_{T_\bullet}$  and let  $X \in \mathcal{G}^{\mathfrak{A}'}$  be such that  $\pi_\perp \in \text{tp}^{\mathfrak{A}'}[X]$ . Then by construction  $X \in \mathcal{G}_P^{\mathfrak{A}}$  is a peasant galaxy and  $\pi \in \text{tp}^{\mathfrak{A}}[X]$  is a peasant type. Since  $\mathfrak{A}$  is peasantly united, there is some  $Y \in \mathcal{G}_P^{\mathfrak{A}} \setminus \{X\}$  having  $\pi \in \text{tp}^{\mathfrak{A}}[Y]$ . So by construction  $\pi_\perp = \text{tp}^{\mathfrak{A}'}[Y]$ , so  $\pi_\perp \in P_{T_\bullet}$ .

Finally, we check that  $\mathfrak{A}'$  is nobly distinguished. Indeed, let  $X \in \mathcal{G}_N^{\mathfrak{A}'}$  be any noble galaxy. Then some  $a \in X$  has  $\text{tp}^{\mathfrak{A}'}[a] \in N_{T_\bullet}$ , so  $X = X_\nu$  for some noble  $\nu \in N_T$ . Let  $b \in X$  be any. Then by construction  $\text{tp}^{\mathfrak{A}'}[b] = \text{tp}^{\mathfrak{A}}[b]_\nu$ , so  $\text{tp}^{\mathfrak{A}'}[X] \subseteq N_{T_\bullet}$ .

Next, suppose that  $T_\bullet$  is any promotion of  $T$  and that  $\mathfrak{A}'$  is model for  $T_\bullet$ . Then the reduct of  $\mathfrak{A}'$  to a  $\Sigma$ -structure is a model for  $T$  by the promotion condition that if  $\tau \in T$  then  $\tau_{\rho\rho'} \in T_\bullet$  for some  $\rho, \rho' \in N_T \cup \{\perp\}$ .  $\square$

**Corollary 4.** *The (finite) type realizability problem is reducible in nondeterministic polynomial time to the (finite) nobly distinguished type realizability problem.*

$$(\text{FIN-})\text{TP-REALIZ-}\mathcal{L}^2eE_{\text{refine}} \leq_m^{\text{NPTIME}} (\text{FIN-})\text{ND-TP-REALIZ-}\mathcal{L}^2eE_{\text{refine}}.$$

**Remark 57.** *Suppose that  $\mathfrak{A}$  is a nobly distinguished model for  $T$ . Then  $\mathfrak{A}$  is peasantly united.*

*Proof.* Suppose that  $\pi \in P_T$  is a peasant type,  $X \in \mathcal{G}_P^{\mathfrak{A}}$  is a peasant galaxy and  $\pi \in \text{tp}^{\mathfrak{A}}[X]$ . Since  $\pi$  is a peasant type, some  $Y \in \mathcal{G}^{\mathfrak{A}} \setminus \{X\}$  has  $\pi \in \text{tp}^{\mathfrak{A}}[Y]$ . Since  $\mathfrak{A}$  is nobly distinguished,  $Y \in \mathcal{G}_P^{\mathfrak{A}}$  is a peasant galaxy. Hence  $\mathfrak{A}$  is peasantly united.  $\square$

### 6.3 Cosmic spectrums

Let  $T$  be a type instance over the  $\mathcal{L}^2eE_{\text{refine}}$ -classified signature  $\langle \Sigma, \bar{m} \rangle$ .

**Definition 75.** *A cosmic spectrum  $\varsigma = (\varsigma^{\mathcal{II}}, \varsigma^{\mathcal{IE}}, \varsigma^{\mathcal{EI}}, \varsigma^{\mathcal{EE}})$  over  $T$  consists of four sets of 2-types satisfying the following conditions:*

( $\varsigma^{\mathcal{II}}$ ) *The set of internal types  $\varsigma^{\mathcal{II}} \subseteq T^g$  is a set of galactic types that is closed under inversion.*

( $\varsigma^{\mathcal{IE}}$ ) *The set of boundary types  $\varsigma^{\mathcal{IE}} \subseteq T^c$  is a nonempty set of cosmic types.*

- ( $\varsigma\mathcal{EI}$ ) The set of inverted boundary types is:  $\varsigma^{\mathcal{EI}} = \{\tau^{-1} \mid \tau \in \varsigma^{\mathcal{IE}}\}$ .
- ( $\varsigma\mathcal{EE}$ ) The set of external types  $\varsigma^{\mathcal{EE}} \subseteq \mathbf{T}$  is a set of 2-types that is closed under inversion.
- ( $\varsigma\mathbf{T}$ ) We require that  $\mathbf{T} = \varsigma^{\mathcal{II}} \cup \varsigma^{\mathcal{IE}} \cup \varsigma^{\mathcal{EI}} \cup \varsigma^{\mathcal{EE}}$ .
- ( $\varsigma\mathbf{NP}$ ) The (nonempty) set  $\mathbf{Tp}_x \varsigma = (\text{tp}_x \upharpoonright \varsigma^{\mathcal{IE}})$  is the set of internal 1-types of  $\varsigma$ . The (nonempty) set  $\mathbf{Tp}_y \varsigma = (\text{tp}_y \upharpoonright \varsigma^{\mathcal{IE}})$  is the set of external 1-types of  $\varsigma$ . We require that either  $\mathbf{Tp}_x \varsigma \subseteq \mathbf{N}_\mathbf{T}$ , in which case  $\varsigma$  is a noble cosmic spectrum, or  $\mathbf{Tp}_x \varsigma \subseteq \mathbf{P}_\mathbf{T}$ , in which case  $\varsigma$  is a peasant cosmic spectrum. Note that a 1-type may be both internal and external.

For any 1-type  $\pi$  or a 2-type  $\tau$  over  $\Sigma$  denote by  $\pi^{-e}$  or  $\tau^{-e}$  the reducts of  $\pi$  and  $\tau$  to the language  $\Sigma - \langle e \rangle$ . That is,  $\pi^{-e} \subset \pi$  and  $\tau^{-e} \subset \tau$  consist of those literals that do not feature  $e$ . Let  $\mathbf{in}$  be a new unary predicate symbol and let  $\Sigma' = \Sigma - \langle e \rangle + \langle \mathbf{in} \rangle$  be the predicate signature obtained from  $\Sigma$  by removing the coarsest equivalence symbol  $e$  and adding the new predicate symbol  $\mathbf{in}$ . Define the following 1-types and 2-types over  $\Sigma'$ :

$$\begin{aligned}\pi_{\mathcal{I}} &= \pi^{-e} \cup \{\mathbf{in}(x)\} \\ \pi_{\mathcal{E}} &= \pi^{-e} \cup \{\neg \mathbf{in}(x)\} \\ \tau_{\mathcal{II}} &= \tau^{-e} \cup \{\mathbf{in}(x), \mathbf{in}(y)\} \\ \tau_{\mathcal{IE}} &= \tau^{-e} \cup \{\mathbf{in}(x), \neg \mathbf{in}(y)\} \\ \tau_{\mathcal{EI}} &= \tau^{-e} \cup \{\neg \mathbf{in}(x), \mathbf{in}(y)\} \\ \tau_{\mathcal{EE}} &= \tau^{-e} \cup \{\neg \mathbf{in}(x), \neg \mathbf{in}(y)\}.\end{aligned}$$

Note that we have  $\text{tp}_x(\tau_{\mathcal{XY}}) = (\text{tp}_x \tau)_{\mathcal{X}}$  and  $\text{tp}_y(\tau_{\mathcal{XY}}) = (\text{tp}_y \tau)_{\mathcal{Y}}$  for  $\mathcal{X}, \mathcal{Y} \in \{\mathcal{I}, \mathcal{E}\}$ .

**Definition 76.** The spectral type instance  $\mathbf{T}^\varsigma$  of the cosmic spectrum  $\varsigma$  is a type instance over the simpler  $\mathcal{L}^2(e-1)\mathbf{E}_{\text{refine}}$ -classified signature  $\langle \Sigma', \bar{\mathbf{m}} \rangle$  defined as follows:

$$\mathbf{T}^\varsigma = \mathbf{T}_{\mathcal{II}}^\varsigma \cup \mathbf{T}_{\mathcal{IE}}^\varsigma \cup \mathbf{T}_{\mathcal{EI}}^\varsigma \cup \mathbf{T}_{\mathcal{EE}}^\varsigma,$$

where  $\mathbf{T}_{\mathcal{XY}}^\varsigma = \{\tau_{\mathcal{XY}} \mid \tau \in \varsigma^{\mathcal{XY}}\}$  for  $\mathcal{X}, \mathcal{Y} \in \{\mathcal{I}, \mathcal{E}\}$ . Note that  $\mathbf{T}^\varsigma$  is constructible in deterministic polynomial time from  $\mathbf{T}$  and  $\varsigma$ .

This is indeed a type instance, since  $\mathbf{T}_{\mathcal{IE}}^\varsigma$  is nonempty by ( $\varsigma\mathcal{IE}$ ) and since  $\mathbf{T}_{\mathcal{II}}^\varsigma$ ,  $(\mathbf{T}_{\mathcal{IE}}^\varsigma \cup \mathbf{T}_{\mathcal{EI}}^\varsigma)$  and  $\mathbf{T}_{\mathcal{EE}}^\varsigma$  are closed under inversion by ( $\varsigma\mathcal{II}$ ), ( $\varsigma\mathcal{EI}$ ) and ( $\varsigma\mathcal{EE}$ ). The size of a cosmic spectrum over a type instance is linear with respect to the size of the type instance. Define  $\Pi_{\mathcal{I}}^\varsigma = \{\pi_{\mathcal{I}} \mid \pi \in \mathbf{Tp}_x \varsigma\} = (\text{tp}_x \upharpoonright \mathbf{T}_{\mathcal{IE}}^\varsigma)$  to be the set of *internal spectral 1-types* and  $\Pi_{\mathcal{E}}^\varsigma = \{\pi_{\mathcal{E}} \mid \pi \in \mathbf{Tp}_y \varsigma\} = (\text{tp}_y \upharpoonright \mathbf{T}_{\mathcal{IE}}^\varsigma)$  to be the set of *external spectral 1-types*.

**Definition 77.** The cosmic spectrum  $\varsigma$  is locally consistent if its spectral type instance  $\mathbf{T}^\varsigma$  has a model.

