Satisfiability with Equivalences in Agreement

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Contents

Abstract

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

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 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 $E = E_1, E_2, \ldots, E_n$ 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 as a some kind of a "skeleton", which combined with a local permutation at every element $a \in A$ completely characterizes the 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 featruing only unary predicate symbols together with e equivalence symbols in agreement: $\mathcal{L}_1 e\mathrm{E}_{\mathsf{refine}}$, $\mathcal{L}_1 e\mathrm{E}_{\mathsf{global}}$ and $\mathcal{L}_1 e\mathrm{E}_{\mathsf{local}}$. We prove that these logics have the finite model property and that the (finite) satisfiability problem for any of them is $\mathrm{N}(e+1)\textsc{ExpTime}$-complete (Proposition 5 and Proposition 9).

- 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, $\mathcal{L}^2 e\mathrm{E}_{\mathsf{refine}}$. 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 beleive 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 Introduction

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

Let A and B be sets and let $R \subseteq A \times B$ be a binary relation. The *domain* of R is $\operatorname{dom} R = A$ and its *range* is $\operatorname{ran} R = B$. 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* $(R \restriction A') \subseteq S \times B$ of R to A' is

$$R \restriction S = \{(a, b) \in R \mid a \in S\}\,.$$

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* $f : A \to B$. is formally just a functional relation $f \subseteq A \times B$. A *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 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 $f(a) \simeq \bot$ means that f is not defined at a. If $S \subseteq A$, the *characteristic function* of S in A is $\mathrm{ch}_S^A : A \to \{0, 1\}$.

A *sequence* is formally just a function with domain an ordinal number. If A is a sequence, its *length* $\|\mathrm{A}\|$ is just the domain of A. The sequence consisting of the elements a, b and c in that order is $\langle a, b, c\rangle$. The *empty sequence* is ε. A *finite sequence* is a sequence of finite length. If A and B are two sequences, their *concatenation* is $\mathrm{A} + \mathrm{B}$, and the sequence obtained from A by dropping all elements of B is $\mathrm{A} - \mathrm{B}$.

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

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

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

An n-vector $\mathrm{v} = (\mathrm{v}_1, \mathrm{v}_2, \ldots, \mathrm{v}_n) \in \mathbb{N}^n$ is just a tuple of natural numbers. The n-vector v is *lexicographically smaller* [1] than the n-vector w (written $\mathrm{v} \prec \mathrm{w}$) if there is a position $p \in [1, n]$ such that $\mathrm{v}_p < \mathrm{w}_p$ and $\mathrm{v}_q = \mathrm{w}_q$ for all $q \in [p+1, n]$.

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

A function $f : \mathbb{N} \to \mathbb{N}$ is *polynomially bounded* if there is a polynomial p and a number $n_0 \in \mathbb{N}$ such that $f(n) \leq p(n)$ for all $n \geq n_0$. The function f is *exponentially bounded* if there is a polynomial p and a number $n_0 \in \mathbb{N}$ such that $f(n) \leq 2^{p(n)}$ for all $n \geq n_0$. 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 by 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 $\exp_a^e(x) = a^{a^{\cdot^{\cdot^{a^x}}}}$ is a tower of e exponentiations.

An *alphabet* Ω is just a nonempty set. The elements of Ω are *characters*. A *word* $w = w_1 w_2 \ldots w_n$ is a finite sequence of characters. The set of words over Ω is Ω^*. The set of nonempty words over Ω is $\Omega^+ = \Omega^* \setminus \{\varepsilon\}$. If $n \in \mathbb{N}$, the set of words of length n over Ω is Ω^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 $\mathrm{b} = 10$ 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 $\mathrm{b} \in \mathbb{B}^t$, the *number encoded by* b is $\underline{\mathrm{b}}$. 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

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

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* $\to$ is right-associative. The quantifiers bind as strong as the negation. We consider logics with *formal equality* $=$.

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

[1] the higher positions to the right are more significant; it may *look like* this ordering is the anti-lexicographic one, for example $(1, 1, 0) \prec (0, 0, 1)$.

A *predicate signature* $\Sigma = \langle \boldsymbol{p}_1, \boldsymbol{p}_2, \dots, \boldsymbol{p}_s \rangle$ is a finite sequence of distinct *predicate symbols* $\boldsymbol{p}_i$ together with their *arities* $\operatorname{ar} \boldsymbol{p}_i \in \mathbb{N}^+$. 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 Σ are disjoint.

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

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

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

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

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

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

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

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

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

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

If φ 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 φ. 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 φ 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 $\operatorname{fvars} \varphi \subseteq \{x_1, x_2, \dots, x_n\}$.

We will omit unnecessary brackets in formulas.

1.2 Semantics

If Σ is a predicate signature, a Σ-*structure* $\mathfrak{A}$ consists of a nonempty set A (the *domain* of $\mathfrak{A}$), together with a relation $p^{\mathfrak{A}} \subseteq A^{\operatorname{ar} p}$ (the *interpretation* of p at $\mathfrak{A}$) for every predicate symbol $p \in \Sigma$. A structure is *finite* if its domain is finite. We omit the standard definition 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 $(\mathfrak{A} \restriction B)$.

A *predicate signature with intended interpretations* Σ is formally a predicate signature together with an *intended interpretation condition* $\mathcal{A}$, which is formally a class of Σ-structures. A Σ-structure $\mathfrak{A}$ is then just an element of $\mathcal{A}$. 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 relativised appropriately in this context. For example, if $\Sigma = \langle \boldsymbol{e} \rangle$ is a predicate signature consisting of the single binary predicate symbol $\boldsymbol{e}$, having intended interpretation as an equivalence, then the Σ-formula $\forall \boldsymbol{x} \boldsymbol{e}(\boldsymbol{x}, \boldsymbol{x})$ is logically valid. From now on, we will use the term *predicate signature* as *predicate signature with possible intended interpretations*.

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

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

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

If Σ is a predicate signature and φ is a Σ-sentence, then φ is *satisfiable* if there is a Σ-structure that is a model for φ; φ is *finitely satisfiable* if there is a *finite* Σ-structure that is a model for φ. If $\mathcal{K} \subseteq \mathcal{L}[\Sigma]$ is a family of formulas over the predicate signature Σ, the set of *satisfiable sentences* is SAT-$\mathcal{K} \subseteq \mathcal{K}$ and the set of *finitely satisfiable sentences* is FIN-SAT-$\mathcal{K} \subseteq \mathcal{K}$. The family $\mathcal{K}$ has the *finite model property* if SAT-$\mathcal{K}$ = FIN-SAT-$\mathcal{K}$. By the Löwenheim-Skolem theorem, every satisfiable sentence φ 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 Σ-sentences φ and ψ are *logically equivalent* (written $\varphi \equiv \psi$) if they have the same models.

Two Σ-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 Σ be a predicate signature and let $\mathfrak{A}$ and $\mathfrak{B}$ be Σ-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 $(\mathfrak{A} \upharpoonright \operatorname{dom} \mathfrak{p})$ and $(\mathfrak{B} \upharpoonright \operatorname{ran} \mathfrak{p})$.

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 $\bar{a} = \langle a_1, a_2, \ldots, a_r \rangle$ and $\bar{b} = \langle b_1, b_2, \ldots, b_r \rangle$. Duplicator wins the match if the relation $\bar{a} \mapsto \bar{b} = \{a_1 \mapsto b_1, a_2 \mapsto b_2, \ldots, a_r \mapsto b_r\} \subseteq A \times B$, 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 $(\mathfrak{I}_0, \mathfrak{I}_1, \ldots, \mathfrak{I}_r)$ 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 $a \in \operatorname{dom} \mathfrak{q}$.*
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 $b \in \operatorname{ran} \mathfrak{q}$.*

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

1.4 Types

Let $\Sigma = \langle \boldsymbol{p}_1, \boldsymbol{p}_2, \ldots, \boldsymbol{p}_s \rangle$ be a predicate signature. A *1-type* π over Σ is a maximal consistent set of literals featuring only the variable symbol $\boldsymbol{x}$[2]. The set of 1-types over Σ is $\Pi[\Sigma]$. Note that consistency here is relativised by the intended interpretations of the predicate signature. For example if Σ contains the binary predicate symbol $\boldsymbol{e}$ with intended interpretation as an equivalence, then every 1-type over Σ includes the literal $\boldsymbol{e}(\boldsymbol{x}, \boldsymbol{x})$. Also note that the cardinality of a 1-type over Σ is polynomially bounded by the length s of Σ and the cardinality of $\Pi[\Sigma]$ is exponentially bounded by s.

A *2-type* τ over Σ is a maximal consistent set of literals featuring only the variable symbols $\boldsymbol{x}$ and $\boldsymbol{y}$ and including the literal $(\boldsymbol{x} \neq \boldsymbol{y})$. The set of 2-types over Σ is $\mathrm{T}[\Sigma]$. Again, consistency is relativised by the intended interpretation of the predicate signature.

[2] this is different than the commonly used notion of type in model theory, where types are sets of general formulas, not just literals

For example, if Σ contains the binary predicate symbol $\boldsymbol{e}$ with intended interpretation as an equivalence, then if $\boldsymbol{e}(\boldsymbol{x},\boldsymbol{y}) \in \tau$, then $\boldsymbol{e}(\boldsymbol{y},\boldsymbol{x}) \in \tau$. Again, the cardinality of a 2-type over Σ is polynomially bounded by s and the cardinality of $\mathrm{T}[\Sigma]$ is exponentially bounded by s.

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

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

$$\mathrm{tp}^{\mathfrak{A}}[a] = \{\lambda(\boldsymbol{x}) \in \mathcal{L}it[\Sigma] \mid \mathfrak{A} \vDash \lambda(a)\}\,.$$

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

$$\pi^{\mathfrak{A}} = \left\{ a \in A \;\middle|\; \mathrm{tp}^{\mathfrak{A}}[a] = \pi \right\}.$$

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

$$\mathrm{tp}^{\mathfrak{A}}[a,b] = \{\lambda(\boldsymbol{x},\boldsymbol{y}) \in \mathcal{L}it[\Sigma] \mid \mathfrak{A} \vDash \lambda(a,b)\}\,.$$

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

$$\tau^{\mathfrak{A}} = \left\{ (a,b) \in A \times A \;\middle|\; a \neq b \wedge \mathrm{tp}^{\mathfrak{A}}[a,b] = \tau \right\}.$$

1.5 Normal forms

In two-variable logics, a common technique of reducing formula quantifier rank while preserving satisfiability is Skolemization [2]: Let φ be a $\mathcal{L}^2$-sentence. By replacing universally quantified subformulas $\forall x\psi$ by twofold existential negations $\neg\exists x\neg\psi$, without loss of generality assume that only existential quantifiers occur in φ. Consider a subformula ψ of φ that has the lowest possible nontrivial quantifier rank 1. Then $\psi = \psi(y) = \exists x\alpha(x,y)$, where the formula α is quantifier-free, $\{x,y\} = \{\boldsymbol{x},\boldsymbol{y}\}$ and y may or may not necessarly occur freely in α. Introduce a new unary predicate symbol $\boldsymbol{u}_\psi$ with the intended interpretation $\forall y(\boldsymbol{u}_\psi(y) \leftrightarrow \exists x\alpha(x,y))$ and let φ' be the formula obtained from φ by replacing the subformula ψ by $\boldsymbol{u}_\psi(y)$. The original formula φ is equisatisfiable with $\varphi_1 = \forall y(\boldsymbol{u}_\psi(y) \leftrightarrow \exists x\alpha(x,y)) \wedge \varphi'$ in a strict sense, that is any model for φ can be $\boldsymbol{u}_\psi$-enriched into a model for φ_1 and any model for φ_1 is a model for φ. By repeating this process linearly many times, 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* $\mathrm{sctr} : \mathcal{L}^2 \to \mathcal{L}^2$ *which reduces every sentence* φ *to a sentence* $\mathrm{sctr}\,\varphi$ *in* Scott normal form*:*

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

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

1.6 Complexity

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

The Grzegorczyk 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 $\mathrm{zero}(n) = 0$, the successor function $\mathrm{succ}(n) = n + 1$ and the projection functions $\mathrm{proj}_i^u(n_1, n_2, \dots, n_u) = n_i$. If $u, v \in \mathbb{N}$, $f : \mathbb{N}^u \to \mathbb{N}$ and $g_1, g_2, \dots, g_u : \mathbb{N}^v \to \mathbb{N}$ are functions, their *superposition* is the function $h : \mathbb{N}^v \to \mathbb{N}$ 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 $u \in \mathbb{N}$, $f : \mathbb{N}^u \to \mathbb{N}$ and $g : \mathbb{N}^{u+2} \to \mathbb{N}$, their *primitive recursion* is the function $h : \mathbb{N}^{u+1} \to \mathbb{N}$ defined by:

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

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

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

For $i \in \mathbb{N}$, the i-th level of the Grzegorczyk 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 $h : \mathbb{N}^{u+1}$ of the functions $f : \mathbb{N}^u \to \mathbb{N}$, $g : \mathbb{N}^{u+2} \to \mathbb{N}$, $f, g \in \mathcal{E}^i$, such that there is a function $b : \mathbb{N}^{u+1} \to \mathbb{N}$, $b \in \mathcal{E}^i$ bounding h: $h(\bar{n}) \le b(\bar{n})$ for all $n \in \mathbb{N}^{u+1}$. A decision problem $A \subseteq \Omega^*$ is in some level of the Grzegorczyk hierarchy just in case its characteristic function occurs at that level. The primitive recursive functions are partitioned by the Grzegorczyk hierarchy. The complexity class ELEMENTARY coincides with the third level of the Grzegorczyk 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 $A \le_{\mathrm{m}}^{\mathrm{PTime}} B$) if there is a polynomial-time algorithm $f : \Omega_1^* \to \Omega_2^*$ 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 $A =_{\mathrm{m}}^{\textsc{PTime}} B$) if $A \leq_{\mathrm{m}}^{\textsc{PTime}} B$ and $B \leq_{\mathrm{m}}^{\textsc{PTime}} A$.

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* $c^0 = \langle t_1^0, t_2^0, \ldots, t_n^0 \rangle$, where $n \leq m$, is a mapping $t : [1, m] \times [1, m] \to T$ 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 NPTime-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 NExpTime-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 N2ExpTime-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 NeExpTime-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 builtin 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.

2.1 Bits

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

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

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

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

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

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

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

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

If $\mathfrak{A}$ is a B-structure and $a, b \in A$, then:

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

2.2 Counters

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

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

$$[\mathrm{C}{:}\mathrm{data}]^{\mathfrak{A}} a = \sum_{1 \le i \le t} 2^{i-1} [\boldsymbol{u}_i{:}\mathrm{data}]^{\mathfrak{A}} a.$$

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

$$[\mathrm{C}{:}\mathsf{eq}\text{-}d](\boldsymbol{x}) = \bigwedge_{1 \le i \le t} [\boldsymbol{u}_i{:}\mathsf{eq}\text{-}\overline{d}_i](\boldsymbol{x}).$$

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

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

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

$$[\mathrm{C}{:}\mathsf{eq}](\boldsymbol{x}, \boldsymbol{y}) = \bigwedge_{1 \le i \le t} [\boldsymbol{u}_i{:}\mathsf{eq}](\boldsymbol{x}, \boldsymbol{y}).$$

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

The bitstring $\mathrm{a} \in \mathbb{B}^t$ encodes a number less than the number encoded by the bitstring $\mathrm{b} \in \mathbb{B}^t$, 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:

$$\mathrm{a}_j = 0 \text{ and } \mathrm{b}_j = 1 \tag{Less1}$$

$$\mathrm{a}_k = \mathrm{b}_k \text{ for all } k \in [j+1, t]. \tag{Less2}$$

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

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

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

The bitstring $\mathrm{b} \in \mathbb{B}^t$ 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:

$$\mathrm{a}_j = 0 \text{ and } \mathrm{b}_j = 1 \tag{Succ1}$$

$$\mathrm{a}_i = 1 \text{ for all } i \in [1, j-1] \tag{Succ2}$$

$$\mathrm{b}_i = 0 \text{ for all } i \in [1, j-1] \tag{Succ3}$$

$$\mathrm{a}_k = \mathrm{b}_k \text{ for all } k \in [j+1, t]. \tag{Succ4}$$

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

$$[\mathrm{C}{:}\mathsf{succ}](\boldsymbol{x},\boldsymbol{y}) = \bigvee_{1\le j\le t} [\boldsymbol{u}_j{:}\mathsf{eq}\text{-}01](\boldsymbol{x},\boldsymbol{y}) \wedge \bigwedge_{1\le i<j} [\boldsymbol{u}_i{:}\mathsf{eq}\text{-}10](\boldsymbol{x},\boldsymbol{y}) \wedge \bigwedge_{j<k\le t} [\boldsymbol{u}_k{:}\mathsf{eq}](\boldsymbol{x},\boldsymbol{y}).$$

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

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

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

$$[\mathrm{C}{:}\mathsf{less}\text{-}d](\boldsymbol{x}) = \bigvee_{1\le j\le t} \neg\boldsymbol{u}_j(\boldsymbol{x}) \wedge \neg[\boldsymbol{u}_j{:}\mathsf{eq}\text{-}\overline{d}_j](\boldsymbol{x}) \wedge \bigwedge_{j<k\le t} [\boldsymbol{u}_k{:}\mathsf{eq}\text{-}\overline{d}_k](\boldsymbol{x}).$$

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

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

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

If $\mathfrak{A}$ is a C-structure, $a \in A$ and $d \le e \in \mathbb{B}_t$, then

$$\mathfrak{A} \vDash [\mathrm{C}{:}\mathsf{betw}\text{-}d\text{-}e](a) \text{ iff } d \le [\mathrm{C}{:}\mathrm{data}]^{\mathfrak{A}} a \le e.$$

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

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

If $\mathfrak{A}$ is a C-structure and $d \le e \in \mathbb{B}_t$, then $\mathfrak{A} \vDash [\mathrm{C}{:}\mathsf{betw}\text{-}d\text{-}e]$ iff $d \le [\mathrm{C}{:}\mathrm{data}]^{\mathfrak{A}} a \le e$ 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 $\mathrm{V} = \langle \boldsymbol{u}_{11}, \boldsymbol{u}_{12}, \ldots, \boldsymbol{u}_{nt}\rangle$ of (nt) distinct unary predicate symbols. The *counter setup* $\mathrm{V}(p)$ of V at position $p \in [1, n]$ is $\mathrm{V}(p) = \langle \boldsymbol{u}_{p1}, \boldsymbol{u}_{p2}, \ldots, \boldsymbol{u}_{pt}\rangle$.