**Definition 78.** Let  $\mathfrak{A}$  be a nobly distinguished model for  $\mathbf{T}$  such that  $E = e^{\mathfrak{A}} \neq A \times A$  is not full on  $A$  (equivalently, there are at least 2 galaxies). If  $X \in \mathcal{G}^{\mathfrak{A}}$  is any galaxy, the cosmic spectrum  $\varsigma = \text{csp}^{\mathfrak{A}}[X]$  of  $X$  is defined by:

$$\begin{aligned}\varsigma^{\mathcal{II}} &= \left\{ \text{tp}^{\mathfrak{A}}[a, b] \mid a \in X, b \in X \setminus \{a\} \right\} \\ \varsigma^{\mathcal{IE}} &= \left\{ \text{tp}^{\mathfrak{A}}[a, b] \mid a \in X, b \in A \setminus X \right\} \\ \varsigma^{\mathcal{EI}} &= \left\{ \text{tp}^{\mathfrak{A}}[a, b] \mid a \in A \setminus X, b \in X \right\} \\ \varsigma^{\mathcal{EE}} &= \left\{ \text{tp}^{\mathfrak{A}}[a, b] \mid a \in A \setminus X, b \in (A \setminus X) \setminus \{a\} \right\}.\end{aligned}$$

**Remark 58.** Indeed  $\varsigma = \text{csp}^{\mathfrak{A}}[X]$  is a locally consistent cosmic spectrum over  $\mathbf{T}$  in the sense of [Definition 77](#).

*Proof.* First we check that  $\varsigma$  is a cosmic spectrum over  $\mathbf{T}$  in the sense of [Definition 75](#).

- ( $\varsigma^{\mathcal{II}}$ ) If  $\tau \in \varsigma^{\mathcal{II}}$ , then  $\tau = \text{tp}^{\mathfrak{A}}[a, b]$  for some  $a \in X$  and  $b \in X \setminus \{a\}$ , so  $\tau$  is galactic and  $\tau^{-1} = \text{tp}^{\mathfrak{A}}[b, a] \in \varsigma^{\mathcal{II}}$ , so  $\varsigma^{\mathcal{II}}$  is closed under inversion.
- ( $\varsigma^{\mathcal{IE}}$ ) First, since  $E$  is not full on  $A$ , there is some  $a \in X$  and  $b \in A \setminus X$ , so  $\text{tp}^{\mathfrak{A}}[a, b] \in \varsigma^{\mathcal{IE}}$ , so  $\varsigma^{\mathcal{IE}}$  is nonempty. Next, if  $\tau \in \varsigma^{\mathcal{IE}}$  then  $\tau = \text{tp}^{\mathfrak{A}}[a, b]$  for some  $a \in X$  and  $b \in A \setminus X$ , so  $\tau$  is cosmic.
- ( $\varsigma^{\mathcal{EI}}$ ) If  $\tau \in \varsigma^{\mathcal{EI}}$ , then  $\tau = \text{tp}^{\mathfrak{A}}[a, b]$  for some  $a \in X$  and  $b \in A \setminus X$ , so  $\tau^{-1} = \text{tp}^{\mathfrak{A}}[b, a] \in \varsigma^{\mathcal{EI}}$ . If  $\tau \in \varsigma^{\mathcal{EI}}$ , then  $\tau = \text{tp}^{\mathfrak{A}}[a, b]$  for some  $a \in A \setminus X$  and  $b \in X$ , so  $\tau^{-1} = \text{tp}^{\mathfrak{A}}[b, a] \in \varsigma^{\mathcal{IE}}$ , so  $\tau = \tau'^{-1}$  for  $\tau' = \tau^{-1} \in \varsigma^{\mathcal{IE}}$ .
- ( $\varsigma^{\mathcal{EE}}$ ) If  $\tau \in \varsigma^{\mathcal{EE}}$ , then  $\tau = \text{tp}^{\mathfrak{A}}[a, b]$  for some  $a \in A \setminus X$  and  $b \in (A \setminus X) \setminus \{a\}$ , so  $\tau^{-1} = \text{tp}^{\mathfrak{A}}[b, a] \in \varsigma^{\mathcal{EE}}$  and hence  $\varsigma^{\mathcal{EE}}$  is closed under inversion.
- ( $\varsigma^{\mathbf{T}}$ ) We have that  $\varsigma^{\mathcal{II}} \cup \varsigma^{\mathcal{IE}} \cup \varsigma^{\mathcal{EI}} \cup \varsigma^{\mathcal{EE}} = \left\{ \text{tp}^{\mathfrak{A}}[a, b] \mid a \in A, b \in A \setminus \{a\} \right\} = \mathbf{T}$  since  $\mathfrak{A}$  is a model for  $\mathbf{T}$ .
- ( $\varsigma^{\text{NP}}$ ) First suppose that  $X$  is a noble galaxy. Let  $\pi \in \text{Tp}_x \varsigma$ , so some  $\tau \in \varsigma^{\mathcal{IE}}$  has  $\text{tp}_x \tau = \pi$ , so some  $a \in X$  and  $b \in A \setminus X$  has  $\text{tp}^{\mathfrak{A}}[a, b] = \tau$ , so  $\pi = \text{tp}^{\mathfrak{A}}[a]$  is noble, since  $\mathfrak{A}$  is nobly distinguished. Next suppose that  $X$  is a peasant galaxy. Similarly, let  $\pi \in \text{Tp}_x \varsigma$ , so some  $\tau \in \varsigma^{\mathcal{EI}}$  has  $\text{tp}_x \tau = \pi$ , so some  $a \in X$  and  $b \in A \setminus X$  has  $\text{tp}^{\mathfrak{A}}[a, b] = \tau$ , so  $\pi = \text{tp}^{\mathfrak{A}}[a]$  is peasant, since  $X$  is a peasant galaxy.

We transform  $\mathfrak{A}$  to a  $\langle \Sigma', \bar{\mathbf{m}} \rangle$ -structure  $\mathfrak{A}'$  by forgetting the interpretation of  $e$  and by interpreting  $\mathbf{in}^{\mathfrak{A}'} = X$ . Then:

$$\begin{aligned}\text{tp}^{\mathfrak{A}'}[a, b] &= \text{tp}^{\mathfrak{A}}[a, b]_{\mathcal{II}} \text{ if } a \in X, b \in X \setminus \{a\} \\ \text{tp}^{\mathfrak{A}'}[a, b] &= \text{tp}^{\mathfrak{A}}[a, b]_{\mathcal{IE}} \text{ if } a \in X, b \in A \setminus X \\ \text{tp}^{\mathfrak{A}'}[a, b] &= \text{tp}^{\mathfrak{A}}[a, b]_{\mathcal{EI}} \text{ if } a \in A \setminus X, b \in X \\ \text{tp}^{\mathfrak{A}'}[a, b] &= \text{tp}^{\mathfrak{A}}[a, b]_{\mathcal{EE}} \text{ if } a \in A \setminus X, b \in (A \setminus X) \setminus \{a\}.\end{aligned}$$

This shows that  $\mathfrak{A}'$  is a model for  $\mathbf{T}^{\varsigma}$ , so  $\varsigma$  is locally consistent.  $\square$

## 6.4 Locally consistent cosmic spectrums

Let  $\varsigma$  be a locally consistent cosmic spectrum over  $T$ .

**Lemma 13** (Spectral characterization). *Let  $\mathfrak{A}^\varsigma$  be a model for the spectral type instance  $T^\varsigma$  and let  $X^\varsigma = \mathbf{in}^{\mathfrak{A}^\varsigma}$  be the set of internal spectral elements. Then:*

$$\begin{aligned} T_{II}^\varsigma &= \left\{ \text{tp}^{\mathfrak{A}^\varsigma}[a, b] \mid a \in X^\varsigma, b \in X^\varsigma \setminus \{a\} \right\} \\ T_{IE}^\varsigma &= \left\{ \text{tp}^{\mathfrak{A}^\varsigma}[a, b] \mid a \in X^\varsigma, b \in A^\varsigma \setminus X^\varsigma \right\} \\ T_{EI}^\varsigma &= \left\{ \text{tp}^{\mathfrak{A}^\varsigma}[a, b] \mid a \in A^\varsigma \setminus X^\varsigma, b \in X^\varsigma \right\} \\ T_{EE}^\varsigma &= \left\{ \text{tp}^{\mathfrak{A}^\varsigma}[a, b] \mid a \in A^\varsigma \setminus X^\varsigma, b \in (A^\varsigma \setminus X^\varsigma) \setminus \{a\} \right\} \\ \Pi_I^\varsigma &= \left\{ \text{tp}^{\mathfrak{A}^\varsigma}[a] \mid a \in X^\varsigma \right\} \\ \Pi_E^\varsigma &= \left\{ \text{tp}^{\mathfrak{A}^\varsigma}[a] \mid a \in A^\varsigma \setminus X^\varsigma \right\}. \end{aligned}$$

In other words:

1. If  $\tau \in \varsigma^{II}$  then  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{II}$  for some  $a \in X^\varsigma$  and  $b \in X^\varsigma \setminus \{a\}$ .  
If  $a \in X^\varsigma$  and  $b \in X^\varsigma \setminus \{a\}$  then some  $\tau \in \varsigma^{II}$  has  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{II}$ .
2. If  $\tau \in \varsigma^{IE}$  then  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{IE}$  for some  $a \in X^\varsigma$  and  $b \in A^\varsigma \setminus X^\varsigma$ .  
If  $a \in X^\varsigma$  and  $b \in A^\varsigma \setminus X^\varsigma$  then some  $\tau \in \varsigma^{IE}$  has  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{IE}$ .
3. If  $\tau \in \varsigma^{EI}$  then  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{EI}$  for some  $a \in A^\varsigma \setminus X^\varsigma$  and  $b \in X^\varsigma$ .  
If  $a \in A^\varsigma \setminus X^\varsigma$  and  $b \in X^\varsigma$  then some  $\tau \in \varsigma^{EI}$  has  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{EI}$ .
4. If  $\tau \in \varsigma^{EE}$  then  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{EE}$  for some  $a \in A^\varsigma \setminus X^\varsigma$  and  $b \in (A^\varsigma \setminus X^\varsigma) \setminus \{a\}$ .  
If  $a \in A^\varsigma \setminus X^\varsigma$  and  $b \in (A^\varsigma \setminus X^\varsigma) \setminus \{a\}$  then some  $\tau \in \varsigma^{EE}$  has  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{EE}$ .
5. Both  $X^\varsigma$  and  $A^\varsigma \setminus X^\varsigma$  are nonempty.
6. If  $\pi \in \text{Tp}_x \varsigma$  then some  $a \in X$  has  $\text{tp}^{\mathfrak{A}^\varsigma}[a] = \pi_I$ .  
If  $a \in X$  then  $\text{tp}^{\mathfrak{A}^\varsigma}[a] = \pi_I$  for some  $\pi \in \text{Tp}_x \varsigma$ .
7. If  $\pi \in \text{Tp}_y \varsigma$  then some  $a \in A^\varsigma \setminus X^\varsigma$  has  $\text{tp}^{\mathfrak{A}^\varsigma}[a] = \pi_E$ .  
If  $a \in A^\varsigma \setminus X^\varsigma$  then  $\text{tp}^{\mathfrak{A}^\varsigma}[a] = \pi_E$  for some  $\pi \in \text{Tp}_y \varsigma$ .

We will be applying this lemma implicitly.

*Proof.* 1. If  $\tau \in \varsigma^{II}$  then  $\tau_{II} \in T_{II}^\varsigma \subseteq T^\varsigma$ , so some  $a \in A^\varsigma$  and  $b \in A^\varsigma \setminus \{a\}$  have  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{II}$ . We have that  $\mathbf{in}(\mathbf{x}) \in (\text{tp}_x \tau)_I = \text{tp}_x(\tau_{II}) = \text{tp}^{\mathfrak{A}^\varsigma}[a]$ , so  $a \in X^\varsigma$ . Similarly,  $\mathbf{in}(\mathbf{x}) \in (\text{tp}_y \tau)_I = \text{tp}_y(\tau_{II}) = \text{tp}^{\mathfrak{A}^\varsigma}[b]$ , so  $b \in X^\varsigma \setminus \{a\}$ .

Next, suppose that  $a \in X^\varsigma$  and  $b \in X^\varsigma \setminus \{a\}$  and let  $\tau' = \text{tp}^{\mathfrak{A}^\varsigma}[a, b]$ . Then  $\mathbf{in}(\mathbf{x}) \in \text{tp}^{\mathfrak{A}^\varsigma}[a] = \text{tp}_x \tau'$  and  $\mathbf{in}(\mathbf{x}) \in \text{tp}^{\mathfrak{A}^\varsigma}[b] = \text{tp}_y \tau'$ , so  $\tau' = \tau_{II}$  for some  $\tau \in \varsigma^{II}$ .

## 6 Two-variable logics

2. If  $\tau \in \varsigma^{\mathcal{IE}}$  then  $\tau_{\mathcal{IE}} \in T_{\mathcal{IE}}^\varsigma \subseteq T^\varsigma$ , so some  $a \in A^\varsigma$  and  $b \in A^\varsigma \setminus \{a\}$  have  $\text{tp}^{\mathfrak{A}}[a, b] = \tau_{\mathcal{IE}}$ . We have that  $\text{in}(\mathbf{x}) \in (\text{tp}_x \tau)_{\mathcal{I}} = \text{tp}_x(\tau_{\mathcal{IE}}) = \text{tp}^{\mathfrak{A}^\varsigma}[a]$ , so  $a \in X^\varsigma$ . Similarly,  $(\neg \text{in}(\mathbf{x})) \in (\text{tp}_y \tau)_{\mathcal{E}} = \text{tp}_y(\tau_{\mathcal{IE}}) = \text{tp}^{\mathfrak{A}}[b]$ , so  $b \in A^\varsigma \setminus X^\varsigma$ .  
Next, suppose that  $a \in X^\varsigma$  and  $b \in A^\varsigma \setminus X^\varsigma$ . and let  $\tau' = \text{tp}^{\mathfrak{A}^\varsigma}[a, b]$ . Then  $\text{in}(\mathbf{x}) \in \text{tp}^{\mathfrak{A}^\varsigma}[a] = \text{tp}_x \tau'$  and  $(\neg \text{in}(\mathbf{x})) \in \text{tp}^{\mathfrak{A}^\varsigma}[b] = \text{tp}_y \tau'$ , so  $\tau' = \tau_{\mathcal{IE}}$  for some  $\tau \in \varsigma^{\mathcal{IE}}$ .
3. If  $\tau \in \varsigma^{\mathcal{EI}}$  then  $\tau^{-1} \in \varsigma^{\mathcal{IE}}$ , so some  $a \in X^\varsigma$  and  $b \in A^\varsigma \setminus X^\varsigma$  have  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = (\tau^{-1})_{\mathcal{IE}}$ , so  $\text{tp}^{\mathfrak{A}^\varsigma}[b, a] = \tau_{\mathcal{EI}}$ .  
If  $a \in A^\varsigma \setminus X^\varsigma$  and  $b \in X^\varsigma$  then some  $\tau \in \varsigma^{\mathcal{IE}}$  has  $\text{tp}^{\mathfrak{A}^\varsigma}[b, a] = \tau_{\mathcal{IE}}$ , so  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau'_{\mathcal{EI}}$  for  $\tau' = \tau^{-1} \in \varsigma^{\mathcal{EI}}$ .
4. If  $\tau \in \varsigma^{\mathcal{EE}}$  then  $\tau_{\mathcal{EE}} \in T_{\mathcal{EE}}^\varsigma \subseteq T^\varsigma$ , so some  $a \in A^\varsigma$  and  $b \in A^\varsigma \setminus \{a\}$  have  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{\mathcal{EE}}$ . We have that  $(\neg \text{in}(\mathbf{x})) \in (\text{tp}_x \tau)_{\mathcal{E}} = \text{tp}_x(\tau_{\mathcal{EE}}) = \text{tp}^{\mathfrak{A}^\varsigma}[a]$ , so  $a \in A^\varsigma \setminus X^\varsigma$ . Similarly,  $(\neg \text{in}(\mathbf{x})) \in (\text{tp}_y \tau)_{\mathcal{E}} = \text{tp}_y(\tau_{\mathcal{EE}}) = \text{tp}^{\mathfrak{A}^\varsigma}[b]$ , so  $b \in (A^\varsigma \setminus X^\varsigma) \setminus \{a\}$ .  
Next, suppose that  $a \in A^\varsigma \setminus X^\varsigma$  and  $b \in (A^\varsigma \setminus X^\varsigma) \setminus \{a\}$  and let  $\tau' = \text{tp}^{\mathfrak{A}^\varsigma}[a, b]$ . Then  $(\neg \text{in}(\mathbf{x})) \in \text{tp}^{\mathfrak{A}^\varsigma}[a] = \text{tp}_x \tau'$  and  $(\neg \text{in}(\mathbf{x})) \in \text{tp}^{\mathfrak{A}^\varsigma}[b] = \text{tp}_y \tau'$ , so  $\tau' = \tau_{\mathcal{EE}}$  for some  $\tau \in \varsigma^{\mathcal{EE}}$ .
5.  $\varsigma^{\mathcal{IE}}$  is nonempty by  $(\varsigma^{\mathcal{IE}})$ , so let  $\tau \in \varsigma^{\mathcal{IE}}$  be any. Then some  $a \in X^\varsigma$  and  $b \in A^\varsigma \setminus X^\varsigma$  have  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{\mathcal{IE}}$ , so in particular both  $X^\varsigma$  and  $A^\varsigma \setminus X^\varsigma$  are nonempty.
6. If  $\pi \in \text{Tp}_x \varsigma$  then some  $\tau \in \varsigma^{\mathcal{IE}}$  has  $\text{tp}_x \tau = \pi$ , so some  $a \in X^\varsigma$  and  $b \in A \setminus X^\varsigma$  have  $\text{tp}^{\mathfrak{A}}[a, b] = \tau_{\mathcal{IE}}$ , so  $\text{tp}^{\mathfrak{A}^\varsigma}[a] = \pi_{\mathcal{I}}$ .  
Next, suppose that  $a \in X^\varsigma$ . Let  $b \in A^\varsigma \setminus X^\varsigma$ , which is nonempty. Then  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{\mathcal{IE}}$  for some  $\tau \in \varsigma^{\mathcal{IE}}$ . Then  $\pi = \text{tp}_x \tau \in \text{Tp}_x \varsigma$ . Then  $\text{tp}^{\mathfrak{A}^\varsigma}[a] = \text{tp}_x(\tau_{\mathcal{IE}}) = \pi_{\mathcal{I}}$ .
7. If  $\pi \in \text{Tp}_y \varsigma$ , then some  $\tau \in \varsigma^{\mathcal{IE}}$  has  $\text{tp}_y \tau = \pi$ , so some  $a \in X^\varsigma$  and  $b \in A \setminus X^\varsigma$  have  $\text{tp}^{\mathfrak{A}}[a, b] = \tau_{\mathcal{IE}}$ , so  $\text{tp}^{\mathfrak{A}^\varsigma}[b] = \pi_{\mathcal{E}}$ .  
Next, suppose that  $b \in X^\varsigma$ . Let  $a \in A^\varsigma \setminus X^\varsigma$ , which is nonempty. Then  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{\mathcal{IE}}$  for some  $\tau \in \varsigma^{\mathcal{IE}}$ . Then  $\pi = \text{tp}_y \tau \in \text{Tp}_y \varsigma$ . Then  $\text{tp}^{\mathfrak{A}^\varsigma}[b] = \text{tp}_y(\tau_{\mathcal{IE}}) = \pi_{\mathcal{E}}$ .

□

**Remark 59.** We have that  $\Pi_{T^\varsigma} = \Pi_{\mathcal{I}}^\varsigma \cup \Pi_{\mathcal{E}}^\varsigma$ .

*Proof.* Let  $\mathfrak{A}^\varsigma$  be a model for  $T^\varsigma$  and let  $X^\varsigma = \text{in}^{\mathfrak{A}^\varsigma}$  be the set of internal spectral elements. Then

$$\Pi_{T^\varsigma} = \left\{ \text{tp}^{\mathfrak{A}^\varsigma}[a] \mid a \in A^\varsigma \right\} = \left\{ \text{tp}^{\mathfrak{A}^\varsigma}[a] \mid a \in X^\varsigma \right\} \cup \left\{ \text{tp}^{\mathfrak{A}^\varsigma}[a] \mid a \in A^\varsigma \setminus X^\varsigma \right\} = \Pi_{\mathcal{I}}^\varsigma \cup \Pi_{\mathcal{E}}^\varsigma$$

by Lemma 8 and by Lemma 13. □

**Remark 60.** If  $\tau \in \varsigma^{\mathcal{II}}$  then  $\text{tp}_x \tau \in \text{Tp}_x \varsigma$ . If  $\tau \in \varsigma^{\mathcal{EE}}$  then  $\text{tp}_x \tau \in \text{Tp}_y \varsigma$ . Equivalently,  $(\text{tp}_x \upharpoonright \varsigma^{\mathcal{II}}) \subseteq \text{Tp}_x \varsigma$  and  $(\text{tp}_x \upharpoonright \varsigma^{\mathcal{EE}}) \subseteq \text{Tp}_y \varsigma$ .



*Proof.* Let  $\mathfrak{A}^\varsigma$  be a model for  $T^\varsigma$  and let  $X^\varsigma = \mathbf{in}^{\mathfrak{A}^\varsigma}$  be the set of internal spectral elements.

If  $\tau \in \varsigma^{\mathcal{II}}$  then some  $a \in X^\varsigma$  and  $b \in X^\varsigma \setminus \{a\}$  have  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{\mathcal{II}}$ , so  $\text{tp}^{\mathfrak{A}^\varsigma}[a] = \text{tp}_x(\tau_{\mathcal{II}}) = (\text{tp}_x \tau)_{\mathcal{I}}$ , so  $\text{tp}_x \tau \in \text{Tp}_x \varsigma$ .