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

$$[\mathrm{V}{:}\mathrm{data}]^{\mathfrak{A}} a = \left([\mathrm{V}(1){:}\mathrm{data}]^{\mathfrak{A}} a, [\mathrm{V}(2){:}\mathrm{data}]^{\mathfrak{A}} a, \ldots, [\mathrm{V}(n){:}\mathrm{data}]^{\mathfrak{A}} a\right).$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2.4 Permutations

Let $n \in \mathbb{N}^+$. An *n-permutation setup* $\mathrm{P} = \langle \boldsymbol{u}_{11}, \boldsymbol{u}_{12}, \ldots, \boldsymbol{u}_{nt} \rangle$ 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 $\mathcal{L}^1[\mathrm{P}]$-sentence* $[\mathrm{P}\mathbf{:}\mathsf{alldiff}]$ *by:*

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

If $\mathfrak{A}$ is a P-structure then $\mathfrak{A} \vDash [\mathrm{P}\mathbf{:}\mathsf{alldiff}]$ iff $[\mathrm{P}(p)\mathbf{:}\mathrm{data}]^{\mathfrak{A}} a \neq [\mathrm{P}(q)\mathbf{:}\mathrm{data}]^{\mathfrak{A}} a$ for all $a \in A$ and $p \neq q \in [1, n]$.

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

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

If $\mathfrak{A}$ is a P-structure then $\mathfrak{A} \vDash [\mathrm{P}\mathbf{:}\mathsf{perm}]$ iff $[\mathrm{P}\mathbf{:}\mathrm{data}]^{\mathfrak{A}} a \in \mathbb{S}_n$ for all $a \in A$.

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

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 $\mathscr{E}E = \{E[a] \mid a \in A\}$.

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

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

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

$$[\boldsymbol{e}\text{:symm}] = \forall \boldsymbol{x} \forall \boldsymbol{y} \left(\boldsymbol{e}(\boldsymbol{x}, \boldsymbol{y}) \to \boldsymbol{e}(\boldsymbol{y}, \boldsymbol{x}) \right).$$

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

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

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

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

Let $\mathfrak{A}$ be an E-structure and let $E = \boldsymbol{e}^{\mathfrak{A}}$. Then E is reflexive iff $\mathfrak{A} \models [\boldsymbol{e}\text{:refl}]$; E is symmetric iff $\mathfrak{A} \models [\boldsymbol{e}\text{:symm}]$; E is transitive iff $\mathfrak{A} \models [\boldsymbol{e}\text{:trans}]$; E is an equivalence on A iff $\mathfrak{A} \models [\boldsymbol{e}\text{:equiv}]$. 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,*

$$(\forall a \in A)(\forall b \in A) \left(D(a, b) \to E(a, b) \right).$$

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,*

$$(\forall a \in A) \left((\forall b \in A) \left(D(a, b) \to E(a, b) \right) \vee (\forall b \in A) \left(E(a, b) \to D(a, b) \right) \right).$$

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

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

$$[\boldsymbol{d}, \boldsymbol{e}{:}\mathsf{refine}] = \forall \boldsymbol{x} \forall \boldsymbol{y} \left(\boldsymbol{d}(\boldsymbol{x}, \boldsymbol{y}) \rightarrow \boldsymbol{e}(\boldsymbol{x}, \boldsymbol{y}) \right).$$

Then $\langle D, E \rangle$ is in refinement iff $\mathfrak{A} \vDash [\boldsymbol{d}, \boldsymbol{e}{:}\mathsf{refine}]$.

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

$$[\boldsymbol{d}, \boldsymbol{e}{:}\mathsf{global}] = [\boldsymbol{d}, \boldsymbol{e}{:}\mathsf{refine}] \vee [\boldsymbol{e}, \boldsymbol{d}{:}\mathsf{refine}].$$

Then $\langle D, E \rangle$ is in global agreement iff $\mathfrak{A} \vDash [\boldsymbol{d}, \boldsymbol{e}{:}\mathsf{global}]$.

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

$$[\boldsymbol{d}, \boldsymbol{e}{:}\mathsf{local}] = \forall \boldsymbol{x} \left(\forall \boldsymbol{y} \left(\boldsymbol{d}(\boldsymbol{x}, \boldsymbol{y}) \rightarrow \boldsymbol{e}(\boldsymbol{x}, \boldsymbol{y}) \right) \vee \forall \boldsymbol{y} \left(\boldsymbol{e}(\boldsymbol{x}, \boldsymbol{y}) \rightarrow \boldsymbol{d}(\boldsymbol{x}, \boldsymbol{y}) \right) \right).$$

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

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 $D[b] \nsubseteq E[b]$ and $E[b] \nsubseteq D[b]$. 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. □

3.2 Many equivalence relations in agreement

Let e be a positive natural number.

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

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

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 $E_{\nu(1)} \subseteq E_{\nu(2)} \subseteq \cdots \subseteq E_{\nu(e)}$.*

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

Let $\mathrm{E} = \langle \boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e \rangle$ be a predicate signature consisting of e binary predicate symbols. Let $\mathfrak{A}$ be an E-structure and suppose that the symbols $\boldsymbol{e}_i$ are interpreted as equivalence relations on A. Let $E_i = \boldsymbol{e}_i^{\mathfrak{A}}$ for $i \in [1, e]$.

Definition 25. *Define the* $\mathcal{L}^2[\mathrm{E}]$*-sentence* $[\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e\textsf{:refine}]$ *by:*

$$[\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e\textsf{:refine}] = \forall \boldsymbol{x} \forall \boldsymbol{y} \bigwedge_{1 \le i < e} (\boldsymbol{e}_i(\boldsymbol{x}, \boldsymbol{y}) \to \boldsymbol{e}_{i+1}(\boldsymbol{x}, \boldsymbol{y}))\,.$$

Then $\langle E_1, E_2, \ldots, E_e \rangle$ is in refinement iff $\mathfrak{A} \vDash [\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e\textsf{:refine}]$.

Definition 26. *Define the* $\mathcal{L}^2[\mathrm{E}]$*-sentence* $[\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e\textsf{:global}]$ *by:*

$$[\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e\textsf{:global}] = \bigvee_{\nu \in \mathbb{S}_e} [\boldsymbol{e}_{\nu(1)}, \boldsymbol{e}_{\nu(2)}, \ldots, \boldsymbol{e}_{\nu(e)}\textsf{:refine}].$$

Then $\langle E_1, E_2, \ldots, E_e \rangle$ is in global agreement iff $\mathfrak{A} \vDash [\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e\textsf{:global}]$. Note that the length of the formula $[\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e\textsf{:global}]$ grows exponentially as e grows.

Definition 27. *Define the* $\mathcal{L}^2[\mathrm{E}]$*-sentence* $[\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e\textsf{:local}]$ *by:*

$$[\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e\textsf{:local}] = \forall \boldsymbol{x} \bigvee_{\nu \in \mathbb{S}_e} \forall \boldsymbol{y} \bigwedge_{1 \le i < e} (\boldsymbol{e}_{\nu(i)}(\boldsymbol{x}, \boldsymbol{y}) \to \boldsymbol{e}_{\nu(i+1)}(\boldsymbol{x}, \boldsymbol{y})).$$

Then $\langle E_1, E_2, \ldots, E_e \rangle$ is in local agreement iff $\mathfrak{A} \vDash [\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e\textsf{:local}]$. Note that the length of the formula $[\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e\textsf{:local}]$ grows exponentially as e grows.

Let $E = \langle E_1, E_2, \ldots, E_e \rangle$ 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 $S = \{E_{i(1)}, E_{i(2)}, \ldots, E_{i(s)}\}$, where $1 \le i(1) < i(2) < \cdots < i(s) \le e$, 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, $D = \cup\{E_{i(1)}, E_{i(2)}, \ldots, E_{i(s-1)}\}$ 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 $D[a] = E_{i(1)}[a] \cup E_{i(2)}[a] \cup \cdots \cup E_{i(s-1)}[a]$ 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. □

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

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

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

That is, $(E \restriction \mathrm{I})$ *just collects the equivalences having indices from* I.

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

$$L_k = \cap \left\{ \cup (E \restriction \mathrm{I}) \;\middle|\; \mathrm{I} \in \wp^k[1,e] \right\}.$$

Remark 1. *All* L_k *are equivalence relations on* A.

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

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

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

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

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

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 $\mathrm{K} = \{\nu(1), \nu(2), \ldots, \nu(k)\}$. By the definition of L_k, followed by eq. (3.1), we have $L_k[a] \subseteq \cup(E \restriction \mathrm{K})[a] = E_{\nu(k)}[a] = E_i[a]$. Next, let $\mathrm{K} \subseteq \wp^k[1,e]$ be any k-index set. By the pigeonhole principle, there is some $k' \geq k$ such that $\nu(k') \in \mathrm{K}$. By eq. (3.1) we have:

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

Hence $E_i[a] \subseteq \cap \left\{ \cup(E \restriction \mathrm{K})[a] \;\middle|\; \mathrm{K} \in \wp^k[1,e] \right\} = L_k[a]$. □

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 builtin equivalence symbols, we use the notation

$$\mathcal{L}_p^v e\mathrm{E}_{\mathsf{a}}$$

where:

- $\mathcal{L}$ is the *ground logic*
- v, if given, bounds the number of variables
- e, if given, bounds the number of builtin equivalence symbols
- $\mathsf{a} \in \{\mathsf{refine}, \mathsf{global}, \mathsf{local}\}$, if given, gives the agreement condition between the builtin 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 builtin equivalence symbols
  - if $p = 1$, the signature consists of unboundedly many unary predicate symbols in addition to the builtin equivalence symbols
  - if p is not given, the signature consists of unboundedly many unary and binary predicate symbols in addition to the builtin 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. $\mathcal{L}_0 1\mathrm{E}$ is the first-order logic of a single equivalence relation. $\mathcal{L}^2 2\mathrm{E}$ is the two-variable logic, featuring unary, binary predicate symbols and two builtin equivalence symbols. $\mathcal{L}_1^2 2\mathrm{E}_{\mathsf{local}}$ is the two-variable logic, featuring unary predicate symbols and two builtin equivalence symbols in local agreement. $\mathcal{L}_1 \mathrm{E}_{\mathsf{global}}$ is the monadic first-order logic featuring many equivalence symbols in global agreement.

When we working with a concrete logic, for example $\mathcal{L}^2 2\mathrm{E}_{\mathsf{local}}$, we implicitly assume an appropriate generic predicate signature Σ for it. In this case, there are two builtin equivalence symbols $\boldsymbol{d}$ and $\boldsymbol{e}$ in Σ and in addition Σ contains arbitrary many unary and binary predicate symbols. The *intended interpretation* of the builtin equivalence symbols is fixed by an appropriate condition θ. In this case:

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

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 $[\boldsymbol{d}\textsf{:equiv}]$ uses the variables $\boldsymbol{x}, \boldsymbol{y}$ and $\boldsymbol{z}$ and the logic $\mathcal{L}^2 2\mathrm{E}_{\mathsf{local}}$ is a two-variable logic. Recall that when talking about semantics, we include the intended interpretation condition in the definition of Σ-structures.

4.1 Global agreement to refinement

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

Let Σ be a predicate signature for the logics $\mathcal{L}e\mathrm{E}_{\mathsf{global}}$ or $\mathcal{L}e\mathrm{E}_{\mathsf{refine}}$. The e builtin equivalence symbols of Σ are $\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e$.

Let φ be a Σ-sentence. The class of $\mathcal{L}e\mathrm{E}_{\mathsf{refine}}$-structures satisfying φ coincides with the class of $\mathcal{L}e\mathrm{E}_{\mathsf{global}}$-structures satisfying

$$\varphi \wedge [\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e\textsf{:refine}].$$

Hence:

$$(\text{FIN-})\text{SAT-}\mathcal{L}e\mathrm{E}_{\mathsf{refine}} \leq_{\mathrm{m}}^{\mathrm{PTIME}} (\text{FIN-})\text{SAT-}\mathcal{L}e\mathrm{E}_{\mathsf{global}}.$$

Since the length of the formula $[\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e\textsf{:refine}]$ grows polynomially as e grows:

$$(\text{FIN-})\text{SAT-}\mathcal{L}\mathrm{E}_{\mathsf{refine}} \leq_{\mathrm{m}}^{\mathrm{PTIME}} (\text{FIN-})\text{SAT-}\mathcal{L}\mathrm{E}_{\mathsf{global}}.$$

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

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

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

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

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

$$[\mathrm{P}\textsf{:globperm}] = [\mathrm{P}\textsf{:perm}] \wedge [\mathrm{P}\textsf{:alleq}].$$

If $\mathfrak{A}$ be a P-structure then $\mathfrak{A} \models [\mathrm{P}\mathbf{:}\mathsf{globperm}]$ iff there is a permutation $\nu \in \mathbb{S}_e$ such that $[\mathrm{P}\mathbf{:}\mathrm{data}]^{\mathfrak{A}} a = \nu$ for all $a \in A$.

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

Let $\mathrm{L} = \langle \boldsymbol{l}_1, \boldsymbol{l}_2, \ldots, \boldsymbol{l}_e \rangle + \mathrm{P}$ be a predicate signature consisting of the binary predicate symbols $\boldsymbol{l}_k$ in addition to the symbols from P.

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

$$[\mathrm{L}\mathbf{:}\mathsf{eg}\text{-}i](\boldsymbol{x}, \boldsymbol{y}) = \bigwedge_{1 \le k \le e} \left([\mathrm{P}(k)\mathbf{:}\mathsf{eq}\text{-}i](\boldsymbol{x}) \to \boldsymbol{l}_k(\boldsymbol{x}, \boldsymbol{y}) \right).$$

Remark 2. *Let $\mathfrak{A}$ be an L-structure and suppose that $\mathfrak{A} \models [\mathrm{P}\mathbf{:}\mathsf{globperm}]$ and that the binary symbols $\boldsymbol{l}_k$ are interpreted as equivalence relations on A in refinement. Recall that there is a permutation $\nu \in \mathbb{S}_e$ such that $[\mathrm{P}\mathbf{:}\mathrm{data}]^{\mathfrak{A}} a = \nu$ for all $a \in A$. Then for all $i \in [1, e]$:*

$$[\mathrm{L}\mathbf{:}\mathsf{eg}\text{-}i]^{\mathfrak{A}} = \boldsymbol{l}^{\mathfrak{A}}_{\nu^{-1}(i)}.$$

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

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

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

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

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

$$\mathfrak{A} \models \neg \left([\mathrm{P}(k')\mathbf{:}\mathsf{eq}\text{-}i](a) \to \boldsymbol{l}_{k'}(a, b) \right) \equiv [\mathrm{P}(k')\mathbf{:}\mathsf{eq}\text{-}i](a) \wedge \neg \boldsymbol{l}_{k'}(a, b).$$

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

Let $\mathrm{E} = \langle \boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e \rangle$ be a predicate signature consisting of the binary predicate symbols $\boldsymbol{e}_i$. Let Σ be a predicate signature enriching E and not containing any symbols from L. Let $\Sigma' = \Sigma \cup \mathrm{L}$ and $\mathrm{L}' = \Sigma' - \mathrm{E}$.

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

$$\mathrm{gtr}\, \varphi = \varphi' \wedge [\mathrm{P}\mathbf{:}\mathsf{globperm}],$$

where φ' is obtained from φ by replacing all occurrences of a subformula of the form $\boldsymbol{e}_i(x, y)$ by the formula $[\mathrm{L}\mathbf{:}\mathsf{eg}\text{-}i](x, y)$, where x and y are (not necessarily distinct) variables and $i \in [1, e]$.

Remark 3. *Let φ be a Σ-formula and let $\mathfrak{A}$ be a Σ-structure. Suppose that $\mathfrak{A} \models \varphi$ and that the symbols $\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e$ are interpreted in $\mathfrak{A}$ as equivalence relations on A in global agreement. Then there is a Σ'-enrichment $\mathfrak{A}'$ of $\mathfrak{A}$ such that $\mathfrak{A}' \models \operatorname{gtr}\varphi$ and that the symbols $\boldsymbol{l}_1, \boldsymbol{l}_2, \ldots, \boldsymbol{l}_e$ are interpreted in $\mathfrak{A}'$ as equivalence relations on A in refinement.*

Proof. There is a permutation $\nu \in \mathbb{S}_e$ such that $\boldsymbol{e}^{\mathfrak{A}}_{\nu(1)} \subseteq \boldsymbol{e}^{\mathfrak{A}}_{\nu(2)} \subseteq \cdots \subseteq \boldsymbol{e}^{\mathfrak{A}}_{\nu(e)}$. Consider an enrichment $\mathfrak{A}'$ of $\mathfrak{A}$ to a Σ'-structure where $\boldsymbol{l}^{\mathfrak{A}'}_k = \boldsymbol{e}^{\mathfrak{A}}_{\nu(k)}$, so the interpretations of $\boldsymbol{l}_k$ 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 $\mathfrak{A}' \models [\mathrm{P}{:}\mathsf{globperm}]$ and $[\mathrm{P}{:}\mathrm{data}]^{\mathfrak{A}} a = \nu$ for all $a \in A$. By Remark 2, for every $i \in [1, e]$:

$$[\mathrm{L}{:}\mathrm{eg}\text{-}i]^{\mathfrak{A}'} = \boldsymbol{l}^{\mathfrak{A}'}_{\nu^{-1}(i)} = \boldsymbol{e}^{\mathfrak{A}'}_{\nu(\nu^{-1}(i))} = \boldsymbol{e}^{\mathfrak{A}'}_i = \boldsymbol{e}^{\mathfrak{A}}_i.$$

Hence $\mathfrak{A}' \models \forall \boldsymbol{x} \forall \boldsymbol{y}\, (\boldsymbol{e}_i(\boldsymbol{x}, \boldsymbol{y}) \leftrightarrow [\mathrm{L}{:}\mathrm{eg}\text{-}i](\boldsymbol{x}, \boldsymbol{y}))$. Since $\mathfrak{A}' \models \varphi$ we have $\mathfrak{A}' \models \operatorname{gtr}\varphi$. □

Remark 4. *Let φ be a Σ-formula and let $\mathfrak{A}$ be an L'-structure. Suppose that $\mathfrak{A} \models \operatorname{gtr}\varphi$ and that the symbols $\boldsymbol{l}_1, \boldsymbol{l}_2, \ldots, \boldsymbol{l}_e$ are interpreted in $\mathfrak{A}$ as equivalence relations on A in refinement. Then there is a Σ'-enrichment $\mathfrak{A}'$ of $\mathfrak{A}$ such that $\mathfrak{A}' \models \varphi$ and that the symbols $\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e$ are interpreted as equivalence relations on A in global agreement in $\mathfrak{A}'$.*

Proof. Consider an enrichment $\mathfrak{A}'$ of $\mathfrak{A}$ to a Σ'-structure where $\boldsymbol{e}^{\mathfrak{A}'}_i = [\mathrm{L}{:}\mathrm{eg}\text{-}i]^{\mathfrak{A}}$. By Remark 2, $\langle \boldsymbol{e}^{\mathfrak{A}'}_1, \boldsymbol{e}^{\mathfrak{A}'}_2, \ldots, \boldsymbol{e}^{\mathfrak{A}'}_e \rangle$ is a sequence of equivalence relations on A in global agreement. For every $i \in [1, e]$ we have $\mathfrak{A}' \models \forall \boldsymbol{x} \forall \boldsymbol{y} (\boldsymbol{e}_i(\boldsymbol{x}, \boldsymbol{y}) \leftrightarrow [\mathrm{L}{:}\mathrm{eg}\text{-}i](\boldsymbol{x}, \boldsymbol{y}))$ by definition. Since $\mathfrak{A}' \models \operatorname{gtr}\varphi$ we have $\mathfrak{A}' \models \varphi$. □

The last two remarks show that a $\mathcal{L}e\mathrm{E}_{\mathsf{global}}$-formula φ has essentially the same models as the $\mathcal{L}e\mathrm{E}_{\mathsf{refine}}$-formula $\operatorname{gtr}\varphi$, so we have shown:

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

Since the relative size of $\operatorname{gtr}\varphi$ with respect to φ grows polynomially as e grows, we have shown:

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

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 $\mathcal{L}^2_0 e\mathrm{E}_{\mathsf{a}}$, $\mathcal{L}^2_1 e\mathrm{E}_{\mathsf{a}}$ and $\mathcal{L}^2_1\mathrm{E}_{\mathsf{a}}$ for $\mathsf{a} \in \{\mathsf{global}, \mathsf{refine}\}$ (but not for the fragment $\mathcal{L}^2_0\mathrm{E}_{\mathsf{a}}$).

4.2 Local agreement to refinement

In this section demonstrate how (finite) satisfiability in logics featuring builtin equivalence symbols in local agreement reduces to (finite) satisfiability in logics featuring builtin 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 Σ be a predicate signature for the logics $\mathcal{L}e\mathrm{E}_{\mathsf{local}}$ and $\mathcal{L}e\mathrm{E}_{\mathsf{refine}}$. The e builtin equivalence symbols of Σ are $\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e$.

Let φ be a Σ-sentence. The class of $\mathcal{L}e\mathrm{E}_{\mathsf{refine}}$-structures satisfying φ coincides with the class of $\mathcal{L}e\mathrm{E}_{\mathsf{local}}$-structures satisfying

$$\varphi \wedge [\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e\mathsf{:refine}].$$

Hence:

$$\text{(FIN-)SAT-}\mathcal{L}e\mathrm{E}_{\mathsf{refine}} \leq_{\mathrm{m}}^{\mathrm{PTIME}} \text{(FIN-)SAT-}\mathcal{L}e\mathrm{E}_{\mathsf{local}}.$$

Since the size of the formula $[\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e\mathsf{:refine}]$ grows polynomially as e grows, we have:

$$\text{(FIN-)SAT-}\mathcal{L}\mathrm{E}_{\mathsf{refine}} \leq_{\mathrm{m}}^{\mathrm{PTIME}} \text{(FIN-)SAT-}\mathcal{L}\mathrm{E}_{\mathsf{local}}.$$

Consider the opposite direction. Let $\mathrm{E} = \langle \boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e \rangle$ be a predicate signature consisting of the binary predicate symbols $\boldsymbol{e}_i$ (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 $\boldsymbol{e}_i$ are interpreted in $\mathfrak{A}$ as equivalence relations on A in local agreement. Let $E_i = \boldsymbol{e}_i^{\mathfrak{A}}$ 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):

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

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

Remark 5. *Let $a \in A$, $\nu = [\mathrm{E}\mathbf{:}\mathrm{chperm}]^{\mathfrak{A}} a$ 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 ν 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, μ is a permutation satisfying eq. (4.2) that is lexicographically smaller than ν — a contradiction. □

Remark 6. *Let $a, b \in A$ and let $\alpha = [\mathrm{E{:}chperm}]^{\mathfrak{A}}a$ and $\beta = [\mathrm{E{:}chperm}]^{\mathfrak{A}}b$. 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 α and $q > p$ is the position of i in the permutation β. By the pigeonhole principle, there is $k \in [1, e]$ that occurs after i in α and before j in β: $p < \alpha^{-1}(k)$ and $\beta^{-1}(k) < q$. Since β 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 α, 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 5, $i < k$. By the contrapositive of Remark 5, $E_k[b] = E_i[b]$ is impossible. Since k occurs before i in β, 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. □

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

Remark 7. *Let $a \in A$, $\alpha = [\mathrm{E{:}chperm}]^{\mathfrak{A}}a$ and let $k \in [1, e]$. Then $L_k[a] = E_{\alpha(k)}[a]$.*

Proof. Since α satisfies eq. (4.2), by Lemma 3:

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

□

Remark 8. *Let $a, b \in A$, $\alpha = [\mathrm{E{:}chperm}]^{\mathfrak{A}}a$, $\beta = [\mathrm{E{:}chperm}]^{\mathfrak{A}}b$ 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 7, $L_k[a] = E_{\alpha(k)}[a]$, thus $(a, b) \in E_{\alpha(k)}$. By Remark 5,

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

Hence $\beta(k) = \alpha(k)$. □

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

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

$$[\mathsf{L{:}fixperm}] = \forall \boldsymbol{x} \forall \boldsymbol{y} \bigwedge_{1 \le k \le e} (\boldsymbol{l}_k(\boldsymbol{x}, \boldsymbol{y}) \to [\mathrm{P}(k){:}\mathsf{eq}](\boldsymbol{x}, \boldsymbol{y}))\,.$$

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

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

Remark 9. *Let* $\mathfrak{A}$ *be an* L*-structure and suppose that* $\mathfrak{A} \models [\mathsf{L{:}locperm}]$*. Let* $a, b \in A$*,* $k \in [1, e]$ *and suppose that* $\mathfrak{A} \models \boldsymbol{l}_k(a, b)$*. Let* $\alpha = [\mathrm{P{:}data}]^{\mathfrak{A}} a$ *and* $\beta = [\mathrm{P{:}data}]^{\mathfrak{A}} b$ *be the* e*-permutations at* a *and* b*,* encoded by the permutation setup P*. Then* $\alpha(k) = \beta(k)$*.*

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

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

$$[\mathsf{L{:}el\text{-}}i](\boldsymbol{x}, \boldsymbol{y}) = \bigwedge_{1 \le k \le e} ([\mathrm{P}(k){:}\mathsf{eq\text{-}}i](\boldsymbol{x}) \to \boldsymbol{l}_k(\boldsymbol{x}, \boldsymbol{y}))\,.$$

Remark 10. *Let* $\mathfrak{A}$ *be an* L*-structure and suppose that* $\mathfrak{A} \models [\mathsf{L{:}locperm}]$ *and that the binary symbols* $\boldsymbol{l}_k$ *are interpreted in* $\mathfrak{A}$ *as equivalence relations on* A *in refinement. Define* $\nu : A \to \mathbb{S}_e$ *by* $\nu(a) = [\mathrm{P{:}data}]^{\mathfrak{A}} a$ *for* $a \in A$*. Let* $a \in A$ *be arbitrary. Then for all* $i \in [1, e]$*:*

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

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

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

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

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

Remark 11. *Let* $\mathfrak{A}$ *and* ν *are declared as in* Remark 10*. Then the sequence of interpretations* $\langle [\mathsf{L{:}el\text{-}1}]^{\mathfrak{A}}, [\mathsf{L{:}el\text{-}2}]^{\mathfrak{A}}, \ldots, [\mathsf{L{:}el\text{-}}e]^{\mathfrak{A}} \rangle$ *is a sequence of equivalence relations on* A *in local agreement.*

Proof. Let $E_i = [\mathsf{L{:}el\text{-}}i]^{\mathfrak{A}}$ and $L_i = \boldsymbol{l}_i^{\mathfrak{A}}$ 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 10, $E_i[a] = L_k[a]$ for $k = \nu(a)^{-1}(i)$. But $L_k[a]$ is an equivalence class, hence $a \in L_k[a]$, so $(a, a) \in E_i$.

- 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 10, $E_i[a] = L_k[a]$. Thus $\mathfrak{A} \models \boldsymbol{l}_k(a, b)$ and by Remark 9, $i = \nu(a)(k) = \nu(b)(k)$. By Remark 10:

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

  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 10, since the relations L_k are in refinement, we have that $E_1, E_2, \ldots, E_e$ are in local agreement. $\square$

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

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

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

where φ' is obtained from φ by replacing all occurrences of a subformula of the form $\boldsymbol{e}_i(x, y)$ by the formula $[\mathrm{L}{:}\mathsf{el}\text{-}i](x, y)$, where x and y are (not necessarily distinct) variable symbols and $i \in [1, e]$.

Remark 12. *Let φ be a Σ-formula and let $\mathfrak{A}$ be a Σ-structure. Suppose that $\mathfrak{A} \vDash \varphi$ and that the symbols $\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e$ are interpreted in $\mathfrak{A}$ as equivalence relations on A in local agreement. Then there is a Σ'-enrichment $\mathfrak{A}'$ of $\mathfrak{A}$ such that $\mathfrak{A}' \vDash \mathrm{ltr}\, \varphi$ and that the symbols $\boldsymbol{l}_1, \boldsymbol{l}_2, \ldots, \boldsymbol{l}_e$ are interpreted in $\mathfrak{A}'$ as equivalence relations on A in refinement.*

Proof. Since the binary symbols $\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e$ are interpreted as equivalence relations on A in local agreement in $\mathfrak{A}$, we may define the levels $L_1, L_2, \ldots, L_e \subseteq A \times A$ and the characteristic E-permutation mapping $\nu = [\mathrm{E}{:}\mathrm{chperm}]^{\mathfrak{A}} : A \to \mathbb{S}_e$. Consider an enrichment $\mathfrak{A}'$ of $\mathfrak{A}$ where $\boldsymbol{l}_i^{\mathfrak{A}'} = L_i$. By Lemma 2, L_i are equivalences on A in refinement. We interpret the unary symbols from the permutation setup P so that $[\mathrm{P}{:}\mathrm{data}]^{\mathfrak{A}'} a = \nu(a)$ for all $a \in A$. By Remark 8, $\mathfrak{A}' \vDash [\mathrm{L}{:}\mathsf{fixperm}]$. By Remark 10, followed by Lemma 3, for every $i \in [1, e]$ and $a \in A$ we have:

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

By Remark 11, the interpretations $[\mathrm{L}{:}\mathsf{el}\text{-}i]^{\mathfrak{A}'}$ are equivalence relations. Since the interpretation of the formula $[\mathrm{L}{:}\mathsf{el}\text{-}i]$ has the same classes as the interpretation of the symbol $\boldsymbol{e}_i$, we have $\mathfrak{A}' \vDash \forall \boldsymbol{x} \forall \boldsymbol{y}\, (\boldsymbol{e}_i(\boldsymbol{x}, \boldsymbol{y}) \leftrightarrow [\mathrm{L}{:}\mathsf{el}\text{-}i](\boldsymbol{x}, \boldsymbol{y}))$. Since $\mathfrak{A}' \vDash \varphi$ we have $\mathfrak{A}' \vDash \mathrm{ltr}\, \varphi$. $\square$

Remark 13. *Let φ be a Σ-formula and let $\mathfrak{A}$ be an L'-structure. Suppose that $\mathfrak{A} \vDash \mathrm{ltr}\, \varphi$ and that the symbols $\boldsymbol{l}_1, \boldsymbol{l}_2, \ldots, \boldsymbol{l}_e$ are interpreted as equivalence relations on A in refinement in $\mathfrak{A}$. Then there is a Σ'-enrichment $\mathfrak{A}'$ of $\mathfrak{A}$ such that $\mathfrak{A}' \vDash \varphi$ and that the binary symbols $\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e$ are interpreted as equivalence relations on A in global agreement in $\mathfrak{A}'$.*

Proof. Consider an enrichment $\mathfrak{A}'$ of $\mathfrak{A}$ to a Σ'-structure where $\boldsymbol{e}_i^{\mathfrak{A}'} = [\mathrm{L}{:}\mathsf{el}\text{-}i]^{\mathfrak{A}}$. By Remark 11, $\boldsymbol{e}_i^{\mathfrak{A}'}$ are equivalence relations on A in local agreement. For every $i \in [1, e]$ we have $\mathfrak{A}' \vDash \forall \boldsymbol{x} \forall \boldsymbol{y}\, (\boldsymbol{e}_i(\boldsymbol{x}, \boldsymbol{y}) \leftrightarrow [\mathrm{L}{:}\mathsf{el}\text{-}i](\boldsymbol{x}, \boldsymbol{y}))$ by definition. Since $\mathfrak{A}' \vDash \mathrm{ltr}\, \varphi$ we have $\mathfrak{A}' \vDash \varphi$. $\square$

The last two remarks show that a $\mathcal{L}e\mathrm{E}_{\mathsf{local}}$-formula φ has essentially the same models as the $\mathcal{L}e\mathrm{E}_{\mathsf{refine}}$-formula $\operatorname{ltr}\varphi$, so we have shown:

Proposition 3. *The logic $\mathcal{L}e\mathrm{E}_{\mathsf{local}}$ has the finite model property iff the logic $\mathcal{L}e\mathrm{E}_{\mathsf{refine}}$ has the finite model property. The corresponding satisfiability problems are polynomial-time equivalent:* (FIN-)SAT-$\mathcal{L}e\mathrm{E}_{\mathsf{local}} =_{\mathrm{m}}^{\mathrm{PT{\scriptsize IME}}}$ (FIN-)SAT-$\mathcal{L}e\mathrm{E}_{\mathsf{refine}}$.

Since the relative size of $\operatorname{ltr}\varphi$ with respect to φ grows polynomially as e grows, we have shown:

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

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 $\mathcal{L}_0^2e\mathrm{E}_{\mathsf{a}}$, $\mathcal{L}_1^2e\mathrm{E}_{\mathsf{a}}$ and $\mathcal{L}_1^2\mathrm{E}_{\mathsf{a}}$ for $\mathsf{a} \in \{\mathsf{local}, \mathsf{refine}\}$.

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 $c : A \to [1, g]$ 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 14. *Let $g \in \mathbb{N}^+$ and let $\langle D, E\rangle$ be g-granular. Then there is a g-granular coloring for the sequence.*

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 $\imath : S \hookrightarrow [1, g]$ be any injective function. Define the color c on X as $c(a) = \imath(D[a])$. □

Remark 15. *Let $E \subseteq A \times A$ be an equivalence relation on A, $g \in \mathbb{N}^+$ and $c : A \to [1, g]$. 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 $D = \{(a, b) \in E \mid c(a) = c(b)\}$. □

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

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

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

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

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

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

where φ' is obtained from the formula φ by replacing all subformulas of the form $\boldsymbol{d}(x, y)$ by $[\Gamma\mathbf{:}\mathsf{d}](x, y)$, where x and y are (not necessarily distinct) variable symbols.

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

Proof. By Remark 14, there exists a g-granular coloring $c : A \to [1, g]$. We interpret the unary symbols in G so that $[\mathrm{G}\mathbf{:}\mathrm{data}]^{\mathfrak{A}} = c$. Since $\mathfrak{A}'$ is an enrichment of $\mathfrak{A}$, we have $\mathfrak{A}' \vDash \varphi$. Let $a, b \in A$. Then $\mathfrak{A}' \vDash [\Gamma\mathbf{:}\mathsf{d}](a, b)$ is equivalent to:

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

which is equivalent to:

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

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

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

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

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

Proof. Since $\mathfrak{A} \vDash [\mathrm{G}\mathbf{:}\mathsf{betw}\text{-}1\text{-}g]$, we have $[\mathrm{G}\mathbf{:}\mathrm{data}]^{\mathfrak{A}} a \in [1, g]$ for all $a \in A$. Define $c : A \to [1, g]$ by $c(a) = [\mathrm{C}\mathbf{:}\mathrm{data}]^{\mathfrak{A}} a$. By Remark 14, 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 Σ'-structure $\mathfrak{A}'$, where $\boldsymbol{d}^{\mathfrak{A}'} = D$. Since $\mathfrak{A}'$ is an enrichment of $\mathfrak{A} \vDash \mathrm{grtr}\, \varphi$, we have $\mathfrak{A}' \vDash \mathrm{grtr}\, \varphi$. Let $a, b \in A$. Then $\mathfrak{A}' \vDash [\Gamma\mathbf{:}\mathsf{d}](a, b)$ is equivalent to:

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

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

5 Monadic logics

In this chapter we investigate questions about (finite) satisfiability of first-order sentences featuring unary predicate symbols and builtin 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 $\mathcal{L}_0 1\mathrm{E}$ has the finite model property and its (finite) satisfiability problem is PSpace-complete [5]
- The first-order logic of two equivalence relations $\mathcal{L}_0 2\mathrm{E}$ 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 $\mathcal{L}_1$ has the finite model property and its (finite) satisfiability problem is $\mathrm{N}(e+1)$ExpTime-complete.

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

5.1 Cells

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

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

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

If $\mathfrak{A}$ is a Σ-structure and $D = \boldsymbol{d}^{\mathfrak{A}}$, then the interpretation $C = [\Sigma{:}\mathsf{cell}]^{\mathfrak{A}} \subseteq A \times A$ 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 $\boldsymbol{u}$-predicates.*

Remark 16. *Let $\mathfrak{A}$ be a Σ-structure, $r \in \mathbb{N}$, $\bar{a} = a_1 a_2 \ldots a_r \in A^r$, $\bar{b} = b_1 b_2 \ldots b_r \in A^r$ 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 $\boldsymbol{u}$-predicates. The equality condition ensures that the mapping is a bijection. $\square$

Lemma 6. *Let $\mathfrak{A}$ be a Σ-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 $\mathfrak{B} = \mathfrak{A} \restriction B$. 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 $a \in A$:

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

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 $\mathfrak{I}_0, \mathfrak{I}_1, \ldots, \mathfrak{I}_r$ satisfies the back-and-forth conditions of Theorem 1. Let $i \in [0, r-1]$ and let

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

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 $\Sigma = \Sigma(u, e) = \langle \boldsymbol{u}_1, \boldsymbol{u}_2, \ldots, \boldsymbol{u}_u, \boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e \rangle$ be a predicate signature. Abbreviate the finest two equivalence symbols $\boldsymbol{d} = \boldsymbol{e}_1$ and $\boldsymbol{e} = \boldsymbol{e}_2$.