If  $\tau \in \varsigma^{\mathcal{EE}}$  then some  $a \in A^\varsigma \setminus X^\varsigma$  and  $b \in A^\varsigma \setminus X^\varsigma \setminus \{a\}$  have  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{\mathcal{EE}}$ , so  $\text{tp}^{\mathfrak{A}^\varsigma}[a] = \text{tp}_x(\tau_{\mathcal{EE}}) = (\text{tp}_x \tau)_{\mathcal{E}}$ , so  $\text{tp}_x \tau \in \text{Tp}_y \varsigma$ .  $\square$

**Remark 61.** We have that  $\Pi_T = \text{Tp}_x \varsigma \cup \text{Tp}_y \varsigma$ .

*Proof.* Let  $\pi \in \Pi_T$  be any 1-type, so some  $\tau \in T$  has  $\text{tp}_x \tau = \pi$ . By  $(\varsigma T)$  we have that  $\tau \in \varsigma^{\mathcal{II}} \cup \varsigma^{\mathcal{IE}} \cup \varsigma^{\mathcal{EI}} \cup \varsigma^{\mathcal{EE}}$ . If  $\tau \in \varsigma^{\mathcal{II}}$ , then  $\pi \in \text{Tp}_x \varsigma$  by Remark 60. If  $\tau \in \varsigma^{\mathcal{IE}}$ , then  $\pi \in \text{Tp}_x \varsigma$  by definition. If  $\tau \in \varsigma^{\mathcal{EI}}$ , then  $\tau^{-1} \in \varsigma^{\mathcal{IE}}$ , so  $\pi = \text{tp}_x \tau = \text{tp}_y(\tau^{-1}) \in \text{Tp}_y \varsigma$  by definition. If  $\tau \in \varsigma^{\mathcal{EE}}$ , then  $\pi \in \text{Tp}_y \varsigma$  by Remark 60.  $\square$

**Remark 62.** If  $\pi \in \text{Tp}_x \varsigma$  and  $\pi' \in \text{Tp}_y \varsigma$ , then some  $\tau \in \varsigma^{\mathcal{IE}}$  has  $\text{tp}_x \tau = \pi$  and  $\text{tp}_y \tau = \pi'$ .

*Proof.* Let  $\mathfrak{A}^\varsigma$  be a model for  $T^\varsigma$  and let  $X^\varsigma = \mathbf{in}^{\mathfrak{A}^\varsigma}$  be the set of internal spectral elements. Then some  $a \in X^\varsigma$  has  $\text{tp}^{\mathfrak{A}^\varsigma}[a] = \pi_{\mathcal{I}}$  and some  $b \in A^\varsigma \setminus X^\varsigma$  has  $\text{tp}^{\mathfrak{A}^\varsigma}[b] = \pi_{\mathcal{E}}$ . Then  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{\mathcal{IE}}$  for some  $\tau \in \varsigma^{\mathcal{IE}}$ . Then  $\text{tp}_x \tau = \pi$  and  $\text{tp}_y \tau = \pi'$ .  $\square$

**Remark 63.** If  $\pi \in P_T$  is any peasant type, then  $\pi \in \text{Tp}_y \varsigma$ .

*Proof.* Let  $\tau \in T^\varsigma$  be any cosmic type connecting the peasant type  $\pi$  with itself. Then by  $(\varsigma T)$ ,  $\tau \in \varsigma^{\mathcal{IE}} \cup \varsigma^{\mathcal{EI}} \cup \varsigma^{\mathcal{EE}}$ .

If  $\tau \in \varsigma^{\mathcal{IE}}$ , then  $\pi = \text{tp}_y \tau \in \text{Tp}_y \varsigma$ . If  $\tau \in \varsigma^{\mathcal{EI}}$ , then  $\pi = \text{tp}_y(\tau^{-1}) \in \text{Tp}_y \varsigma$ . Suppose that  $\tau \in \varsigma^{\mathcal{EE}}$ . Let  $\mathfrak{A}^\varsigma$  be a model for  $T^\varsigma$  and let  $X^\varsigma = \mathbf{in}^{\mathfrak{A}^\varsigma}$  be the set of internal spectral elements. Then  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{\mathcal{EE}}$  for some  $a \in A^\varsigma \setminus X^\varsigma$  and  $b \in (A^\varsigma \setminus X^\varsigma) \setminus \{a\}$ . Then  $\text{tp}^{\mathfrak{A}^\varsigma}[a] = \pi_{\mathcal{E}}$ , so  $\pi \in \text{Tp}_y \varsigma$ .  $\square$

**Remark 64.** If  $\nu \in \text{Tp}_x \varsigma \cap N_T$  is an internal noble type, then  $\nu \notin \text{Tp}_y \varsigma$ .

*Proof.* Suppose towards a contradiction that  $\nu \in \text{Tp}_y \varsigma$ . Then by Remark 62, some  $\tau \in \varsigma^{\mathcal{IE}}$  has  $\text{tp}_x \tau = \text{tp}_y \tau = \nu$ . By  $(\varsigma \mathcal{IE})$ ,  $\tau$  is cosmic — a contradiction.  $\square$

**Remark 65.** If  $\kappa \in \text{Tp}_x \varsigma \cap K_T$  is an internal king type, then  $\kappa_{\mathcal{I}} \in K_{T^\varsigma}$  is an internal spectral king type.

*Proof.* Suppose towards a contradiction that  $\kappa_{\mathcal{I}}$  is not a king type, so some  $\tau' \in T^\varsigma$  connects  $\kappa_{\mathcal{I}}$  with itself. We must have that  $\tau' \in T_{\mathcal{II}}^\varsigma$ , so  $\tau' = \tau_{\mathcal{II}}$  for some  $\tau \in \varsigma^{\mathcal{II}}$ , so  $\tau$  connects  $\kappa$  with itself — a contradiction.  $\square$

**Remark 66.** If  $\kappa \in \text{Tp}_y \varsigma \cap K_T$  is an external king type, then  $\kappa_{\mathcal{E}} \in K_{T^\varsigma}$  is an external spectral king type.

*Proof.* Suppose towards a contradiction that  $\kappa_{\mathcal{E}}$  is not a king type, so some  $\tau' \in T^\varsigma$  connects  $\kappa_{\mathcal{E}}$  with itself. We must have that  $\tau' \in T_{\mathcal{EE}}^\varsigma$ , so  $\tau' = \tau_{\mathcal{EE}}$  for some  $\tau \in \varsigma^{\mathcal{EE}}$ , so  $\tau$  connects  $\kappa$  with itself — a contradiction.  $\square$

**Remark 67.** Suppose that  $\varsigma$  is noble. Then:

1. If  $\nu \in \text{Tp}_x \varsigma \cap W_T$  is an internal worker type, then  $\nu_I \in W_{T^\varsigma}$  is an internal spectral worker type.
2. If  $\pi \in \text{Tp}_y \varsigma \cap W_T$  is an external worker type, then  $\pi_E \in W_{T^\varsigma}$  is an external spectral worker type.

*Proof.* 1. Since  $\varsigma$  is noble, by  $(\varsigma\text{NP})$  we have that  $\nu$  must be noble. Since  $\nu$  is noble and is not a king type, there must be some galactic  $\tau \in T^g$  connecting  $\nu$  with itself. Then by  $(\varsigma\text{T})$  we have  $\tau \in \varsigma^{II} \cup \varsigma^{\mathcal{EE}}$ .

If  $\tau \in \varsigma^{II}$ , then  $\tau_{II} \in T_{II}^\varsigma$  connects  $\nu_I$  with itself, so  $\nu_I$  is a worker type.

If  $\tau \in \varsigma^{\mathcal{EE}}$ , then by Remark 60  $\nu \in \text{Tp}_y \varsigma$ . Then by Remark 62 some  $\tau \in \varsigma^{\mathcal{IE}}$  connects  $\nu$  with itself. But then  $\tau$  is cosmic — a contradiction.

2. Since  $\pi$  is a worker type,  $\pi \notin \text{Tp}_x \varsigma$  and some  $\tau \in T$  connects  $\pi$  with itself. Then we must have that  $\tau \in \varsigma^{\mathcal{EE}}$ . Hence  $\tau_{EE}$  connects  $\pi_E$  with itself, so  $\pi_E$  is an external spectral worker type.

□

For any  $\pi_\varsigma \in \Pi_{T^\varsigma}$  or  $\tau_\varsigma \in T^\varsigma$ , denote by  $\pi_\varsigma^{-in}$  and  $\tau_\varsigma^{-in}$  the reducts of  $\pi_\varsigma$  and  $\tau_\varsigma$  to the language  $\Sigma - \langle e \rangle = \Sigma' - \langle in \rangle$ . Define the following types over  $\Sigma$ :

$$\begin{aligned}\pi_\varsigma^I &= \pi_\varsigma^{\mathcal{E}} = \pi_\varsigma^{-in} \cup \{e(x, x)\} \\ \tau_\varsigma^{II} &= \tau_\varsigma^{-in} \cup \{e(x, x), e(y, y), e(x, y), e(y, x)\} \\ \tau_\varsigma^{\mathcal{IE}} &= \tau_\varsigma^{-in} \cup \{e(x, x), e(y, y), \neg e(x, y), \neg e(y, x)\}.\end{aligned}$$

That is, these are *inverses* of the previous operations:  $(\pi_I)^I = (\pi_E)^{\mathcal{E}} = \pi$  for  $\pi \in \Pi_T$  and  $(\tau_{II})^{II} = (\tau_{IE})^{\mathcal{IE}} = \tau$  for  $\tau \in T$ .

**Definition 79.** Let  $\mathfrak{A}^\varsigma$  be a model for  $T^\varsigma$ , and let  $X^\varsigma = in^{\mathfrak{A}^\varsigma}$  be the set of internal spectral elements. Recall that both  $X^\varsigma$  and  $\mathfrak{A}^\varsigma \setminus X^\varsigma$  are nonempty. Transform  $(\mathfrak{A}^\varsigma \upharpoonright X^\varsigma)$  to a model  $\mathfrak{X}^\varsigma$  for  $\Sigma$  by forgetting the interpretation of  $in$  and by interpreting  $e^{\mathfrak{X}^\varsigma} = X^\varsigma \times X^\varsigma$  as the full relation on  $X^\varsigma$ . Call  $\mathfrak{X}^\varsigma$  the galaxy of the model  $\mathfrak{A}^\varsigma$ . Note that  $\mathfrak{X}^\varsigma$  is a  $\Sigma$ -structure, but is not necessarily a  $\langle \Sigma, \bar{m} \rangle$ -structure, since some message symbols might be witnessed only by an element outside of  $X^\varsigma$  in  $\mathfrak{A}^\varsigma$ .