Definition 44. *Let $\mathfrak{A}$ be a Σ-structure and let $D = \boldsymbol{d}^{\mathfrak{A}}$ and $E = \boldsymbol{e}^{\mathfrak{A}}$. Recall that the set of D-classes is $\mathscr{E}D$. Two D-classes $X, Y \in \mathscr{E}D$ 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 $\mathcal{O} \subseteq \mathscr{E}D \times \mathscr{E}D$. Since D refines E, organ-equivalence is an equivalence relation on $\mathscr{E}D$. 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 $\mathfrak{h}_{XX} = \mathrm{id}_X$, $\mathfrak{h}_{YX} = \mathfrak{h}_{XY}^{-1}$ 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 $O \subseteq A \times A$ is an equivalence relation on A that refines E.*

Remark 17. *Let $\mathfrak{A}$ be a Σ-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 $\mathfrak{A} \vDash \boldsymbol{d}(a_i, a_j)$ iff $\mathfrak{A} \vDash \boldsymbol{d}(b_i, b_j)$ 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 $\boldsymbol{d}$ ensures that the interpretation of $\boldsymbol{d}$ 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 $O \subseteq A \times A$ refines the second finest equivalence relation E, the interpretation of all remaining equivalence symbols $\boldsymbol{e}_j$ is preserved. □

Lemma 7. *Let $\mathfrak{A}$ be a Σ-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 $D = \boldsymbol{d}^{\mathfrak{A}}$, $E = \boldsymbol{e}^{\mathfrak{A}}$ and let $\mathcal{A} = \mathscr{E}D$ 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 folloing 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 $a \in A$:

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

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 $\bar{a}a \mapsto \bar{b}b \in \mathfrak{I}_{i+1}$. 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 $\bar{a}a \mapsto \bar{b}b \in \mathfrak{I}$. 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 18. *Let $u, e \in \mathbb{N}$, $e \geq 2$ and consider the predicate signature $\Sigma = \Sigma(u, e) = \langle \boldsymbol{u}_1, \boldsymbol{u}_2, \ldots, \boldsymbol{u}_u, \boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e \rangle$. Abbreviate $\boldsymbol{d} = \boldsymbol{e}_1$ and $\boldsymbol{e} = \boldsymbol{e}_2$. Let $r \in \mathbb{N}^+$. There is $\mathfrak{B} \subseteq \mathfrak{A}$ such that $\mathfrak{B} \equiv_r \mathfrak{A}$ and $\langle \boldsymbol{d}^{\mathfrak{B}}, \boldsymbol{e}^{\mathfrak{B}} \rangle$ is g-granular for $g = g(u, r) = r.((r + 1)^{2^u} - 1)$. 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 $D = \boldsymbol{d}^{\mathfrak{B}}$ and $E = \boldsymbol{e}^{\mathfrak{B}}$. 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 $\big((r + 1)^{2^u} - 1\big)$ 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 φ be a $\mathcal{L}[\Sigma]$-sentence having quantifier rank r. By Lemma 4 and Lemma 5 about granularity, the formula φ is essentially equisatisfiable with the formula $\operatorname{grtr} \varphi$, which is a $\Sigma(u + \|g(u, r)\|, e - 1)$-sentence. Note that $\|g(u, r)\|$ is exponentially bounded by the length $\|\varphi\|$ of the formula. So we have a reduction:*

$$\text{(FIN-)SAT-}\mathcal{L}_1 e\mathrm{E}_{\mathsf{refine}} \leq_{\mathrm{m}}^{\textsc{ExpTime}} \text{(FIN-)SAT-}\mathcal{L}_1 (e-1)\mathrm{E}_{\mathsf{refine}}.$$

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

$$\text{(FIN-)SAT-}\mathcal{L}_0 e\mathrm{E}_{\mathsf{refine}} \leq_{\mathrm{m}}^{\textsc{PTime}} \text{(FIN-)SAT-}\mathcal{L}_1 (e-1)\mathrm{E}_{\mathsf{refine}}.$$

Remark 19. *Let $u \in \mathbb{N}$ and consider $\Sigma = \Sigma(u,1) = \langle \boldsymbol{u}_1, \boldsymbol{u}_2, \ldots, \boldsymbol{u}_u, \boldsymbol{d} \rangle$. 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 $\Sigma' = \Sigma + \langle \boldsymbol{e} \rangle$ be an enrichment of Σ with the builtin equivalence symbols $\boldsymbol{e}$. Consider an enrichment $\mathfrak{A}'$ of $\mathfrak{A}$ to a Σ'-structure, where $\boldsymbol{e}^{\mathfrak{A}'} = A \times A$ is interpreted as the full relation on A. Then $\langle \boldsymbol{d}^{\mathfrak{A}'}, \boldsymbol{e}^{\mathfrak{A}'} \rangle$ is a sequence of equivalence relations on A in refinement. By Remark 18, there is $\mathfrak{B}' \subseteq \mathfrak{A}'$ such that $\mathfrak{B}' \equiv_r \mathfrak{A}'$ and $\langle \boldsymbol{d}^{\mathfrak{B}'}, \boldsymbol{e}^{\mathfrak{B}'} \rangle$ is g-granular. Consider the reduct $\mathfrak{B}$ of $\mathfrak{B}'$ to a Σ-structure. Let $D = \boldsymbol{d}^{\mathfrak{B}}$ and $E = \boldsymbol{e}^{\mathfrak{B}}$. 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 $\boldsymbol{e}$ 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 $|B| \leq g.r.2^u$. □

Corollary 2. *The logic $\mathcal{L}_1$1E has the finite model property and its (finite) satisfiability problem is in* N2ExpTime.

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

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

By Proposition 1 and Proposition 3, the same holds for $\mathcal{L}_1 e\mathrm{E}_{\mathsf{global}}$ and $\mathcal{L}_1 e\mathrm{E}_{\mathsf{local}}$.

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

By Proposition 2 and Proposition 4, the same holds for $\mathcal{L}_1\mathrm{E}_{\mathsf{global}}$ and $\mathcal{L}_1\mathrm{E}_{\mathsf{local}}$.

Proposition 7. *For $e \geq 2$, the logic $\mathcal{L}_0 e\mathrm{E}_{\mathsf{refine}}$ has the finite model property and its (finite) satisfiability problem is in* NeExpTime.

By Proposition 1 and Proposition 3, the same holds for $\mathcal{L}_0 e\mathrm{E}_{\mathsf{global}}$ and $\mathcal{L}_0 e\mathrm{E}_{\mathsf{local}}$.

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 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 coordinaes of a cell of the doubly exponential tiling square.

Consider the counter setup $\mathrm{C}(u) = \langle \boldsymbol{u}_1, \boldsymbol{u}_2, \ldots, \boldsymbol{u}_u \rangle$ 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 $\mathrm{D}(u) = \mathrm{C}(u) + \langle \boldsymbol{d} \rangle$ be a predicate signature enriching $\mathrm{C}(u)$ with the builtin equivalence symbol $\boldsymbol{d}$. We will define a system where every $\boldsymbol{d}$-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 $\boldsymbol{d}$-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 $\boldsymbol{d}$-class. Call the data $[\mathrm{C}\mathbf{:}\mathrm{data}]^{\mathfrak{A}}a$, encoded by the counter setup at a the *position* of a.

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

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

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

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

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

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

Then $\mathfrak{A} \vDash [\mathrm{D}\mathbf{:}\mathsf{bit\text{-}0}](a)$ iff the cell of a has cardinality 1.

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

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

Then $\mathfrak{A} \vDash [\mathrm{D}\mathbf{:}\mathsf{bit\text{-}1}](a)$ iff the cell of a has cardinality greater than 1.

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

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

Then $\mathfrak{A} \vDash [\mathrm{D}\mathbf{:}\mathsf{pos\text{-}zero}](a)$ iff the position of a is 0.

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

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

Then $\mathfrak{A} \vDash [\mathrm{D}\mathbf{:}\mathsf{pos\text{-}largest}](a)$ iff the position of a is the largest u-bit number N_u.

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

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

Then $\mathfrak{A} \vDash [\mathrm{D}\mathbf{:}\mathsf{pos\text{-}less}](a, b)$ iff a and b are in the same $\boldsymbol{d}$-class and the position of a is less than the position of b.

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

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

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

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

$$[\mathrm{D}\textsf{:pos-full}] = \forall \boldsymbol{x} \exists \boldsymbol{y} \Big(\boldsymbol{d}(\boldsymbol{y}, \boldsymbol{x}) \wedge [\mathrm{D}\textsf{:pos-zero}](\boldsymbol{y}) \Big) \wedge \\ \forall \boldsymbol{x} \Big(\neg [\mathrm{D}\textsf{:pos-largest}](\boldsymbol{x}) \rightarrow \exists \boldsymbol{y} [\mathrm{D}\textsf{:pos-succ}](\boldsymbol{x}, \boldsymbol{y}) \Big).$$

The first part of this formula asserts that every $\boldsymbol{d}$-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 $\boldsymbol{d}$-class at position $p+1$. Therefore in any model of $[\mathrm{D}\textsf{:pos-full}]$, every $\boldsymbol{d}$-class has 2^u cells. For example, in particular, every $\boldsymbol{d}$-class has cardinality at least 2^u. For the rest of the section, suppose that $\mathfrak{A} \models [\mathrm{D}\textsf{:pos-full}]$.

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

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

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

$$[\mathrm{D}\textsf{:pos-}(p+1)](\boldsymbol{x}) = \exists \boldsymbol{y} \Big([\mathrm{D}\textsf{:pos-}p](\boldsymbol{y}) \wedge [\mathrm{D}\textsf{:pos-succ}](\boldsymbol{y}, \boldsymbol{x}) \Big).$$

In this case, for the formula to be a two-variable formula, the formula $[\mathrm{D}\textsf{:pos-}p](\boldsymbol{y})$ *is obtained from* $[\mathrm{D}\textsf{:pos-}p](\boldsymbol{x})$ *by swapping all occurences (not only the unbounded ones) of the variables* $\boldsymbol{x}$ *and* $\boldsymbol{y}$[1]*. Note that the length of the formula* $[\mathrm{D}\textsf{:pos-}p](\boldsymbol{x})$ *grows linearly as p grows.*

Then $\mathfrak{A} \models [\mathrm{D}\textsf{:pos-}p](a)$ iff p is the position of a.

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

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

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

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

$$[\mathrm{D}\textsf{:Zero}](\boldsymbol{x}) = \forall \boldsymbol{y} \Big(\boldsymbol{d}(\boldsymbol{y}, \boldsymbol{x}) \rightarrow [\mathrm{D}\textsf{:bit-0}](\boldsymbol{y}) \Big).$$

Then $\mathfrak{A} \models [\mathrm{D}\textsf{:Zero}](a)$ iff the data at the D-class of a encodes 0: $\underline{[\mathrm{D{:}Data}]^{\mathfrak{A}} D[a]} = 0$.

[1] this is reminiscent to the process of defining a standard translation of modal logic to the two-variable first-order fragment

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

$$[\mathsf{D{:}Largest}](\boldsymbol{x}) = \forall \boldsymbol{y}\Big(\boldsymbol{d}(\boldsymbol{y},\boldsymbol{x}) \to [\mathsf{D{:}bit}\text{-}1](\boldsymbol{y})\Big).$$

Then $\mathfrak{A} \vDash [\mathsf{D{:}Largest}](a)$ iff the data at the D-class of a encodes the largest 2^u-bit number: $\underline{[\mathrm{D{:}Data}]^{\mathfrak{A}} D[a]} = N_{2^u}$.

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

$$[\mathsf{D{:}Eq}\text{-}M](\boldsymbol{x}) = \forall \boldsymbol{y}\Big(\boldsymbol{d}(\boldsymbol{y},\boldsymbol{x}) \to \bigwedge_{0\le p<t}\Big([\mathsf{D{:}pos}\text{-}p](\boldsymbol{y}) \to [\mathsf{D{:}bit}\text{-}(\overline{M}_{p+1})](\boldsymbol{y})\Big) \wedge$$
$$\forall \boldsymbol{x}\Big([\mathsf{D{:}pos}\text{-}(t-1)](\boldsymbol{y}) \wedge [\mathsf{D{:}pos\text{-}less}](\boldsymbol{y},\boldsymbol{x}) \to [\mathsf{D{:}bit}\text{-}0](\boldsymbol{x})\Big)\Big).$$

The first part of this formula asserts that the bits at the first t positions of the $\boldsymbol{d}$-class of $\boldsymbol{x}$ 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 by t, the bitsize of M. We have $\mathfrak{A} \vDash [\mathsf{D{:}Eq}\text{-}M](a)$ iff the data at the D-class of a encodes M: $\underline{[\mathrm{D{:}Data}]^{\mathfrak{A}} D[a]} = M$.

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

$$[\mathsf{D{:}Less}](\boldsymbol{x},\boldsymbol{y}) = \exists \boldsymbol{x}'\exists \boldsymbol{y}'\Bigg(\boldsymbol{d}(\boldsymbol{x}',\boldsymbol{x}) \wedge \boldsymbol{d}(\boldsymbol{y}',\boldsymbol{y}) \wedge$$
$$\Big([\mathsf{D{:}pos\text{-}eq}](\boldsymbol{x}',\boldsymbol{y}') \wedge [\mathsf{D{:}bit}\text{-}0](\boldsymbol{x}') \wedge [\mathsf{D{:}bit}\text{-}1](\boldsymbol{y}')\Big)\wedge \tag{Less1}$$
$$\forall \boldsymbol{x}''\Big([\mathsf{D{:}pos\text{-}less}](\boldsymbol{x}',\boldsymbol{x}'') \to \exists \boldsymbol{y}''\Big(\boldsymbol{d}(\boldsymbol{y}'',\boldsymbol{y}')\wedge$$
$$[\mathsf{D{:}pos\text{-}eq}](\boldsymbol{y}'',\boldsymbol{x}'') \wedge ([\mathsf{D{:}bit}\text{-}0](\boldsymbol{y}'') \leftrightarrow [\mathsf{D{:}bit}\text{-}0](\boldsymbol{x}''))\Big)\Big)\Bigg). \tag{Less2}$$

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

$$\exists \boldsymbol{z}\Bigg(\boldsymbol{d}(\boldsymbol{z},\boldsymbol{x}) \wedge \exists \boldsymbol{x}\Bigg(\boldsymbol{x} = \boldsymbol{z} \wedge \exists \boldsymbol{z}\Bigg(\boldsymbol{d}(\boldsymbol{z},\boldsymbol{y}) \wedge \exists \boldsymbol{y}\Bigg(\boldsymbol{y} = \boldsymbol{z}\wedge$$
$$\Big([\mathsf{D{:}pos\text{-}eq}](\boldsymbol{x},\boldsymbol{y}) \wedge [\mathsf{D{:}bit}\text{-}0](\boldsymbol{x}) \wedge [\mathsf{D{:}bit}\text{-}1](\boldsymbol{y})\Big)\wedge \tag{Less1}$$
$$\forall \boldsymbol{z}\Big([\mathsf{D{:}pos\text{-}less}](\boldsymbol{x},\boldsymbol{z}) \to \exists \boldsymbol{x}\Big(\boldsymbol{x} = \boldsymbol{z} \wedge \exists \boldsymbol{z}\Big(\boldsymbol{d}(\boldsymbol{z},\boldsymbol{y}) \wedge \exists \boldsymbol{y}\Big(\boldsymbol{y} = \boldsymbol{z}\wedge$$
$$[\mathsf{D{:}pos\text{-}eq}](\boldsymbol{y},\boldsymbol{x}) \wedge ([\mathsf{D{:}bit}\text{-}0](\boldsymbol{y}) \leftrightarrow [\mathsf{D{:}bit}\text{-}0](\boldsymbol{x}))\Big)\Big)\Big)\Big)\Bigg)\Bigg)\Bigg)\Bigg). \tag{Less2}$$

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

$$[\mathrm{D}{:}\mathsf{Succ}](\boldsymbol{x},\boldsymbol{y}) = \exists \boldsymbol{x}'\exists \boldsymbol{y}'\Big(\boldsymbol{d}(\boldsymbol{x}',\boldsymbol{x}) \wedge \boldsymbol{d}(\boldsymbol{y}',\boldsymbol{y}) \wedge$$

$$\Big([\mathrm{D}{:}\mathsf{pos\text{-}eq}](\boldsymbol{x}',\boldsymbol{y}') \wedge [\mathrm{D}{:}\mathsf{bit}\text{-}0](\boldsymbol{x}') \wedge [\mathrm{D}{:}\mathsf{bit}\text{-}1](\boldsymbol{y}')\Big) \wedge \tag{Succ1}$$

$$\forall \boldsymbol{x}''\Big([\mathrm{D}{:}\mathsf{pos\text{-}less}](\boldsymbol{x}'',\boldsymbol{x}') \to [\mathrm{D}{:}\mathsf{bit}\text{-}1](\boldsymbol{x}'')\Big) \wedge \tag{Succ2}$$

$$\forall \boldsymbol{y}''\Big([\mathrm{D}{:}\mathsf{pos\text{-}less}](\boldsymbol{y}'',\boldsymbol{y}') \to [\mathrm{D}{:}\mathsf{bit}\text{-}0](\boldsymbol{y}'')\Big) \wedge \tag{Succ3}$$

$$\forall \boldsymbol{x}''\Big([\mathrm{D}{:}\mathsf{pos\text{-}less}](\boldsymbol{x}',\boldsymbol{x}'') \to \exists \boldsymbol{y}''\Big(\boldsymbol{d}(\boldsymbol{y}'',\boldsymbol{y}') \wedge$$

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

By rearrangement and reusing variables, this can be also written using just three variables (but not using just two variables).

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

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

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

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

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

$$[\mathrm{D}{:}\mathsf{Eq}](\boldsymbol{x},\boldsymbol{y}) = \forall \boldsymbol{x}'\forall \boldsymbol{y}'\Big(\boldsymbol{d}(\boldsymbol{x}',\boldsymbol{x}) \wedge \boldsymbol{d}(\boldsymbol{y}',\boldsymbol{y}) \wedge$$

$$[\mathrm{D}{:}\mathsf{pos\text{-}eq}](\boldsymbol{x}',\boldsymbol{y}') \to ([\mathrm{D}{:}\mathsf{bit}\text{-}0](\boldsymbol{x}') \leftrightarrow [\mathrm{D}{:}\mathsf{bit}\text{-}0](\boldsymbol{y}'))\Big).$$

By rearrangement and reusing variables, this can be also written using just three variables (but not using just two variables).

Then $\mathfrak{A} \models [\mathrm{D}{:}\mathsf{Eq}](\boldsymbol{x},\boldsymbol{y})$ iff $[\mathrm{D}{:}\mathrm{Data}]^{\mathfrak{A}} D[a] = [\mathrm{D}{:}\mathrm{Data}]^{\mathfrak{A}} D[b]$.

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

$$[\mathrm{D}{:}\mathsf{Alldiff}] = \forall \boldsymbol{x}\forall \boldsymbol{y}\Big(\neg \boldsymbol{d}(\boldsymbol{x},\boldsymbol{y}) \to \exists \boldsymbol{x}'\exists \boldsymbol{y}'\Big(\boldsymbol{d}(\boldsymbol{x}',\boldsymbol{x}) \wedge \boldsymbol{d}(\boldsymbol{y}',\boldsymbol{y}) \wedge$$

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

By rearrangement and reusing variables, this can be also written using just three variables (but not using just two variables).

If $\mathfrak{A}$ satisfies [D: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 $c^0 = \langle t_1^0, t_2^0, \ldots, t_n^0 \rangle \subseteq T = [1,k]$ 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

$$\mathrm{D} = \left\langle \boldsymbol{u}_1^H, \boldsymbol{u}_2^H, \ldots, \boldsymbol{u}_n^H; \boldsymbol{u}_1^V, \boldsymbol{u}_2^V, \ldots, \boldsymbol{u}_n^V; \boldsymbol{u}_1^T, \boldsymbol{u}_2^T, \ldots, \boldsymbol{u}_k^T; \boldsymbol{d} \right\rangle.$$

It has the following relevant subsignatures:

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

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

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

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

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

asserts that every element has a unique type. The sentence

$$\forall \boldsymbol{x} \forall \boldsymbol{y} \Big(\boldsymbol{d}(\boldsymbol{x}, \boldsymbol{y}) \to \bigwedge_{1 \le i \le k} (\boldsymbol{u}_i^T(\boldsymbol{x}) \leftrightarrow \boldsymbol{u}_i^T(\boldsymbol{x})) \Big) \tag{5.5}$$

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

$$\forall \boldsymbol{x} \Big([\mathrm{D}^H\text{:Eq-}(j-1)](\boldsymbol{x}) \wedge [\mathrm{D}^V\text{:Zero}](\boldsymbol{x}) \to \boldsymbol{u}_{t_j^0}^T(\boldsymbol{x}) \Big) \tag{5.6}$$

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

$$\forall \boldsymbol{x} \forall \boldsymbol{y} \Big([\mathrm{D}^H\text{:Succ}](\boldsymbol{x}, \boldsymbol{y}) \wedge [\mathrm{D}^V\text{:Eq}](\boldsymbol{x}, \boldsymbol{y}) \to \bigvee_{(i,j) \in H} \boldsymbol{u}_i^T(\boldsymbol{x}) \wedge \boldsymbol{u}_j^T(\boldsymbol{y}) \Big) \tag{5.7}$$

encodes the horizontal matching condition. The sentence

$$\forall \boldsymbol{x} \forall \boldsymbol{y} \Big([\mathrm{D}^V\text{:Succ}](\boldsymbol{x}, \boldsymbol{y}) \wedge [\mathrm{D}^H\text{:Eq}](\boldsymbol{x}, \boldsymbol{y}) \to \bigvee_{(i,j) \in V} \boldsymbol{u}_i^T(\boldsymbol{x}) \wedge \boldsymbol{u}_j^T(\boldsymbol{y}) \Big) \tag{5.8}$$

encodes the vertical matching condition.

Combining $[\mathrm{D}^{HV}\mathsf{:pos\text{-}full}]$ with the formulas 5.3–5.8, 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 $\mathcal{L}_1 1\mathrm{E}$ is* N2ExpTime*-hard. More precisely, even the three-variable fragment $\mathcal{L}_1^3 1\mathrm{E}$ 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 builtin equivalence symbols in refinement $\mathcal{L}_1 e\mathrm{E}_{\mathsf{refine}}$. 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 $\mathrm{E}(e) = \langle \boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e \rangle$ consisting of the builtin equivalence symbols $\boldsymbol{e}_i$ in refinement. Abbreviate the *coarsest* equivalence symbol $\boldsymbol{d} = \boldsymbol{e}_e$.

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

E1 There is a $\mathcal{L}^3[\mathrm{D}(e, u)]$-sentence $[\mathrm{D}(e, u)\mathsf{:pos\text{-}full}]$, whose length grows polynomially as u grows.

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

E3 There is a $\mathcal{L}^3[\mathrm{D}(e, u)]$-formula $[\mathrm{D}(e, u)\mathsf{:Eq}](\boldsymbol{x}, \boldsymbol{y})$ whose length grows polynomially as u grows, such that for all $a, b \in A$:

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

E4 There is a $\mathcal{L}^3[\mathrm{D}(e, u)]$-formula $[\mathrm{D}(e, u)\mathsf{:Zero}](\boldsymbol{x})$, whose length grows polynomially as u grows, such that for all $a \in A$:

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

E5 There is a $\mathcal{L}^3[\mathrm{D}(e, u)]$-formula $[\mathrm{D}(e, u)\mathsf{:Largest}](\boldsymbol{x})$, whose length grows polynomially as u grows, such that for all $a \in A$:

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

E6 *There is a* $\mathcal{L}^3[\mathrm{D}(e,u)]$*-formula* $[\mathrm{D}(e,u)\mathsf{:Less}](\boldsymbol{x},\boldsymbol{y})$*, whose length grows polynomially as* u *grows, such that for all* $a, b \in A$*:*

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

E7 *There is a* $\mathcal{L}^3[\mathrm{D}(e,u)]$*-formula* $[\mathrm{D}(e,u)\mathsf{:Succ}](\boldsymbol{x},\boldsymbol{y})$*, whose length grows polynomially as* u *grows, such that for all* $a, b \in A$*:*

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

E8 *For every* $\exp_2^e(u)$*-bit number* M*, there is a* $\mathcal{L}^3[\mathrm{D}(e,u)]$*-formula* $[\mathrm{D}(e,u)\mathsf{:Eq}\text{-}M](\boldsymbol{x})$*, whose length grows polynomially as* u *and* M *grow, such that for all* $a \in A$*:*

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

The previous section defines a 1-exponential setup. Suppose that we have an e-exponential setup having predicate signature $\mathrm{D} = \mathrm{D}(e,u)$. Analogously to the previous section, we will describe an $(e+1)$-exponential setup $\mathrm{D}' = \mathrm{D}(e+1,u) = \mathrm{D} + \langle \boldsymbol{e} \rangle$ which is based on D, where $\boldsymbol{e} = \boldsymbol{e}_{e+1}$ is the new coarsest builtin equivalence symbol in D'. Define the following formulas:

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

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

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

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

Define the following formulas:

$$[\mathrm{D}'\textsf{:Eq}](\boldsymbol{x}, \boldsymbol{y}) = \forall \boldsymbol{x}' \forall \boldsymbol{y}' \Big(\boldsymbol{e}(\boldsymbol{x}', \boldsymbol{x}) \wedge \boldsymbol{e}(\boldsymbol{y}', \boldsymbol{y}) \wedge \tag{E3}$$

$$[\mathrm{D}'\textsf{:pos-eq}](\boldsymbol{x}', \boldsymbol{y}') \to ([\mathrm{D}'\textsf{:bit-}0](\boldsymbol{x}') \leftrightarrow [\mathrm{D}'\textsf{:bit-}0](\boldsymbol{y}')) \Big)$$

$$[\mathrm{D}'\textsf{:Zero}](\boldsymbol{x}) = \forall \boldsymbol{y} \Big(\boldsymbol{e}(\boldsymbol{y}, \boldsymbol{x}) \to [\mathrm{D}'\textsf{:bit-}0](\boldsymbol{y}) \Big) \tag{E4}$$

$$[\mathrm{D}'\textsf{:Largest}](\boldsymbol{x}) = \forall \boldsymbol{y} \Big(\boldsymbol{e}(\boldsymbol{y}, \boldsymbol{x}) \to [1\textsf{:bit-}\mathrm{D}'](\boldsymbol{y}) \Big) \tag{E5}$$

$$[\mathrm{D}'\textsf{:Less}](\boldsymbol{x}, \boldsymbol{y}) = \exists \boldsymbol{x}' \exists \boldsymbol{y}' \Bigg(\boldsymbol{e}(\boldsymbol{x}', \boldsymbol{x}) \wedge \boldsymbol{e}(\boldsymbol{y}', \boldsymbol{y}) \wedge \tag{E6}$$

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

$$\forall \boldsymbol{x}'' \Big([\mathrm{D}'\textsf{:pos-less}](\boldsymbol{x}', \boldsymbol{x}'') \to \exists \boldsymbol{y}'' \Big(\boldsymbol{e}(\boldsymbol{y}'', \boldsymbol{y}') \wedge$$

$$[\mathrm{D}'\textsf{:pos-eq}](\boldsymbol{y}'', \boldsymbol{x}'') \wedge ([\mathrm{D}'\textsf{:bit-}0](\boldsymbol{y}'') \leftrightarrow [\mathrm{D}'\textsf{:bit-}0](\boldsymbol{x}'')) \Big) \Big) \Bigg)$$

$$[\mathrm{D}'\textsf{:Succ}](\boldsymbol{x}, \boldsymbol{y}) = \exists \boldsymbol{x}' \exists \boldsymbol{y}' \Bigg(\boldsymbol{e}(\boldsymbol{x}', \boldsymbol{x}) \wedge \boldsymbol{e}(\boldsymbol{y}', \boldsymbol{y}) \wedge \tag{E7}$$

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

$$\forall \boldsymbol{x}'' \Big([\mathrm{D}'\textsf{:pos-less}](\boldsymbol{x}'', \boldsymbol{x}') \to [\mathrm{D}'\textsf{:bit-}1](\boldsymbol{x}'') \Big) \wedge$$

$$\forall \boldsymbol{y}'' \Big([\mathrm{D}'\textsf{:pos-less}](\boldsymbol{y}'', \boldsymbol{y}') \to [\mathrm{D}'\textsf{:bit-}0](\boldsymbol{y}'') \Big) \wedge$$

$$\forall \boldsymbol{x}'' \Big([\mathrm{D}'\textsf{:pos-less}](\boldsymbol{x}', \boldsymbol{x}'') \to \exists \boldsymbol{y}'' \Big(\boldsymbol{e}(\boldsymbol{y}'', \boldsymbol{y}') \wedge$$

$$[\mathrm{D}'\textsf{:pos-eq}](\boldsymbol{y}'', \boldsymbol{x}'') \wedge ([\mathrm{D}'\textsf{:bit-}0](\boldsymbol{y}'') \leftrightarrow [\mathrm{D}'\textsf{:bit-}0](\boldsymbol{x}'')) \Big) \Big) \Bigg).$$

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:

$$[\mathrm{D}'\textsf{:Eq-}M](\boldsymbol{x}) = \forall \boldsymbol{y} \Bigg(\boldsymbol{e}(\boldsymbol{y}, \boldsymbol{x}) \to \bigwedge_{0 \le p < t} \Big([\mathrm{D}'\textsf{:pos-}p](\boldsymbol{y}) \to [\mathrm{D}'\textsf{:bit-}\overline{M}_{p+1}](\boldsymbol{y}) \Big) \wedge \tag{E8}$$

$$\forall \boldsymbol{x} \Big([\mathrm{D}'\textsf{:pos-}(t-1)](\boldsymbol{y}) \wedge [\mathrm{D}'\textsf{:pos-less}](\boldsymbol{y}, \boldsymbol{x}) \to [\mathrm{D}'\textsf{:bit-}0](\boldsymbol{x}) \Big) \Bigg).$$

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 $\mathcal{L}_1 e\mathrm{E}_{\mathsf{refine}}$ is* N(e+1)EXPTIME*-hard. Even the three-variable fragment $\mathcal{L}_1^3 e\mathrm{E}_{\mathsf{refine}}$ has this property.*

By Proposition 1 and Proposition 3, the same holds for $\mathcal{L}_1^{(3)} e\mathrm{E}_{\mathsf{global}}$ and $\mathcal{L}_1^{(3)} e\mathrm{E}_{\mathsf{local}}$.

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

By Proposition 2 and Proposition 4, the same holds for $\mathcal{L}_1^{(3)}\mathrm{E}_{\mathsf{global}}$ and $\mathcal{L}_1^{(3)}\mathrm{E}_{\mathsf{local}}$.

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 builtin 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* builtin 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 builtin equivalence symbol $\mathcal{L}^2$1E has the finite model property and its (finite) satisfiability problem is NExpTime-complete [11].
- The two-variable first-order logic with two *unrelated* builtin equivalence symbols $\mathcal{L}^2$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 builtin equivalence symbols $\mathcal{L}^2e$E are both undecidable for $e \geq 3$ [13].

In this chapter we prove that the logic $\mathcal{L}^2e\mathrm{E}_{\mathsf{refine}}$ has the finite model property and its (finite) satisfiability problem is in NExpTime for every $e \geq 0$. We do this by defining an auxilliary 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 realizibility

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

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

where $m \geq 1$, all the formulas α_i are quantifier-free and use at most linearly many new unary predicate symbols. The semantic connection between φ and $\operatorname{sctr}\varphi$ is that they are essentially equisatisfiable. More precisely, every model for φ of cardinality at least 2 can be enriched to a model for $\operatorname{sctr}\varphi$ and also every model of $\operatorname{sctr}\varphi$ (which by $m \geq 1$ must have cardinality at least 2) is a model for φ. We refer to α_0 as the *universal part* of the formula $\operatorname{sctr}\varphi$ and to α_i for $i \in [1, m]$ as the *existential parts* of $\operatorname{sctr}\varphi$.

For any formula $\operatorname{sctr}\varphi$ in Scott normal form, we may replace its existential parts by fresh binary predicate symbols: for $i \in [1, m]$ let $\boldsymbol{m}_i$ be a fresh binary predicate symbol with intended interpretation $\forall \boldsymbol{x} \forall \boldsymbol{y} (\boldsymbol{m}_i(\boldsymbol{x}, \boldsymbol{y}) \leftrightarrow \alpha_i(\boldsymbol{x}, \boldsymbol{y}))$. Since this is a universal sentence, it can be added to the universal part α_0. The symbols $\boldsymbol{m}_i$ are the *message symbols*. Hence $\operatorname{sctr}\varphi$ can be transformed in deterministic polynomial time to the form:

$$\forall \boldsymbol{x} \forall \boldsymbol{y} (\alpha(\boldsymbol{x}, \boldsymbol{y}) \lor \boldsymbol{x} = \boldsymbol{y}) \land \bigwedge_{1 \leq i \leq m} \forall \boldsymbol{x} \exists \boldsymbol{y} (\boldsymbol{m}_i(\boldsymbol{x}, \boldsymbol{y}) \land \boldsymbol{x} \neq \boldsymbol{y}), \tag{6.1}$$

where the universal part α 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 $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$ *for the two-variable first-order logic* $\mathcal{L}^2$ *is a predicate signature* Σ *together with a nonempty sequence* $\bar{\boldsymbol{m}} = \boldsymbol{m}_1 \boldsymbol{m}_2 \ldots \boldsymbol{m}_m$ *of distinct binary predicate symbols from* Σ *having intended interpretation*

$$\bigwedge_{1 \leq i \leq m} \forall \boldsymbol{x} \exists \boldsymbol{y} (\boldsymbol{m}_i(\boldsymbol{x}, \boldsymbol{y}) \land \boldsymbol{x} \neq \boldsymbol{y}). \tag{6.2}$$

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

Definition 65. *A structure* $\mathfrak{A}$ *for the classified signature* $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$ *is a structure for the predicate signature* Σ *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* $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$ *and a quantifier-free* $\mathcal{L}^2[\Sigma]$*-formula* $\alpha(\boldsymbol{x}, \boldsymbol{y})$*, is there a (finite)* $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$*-structure* $\mathfrak{A}$ *satisfying eq. (6.1). Note that since* $\mathfrak{A}$ *is a* $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$*-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 20. *The problem of (finite) satisfiability reduces in nondeterministic polynomial time to the problem of (finite) classified satisfiability:*

$$\text{(FIN-)SAT-}\mathcal{L}^2 \leq_{\mathrm{m}}^{\mathrm{NP\textsc{Time}}} \text{(FIN-)CL-SAT-}\mathcal{L}^2.$$

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 by 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 (Σ, φ) of the (finite) satisfiability problem to an instance $(\langle \Sigma', \bar{\boldsymbol{m}} \rangle, \alpha)$ of the (finite) classified satisfiability problem: First check if φ is satisfiable in the class of models of cardinality 1. If that is the case, then extend Σ to Σ' by adding a single message symbol $\boldsymbol{m}_1$ and let $\alpha = (\boldsymbol{x} = \boldsymbol{x})$ be a fixed predicate tautology. Otherwise transform φ into the form eq. (6.1) and let α be the universal part of that normal form. $\square$

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

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

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

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

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

$$\mathrm{T}[\mathfrak{A}] = \left\{ \mathrm{tp}^{\mathfrak{A}}[a, b] \;\middle|\; a \in A, b \in A \setminus \{a\} \right\}.$$

That is $\mathrm{T} = \mathrm{T}[\mathfrak{A}]$ is the set of 2-types realized in $\mathfrak{A}$. Note that this is indeed a type instance over $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$: $\mathrm{T}[\mathfrak{A}]$ is nonempty since $\mathfrak{A}$ has cardinality at least 2 and $\mathrm{T}[\mathfrak{A}]$ is closed under inversion by construction. If T is the type instance of $\mathfrak{A}$, then $\mathfrak{A}$ is a *model* for 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 $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$ and a type instance* T *over $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$, is there a (finite) model for* T*. Denote the type realizability problem by* TP-REALIZ-$\mathcal{L}^2$ *and its finite version by* FIN-TP-REALIZ-$\mathcal{L}^2$*.*

Remark 21. *Let $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$ be a classified signature and let $\alpha(\boldsymbol{x}, \boldsymbol{y})$ be a quantifier-free $\mathcal{L}^2[\Sigma]$-formula. Let $\mathrm{T}^\alpha \subseteq \mathrm{T}[\Sigma]$ is the set of those 2-types that are consistent with $\alpha(\boldsymbol{x}, \boldsymbol{y})$ and the intended interpretation for classified signatures eq. (6.2). Then a $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$-structure $\mathfrak{A}$ is a classified model for $\alpha(\boldsymbol{x}, \boldsymbol{y})$ iff $\mathrm{T}[\mathfrak{A}] \subseteq \mathrm{T}^\alpha$.*

Recall that the number of possible 1-types or 2-types over Σ is exponentially bounded by the size of Σ and that the size of a 1-type or a 2-type over Σ is linearly bounded by the size of Σ. Hence the (finite) classified satisfiability problem reduces to the (finite) type realizability problem in nondeterministic exponential time:

$$\text{(FIN-)CL-SAT-}\mathcal{L}^2 \leq_\mathrm{m}^{\textsc{NExpTime}} \text{(FIN-)TP-REALIZ-}\mathcal{L}^2.$$

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

1. *If $\tau \in \mathrm{T}$ then some $a \in A$ and $b \in A \setminus \{a\}$ have $\mathrm{tp}^{\mathfrak{A}}[a,b] = \tau$.*

   If $a \in A$ and $b \in A \setminus \{a\}$, then $\mathrm{tp}^{\mathfrak{A}}[a,b] = \tau$ for some $\tau \in \mathrm{T}$.