For any internal spectral element  $a \in X^\varsigma$  define its intended star-type  $\sigma(a)$  by:

$$\sigma(a) = \left\{ \text{tp}^{\mathfrak{A}^\varsigma}[a, b]^{II} \mid b \in X^\varsigma \setminus \{a\} \right\} \cup \left\{ \text{tp}^{\mathfrak{A}^\varsigma}[a, b]^{\mathcal{IE}} \mid b \in A^\varsigma \setminus X^\varsigma \right\}.$$

Define the intended 1-type of  $a$  by:  $\pi(a) = \text{tp}_x(\sigma(a)) = \text{tp}^{\mathfrak{A}^\varsigma}[a]^I = \text{tp}^{\mathfrak{X}^\varsigma}[a]$ .

**Lemma 14.** The intended star-type  $\sigma = \sigma(a)$  is a star-type over  $T$ .

*Proof.* Since  $A^\varsigma \setminus X^\varsigma$  is nonempty,  $\sigma$  is nonempty. We verify the conditions for a star-type over  $T$ :

**(σx)** If  $\tau, \tau' \in \sigma$ , then  $\text{tp}_x \tau = \text{tp}_x \tau' = \text{tp}^{\mathfrak{A}^\varsigma}[a]^\mathcal{I} = \pi(a)$ . Let  $\pi = \pi(a)$  be the intended 1-type of  $a$ .

**(σpy)** Let  $\pi' \in \mathcal{T}[\pi]$ . We have to find some  $\tau \in \sigma$  having  $\text{tp}_y \tau = \pi'$ . By [Remark 61](#),  $\pi' \in \text{Tp}_x \varsigma \cup \text{Tp}_y \varsigma$ .

First suppose that  $\pi' \neq \pi$ . If  $\pi' \in \text{Tp}_x \varsigma$ , then some  $b \in X^\varsigma$  has  $\text{tp}^{\mathfrak{A}^\varsigma}[b] = \pi'_\mathcal{I}$  and since  $\pi' \neq \pi$  we have  $b \in X^\varsigma \setminus \{a\}$ . Then  $\tau = \text{tp}^{\mathfrak{A}^\varsigma}[a, b]^{\mathcal{II}} \in \sigma$  has  $\text{tp}_y \tau = \text{tp}^{\mathfrak{A}^\varsigma}[b]^\mathcal{I} = (\pi'_\mathcal{I})^\mathcal{I} = \pi'$ . If  $\pi' \in \text{Tp}_y \varsigma$ , then some  $b \in A^\varsigma \setminus X^\varsigma$  has  $\text{tp}^{\mathfrak{A}^\varsigma}[b] = \pi'_\mathcal{E}$ . Then  $\tau = \text{tp}^{\mathfrak{A}^\varsigma}[a, b]^{\mathcal{IE}} \in \sigma$  has  $\text{tp}_y \tau = \text{tp}^{\mathfrak{A}^\varsigma}[b]^\mathcal{E} = (\pi'_\mathcal{E})^\mathcal{E} = \pi'$ .

Next suppose that  $\pi' = \pi$ , so  $\pi$  is not a king type. So some  $\tau' \in \mathcal{T}$  connects  $\pi$  with itself. By [\(ςT\)](#),  $\tau' \in \varsigma^{\mathcal{II}} \cup \varsigma^{\mathcal{IE}} \cup \varsigma^{\mathcal{EI}} \cup \varsigma^{\mathcal{EE}}$ .

If  $\tau' \in \varsigma^{\mathcal{II}}$  then some  $a' \in X^\varsigma$  and  $b' \in X^\varsigma \setminus \{a'\}$  have  $\text{tp}^{\mathfrak{A}^\varsigma}[a', b'] = \tau'_{\mathcal{II}}$ . So  $\text{tp}^{\mathfrak{A}^\varsigma}[a] = \text{tp}_x(\tau'_{\mathcal{II}}) = (\text{tp}_x \tau')_\mathcal{I} = \pi'_\mathcal{I}$  and  $\text{tp}^{\mathfrak{A}^\varsigma}[b] = \text{tp}_y(\tau'_{\mathcal{II}}) = (\text{tp}_y \tau')_\mathcal{I} = \pi'_\mathcal{I}$ . Let  $b \in \{a', b'\} \setminus \{a\}$ , which is nonempty. Then  $\tau = \text{tp}^{\mathfrak{A}^\varsigma}[a, b]^{\mathcal{II}} \in \sigma$  has  $\text{tp}_y \tau = \text{tp}^{\mathfrak{A}^\varsigma}[b]^\mathcal{I} = (\pi'_\mathcal{I})^\mathcal{I} = \pi'$ .

If  $\tau' \in \varsigma^{\mathcal{IE}}$  then some  $a' \in X^\varsigma$  and  $b' \in A^\varsigma \setminus X^\varsigma$  have  $\text{tp}^{\mathfrak{A}^\varsigma}[a', b'] = \tau'_{\mathcal{IE}}$ . So for  $b = b'$ ,  $\text{tp}^{\mathfrak{A}^\varsigma}[b] = \text{tp}_y(\tau'_{\mathcal{IE}}) = (\text{tp}_y \tau')_\mathcal{E} = \pi'_\mathcal{E}$ . Then  $\tau = \text{tp}^{\mathfrak{A}^\varsigma}[a, b]^{\mathcal{IE}} \in \sigma$  has  $\text{tp}_y \tau = \text{tp}^{\mathfrak{A}^\varsigma}[b]^\mathcal{E} = (\pi'_\mathcal{E})^\mathcal{E} = \pi'$ .

If  $\tau' \in \varsigma^{\mathcal{EI}}$  then some  $a' \in A^\varsigma \setminus X^\varsigma$  and  $b' \in X^\varsigma$  have  $\text{tp}^{\mathfrak{A}^\varsigma}[a', b'] = \tau'_{\mathcal{EI}}$ . So for  $b = a'$ ,  $\text{tp}^{\mathfrak{A}^\varsigma}[b] = \text{tp}_x(\tau'_{\mathcal{EI}}) = (\text{tp}_x \tau')_\mathcal{E} = \pi'_\mathcal{E}$ . Then  $\tau = \text{tp}^{\mathfrak{A}^\varsigma}[a, b]^{\mathcal{IE}} \in \sigma$  has  $\text{tp}_y \tau = (\pi'_\mathcal{E})^\mathcal{E} = \pi'$ .

If  $\tau' \in \varsigma^{\mathcal{EE}}$  then some  $a' \in A^\varsigma \setminus X^\varsigma$  and  $b' \in (A^\varsigma \setminus X^\varsigma) \setminus \{a'\}$  have  $\text{tp}^{\mathfrak{A}^\varsigma}[a', b'] = \tau'_{\mathcal{EE}}$ . So for  $b = a'$ ,  $\text{tp}^{\mathfrak{A}^\varsigma}[b] = \text{tp}_x(\tau'_{\mathcal{EE}}) = (\text{tp}_x \tau')_\mathcal{E} = \pi'_\mathcal{E}$ . Then  $\tau = \text{tp}^{\mathfrak{A}^\varsigma}[a, b]^{\mathcal{IE}} \in \sigma$  has  $\text{tp}_y \tau = (\pi'_\mathcal{E})^\mathcal{E} = \pi'$ .

**(σκy)** Suppose that  $\kappa' \in \mathcal{T}[\pi] \cap \mathcal{K}_\mathcal{T}$  and that  $\tau, \tau' \in \sigma$  have  $\text{tp}_y \tau = \text{tp}_y \tau' = \kappa'$ .

If  $\tau = \text{tp}^{\mathfrak{A}^\varsigma}[a, b]^{\mathcal{II}}$  for some  $b \in X^\varsigma \setminus \{a\}$  and  $\tau' = \text{tp}^{\mathfrak{A}^\varsigma}[a, b']^{\mathcal{II}}$  for some  $b' \in X^\varsigma \setminus \{a\}$ , then  $\text{tp}^{\mathfrak{A}^\varsigma}[b] = \text{tp}^{\mathfrak{A}^\varsigma}[b'] = \kappa'_\mathcal{I}$ . Suppose towards a contradiction that  $b \neq b'$ , so  $\text{tp}^{\mathfrak{A}^\varsigma}[b, b'] = \tau''_{\mathcal{II}}$  for some  $\tau'' \in \varsigma^{\mathcal{II}}$ , so  $\tau''$  connects  $\kappa'$  with itself — a contradiction. Hence  $b = b'$  so  $\tau = \tau'$ .

If  $\tau = \text{tp}^{\mathfrak{A}^\varsigma}[a, b]^{\mathcal{IE}}$  for some  $b \in X^\varsigma \setminus \{a\}$  and  $\tau' = \text{tp}^{\mathfrak{A}^\varsigma}[a, b']^{\mathcal{IE}}$  for some  $b' \in X^\varsigma \setminus \{a\}$ , then  $\text{tp}^{\mathfrak{A}^\varsigma}[b] = \kappa'_\mathcal{I}$  and  $\text{tp}^{\mathfrak{A}^\varsigma}[b'] = \kappa'_\mathcal{E}$ . Then  $\text{tp}^{\mathfrak{A}^\varsigma}[b, b'] = \tau''_{\mathcal{IE}}$  for some  $\tau'' \in \varsigma^{\mathcal{IE}}$ , so  $\tau''$  connects  $\kappa'$  with itself — a contradiction.

If  $\tau = \text{tp}^{\mathfrak{A}^\varsigma}[a, b]^{\mathcal{IE}}$  for some  $b \in A^\varsigma \setminus X^\varsigma$  and  $\tau' = \text{tp}^{\mathfrak{A}^\varsigma}[a, b']^{\mathcal{IE}}$  for some  $b' \in A^\varsigma \setminus X^\varsigma$ , then  $\text{tp}^{\mathfrak{A}^\varsigma}[b] = \text{tp}^{\mathfrak{A}^\varsigma}[b'] = \kappa'_\mathcal{E}$ . Suppose towards a contradiction that  $b \neq b'$ , so  $\text{tp}^{\mathfrak{A}^\varsigma}[b, b'] = \tau''_{\mathcal{EE}}$  for some  $\tau'' \in \varsigma^{\mathcal{EE}}$ , so  $\tau''$  connects  $\kappa'$  with itself — contradiction. Hence  $b = b'$  so  $\tau = \tau'$ .

**(σm)** Let  $\mathbf{m} \in \bar{\mathbf{m}}$ . Since  $\mathfrak{A}^\varsigma$  is a model for  $\mathcal{T}^\varsigma$ , some  $b \in A \setminus \{a\}$  has  $\mathbf{m}(\mathbf{x}, \mathbf{y}) \in \text{tp}^{\mathfrak{A}^\varsigma}[a, b]$ . If  $b \in X$ , then  $\mathbf{m}(\mathbf{x}, \mathbf{y}) \in \text{tp}^{\mathfrak{A}^\varsigma}[a, b]^{\mathcal{II}} \in \sigma$ . If  $b \in A \setminus X$ , then  $\mathbf{m}(\mathbf{x}, \mathbf{y}) \in \text{tp}^{\mathfrak{A}^\varsigma}[a, b]^{\mathcal{IE}} \in \sigma$ .