   Equivalently $\mathrm{T} = \left\{ \mathrm{tp}^{\mathfrak{A}}[a,b] \;\middle|\; a \in A, b \in A \setminus \{a\} \right\}$.

2. *If $\pi \in \Pi_{\mathrm{T}}$ then some $a \in A$ has $\mathrm{tp}^{\mathfrak{A}}[a] = \pi$.*

   If $a \in A$ then $\mathrm{tp}^{\mathfrak{A}}[a] = \pi$ for some $\pi \in \Pi_{\mathrm{T}}$.

   Equivalently $\Pi_{\mathrm{T}} = \left\{ \mathrm{tp}^{\mathfrak{A}}[a] \;\middle|\; a \in A \right\}$.

3. *Let $\kappa \in \Pi_{\mathrm{T}}$. Then $\kappa \in \mathrm{K}_{\mathrm{T}}$ iff a unique $a \in A$ has $\mathrm{tp}^{\mathfrak{A}}[a] = \kappa$.*

4. *Let $\pi \in \Pi_{\mathrm{T}}$. Then $\pi \in \mathrm{W}_{\mathrm{T}}$ iff for every $a \in A$ such that $\mathrm{tp}^{\mathfrak{A}}[a] = \pi$ there is some $b \in A \setminus \{a\}$ having $\mathrm{tp}^{\mathfrak{A}}[b] = \pi$.*

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

   If $\pi' \in \mathrm{T}[\pi]$ then some $b \in A \setminus \{a\}$ has $\mathrm{tp}^{\mathfrak{A}}[b] = \pi'$.

   If $b \in A \setminus \{a\}$ then $\mathrm{tp}^{\mathfrak{A}}[b] = \pi'$ for some $\pi' \in \mathrm{T}[\pi]$.

We will be applying this lemma implicitly.

Proof.

1. By definition $\mathrm{T} = \mathrm{T}[\mathfrak{A}] = \left\{ \mathrm{tp}^{\mathfrak{A}}[a,b] \;\middle|\; a \in A, b \in A \setminus \{a\} \right\}$.

2. If $\pi \in \Pi_{\mathrm{T}}$ then some $\tau \in \mathrm{T}$ has $\mathrm{tp}_{\boldsymbol{x}}\tau = \pi$, so some $a \in A$ and $b \in A \setminus \{a\}$ has $\mathrm{tp}^{\mathfrak{A}}[a,b] = \tau$, so $\mathrm{tp}^{\mathfrak{A}}[a] = \pi$.

   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 $\mathrm{tp}^{\mathfrak{A}}[a,b] = \tau \in \mathrm{T}$, so $\pi = \mathrm{tp}^{\mathfrak{A}}[a] = \mathrm{tp}_{\boldsymbol{x}}\tau \in \Pi_{\mathrm{T}}$.

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

   Next suppose that $\pi \in \Pi_{\mathrm{T}} \setminus \mathrm{K}_{\mathrm{T}} = \mathrm{W}_{\mathrm{T}}$, so some $\tau \in \mathrm{T}$ connects κ with itself. Then some $a \in A$ and $b \in A \setminus \{a\}$ have $\mathrm{tp}^{\mathfrak{A}}[a,b] = \tau$, so $\mathrm{tp}^{\mathfrak{A}}[a] = \mathrm{tp}^{\mathfrak{A}}[b] = \pi$, so there is not a unique $a \in A$ having $\mathrm{tp}^{\mathfrak{A}}[a] = \pi$.

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

   Next suppose that $\pi \in \Pi_{\mathrm{T}}$ and that for every $a \in A$ such that $\mathrm{tp}^{\mathfrak{A}}[a] = \pi$ there is some $b \in A \setminus \{a\}$ having $\mathrm{tp}^{\mathfrak{A}}[b] = \pi$. Since $\pi \in \Pi_{\mathrm{T}}$, some $a \in A$ has $\mathrm{tp}^{\mathfrak{A}}[a] = \pi$, so some $b \in A \setminus \{a\}$ has $\mathrm{tp}^{\mathfrak{A}}[b] = \pi$, so there is not a unique $a \in A$ having $\mathrm{tp}^{\mathfrak{A}}[a] = \pi$, so $\pi \notin \mathrm{K}_{\mathrm{T}}$, so $\pi \in \mathrm{W}_{\mathrm{T}}$.

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

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

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

□

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

($\sigma\boldsymbol{x}$) *If* $\tau, \tau' \in \sigma$*, then* $\mathrm{tp}_{\boldsymbol{x}}\tau = \mathrm{tp}_{\boldsymbol{x}}\tau'$*. Denote* $\mathrm{tp}_{\boldsymbol{x}}\tau$ *for any* $\tau \in \sigma$ *by* $\pi = \mathrm{tp}_{\boldsymbol{x}}\sigma$*.*

($\sigma\pi\boldsymbol{y}$) *If* $\pi' \in \mathrm{T}[\pi]$*, then some* $\tau \in \sigma$ *has* $\mathrm{tp}_{\boldsymbol{y}}\tau = \pi'$*.*

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

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

A star-type σ is a *king star-type* if $\mathrm{tp}_{\boldsymbol{x}}\sigma$ 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 22. *If* σ *is a star-type over* T*, then:*

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

Proof. By ($\sigma\pi\boldsymbol{y}$), some $\tau \in \sigma$ has $\mathrm{tp}_{\boldsymbol{y}}\tau = \kappa$. By ($\sigma\kappa\boldsymbol{y}$), such τ is unique. □

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

$$\mathrm{stp}^{\mathfrak{A}}[a] = \left\{ \mathrm{tp}^{\mathfrak{A}}[a, b] \;\middle|\; b \in A \setminus \{a\} \right\}.$$

Remark 23. *Indeed* $\sigma = \mathrm{stp}^{\mathfrak{A}}[a]$ *is a star-type over* T*.*

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

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

Let $\pi = \mathrm{tp}_{\boldsymbol{x}}\sigma = \mathrm{tp}^{\mathfrak{A}}[a]$.

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

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

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

□

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

($\mathcal{S}\tau$) *If* $\tau \in \mathrm{T}$, *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* $\kappa \in \mathrm{K}_\mathrm{T}$ *and if* $\sigma, \sigma' \in \mathcal{S}$ *have* $\mathrm{tp}_{\boldsymbol{x}}\sigma = \mathrm{tp}_{\boldsymbol{x}}\sigma' = \kappa$, *then* $\sigma = \sigma'$.

Remark 24. *Let* $\mathcal{S}$ *be a certificate over* T. *Then:*

($\mathcal{S}\pi$) *If* $\pi \in \Pi_\mathrm{T}$, *then some* $\sigma \in \mathcal{S}$ *has* $\mathrm{tp}_{\boldsymbol{x}}\sigma = \pi$.

($\mathcal{S}\kappa'$) *If* $\kappa \in \mathrm{K}_\mathrm{T}$, *then a unique* $\sigma \in \mathcal{S}$ *has* $\mathrm{tp}_{\boldsymbol{x}}\sigma = \pi$.

Proof. ($\mathcal{S}\pi$) If $\pi \in \Pi_\mathrm{T}$, then some $\tau \in \mathrm{T}$ has $\mathrm{tp}_{\boldsymbol{x}}\tau = \pi$, so by ($\mathcal{S}\tau$) some $\sigma \in \mathcal{S}$ has $\tau \in \sigma$, so $\mathrm{tp}_{\boldsymbol{x}}\sigma = \mathrm{tp}_{\boldsymbol{x}}\tau = \pi$.

($\mathcal{S}\kappa'$) If $\kappa \in \mathrm{K}_\mathrm{T}$, then by ($\mathcal{S}\pi$) some $\sigma \in \mathcal{S}$ has $\mathrm{tp}_{\boldsymbol{x}}\sigma = \kappa$. By ($\mathcal{S}\kappa$), such σ 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* $\tau \in \mathrm{T}$, *let* $a_\tau \in A$ *and* $b_\tau \in A \setminus \{a_\tau\}$ *have* $\mathrm{tp}^{\mathfrak{A}}[a_\tau, b_\tau] = \tau$. *Let*

$$\mathcal{S} = \left\{ \mathrm{stp}^{\mathfrak{A}}[a_\tau] \;\middle|\; \tau \in \mathrm{T} \right\}.$$

Then $\mathcal{S}$ *is a certificate for* T. *The size of* $\mathcal{S}$ *is quadratic 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 $\tau \in \mathrm{T}$, then $\tau = \mathrm{tp}^{\mathfrak{A}}[a_\tau, b_\tau] \in \mathrm{stp}^{\mathfrak{A}}[a_\tau] \in \mathcal{S}$.

($\mathcal{S}\kappa$) Let $\kappa \in \mathrm{K}_\mathrm{T}$ and let $\sigma, \sigma' \in \mathcal{S}$ have $\mathrm{tp}_{\boldsymbol{x}}\sigma = \mathrm{tp}_{\boldsymbol{x}}\sigma' = \kappa$. Then $\sigma = \mathrm{stp}^{\mathfrak{A}}[a_\tau]$ and $\sigma' = \mathrm{stp}^{\mathfrak{A}}[a_{\tau'}]$ for some $\tau, \tau' \in \mathrm{T}$. Then $\mathrm{tp}_{\boldsymbol{x}}\tau = \mathrm{tp}_{\boldsymbol{x}}\tau' = \kappa$. Then $\mathrm{tp}^{\mathfrak{A}}[a_\tau] = \mathrm{tp}_{\boldsymbol{x}}\kappa = \mathrm{tp}^{\mathfrak{A}}[a_{\tau'}]$. Since κ 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* $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$. *Then* T *has a finite model. More precisely, let* $t \geq |\mathrm{T}|$ *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[1] 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 $\sigma \in \mathcal{S}$, $\mathrm{tp}_{\boldsymbol{x}}\,\sigma \in \mathrm{K_T}$. The elements a^σ 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 $\sigma \in \mathcal{S}$, $\mathrm{tp}_{\boldsymbol{x}}\,\sigma \in \mathrm{W_T}$, where $A_i^\sigma = \{a_{i1}^\sigma, a_{i2}^\sigma, \dots, a_{it}^\sigma\}$ for $i \in \{0,1,2\}$. The elements a_{ij}^σ are the *workers*.

Let $\sigma : A \to \mathcal{S}$ denote the intended star-type of the elements: $\sigma(a) = \sigma$ on A^σ. Let $\pi : A \to \Pi_\mathrm{T}$ denote the intended 1-type of the elements: $\pi(a) = \mathrm{tp}_{\boldsymbol{x}}(\sigma(a))$. 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 $\kappa' = \pi(a) = \mathrm{tp}_{\boldsymbol{x}}\sigma' \in \mathrm{K_T}$ be the intended (king) type of a. Let $b \in A \setminus \{a\}$ be any other element and let $\sigma = \sigma(b)$ and $\pi = \pi(b) = \mathrm{tp}_{\boldsymbol{x}}\sigma$ 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 $\kappa' \in \mathrm{T}[\pi] \cap \mathrm{K_T}$. By $(\sigma\kappa\boldsymbol{y}')$, a unique $\tau \in \sigma$ has $\mathrm{tp}_{\boldsymbol{y}}\tau = \kappa'$. We assign $\mathrm{tp}^{\mathfrak{A}}[b,a] = \tau$. 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 $\kappa' \neq \kappa$, $\kappa \in \mathrm{T}[\kappa'] \cap \mathrm{K_T}$. By $(\sigma\kappa\boldsymbol{y}')$, a unique $\tau' \in \sigma'$ has $\mathrm{tp}_{\boldsymbol{y}}\tau' = \kappa$ and we would want to assign $\mathrm{tp}^{\mathfrak{A}}[a,b] = \tau'$. We claim that $\tau' = \tau^{-1}$. Indeed, by $(\mathcal{S}\tau)$, $\tau^{-1} \in \sigma''$ for some $\sigma'' \in \mathcal{S}$. Then $\mathrm{tp}_{\boldsymbol{x}}\sigma'' = \mathrm{tp}_{\boldsymbol{x}}(\tau^{-1}) = \kappa$, so by $(\mathcal{S}\kappa)$, $\sigma'' = \sigma$. Then $\tau^{-1} \in \sigma$ has $\mathrm{tp}_{\boldsymbol{y}}\tau^{-1} = \kappa$, so $\tau^{-1} = \tau'$.

Next, these assignments cover σ'. 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 $\mathrm{tp}_{\boldsymbol{y}}\tau' = \mathrm{tp}_{\boldsymbol{x}}\tau = \mathrm{tp}_{\boldsymbol{x}}\sigma = \kappa$, so τ' would connect κ with itself — a contradiction. So $\sigma \neq \sigma'$. By $(\mathcal{S}\kappa)$, $\pi \neq \kappa$, so $\kappa \in \mathrm{T}[\pi]$. Then by $(\sigma\kappa\boldsymbol{y}')$, $\tau \in \sigma$ is the unique having $\mathrm{tp}_{\boldsymbol{y}}\tau = \kappa$. Since $\mathfrak{A}$ contains some element for each star-type, some $b \in A \setminus \{a\}$ has $\sigma(b) = \sigma$, so we had assigned $\mathrm{tp}^{\mathfrak{A}}[b,a] = \tau$.

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

[1] 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 $\mathrm{tp}_{\boldsymbol{y}}\tau = \pi' \in \mathrm{W_T}$ is a worker type. Let $\mathrm{U} = \left\{\eta \in \sigma \,\middle|\, \mathrm{tp}_{\boldsymbol{y}}\eta = \pi'\right\}$ be the set of all 2-types from σ parallel to τ. We simultaneously find distinct elements b_η that are distinct from a for the assignments $\mathrm{tp}^{\mathfrak{A}}[a, b_\eta] = \eta$. By $(\mathcal{S}\tau)$, for each $\eta \in \mathrm{U}$ there is some star-type $\sigma'_\eta \in \mathcal{S}$ such that $\eta^{-1} \in \sigma'_\eta$. Note that $\mathrm{tp}_{\boldsymbol{x}}\sigma'_\eta = \pi'$ is a worker type. Since $\mathrm{U} \subseteq \mathrm{T}$ we have $|\mathrm{U}| \leq t$, so there are enough distinct workers from the next copy $b_\eta \in A^{\sigma'_\eta}_{i'}$ for the assignments $\mathrm{tp}^{\mathfrak{A}}[a, b_\eta] = \eta$. 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 $\mathrm{tp}^{\mathfrak{A}}[a, b]$ has not yet been assigned. Then both $\pi(a)$ and $\pi(b)$ are worker types, so $\pi(b) \in \mathrm{T}[\pi(a)] = \Pi_\mathrm{T}$. By $(\sigma\pi\boldsymbol{y})$, some $\tau \in \sigma(a)$ has $\mathrm{tp}_{\boldsymbol{y}}\tau = \pi(b)$, so we may assign $\mathrm{tp}^{\mathfrak{A}}[a, b] = \tau$. Note that this may extend the actual star-type of a and b, but this is appropriate.

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

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 $\langle\Sigma, \bar{\boldsymbol{m}}\rangle$. 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. ☐

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

6.2 Type realizibility with equivalences

In this section we consider the logic $\mathcal{L}^2e\mathrm{E}_{\mathsf{refine}}$ featuring $e \geq 1$ equivalence symbols $\boldsymbol{e}_1, \boldsymbol{e}_2, \ldots, \boldsymbol{e}_e$ in refinement. By convention let $\boldsymbol{e}_0$ be the formal equality, so that $\mathcal{L}^2 0\mathrm{E}_{\mathsf{refine}}$ means $\mathcal{L}^2$. Abbreviate the coarsest equivalence symbol $\boldsymbol{e} = \boldsymbol{e}_e$.

The following reductions carry over from the previous section:

$$\text{(FIN-)SAT-}\mathcal{L}^2e\mathrm{E}_{\mathsf{refine}} \leq_{\mathrm{m}}^{\mathrm{NPTIME}} \text{(FIN-)CL-SAT-}\mathcal{L}^2e\mathrm{E}_{\mathsf{refine}}$$
$$\text{(FIN-)CL-SAT-}\mathcal{L}^2e\mathrm{E}_{\mathsf{refine}} \leq_{\mathrm{m}}^{\mathrm{NEXPTIME}} \text{(FIN-)TP-REALIZ-}\mathcal{L}^2e\mathrm{E}_{\mathsf{refine}}.$$

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

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

We think of the $\boldsymbol{e}$-classes in a $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$-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 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 $\mathcal{G}^{\mathfrak{A}} = \mathscr{E}\boldsymbol{e}^{\mathfrak{A}}$. 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 $\mathcal{G}^{\mathfrak{A}}_{\mathrm{N}}$ and $\mathcal{G}^{\mathfrak{A}}_{\mathrm{P}}$, respectively. So we have $\mathcal{G}^{\mathfrak{A}} = \mathcal{G}^{\mathfrak{A}}_{\mathrm{N}} \cup \mathcal{G}^{\mathfrak{A}}_{\mathrm{P}}$. If $X \in \mathcal{G}^{\mathfrak{A}}$ is a galaxy, denote $\mathrm{tp}^{\mathfrak{A}}[X] = \left\{ \mathrm{tp}^{\mathfrak{A}}[a] \;\middle|\; a \in X \right\}$ to be the set of 1-types realized by elements of X.

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

1. *If $\pi \in \Pi_{\mathrm{T}}$ then some $X \in \mathcal{G}^{\mathfrak{A}}$ has $\pi \in \mathrm{tp}^{\mathfrak{A}}[X]$.*

   If $X \in \mathcal{G}^{\mathfrak{A}}$ then $\mathrm{tp}^{\mathfrak{A}}[X] \subseteq \Pi_{\mathrm{T}}$, or equivalently every $\pi \in \mathrm{tp}^{\mathfrak{A}}[X]$ has $\pi \in \Pi_{\mathrm{T}}$.

2. *Let $X \in \mathcal{G}^{\mathfrak{A}}$. Then $X \in \mathcal{G}^{\mathfrak{A}}_{\mathrm{N}}$ iff $\mathrm{tp}^{\mathfrak{A}}[X] \cap \mathrm{N}_{\mathrm{T}} \neq \varnothing$, or equivalently iff some $\nu \in \mathrm{tp}^{\mathfrak{A}}[X]$ has $\nu \in \mathrm{N}_{\mathrm{T}}$.*

3. *Let $X \in \mathcal{G}^{\mathfrak{A}}$. Then $X \in \mathcal{G}^{\mathfrak{A}}_{\mathrm{P}}$ iff $\mathrm{tp}^{\mathfrak{A}}[X] \subseteq \mathrm{P}_{\mathrm{T}}$, or equivalently iff every $\pi \in \mathrm{tp}^{\mathfrak{A}}[X]$ has $\pi \in \Pi_{\mathrm{T}}$.*

4. *Let $\nu \in \Pi_{\mathrm{T}}$. Then $\nu \in \mathrm{N}_{\mathrm{T}}$ iff a unique $X \in \mathcal{G}^{\mathfrak{A}}$ has $\nu \in \mathrm{tp}^{\mathfrak{A}}[X]$.*

5. *Let $\pi \in \Pi_{\mathrm{T}}$. Then $\pi \in \mathrm{P}_{\mathrm{T}}$ iff for every $X \in \mathcal{G}^{\mathfrak{A}}$ such that $\pi \in \mathrm{tp}^{\mathfrak{A}}[X]$ there is some $Y \in \mathcal{G}^{\mathfrak{A}} \setminus \{X\}$ having $\pi \in \mathrm{tp}^{\mathfrak{A}}[Y]$.*

We will be applying this lemma implicitly.