□

**Lemma 15** (Type characterization). *Let  $T$  be a type instance,  $\varsigma$  be a locally consistent cosmic spectrum over  $T$ ,  $\mathfrak{A}^\varsigma$  be a model for the spectral type instance  $T^\varsigma$ ,  $X^\varsigma$  be the set of internal spectral elements of  $\mathfrak{A}^\varsigma$  and let  $\mathfrak{X}^\varsigma$  be the galaxy of  $\mathfrak{A}^\varsigma$ . Then:*

1. *If  $\pi \in \text{Tp}_x \varsigma$  then some  $a \in X^\varsigma$  has  $\pi(a) = \pi$ .  
If  $a \in X^\varsigma$  then  $\pi(a) \in \text{Tp}_x \varsigma$ .  
Equivalently  $\text{Tp}_x \varsigma = \{\pi(a) \mid a \in X^\varsigma\}$ .*
2. *If  $\tau \in \varsigma^{\mathcal{II}}$  then some  $a \in X^\varsigma$  and  $b \in X^\varsigma \setminus \{a\}$  have  $\text{tp}^{\mathfrak{X}^\varsigma}[a, b] = \tau$ .  
If  $a \in X^\varsigma$  and  $b \in A^\varsigma \setminus X^\varsigma$  then  $\text{tp}^{\mathfrak{X}^\varsigma}[a, b] \in \varsigma^{\mathcal{II}}$ .  
Equivalently  $\varsigma^{\mathcal{II}} = \{\text{tp}^{\mathfrak{X}^\varsigma}[a, b] \mid a \in X^\varsigma, b \in X^\varsigma \setminus \{a\}\}$ .*
3. *If  $\tau \in \varsigma^{\mathcal{IE}}$  then some  $a \in X^\varsigma$  has  $\tau \in \sigma(a)$ .  
If  $a \in X^\varsigma$  and  $\tau \in \sigma(a)$  is cosmic, then  $\tau \in \varsigma^{\mathcal{IE}}$ .  
Equivalently  $\varsigma^{\mathcal{IE}} = \{\sigma(a) \mid a \in X^\varsigma\} \cap T^c$ .*

We will be applying this lemma implicitly.

*Proof.* 1. If  $\pi \in \text{Tp}_x \varsigma$  then some  $a \in X^\varsigma$  has  $\text{tp}^{\mathfrak{A}^\varsigma}[a] = \pi_{\mathcal{I}}$ , so  $\pi(a) = \text{tp}^{\mathfrak{A}^\varsigma}[a]^{\mathcal{I}} = \pi$ .  
If  $a \in X^\varsigma$  then  $\text{tp}^{\mathfrak{A}^\varsigma}[a] = \pi_{\mathcal{I}}$  for some  $\pi \in \text{Tp}_x \varsigma$ , so  $\pi(a) = \text{tp}^{\mathfrak{A}^\varsigma}[a]^{\mathcal{I}} = \pi$ .

2. If  $\tau \in \varsigma^{\mathcal{II}}$  then some  $a \in X^\varsigma$  and  $b \in X^\varsigma \setminus \{a\}$  have  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{\mathcal{II}}$ , so  $\text{tp}^{\mathfrak{X}^\varsigma}[a, b] = \text{tp}^{\mathfrak{A}^\varsigma}[a, b]^{\mathcal{II}} = \tau$ .  
If  $a \in X^\varsigma$  and  $b \in X^\varsigma \setminus \{a\}$  then  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{\mathcal{II}}$  for some  $\tau \in \varsigma^{\mathcal{II}}$ , so  $\text{tp}^{\mathfrak{X}^\varsigma}[a, b] = \tau$ .

3. If  $\tau \in \varsigma^{\mathcal{IE}}$  then some  $a \in X^\varsigma$  and  $b \in A^\varsigma \setminus X^\varsigma$  have  $\text{tp}^{\mathfrak{A}^\varsigma}[a, b] = \tau_{\mathcal{IE}}$ , so  $\tau = \text{tp}^{\mathfrak{A}^\varsigma}[a, b]^{\mathcal{IE}} \in \sigma(a)$ .  
Let  $a \in X^\varsigma$  and let  $\tau \in \sigma(a)$  be cosmic. Then  $\tau = \text{tp}^{\mathfrak{A}^\varsigma}[a, b]^{\mathcal{IE}}$  for some  $b \in A^\varsigma \setminus X^\varsigma$ , so  $\tau \in \varsigma^{\mathcal{IE}}$ .

□

**Definition 80.** A certificate  $\mathcal{S}$  for the type instance  $T$  is a nonempty set of locally consistent cosmic spectra over  $T$  satisfying the following conditions:

- ( $\mathcal{ST}^c$ ) If  $\tau \in T^c$  then some  $\varsigma \in \mathcal{S}$  has  $\tau \in \varsigma^{\mathcal{IE}}$ .
- ( $\mathcal{ST}^g$ ) If  $\tau \in T^g$  then some  $\varsigma \in \mathcal{S}$  has  $\tau \in \varsigma^{\mathcal{II}}$ .
- ( $\mathcal{S}\nu$ ) If  $\nu \in N_T$  and  $\varsigma, \varsigma' \in \mathcal{S}$  have  $\nu \in \text{Tp}_x \varsigma$  and  $\nu \in \text{Tp}_x \varsigma'$ , then  $\varsigma' = \varsigma$ .

**Remark 68.** Let  $\mathcal{S}$  be a certificate for the type instance  $T$ . If  $\pi \in \Pi_T$  then some  $\varsigma \in \mathcal{S}$  has  $\pi \in \text{Tp}_x \varsigma$ .

*Proof.* Let  $\pi \in \Pi_T$ , so some  $\tau \in T$  has  $\text{tp}_x \tau = \pi$ . If  $\tau$  is cosmic, by  $(\mathcal{ST}^c)$  some  $\varsigma \in \mathcal{S}$  has  $\tau \in \varsigma^{\mathcal{IE}}$ , so  $\pi \in \text{Tp}_x \varsigma$ . If  $\tau$  is galactic, by  $(\mathcal{ST}^g)$  some  $\varsigma \in \mathcal{S}$  has  $\tau \in \varsigma^{\mathcal{II}}$ , so by Remark 60  $\pi \in \text{Tp}_x \varsigma$ .  $\square$

**Remark 69.** Let  $\mathcal{S}$  be a certificate for the type instance  $T$ . If  $\nu \in N_T$ , then a unique  $\varsigma \in \mathcal{S}$  has  $\nu \in \text{Tp}_x \varsigma$ .

*Proof.* Let  $\nu \in N_T$ . By Remark 68, some  $\varsigma \in \mathcal{S}$  has  $\nu \in \text{Tp}_x \varsigma$ . By  $(\mathcal{S}\nu)$  such  $\varsigma \in \mathcal{S}$  is unique.  $\square$

**Lemma 16** (Certificate extraction). Let  $\mathfrak{A}$  be a nobly distinguished model for the type instance  $T$  over the  $\mathcal{L}^2 eE_{\text{refine}}$ -classified signature  $\langle \Sigma, \bar{\mathbf{m}} \rangle$  such that  $E = e^{\mathfrak{A}}$  is not full on  $A$ . For each 2-type  $\tau \in T$  let  $a_\tau \neq b_\tau \in A$  realize  $\tau$ , that is  $\text{tp}^{\mathfrak{A}}[a_\tau, b_\tau] = \tau$ . Let

$$\mathcal{S} = \left\{ \text{csp}^{\mathfrak{A}}[E[a_\tau]] \mid \tau \in T \right\}.$$

Then  $\mathcal{S}$  is a certificate for  $T$ . Note that the size of  $\mathcal{S}$  is polynomially bounded with respect to the size of  $T$ .

*Proof.* That  $\mathcal{S}$  is nonempty follows since  $E$  is not full on  $A$ . That the elements of  $\mathcal{S}$  are locally consistent cosmic spectrums follows from Remark 58. We check the conditions for a certificate:

- $(\mathcal{ST}^c)$  Let  $\tau \in T^c$  be any cosmic type, let  $a_\tau \in A$  be the selected  $x$ -element for  $\tau$  and let  $\varsigma = \text{csp}^{\mathfrak{A}}[E[a_\tau]]$ . Then  $b_\tau \in A \setminus E[a_\tau]$  and so  $\tau = \text{tp}^{\mathfrak{A}}[a_\tau, b_\tau] \in \varsigma^{\mathcal{IE}}$ .
- $(\mathcal{ST}^g)$  Let  $\tau \in T^g$  be any galactic type, and consider  $a_\tau$  and  $b_\tau$ . Then  $(a_\tau, b_\tau) \in E$ , so  $\tau = \text{tp}^{\mathfrak{A}}[a_\tau, b_\tau] \in \varsigma^{\mathcal{II}}$  for  $\varsigma = \text{csp}^{\mathfrak{A}}[a_\tau]$ .
- $(\mathcal{S}\nu)$  Let  $\nu \in N_T$  be any noble type. Then a unique galaxy  $X$  realizes  $\nu$ . Then if  $\varsigma \in \mathcal{S}$  has  $\nu \in \text{Tp}_x \varsigma$ , then  $\varsigma = \text{csp}^{\mathfrak{A}}[X]$ .

$\square$

**Theorem 5** (Certificate expansion). Let  $\mathcal{S}$  be a certificate for the type instance  $T$  over the  $\mathcal{L}^2 eE_{\text{refine}}$ -classified signature  $\langle \Sigma, \bar{\mathbf{m}} \rangle$ . Then  $T$  has a finite model. More precisely, let  $t \geq |T|$  be a parameter. Then  $T$  has a finite model in which each worker type is realized at least  $t$  times.

*Proof.* We use induction on  $e$ . We build a model  $\mathfrak{A}$  for  $T$ . Note that  $\mathcal{S}$  is a nonempty set of cosmic spectrums over  $T$ , and by  $(\varsigma^{\mathcal{IE}})$ ,  $T$  must contain a cosmic type. Hence any model of  $T$  has at least 2 galaxies.

First for every  $\varsigma \in \mathcal{S}$ , we obtain a finite model  $\mathfrak{A}^\varsigma$  for  $T^\varsigma$  having the property that if  $\varsigma$  is noble then every worker type over  $T^\varsigma$  is realized at least  $(3t)$  times in  $\mathfrak{A}^\varsigma$ .

- First suppose  $e = 1$ . Let  $\varsigma \in \mathcal{S}$  be any locally consistent cosmic spectrum from  $\mathcal{S}$ . Consider the spectral type instance  $T^\varsigma$ . Let  $t' = \max\{t, |T^\varsigma|\}$ . Then  $T^\varsigma$  is realizable over  $\mathcal{L}^2$ . By Lemma 9 the type instance  $T^\varsigma$  has a finite  $\mathcal{L}^2$ -model  $\mathfrak{A}^\varsigma$  in which every worker type is realized at least  $(3t')$  times, so also at least  $(3t)$  times.

- Next suppose  $e > 1$  and the induction hypothesis for  $(e - 1)$ . Let  $\varsigma \in \mathcal{S}$  be any locally consistent cosmic spectrum from  $\mathcal{S}$ , so  $T^\varsigma$  is realizable over  $\mathcal{L}^2(e - 1)E_{\text{refine}}$ . By Lemma 12, some promotion  $T^\varsigma_\bullet$  of  $T^\varsigma$  has a nobly distinguished  $\mathcal{L}^2(e - 1)E_{\text{refine}}$ -model  $\mathfrak{B}^\varsigma_\bullet$ . Note that since  $T$  is realizable and contains a cosmic type,  $T^\varsigma_\bullet$  must also contain a cosmic type, so  $\mathfrak{B}^\varsigma_\bullet$  must have at least two galaxies. By Lemma 16, there exists a certificate  $\mathcal{S}^\varsigma_\bullet$  for  $T^\varsigma_\bullet$  over  $\mathcal{L}^2(e - 1)E_{\text{refine}}$ . Let  $t' = \max\{t, |T^\varsigma_\bullet|\}$ . By induction hypothesis,  $T^\varsigma_\bullet$  has a finite  $\mathcal{L}^2(e - 1)E_{\text{refine}}$ -model  $\mathfrak{A}^\varsigma_\bullet$  in which every worker type is realized at least  $(3t')$  times. Then the reduct  $\mathfrak{A}^\varsigma$  of  $\mathfrak{A}^\varsigma_\bullet$  to the language of  $T^\varsigma$  is a finite model for  $T^\varsigma$ . If  $\varsigma$  is noble, by Remark 67 any worker type over  $T$  is realized at least  $(3t)$  times in  $\mathfrak{A}^\varsigma$ .

Let  $\mathfrak{X}^\varsigma$  be the galaxy of  $\mathfrak{A}^\varsigma$ . The galaxies of  $\mathfrak{A}$  are:

- A single copy of  $\mathfrak{X}^\varsigma$  for every noble  $\varsigma \in \mathcal{S}$ . These galaxies are the *noble galaxies*.
- $3t$  copies  $\mathfrak{X}^\varsigma_{ij}$  of  $\mathfrak{X}^\varsigma$  for every peasant  $\varsigma \in \mathcal{S}$ , where  $i \in \{0, 1, 2\}$  and  $j \in [1, t]$ . These galaxies are the *peasant galaxies*.

Let  $\sigma(a)$  be the intended star-type of  $a$  and let  $\pi(a) = \text{tp}_x(\sigma(a))$  be the intended 1-type of  $a$  for  $a \in A$ . Let  $A^\pi = \{a \in A \mid \pi(a) = \pi\}$  be the set of elements having intended 1-type  $\pi \in \Pi_T$ . Consider any noble  $\nu \in N_T$ . By Remark 69 a unique  $\varsigma \in \mathcal{S}$  has  $\nu \in \text{Tp}_x \varsigma$ . Note that  $\varsigma$  is noble and  $A^\nu \subseteq X^\varsigma$ .

If  $\kappa \in K_T$  is any king type, then since  $\kappa$  is noble, there is a unique  $\varsigma \in \mathcal{S}$  having  $\kappa \in \text{Tp}_x \varsigma$ . By Remark 65,  $\kappa_{\mathcal{I}} \in K_{T^\varsigma}$  is an internal spectral king type, so  $A^\kappa = \{a^\kappa\} \subseteq X^\varsigma$  is a singleton, so  $a = a^\kappa$  is the unique  $a \in A$  having  $\pi(a) = \kappa$ .

If  $\nu \in N_T \setminus K_T$  is any noble type that is not a king type, then by Remark 67  $\nu_{\mathcal{I}} \in W_{T^\varsigma}$  is an internal worker spectral type for the unique (noble)  $\varsigma \in \mathcal{S}$  having  $\nu \in \text{Tp}_x \varsigma$ . So  $A^\nu = \{a \in X^\varsigma \mid \text{tp}^{\mathfrak{A}^\varsigma}[a] = \nu_{\mathcal{I}}\}$  and since there are at least  $3t$  elements from  $\mathfrak{A}^\varsigma$  realizing the worker type  $\nu_{\mathcal{I}}$ , we may choose a partition  $A^\nu = A^\nu_0 \cup A^\nu_1 \cup A^\nu_2$  such that  $|A^\nu_i| \geq t$  for  $i \in \{0, 1, 2\}$ .

If  $\pi \in P_T$  is any peasant type, let  $\mathcal{S}^\pi = \{\varsigma \in \mathcal{S} \mid \pi \in \text{Tp}_x \varsigma\}$  be the set of (peasant) cosmic spectrums including  $\pi$ . By Remark 68,  $\mathcal{S}^\pi$  is nonempty. Then:

$$A^\pi = \left\{a \in X^\varsigma_{ij} \mid \varsigma \in \mathcal{S}^\pi, i \in \{0, 1, 2\}, j \in [1, t], \pi(a) = \pi\right\}.$$

By Lemma 15:

$$A^\pi = \left\{a \in X^\varsigma_{ij} \mid \varsigma \in \mathcal{S}^\pi, i \in \{0, 1, 2\}, j \in [1, t], \text{tp}^{\mathfrak{A}^\varsigma}[a] = \pi_{\mathcal{I}}\right\}.$$

Consider the partition  $A^\pi = A^\pi_0 \cup A^\pi_1 \cup A^\pi_2$ , where:

$$A^\pi_i = \left\{a \in X^\varsigma_{ij} \mid \varsigma \in \mathcal{S}^\pi, j \in [1, t], \pi(a) = \pi\right\}.$$

Then  $|A^\pi_i| \geq t$  and whenever  $\pi, \pi' \in \Pi_T$  and  $i \neq i' \in \{0, 1, 2\}$ , no  $a \in A^\pi_i$  and  $a' \in A^{\pi'}_{i'}$  are in the same galaxy.

**Realization of kings** Let  $\kappa' \in K_T$  be any king type, let  $\varsigma' \in \mathcal{S}$  be the unique (noble) cosmic spectrum having  $\kappa' \in \text{Tp}_x \varsigma'$  and let  $a = a^{\kappa'} \in X^{\varsigma'}$  be the unique element in  $A$  having  $\pi(a) = \kappa'$ . Let  $\sigma' = \sigma(a)$  be the intended star-type of  $a$ , so  $\kappa' = \text{tp}_x \sigma'$ . Note that some 2-type is already assigned between  $a$  and each other element from the galaxy  $X^{\varsigma'}$  of  $a$ . Let  $b \in A \setminus X^{\varsigma'}$  be any element outside the galaxy of  $a$ . Let  $\pi = \pi(b)$  and  $\sigma = \sigma(b)$  be the intended 1-type and star-type of  $b$ , respectively. Let  $\mathfrak{X}_{(ij)}^{\varsigma}$  be the galaxy of  $b$ , so  $\pi \in \text{Tp}_x \varsigma$  and  $b \in X_{(ij)}^{\varsigma} \neq X^{\varsigma'}$ . By construction  $\varsigma' \neq \varsigma$ , since  $\mathfrak{A}$  contains a unique noble galaxy for each noble cosmic spectrum from  $\mathcal{S}$  and since  $\varsigma'$  is noble. Then  $\kappa' \notin \text{Tp}_x \varsigma$ . Indeed, if  $\kappa' \in \text{Tp}_x \varsigma$  then since  $\kappa' \in \text{Tp}_x \varsigma'$ , we have a contradiction of **(S $\nu$ )**. Then  $\pi \neq \kappa'$ , since  $\pi \in \text{Tp}_x \varsigma$ . So  $\kappa' \in T[\pi] \cap K_T$  and by **( $\sigma\kappa y$ )** there is a unique  $\tau \in \sigma$  having  $\text{tp}_y \tau = \kappa'$ . If  $\tau$  is galactic, then  $\tau \in \varsigma^{\text{IE}}$  by construction, so  $\kappa' = \text{tp}_y \tau \in \text{Tp}_x \varsigma$  — a contradiction. So  $\tau$  must be cosmic. Assign  $\text{tp}^{\mathfrak{A}}[b, a] = \tau$ . We claim that this assignments are appropriate.

First, these assignments are symmetric between kings: suppose that  $b$  is a king and let  $\kappa = \pi = \pi(b) \neq \kappa'$  be its intended 1-type. Then  $\kappa \in T[\kappa'] \cap K_T$  and by **( $\sigma\kappa y$ )**, there is a unique  $\tau' \in \sigma(a) = \sigma'$  such that  $\text{tp}_y \tau' = \kappa'$ . We claim that  $\tau' = \tau^{-1}$ . Indeed, since  $\tau \in \sigma$  is cosmic we have  $\tau \in \varsigma^{\text{IE}}$ , so  $\tau^{-1} \in T^c$ , so some  $\varsigma'' \in \mathcal{S}$  has  $\tau^{-1} \in \varsigma''^{\text{IE}}$  by **(S $T^c$ )**. So  $\kappa = \text{tp}_x(\tau^{-1}) \in \text{Tp}_x \varsigma''$ , so  $\varsigma'' = \varsigma$ . Then some  $a' \in X^{\varsigma}$  has  $\tau^{-1} \in \sigma(a')$ . But then  $\pi(a') = \kappa$ , so  $a' = a$ . So  $\tau^{-1} \in \sigma'$  and since  $\text{tp}_y(\tau^{-1}) = \kappa' \in K_T$ , by **( $\sigma\kappa y$ )** we must have  $\tau' = \tau^{-1}$ .

Next, every  $\tau \in \sigma' = \sigma(a)$  is realized. If  $\tau$  is galactic, then some  $b \in X^{\varsigma} \setminus \{a\}$  has  $\text{tp}^{\mathfrak{A}}[a, b] = \tau$ , so  $\tau$  is realized within the galaxy of  $a$ . If  $\tau$  is cosmic, then  $\tau^{-1}$  is cosmic and by **(S $T^c$ )** some  $\varsigma \in \mathcal{S}$  has  $\tau^{-1} \in \varsigma^{\text{IE}}$ . Then some  $b \in X^{\varsigma}$  has  $\tau^{-1} \in \sigma(b)$ , so some  $b \in A \setminus X^{\varsigma}$  has  $\tau^{-1} \in \sigma(b)$ . But  $\text{tp}_y(\tau^{-1}) = \kappa' \in K_T$ , so  $\tau^{-1} \in \sigma(b)$  is the unique having  $\text{tp}_y(\tau^{-1}) = \kappa'$ , so we had assigned  $\text{tp}^{\mathfrak{A}}[b, a] = \tau^{-1}$ .