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

2. This follows by the definition of noble galaxy.

3. This follows by the definition of peasant galaxy.

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

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

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

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

□

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 $\pi \in \Pi_\mathrm{T}$ is a peasant type that is realized in some peasant galaxy: $\pi \in \mathrm{tp}^{\mathfrak{A}}[X]$ for some $X \in \mathcal{G}^{\mathfrak{A}}_\mathrm{P}$, then π is also realized in some other peasant galaxy: $\pi \in \mathrm{tp}^{\mathfrak{A}}[Y]$ for some $Y \in \mathcal{G}^{\mathfrak{A}}_\mathrm{P} \setminus \{X\}$.*

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 $\mathcal{G}^{\mathfrak{A}'}_\mathrm{N}$ of $\mathfrak{A}'$ coincide with the noble galaxies $\mathcal{G}^{\mathfrak{A}}_\mathrm{N}$ of $\mathfrak{A}$. The peasant galaxies $\mathcal{G}^{\mathfrak{A}'}_\mathrm{P}$ of $\mathfrak{A}'$ consist of two copies X_1, X_2 of each peasant galaxy $X \in \mathcal{G}^{\mathfrak{A}}_\mathrm{P}$ 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* $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$-structure. We proceed to complete $\mathfrak{A}'$. Let $X \in \mathcal{G}^{\mathfrak{A}}_\mathrm{P}$ 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 $\pi = \mathrm{tp}^{\mathfrak{A}'}[a] = \mathrm{tp}^{\mathfrak{A}}[a]$. Since X is a peasant galaxy, π must be a peasant type, so some $Y \in \mathcal{G}^{\mathfrak{A}} \setminus \{X\}$ has $\pi \in \mathrm{tp}^{\mathfrak{A}}[Y]$, so some $a' \in Y$ has $\mathrm{tp}^{\mathfrak{A}}[a'] = \pi$. Then $\tau = \mathrm{tp}^{\mathfrak{A}}[a', b]$ is cosmic and the assignment $\mathrm{tp}^{\mathfrak{A}'}[a_1, b_2] = \mathrm{tp}^{\mathfrak{A}}[a', b]$ 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}. □

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

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

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

$$\boldsymbol{p}_\nu(\boldsymbol{x}) = \{\boldsymbol{p}^\nu(\boldsymbol{x})\} \cup \left\{ \neg \boldsymbol{p}^{\nu'}(\boldsymbol{x}) \;\middle|\; \nu' \in \mathrm{N_T} \setminus \{\nu\} \right\}.$$

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

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

If $\pi \in \Pi_\mathrm{T}$ is a 1-type and $\rho \in \mathrm{N_T} \cup \{\perp\}$, let π_ρ be the following 1-type over Σ':

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

We refer to π_ρ as the *ρ-copy of* π. If $\tau \in \mathrm{T}$ and $\rho, \rho' \in \mathrm{N_T} \cup \{\perp\}$, let $\tau_{\rho\rho'}$ be the following 2-type over Σ':

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

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

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

Note that the size of T' is quadratic with respect to the size of T.

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

Lemma 12 (Noble distinguishability)**.** *The type instance* T *has a (finite) model iff there is some promotion* $\mathrm{T}_\bullet$ *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 $\mathrm{T}_\bullet$ for T and a Σ'-enrichment $\mathfrak{A}'$ that is a nobly distinguished model for $\mathrm{T}_\bullet$. For every noble galaxy $X \in \mathcal{G}^{\mathfrak{A}}_{\mathrm{N}}$ choose any noble type $\nu \in \mathrm{tp}^{\mathfrak{A}}[X]$ 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 $\mathrm{tp}^{\mathfrak{A}'}[a] = \mathrm{tp}^{\mathfrak{A}}[a]_\nu$.
2. Otherwise, if $a \in X$ is an element of a peasant galaxy, then let $\mathrm{tp}^{\mathfrak{A}'}[a] = \mathrm{tp}^{\mathfrak{A}}[a]_\perp$.

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

1. If $\nu \in \mathrm{N_T}$ and $\pi_\nu \in \mathrm{tp}^{\mathfrak{A}'}[X]$ for some $\pi \in \Pi_\mathrm{T}$, then $\nu \in \mathrm{tp}^{\mathfrak{A}}[X]$.

   Indeed, if $\pi_\nu \in \mathrm{tp}^{\mathfrak{A}'}[X]$ then some $a \in X$ has $\mathrm{tp}^{\mathfrak{A}'}[a] = \pi_\nu$, so by construction $X = X_\nu$, so $\nu \in X$.

2. If $\pi \in \Pi_\mathrm{T}$ and $\pi_\perp \in \mathrm{tp}^{\mathfrak{A}'}[X]$, then $X \in \mathcal{G}^{\mathfrak{A}}_{\mathrm{P}}$ is a peasant galaxy and $\pi \in \mathrm{tp}^{\mathfrak{A}}[X]$ is a peasant type.

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

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

We claim that $\pi' \in \Pi_{\mathrm{T}_\bullet}$ is a noble type iff $\pi' = \pi_\nu$ for some $\pi \in \Pi_\mathrm{T}$ and $\nu \in \mathrm{N}_\mathrm{T}$, or equivalently:

$$\mathrm{N}_{\mathrm{T}_\bullet} = \{\pi_\nu \in \Pi_{\mathrm{T}_\bullet} \mid \pi \in \Pi_\mathrm{T}, \nu \in \mathrm{N}_\mathrm{T}\}\,.$$

First, suppose that $\pi_\nu \in \Pi_{\mathrm{T}_\bullet}$ for some $\pi \in \Pi_\mathrm{T}$ and $\nu \in \mathrm{N}_\mathrm{T}$. Let $X \in \mathcal{G}^{\mathfrak{A}'}$ be such that $\pi_\nu \in \mathrm{tp}^{\mathfrak{A}'}[X]$. Suppose towards a contradiction that $\pi_\nu \in \mathrm{P}_{\mathrm{T}_\bullet}$ is a peasant type. Then there is some $Y \in \mathcal{G}^{\mathfrak{A}'} \setminus \{X\}$ such that $\pi_\nu \in \mathrm{tp}^{\mathfrak{A}'}[Y]$. Then by construction $\nu \in \mathrm{tp}^{\mathfrak{A}}[X]$ and $\nu \in \mathrm{tp}^{\mathfrak{A}}[Y]$ — a contradiction.

Next, suppose that $\pi_\perp \in \Pi_{\mathrm{T}_\bullet}$ and let $X \in \mathcal{G}^{\mathfrak{A}'}$ be such that $\pi_\perp \in \mathrm{tp}^{\mathfrak{A}'}[X]$. Then by construction $X \in \mathcal{G}^{\mathfrak{A}}_\mathrm{P}$ is a peasant galaxy and $\pi \in \mathrm{tp}^{\mathfrak{A}}[X]$ is a peasant type. Since $\mathfrak{A}$ is peasantly united, there is some $Y \in \mathcal{G}^{\mathfrak{A}}_\mathrm{P} \setminus \{X\}$ having $\pi \in \mathrm{tp}^{\mathfrak{A}}[Y]$. So by construction $\pi_\perp = \mathrm{tp}^{\mathfrak{A}'}[Y]$, so $\pi_\perp \in \mathrm{P}_{\mathrm{T}_\bullet}$.

Finally, we check that $\mathfrak{A}'$ is nobly distinguished. Indeed, let $X \in \mathcal{G}^{\mathfrak{A}'}_\mathrm{N}$ be any noble galaxy. Then some $a \in X$ has $\mathrm{tp}^{\mathfrak{A}'}[a] \in \mathrm{N}_{\mathrm{T}_\bullet}$, so $X = X_\nu$ for some noble $\nu \in \mathrm{N}_\mathrm{T}$. Let $b \in X$ be any. Then by construction $\mathrm{tp}^{\mathfrak{A}'}[b] = \mathrm{tp}^{\mathfrak{A}}[b]_\nu$, so $\mathrm{tp}^{\mathfrak{A}'}[X] \subseteq \mathrm{N}_{\mathrm{T}_\bullet}$.

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

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

$$\text{(FIN-)TP-REALIZ-}\mathcal{L}^2e\mathrm{E}_{\mathsf{refine}} \leq_\mathrm{m}^{\mathrm{NPT{\scriptsize IME}}} \text{(FIN-)ND-TP-REALIZ-}\mathcal{L}^2e\mathrm{E}_{\mathsf{refine}}.$$

Remark 25. *Suppose that $\mathfrak{A}$ is a nobly distinguished model for* T. *Then $\mathfrak{A}$ is peasantly united.*

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

6.3 Cosmic spectrums

Let T be a type instance over the $\mathcal{L}^2e\mathrm{E}_{\mathsf{refine}}$-classified signature $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$.

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

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

($\varsigma\mathcal{E}\mathcal{I}$) *The set of* inverted boundary types *is:* $\varsigma^{\mathcal{E}\mathcal{I}} = \left\{\tau^{-1} \,\middle|\, \tau \in \varsigma^{\mathcal{I}\mathcal{E}}\right\}$.

($\varsigma\mathcal{E}\mathcal{E}$) *The set of* external types $\varsigma^{\mathcal{E}\mathcal{E}} \subseteq \mathrm{T}$ *is a set of* 2*-types that is closed under inversion.*

($\varsigma\mathrm{T}$) *We require that* $\mathrm{T} = \varsigma^{\mathcal{I}\mathcal{I}} \cup \varsigma^{\mathcal{I}\mathcal{E}} \cup \varsigma^{\mathcal{E}\mathcal{I}} \cup \varsigma^{\mathcal{E}\mathcal{E}}$.

($\varsigma\mathrm{NP}$) *The (nonempty) set* $\mathrm{Tp}_{\boldsymbol{x}}\,\varsigma = (\mathrm{tp}_{\boldsymbol{x}} \restriction \varsigma^{\mathcal{I}\mathcal{E}})$ *is the set of* internal 1-types *of* ς*. The (nonempty) set* $\mathrm{Tp}_{\boldsymbol{y}}\,\varsigma = (\mathrm{tp}_{\boldsymbol{y}} \restriction \varsigma^{\mathcal{I}\mathcal{E}})$ *is the set of* external 1-types *of* ς*. We require that either* $\mathrm{Tp}_{\boldsymbol{x}}\,\varsigma \subseteq \mathrm{N}_{\mathrm{T}}$*, in which case* ς *is a* noble cosmic spectrum*, or* $\mathrm{Tp}_{\boldsymbol{x}}\,\varsigma \subseteq \mathrm{P}_{\mathrm{T}}$*, in which case* ς *is a* peasant cosmic spectrum*. Note that a* 1*-type may be both internal and external.*

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

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

Note that we have $\mathrm{tp}_{\boldsymbol{x}}(\tau_{\mathcal{X}\mathcal{Y}}) = (\mathrm{tp}_{\boldsymbol{x}}\tau)_{\mathcal{X}}$ and $\mathrm{tp}_{\boldsymbol{y}}(\tau_{\mathcal{X}\mathcal{Y}}) = (\mathrm{tp}_{\boldsymbol{y}}\tau)_{\mathcal{Y}}$ for $\mathcal{X}, \mathcal{Y} \in \{\mathcal{I}, \mathcal{E}\}$.

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

$$\mathrm{T}^{\varsigma} = \mathrm{T}^{\varsigma}_{\mathcal{I}\mathcal{I}} \cup \mathrm{T}^{\varsigma}_{\mathcal{I}\mathcal{E}} \cup \mathrm{T}^{\varsigma}_{\mathcal{E}\mathcal{I}} \cup \mathrm{T}^{\varsigma}_{\mathcal{E}\mathcal{E}},$$

where $\mathrm{T}^{\varsigma}_{\mathcal{X}\mathcal{Y}} = \left\{\tau_{\mathcal{X}\mathcal{Y}} \,\middle|\, \tau \in \varsigma^{\mathcal{X}\mathcal{Y}}\right\}$ *for* $\mathcal{X}, \mathcal{Y} \in \{\mathcal{I}, \mathcal{E}\}$.

This is indeed a type instance, since $\mathrm{T}^{\varsigma}_{\mathcal{I}\mathcal{E}}$ is nonempty by ($\varsigma\mathcal{I}\mathcal{E}$) and since $\mathrm{T}^{\varsigma}_{\mathcal{I}\mathcal{I}}$, $(\mathrm{T}^{\varsigma}_{\mathcal{I}\mathcal{E}} \cup \mathrm{T}^{\varsigma}_{\mathcal{E}\mathcal{I}})$ and $\mathrm{T}^{\varsigma}_{\mathcal{E}\mathcal{E}}$ are closed under inversion by ($\varsigma\mathcal{I}\mathcal{I}$), ($\varsigma\mathcal{E}\mathcal{I}$) and ($\varsigma\mathcal{E}\mathcal{E}$). The size of a cosmic spectrum over a type instance is linear with respect to the size of the type instance. Define $\Pi^{\varsigma}_{\mathcal{I}} = \{\pi_{\mathcal{I}} \mid \pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma\} = (\mathrm{tp}_{\boldsymbol{x}} \restriction \mathrm{T}^{\varsigma}_{\mathcal{I}\mathcal{E}})$ to be the set of *internal spectral* 1*-types* and $\Pi^{\varsigma}_{\mathcal{E}} = \left\{\pi_{\mathcal{E}} \,\middle|\, \pi \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma\right\} = (\mathrm{tp}_{\boldsymbol{y}} \restriction \mathrm{T}^{\varsigma}_{\mathcal{I}\mathcal{E}})$ to be the set of *external spectral* 1*-types*.

The cosmic spectrum ς is *locally consistent* if its spectral type instance T^{ς} has a model.

Definition 77. *Let* $\mathfrak{A}$ *be a nobly distinguished model for* T *such that* $E = \boldsymbol{e}^{\mathfrak{A}} \neq A \times A$ *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 $\varsigma = \mathrm{csp}^{\mathfrak{A}}[X]$ *of* X *is defined by:*

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

Remark 26. *Indeed* $\varsigma = \mathrm{csp}^{\mathfrak{A}}[X]$ *is a locally consistent cosmic spectrum over* T*.*

Proof. First we check that ς is a cosmic spectrum over T:

($\varsigma\mathcal{II}$) If $\tau \in \varsigma^{\mathcal{II}}$, then $\tau = \mathrm{tp}^{\mathfrak{A}}[a,b]$ for some $a \in X$ and $b \in X \setminus \{a\}$, so τ is galactic and $\tau^{-1} = \mathrm{tp}^{\mathfrak{A}}[b,a] \in \varsigma^{\mathcal{II}}$, 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 $\mathrm{tp}^{\mathfrak{A}}[a,b] \in \varsigma^{\mathcal{IE}}$, so $\varsigma^{\mathcal{IE}}$ is nonempty. Next, if $\tau \in \varsigma^{\mathcal{IE}}$ then $\tau = \mathrm{tp}^{\mathfrak{A}}[a,b]$ for some $a \in X$ and $b \in A \setminus X$, so τ is cosmic.

($\varsigma\mathcal{EI}$) If $\tau \in \varsigma^{\mathcal{IE}}$, then $\tau = \mathrm{tp}^{\mathfrak{A}}[a,b]$ for some $a \in X$ and $b \in A \setminus X$, so $\tau^{-1} = \mathrm{tp}^{\mathfrak{A}}[b,a] \in \varsigma^{\mathcal{EI}}$. If $\tau \in \varsigma^{\mathcal{EI}}$, then $\tau = \mathrm{tp}^{\mathfrak{A}}[a,b]$ for some $a \in A \setminus X$ and $b \in X$, so $\tau^{-1} = \mathrm{tp}^{\mathfrak{A}}[b,a] \in \varsigma^{\mathcal{IE}}$, so $\tau = \tau'^{-1}$ for $\tau' = \tau^{-1} \in \varsigma^{\mathcal{IE}}$.

($\varsigma\mathcal{EE}$) If $\tau \in \varsigma^{\mathcal{EE}}$, then $\tau = \mathrm{tp}^{\mathfrak{A}}[a,b]$ for some $a \in A \setminus X$ and $b \in (A \setminus X) \setminus \{a\}$, so $\tau^{-1} = \mathrm{tp}^{\mathfrak{A}}[b,a] \in \varsigma^{\mathcal{EE}}$ and hence $\varsigma^{\mathcal{EE}}$ is closed under inversion.

($\varsigma\mathrm{T}$) We have that $\varsigma^{\mathcal{II}} \cup \varsigma^{\mathcal{IE}} \cup \varsigma^{\mathcal{EI}} \cup \varsigma^{\mathcal{EE}} = \left\{\mathrm{tp}^{\mathfrak{A}}[a,b] \;\middle|\; a \in A, b \in A \setminus \{a\}\right\} = \mathrm{T}$ since $\mathfrak{A}$ is a model for T.

($\varsigma\mathrm{NP}$) First suppose that X is a noble galaxy. Let $\pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$, so some $\tau \in \varsigma^{\mathcal{IE}}$ has $\mathrm{tp}_{\boldsymbol{x}}\tau = \pi$, so some $a \in X$ and $b \in A \setminus X$ has $\mathrm{tp}^{\mathfrak{A}}[a,b] = \tau$, so $\pi = \mathrm{tp}^{\mathfrak{A}}[a]$ is noble, since $\mathfrak{A}$ is nobly distinguished. Next suppose that X is a peasant galaxy. Similarly, let $\pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$, so some $\tau \in \varsigma^{\mathcal{IE}}$ has $\mathrm{tp}_{\boldsymbol{x}}\tau = \pi$, so some $a \in X$ and $b \in A \setminus X$ has $\mathrm{tp}^{\mathfrak{A}}[a,b] = \tau$, so $\pi = \mathrm{tp}^{\mathfrak{A}}[a]$ is peasant, since X is a peasant galaxy.