**Realization of workers** Let  $\pi \in W_T$  be any worker type and let  $a \in A_i^{\pi}$  be any element having intended 1-type  $\pi$ . Let  $i' = (i + 1 \bmod 3) \in \{0, 1, 2\}$  be the index of the next copy of elements. Consider the cosmic spectrum  $\varsigma \in \mathcal{S}$  for  $a$ : if  $\pi$  is noble, then let  $\varsigma \in \mathcal{S}$  be such that  $a \in X^{\varsigma}$ ; otherwise  $\pi$  is peasant so let  $\varsigma \in \mathcal{S}$  and  $j \in [1, t]$  be such that  $a \in X_{ij}^{\varsigma}$ . Consider  $\sigma = \sigma(a)$  and let  $\tau \in \sigma$  be any. If  $\tau$  is galactic, then it is realized between  $a$  and some other element in the galaxy of  $a$ . If  $\text{tp}_y \tau \in K_T$  is a king type, then we have already seen that it is realized during the realization of kings.

So only the case where  $\tau$  is cosmic and  $\pi' = \text{tp}_y \tau \in W_T$  is a worker type remains. Let  $U = \{\eta \in \sigma \mid \text{tp}_y \eta = \pi'\}$  be the set of all 2-types parallel to  $\tau$  in  $\sigma$ . Note that  $|U| \leq t$ . We simultaneously find distinct  $b_{\eta}$  from the *next copy* of elements for the assignments  $\text{tp}^{\mathfrak{A}}[a, b_{\eta}] = \eta$ : Since  $|A_{i'}^{\pi'}| \geq t$ , there are enough such elements. We claim that every element from  $A_{i'}^{\pi'}$  is from a galaxy different than the galaxy of  $a$ . If  $\pi'$  is a peasant type, this is immediate by our remark right after we defined  $A_{i'}^{\pi'}$ .

Next, suppose that  $\pi' \in N_T$  is a noble worker type. We claim that  $\pi' \notin \text{Tp}_x \varsigma$ . Suppose that  $\pi' \in \text{Tp}_x \varsigma$ . Since  $\tau \in \sigma$  is cosmic, we have that  $\tau \in \varsigma^{\text{IE}}$ . Since  $\text{tp}_y \tau = \pi'$ , we

## 6 Two-variable logics

have  $\pi' \in \text{Tp}_y \varsigma$ . By [Remark 62](#), some (cosmic)  $\tau' \in \varsigma^{\mathcal{IE}}$  connects  $\pi'$  with itself — a contradiction. So  $\pi' \notin \text{Tp}_x \varsigma$ , so each element from  $A_{i'}^{\pi'}$  is not from the galaxy of  $a$ .

These assignments are consistent, since they have been made between elements from consecutive copies.

**Completion** Suppose that  $a \neq b \in A$  are any elements that have not yet been assigned a 2-type. Then  $a$  and  $b$  come from distinct galaxies. We claim that some cosmic  $\tau \in \mathbb{T}^c$  has  $\text{tp}_x \tau = \pi$  and  $\text{tp}_y \tau = \pi'$ . Let  $\pi = \pi(a)$  and  $\pi' = \pi(b)$  and let  $\mathfrak{X}^\varsigma$  be the galaxy of  $a$ .

First suppose that  $\pi'$  is noble. If  $\pi' \in \text{Tp}_x \varsigma$ , then  $\varsigma$  is noble, so  $b$  and  $a$  come from the same galaxy — a contradiction. Otherwise  $\pi' \in \text{Tp}_y \varsigma$  and by [Remark 62](#) some  $\tau \in \varsigma^{\mathcal{IE}}$  has  $\text{tp}_x \tau = \pi$  and  $\text{tp}_y \tau = \pi'$ .

Next suppose that  $\pi'$  is peasant. Then by [Remark 63](#)  $\pi' \in \text{Tp}_y \varsigma$  and so by [Remark 62](#) some  $\tau \in \varsigma^{\mathcal{IE}}$  has  $\text{tp}_x \tau = \pi$  and  $\text{tp}_y \tau = \pi'$ .

□

**Remark 70.** Let  $e \geq 1$  and let  $T$  be a type instance over the classified signature  $\langle \Sigma, \bar{\mathbf{m}} \rangle$  over  $\mathcal{L}^2 e E_{\text{refine}}$ . Suppose that  $T$  contains no cosmic type. Then  $T$  has a (finite) model over  $\mathcal{L}^2 e E_{\text{refine}}$  iff  $T$  has a (finite) model over  $\mathcal{L}^2 (e - 1) E_{\text{refine}}$ .

*Proof.* The forward direction is immediate. For the backward direction, let  $\mathbf{e}$  be the coarsest equivalence symbol over  $\Sigma$  and suppose that  $\mathfrak{A}$  is a (finite) model for  $T$  over  $\mathcal{L}^2 (e - 1) E_{\text{refine}}$ . Since  $T$  contains no cosmic type and  $\mathbf{e}(x, x) \in \tau$  for every  $\tau \in T$ , the symbol  $\mathbf{e}$  must be interpreted as the full relation on  $A$ . Hence  $\mathfrak{A}$  is a  $\mathcal{L}^2 e E_{\text{refine}}$ -structure, so  $\mathfrak{A}$  is a (finite) model for  $T$  over  $\mathcal{L}^2 e E_{\text{refine}}$ . □

**Proposition 12.** Let  $e \geq 0$ . The type realizability problem for  $\mathcal{L}^2 e E_{\text{refine}}$  coincides with the finite type realizability problem for  $\mathcal{L}^2 e E_{\text{refine}}$  and is in NP TIME.

*Proof.* We use induction on  $e$ . If  $e = 0$ , this is [Proposition 11](#). Suppose that  $e \geq 1$  and assume the induction hypothesis for  $(e - 1)$ . Consider any type instance  $T$  over the classified signature  $\langle \Sigma, \bar{\mathbf{m}} \rangle$  over  $\mathcal{L}^2 e E_{\text{refine}}$ .

First suppose that  $T$  contains no cosmic types. Then by [Remark 70](#)  $T$  has a (finite) model over  $\mathcal{L}^2 e E_{\text{refine}}$  iff  $T$  has a (finite) model over  $\mathcal{L}^2 (e - 1) E_{\text{refine}}$  so the claim follows by induction hypothesis.

Next suppose that  $T$  contains a cosmic type. Then guess a promotion  $T_\bullet$  of  $T$  and a polynomial certificate  $\mathcal{S}_\bullet$  for  $T_\bullet$  and declare that  $T$  has a (finite) model. By induction hypothesis, the property that the certificate  $\mathcal{S}$  consists of *locally consistent* cosmic spectrums can be *verified in nondeterministic polynomial time*. Let us check the correctness of this procedure.

- If  $T$  has a (finite) model, then by [Lemma 12](#) some promotion  $T_\bullet$  has a (finite) nobly distinguished model. In this case since  $T$  is realizable and contains a cosmic type,  $T_\bullet$  must contain a cosmic type, so any model of  $T_\bullet$  must contain at least two



galaxies. Let  $\mathfrak{A}_\bullet$  be a nobly distinguished model for  $T_\bullet$ . By [Lemma 16](#), there is a polynomial certificate  $\mathcal{S}_\bullet$  for  $T_\bullet$ .

- Suppose that  $T_\bullet$  is a promotion for  $T$  and  $\mathcal{S}_\bullet$  is a certificate for  $T_\bullet$ . By [Theorem 5](#),  $T_\bullet$  has a finite model  $\mathfrak{A}_\bullet$ . Then the reduct  $\mathfrak{A}$  of  $\mathfrak{A}_\bullet$  to the language of  $T$  is a finite model for  $T$ .

□

**Corollary 5.** *For any  $e \geq 1$ , the logic  $\mathcal{L}^2eE_{\text{refine}}$  has the finite model property and its (finite) satisfiability problem is in NEXPTIME.*

*By [Proposition 1](#) and [Proposition 3](#), the same holds for  $\mathcal{L}^2eE_{\text{global}}$  and  $\mathcal{L}^2eE_{\text{local}}$ .*

**Corollary 6.** *The logic  $\mathcal{L}^2E_{\text{refine}}$  has the finite model property and its (finite) satisfiability problem is in N2EXPTIME.*

*By [Proposition 2](#) and [Proposition 4](#), the same holds for  $\mathcal{L}^2E_{\text{global}}$  and  $\mathcal{L}^2eE_{\text{local}}$ .*



# Bibliography

- [1] H.D. Ebbinghaus and J. Flum. *Finite Model Theory*. Perspectives in Mathematical Logic. Springer Berlin Heidelberg, 1999.
- [2] E. Grädel and M. Otto. On logics with two variables. *Theoretical computer science*, 224(1):73–113, 1999.
- [3] D. Scott. A decision method for validity of sentences in two variables. *Journal of Symbolic Logic*, 27(377):74, 1962.
- [4] I. Cervesato, H. Veith, and A. Voronkov. *Logic for Programming, Artificial Intelligence, and Reasoning: 15th International Conference, LPAR 2008, Doha, Qatar, November 22-27, 2008, Proceedings*. Lecture Notes in Computer Science. Springer Berlin Heidelberg, 2008.
- [5] E. Boerger, E. Grädel, and Y. Gurevich. *The classical decision problem*. Perspectives in mathematical logic. Springer, 1997.
- [6] P. van Emde Boas. The convenience of tilings. *Lecture Notes in Pure and Applied Mathematics*, pages 331–363, 1997.
- [7] L. Löwenheim. Über Möglichkeiten im Relativkalkül. *Mathematische Annalen*, 76(4):447–470, 1915.
- [8] A. Janiczak. Undecidability of some simple formalized theories. *Fundamenta Mathematicae*, 40(1):131–139, 1953.
- [9] M. Mortimer. On languages with two variables. *Mathematical Logic Quarterly*, 21(1):135–140, 1975.
- [10] E. Grädel, P.G. Kolaitis, and M.Y. Vardi. On the decision problem for two-variable first-order logic. *Bulletin of symbolic logic*, 3(01):53–69, 1997.
- [11] E. Kieroński. Results on the guarded fragment with equivalence or transitive relations. In *Computer Science Logic*, pages 309–324. Springer, 2005.
- [12] E. Kieroński, J. Michaliszyn, I. Pratt-Hartmann, and L. Tendera. Two-variable first-order logic with equivalence closure. *SIAM Journal on Computing*, 43(3):1012–1063, 2014.
- [13] E. Kieronski and M. Otto. Small substructures and decidability issues for first-order logic with two variables. In *Logic in Computer Science, 2005. LICS 2005. Proceedings. 20th Annual IEEE Symposium on*, pages 448–457. IEEE, 2005.

## *Bibliography*

- [14] I. Pratt-Hartmann. The two-variable fragment with counting and equivalence. *Mathematical Logic Quarterly*, 61(6):474–515, 2015.