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

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

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

6.4 Locally consistent cosmic spectrums

Let ς 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^ς *and let $X^\varsigma = \boldsymbol{in}^{\mathfrak{A}^\varsigma}$ be the set of* internal spectral elements*. Then:*

$$\begin{aligned}
\mathrm{T}^\varsigma_{\mathcal{I}\mathcal{I}} &= \left\{ \mathrm{tp}^{\mathfrak{A}^\varsigma}[a,b] \;\middle|\; a \in X^\varsigma, b \in X^\varsigma \setminus \{a\} \right\} \\
\mathrm{T}^\varsigma_{\mathcal{I}\mathcal{E}} &= \left\{ \mathrm{tp}^{\mathfrak{A}^\varsigma}[a,b] \;\middle|\; a \in X^\varsigma, b \in A^\varsigma \setminus X^\varsigma \right\} \\
\mathrm{T}^\varsigma_{\mathcal{E}\mathcal{I}} &= \left\{ \mathrm{tp}^{\mathfrak{A}^\varsigma}[a,b] \;\middle|\; a \in A^\varsigma \setminus X^\varsigma, b \in X^\varsigma \right\} \\
\mathrm{T}^\varsigma_{\mathcal{E}\mathcal{E}} &= \left\{ \mathrm{tp}^{\mathfrak{A}^\varsigma}[a,b] \;\middle|\; a \in A^\varsigma \setminus X^\varsigma, b \in (A^\varsigma \setminus X^\varsigma) \setminus \{a\} \right\} \\
\Pi^\varsigma_{\mathcal{I}} &= \left\{ \mathrm{tp}^{\mathfrak{A}^\varsigma}[a] \;\middle|\; a \in X^\varsigma \right\} \\
\Pi^\varsigma_{\mathcal{E}} &= \left\{ \mathrm{tp}^{\mathfrak{A}^\varsigma}[a] \;\middle|\; a \in A^\varsigma \setminus X^\varsigma \right\}.
\end{aligned}$$

In other words:

1. *If $\tau \in \varsigma^{\mathcal{I}\mathcal{I}}$ then $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a,b] = \tau_{\mathcal{I}\mathcal{I}}$ 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 $\tau \in \varsigma^{\mathcal{I}\mathcal{I}}$ has $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a,b] = \tau_{\mathcal{I}\mathcal{I}}$.
2. *If $\tau \in \varsigma^{\mathcal{I}\mathcal{E}}$ then $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a,b] = \tau_{\mathcal{I}\mathcal{E}}$ 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 $\tau \in \varsigma^{\mathcal{I}\mathcal{E}}$ has $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a,b] = \tau_{\mathcal{I}\mathcal{E}}$.
3. *If $\tau \in \varsigma^{\mathcal{E}\mathcal{I}}$ then $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a,b] = \tau_{\mathcal{E}\mathcal{I}}$ for some $a \in A^\varsigma \setminus X^\varsigma$ and $b \in X^\varsigma$.*
   If $a \in A^\varsigma \setminus X^\varsigma$ and $b \in X$ then some $\tau \in \varsigma^{\mathcal{E}\mathcal{I}}$ has $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a,b] = \tau_{\mathcal{E}\mathcal{I}}$.
4. *If $\tau \in \varsigma^{\mathcal{E}\mathcal{E}}$ then $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a,b] = \tau_{\mathcal{E}\mathcal{E}}$ 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 $\tau \in \varsigma^{\mathcal{E}\mathcal{E}}$ has $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a,b] = \tau_{\mathcal{E}\mathcal{E}}$.
5. *Both X^ς and $A^\varsigma \setminus X^\varsigma$ are nonempty.*
6. *If $\pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$ then some $a \in X$ has $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a] = \pi_{\mathcal{I}}$*
   If $a \in X$ then $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a] = \pi_{\mathcal{I}}$ for some $\pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$.
7. *If $\pi \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$ then some $a \in A^\varsigma \setminus X^\varsigma$ has $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a] = \pi_{\mathcal{E}}$*
   If $a \in A^\varsigma \setminus X^\varsigma$ then $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a] = \pi_{\mathcal{E}}$ for some $\pi \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$.

We will be applying this lemma implicitly.

Proof. 1. If $\tau \in \varsigma^{\mathcal{I}\mathcal{I}}$ then $\tau_{\mathcal{I}\mathcal{I}} \in \mathrm{T}^\varsigma_{\mathcal{I}\mathcal{I}} \subseteq \mathrm{T}^\varsigma$, so some $a \in A^\varsigma$ and $b \in A^\varsigma \setminus \{a\}$ have $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a,b] = \tau_{\mathcal{I}\mathcal{I}}$. We have that $\boldsymbol{in}(\boldsymbol{x}) \in (\mathrm{tp}_{\boldsymbol{x}}\tau)_{\mathcal{I}} = \mathrm{tp}_{\boldsymbol{x}}(\tau_{\mathcal{I}\mathcal{I}}) = \mathrm{tp}^{\mathfrak{A}^\varsigma}[a]$, so $a \in X^\varsigma$. Similarly, $\boldsymbol{in}(\boldsymbol{x}) \in (\mathrm{tp}_{\boldsymbol{y}}\tau)_{\mathcal{I}} = \mathrm{tp}_{\boldsymbol{y}}(\tau_{\mathcal{I}\mathcal{I}}) = \mathrm{tp}^{\mathfrak{A}^\varsigma}[b]$, so $b \in X^\varsigma \setminus \{a\}$.

Next, suppose that $a \in X^\varsigma$ and $b \in X^\varsigma \setminus \{a\}$ and let $\tau' = \mathrm{tp}^{\mathfrak{A}^\varsigma}[a,b]$. Then $\boldsymbol{in}(\boldsymbol{x}) \in \mathrm{tp}^{\mathfrak{A}^\varsigma}[a] = \mathrm{tp}_{\boldsymbol{x}}\tau'$ and $\boldsymbol{in}(\boldsymbol{x}) \in \mathrm{tp}^{\mathfrak{A}^\varsigma}[b] = \mathrm{tp}_{\boldsymbol{y}}\tau'$, so $\tau' = \tau_{\mathcal{I}\mathcal{I}}$ for some $\tau \in \varsigma^{\mathcal{I}\mathcal{I}}$.

2. If $\tau \in \varsigma^{\mathcal{IE}}$ then $\tau_{\mathcal{IE}} \in \mathrm{T}^{\varsigma}_{\mathcal{IE}} \subseteq \mathrm{T}^{\varsigma}$, so some $a \in A^{\varsigma}$ and $b \in A^{\varsigma} \setminus \{a\}$ have $\mathrm{tp}^{\mathfrak{A}}[a,b] = \tau_{\mathcal{IE}}$. We have that $\boldsymbol{in}(\boldsymbol{x}) \in (\mathrm{tp}_{\boldsymbol{x}}\tau)_{\mathcal{I}} = \mathrm{tp}_{\boldsymbol{x}}(\tau_{\mathcal{IE}}) = \mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a]$, so $a \in X^{\varsigma}$. Similarly, $(\neg\boldsymbol{in}(\boldsymbol{x})) \in (\mathrm{tp}_{\boldsymbol{y}}\tau)_{\mathcal{E}} = \mathrm{tp}_{\boldsymbol{y}}(\tau_{\mathcal{IE}}) = \mathrm{tp}^{\mathfrak{A}}[b]$, 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 $\tau' = \mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a,b]$. Then $\boldsymbol{in}(\boldsymbol{x}) \in \mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a] = \mathrm{tp}_{\boldsymbol{x}}\tau'$ and $\boldsymbol{in}(\boldsymbol{x}) \in \mathrm{tp}^{\mathfrak{A}}[b] = \mathrm{tp}_{\boldsymbol{y}}\tau'$, 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 $\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a,b] = (\tau^{-1})_{\mathcal{IE}}$, so $\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[b,a] = \tau_{\mathcal{EI}}$.

   If $a \in A^{\varsigma} \setminus X^{\varsigma}$ and $b \in X^{\varsigma}$ then some $\tau \in \varsigma^{\mathcal{IE}}$ has $\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[b,a] = \tau_{\mathcal{IE}}$, so $\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a,b] = \tau'_{\mathcal{EI}}$ for $\tau' = \tau^{-1} \in \varsigma^{\mathcal{EI}}$.

4. If $\tau \in \varsigma^{\mathcal{EE}}$ then $\tau_{\mathcal{EE}} \in \mathrm{T}^{\varsigma}_{\mathcal{EE}} \subseteq \mathrm{T}^{\varsigma}$, so some $a \in A^{\varsigma}$ and $b \in A^{\varsigma} \setminus \{a\}$ have $\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a,b] = \tau_{\mathcal{EE}}$. We have that $(\neg\boldsymbol{in}(\boldsymbol{x})) \in (\mathrm{tp}_{\boldsymbol{x}}\tau)_{\mathcal{E}} = \mathrm{tp}_{\boldsymbol{x}}(\tau_{\mathcal{EE}}) = \mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a]$, so $a \in A^{\varsigma} \setminus X^{\varsigma}$. Similarly, $(\neg\boldsymbol{in}(\boldsymbol{x})) \in (\mathrm{tp}_{\boldsymbol{y}}\tau)_{\mathcal{E}} = \mathrm{tp}_{\boldsymbol{y}}(\tau_{\mathcal{EE}}) = \mathrm{tp}^{\mathfrak{A}^{\varsigma}}[b]$, 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 $\tau' = \mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a,b]$. Then $(\neg\boldsymbol{in}(\boldsymbol{x})) \in \mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a] = \mathrm{tp}_{\boldsymbol{x}}\tau'$ and $(\neg\boldsymbol{in}(\boldsymbol{x})) \in \mathrm{tp}^{\mathfrak{A}^{\varsigma}}[b] = \mathrm{tp}_{\boldsymbol{y}}\tau'$, 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 $\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a,b] = \tau_{\mathcal{IE}}$, so in particular both X^{ς} and $A^{\varsigma} \setminus X^{\varsigma}$ are nonempty.

6. If $\pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$ then some $\tau \in \varsigma^{\mathcal{IE}}$ has $\mathrm{tp}_{\boldsymbol{x}}\tau = \pi$, so some $a \in X^{\varsigma}$ and $b \in A \setminus X^{\varsigma}$ have $\mathrm{tp}^{\mathfrak{A}}[a,b] = \tau_{\mathcal{IE}}$, so $\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a] = \pi_{\mathcal{I}}$.

   Next, suppose that $a \in X^{\varsigma}$. Let $b \in A^{\varsigma} \setminus X^{\varsigma}$, which is nonempty. Then $\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a,b] = \tau_{\mathcal{IE}}$ for some $\tau \in \varsigma^{\mathcal{IE}}$. Then $\pi = \mathrm{tp}_{\boldsymbol{x}}\tau \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$. Then $\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a] = \mathrm{tp}_{\boldsymbol{x}}(\tau_{\mathcal{IE}}) = \pi_{\mathcal{I}}$.

7. If $\pi \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$, then some $\tau \in \varsigma^{\mathcal{IE}}$ has $\mathrm{tp}_{\boldsymbol{y}}\tau = \pi$, so some $a \in X^{\varsigma}$ and $b \in A \setminus X^{\varsigma}$ have $\mathrm{tp}^{\mathfrak{A}}[a,b] = \tau_{\mathcal{IE}}$, so $\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[b] = \pi_{\mathcal{E}}$.

   Next, suppose that $b \in X^{\varsigma}$. Let $a \in X^{\varsigma}$, which is nonempty. Then $\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a,b] = \tau_{\mathcal{IE}}$ for some $\tau \in \varsigma^{\mathcal{IE}}$. Then $\pi = \mathrm{tp}_{\boldsymbol{y}}\tau \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$. Then $\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[b] = \mathrm{tp}_{\boldsymbol{y}}(\tau_{\mathcal{IE}}) = \pi_{\mathcal{E}}$.

□

Remark 27. *We have that* $\Pi_{\mathrm{T}^{\varsigma}} = \Pi^{\varsigma}_{\mathcal{I}} \cup \Pi^{\varsigma}_{\mathcal{E}}$.

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

$$\Pi_{\mathrm{T}^{\varsigma}} = \left\{\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a] \;\middle|\; a \in A^{\varsigma}\right\} = \left\{\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a] \;\middle|\; a \in X^{\varsigma}\right\} \cup \left\{\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a] \;\middle|\; a \in A^{\varsigma} \setminus X^{\varsigma}\right\} = \Pi^{\varsigma}_{\mathcal{I}} \cup \Pi^{\varsigma}_{\mathcal{E}}$$

by Lemma 8 and by Lemma 13. □

Remark 28. *If* $\tau \in \varsigma^{\mathcal{II}}$ *then* $\mathrm{tp}_{\boldsymbol{x}}\tau \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$. *If* $\tau \in \varsigma^{\mathcal{EE}}$ *then* $\mathrm{tp}_{\boldsymbol{x}}\tau \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$. *Equivalently,* $(\mathrm{tp}_{\boldsymbol{x}} \restriction \varsigma^{\mathcal{II}}) \subseteq \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$ *and* $(\mathrm{tp}_{\boldsymbol{x}} \restriction \varsigma^{\mathcal{EE}}) \subseteq \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$.

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

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

If $\tau \in \varsigma^{\mathcal{E}\mathcal{E}}$ then some $a \in A^\varsigma \setminus X^\varsigma$ and $b \in A^\varsigma \setminus X^\varsigma \setminus \{a\}$ have $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a,b] = \tau_{\mathcal{E}\mathcal{E}}$, so $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a] = \mathrm{tp}_{\boldsymbol{x}}(\tau_{\mathcal{E}\mathcal{E}}) = (\mathrm{tp}_{\boldsymbol{x}}\tau)_{\mathcal{E}}$, so $\mathrm{tp}_{\boldsymbol{x}}\tau \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$. □

Remark 29. *We have that* $\Pi_{\mathrm{T}} = \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma \cup \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$.

Proof. Let $\pi \in \Pi_{\mathrm{T}}$ be any 1-type, so some $\tau \in \mathrm{T}$ has $\mathrm{tp}_{\boldsymbol{x}}\tau = \pi$. By ($\varsigma$T) we have that $\tau \in \varsigma^{\mathcal{I}\mathcal{I}} \cup \varsigma^{\mathcal{I}\mathcal{E}} \cup \varsigma^{\mathcal{E}\mathcal{I}} \cup \varsigma^{\mathcal{E}\mathcal{E}}$. If $\tau \in \varsigma^{\mathcal{I}\mathcal{I}}$, then $\pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$ by Remark 28. If $\tau \in \varsigma^{\mathcal{I}\mathcal{E}}$, then $\pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$ by definition. If $\tau \in \varsigma^{\mathcal{E}\mathcal{I}}$, then $\tau^{-1} \in \varsigma^{\mathcal{I}\mathcal{E}}$, so $\pi = \mathrm{tp}_{\boldsymbol{x}}\tau = \mathrm{tp}_{\boldsymbol{y}}(\tau^{-1}) \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$ by definition. If $\tau \in \varsigma^{\mathcal{E}\mathcal{E}}$, then $\pi \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$ by Remark 28. □

Remark 30. *If* $\pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$ *and* $\pi' \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$*, then some* $\tau \in \varsigma^{\mathcal{I}\mathcal{E}}$ *has* $\mathrm{tp}_{\boldsymbol{x}}\tau = \pi$ *and* $\mathrm{tp}_{\boldsymbol{y}}\tau = \pi'$.

Proof. Let $\mathfrak{A}^\varsigma$ be a model for T^ς and let $X^\varsigma = \boldsymbol{in}^{\mathfrak{A}^\varsigma}$ be the set of internal spectral elements. Then some $a \in X^\varsigma$ has $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a] = \pi_{\mathcal{I}}$ and some $b \in A^\varsigma \setminus X^\varsigma$ has $\mathrm{tp}^{\mathfrak{A}^\varsigma}[b] = \pi_{\mathcal{E}}$. Then $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a,b] = \tau_{\mathcal{I}\mathcal{E}}$ for some $\tau \in \varsigma^{\mathcal{I}\mathcal{E}}$. Then $\mathrm{tp}_{\boldsymbol{x}}\tau = \pi$ and $\mathrm{tp}_{\boldsymbol{y}}\tau = \pi'$. □

Remark 31. *If* $\pi \in \mathrm{P}_{\mathrm{T}}$ *is any peasant type, then* $\pi \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$.

Proof. Let $\tau \in \mathrm{T}^{\mathrm{c}}$ be any cosmic type connecting the peasant type π with itself. Then by (ςT), $\tau \in \varsigma^{\mathcal{I}\mathcal{E}} \cup \varsigma^{\mathcal{E}\mathcal{I}} \cup \varsigma^{\mathcal{E}\mathcal{E}}$.

If $\tau \in \varsigma^{\mathcal{I}\mathcal{E}}$, then $\pi = \mathrm{tp}_{\boldsymbol{y}}\tau \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$. If $\tau \in \varsigma^{\mathcal{E}\mathcal{I}}$, then $\pi = \mathrm{tp}_{\boldsymbol{y}}(\tau^{-1}) \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$. Suppose that $\tau \in \varsigma^{\mathcal{E}\mathcal{E}}$. Let $\mathfrak{A}^\varsigma$ be a model for T^ς and let $X^\varsigma = \boldsymbol{in}^{\mathfrak{A}^\varsigma}$ be the set of internal spectral elements. Then $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a,b] = \tau_{\mathcal{E}\mathcal{E}}$ for some $a \in A^\varsigma \setminus X^\varsigma$ and $b \in (A^\varsigma \setminus X^\varsigma) \setminus \{a\}$. Then $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a] = \pi_{\mathcal{E}}$, so $\pi \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$. □

Remark 32. *If* $\nu \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma \cap \mathrm{N}_{\mathrm{T}}$ *is an internal noble type, then* $\nu \notin \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$.

Proof. Suppose towards a contradiction that $\nu \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$. Then by Remark 30, some $\tau \in \varsigma^{\mathcal{I}\mathcal{E}}$ has $\mathrm{tp}_{\boldsymbol{x}}\tau = \mathrm{tp}_{\boldsymbol{y}}\tau = \nu$. By ($\varsigma\mathcal{I}\mathcal{E}$), τ is cosmic — a contradiction. □

Remark 33. *If* $\kappa \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma \cap \mathrm{K}_{\mathrm{T}}$ *is an internal king type, then* $\kappa_{\mathcal{I}} \in \mathrm{K}_{\mathrm{T}^\varsigma}$ *is an internal spectral king type.*

Proof. Suppose towards a contradiction that $\kappa_{\mathcal{I}}$ is not a king type, so some $\tau' \in \mathrm{T}^\varsigma$ connects $\kappa_{\mathcal{I}}$ with itself. We must have that $\tau' \in \mathrm{T}^\varsigma_{\mathcal{I}\mathcal{I}}$, so $\tau' = \tau_{\mathcal{I}\mathcal{I}}$ for some $\tau \in \varsigma^{\mathcal{I}\mathcal{I}}$, so τ connects κ with itself — a contradiction. □

Remark 34. *If* $\kappa \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma \cap \mathrm{K}_{\mathrm{T}}$ *is an external king type, then* $\kappa_{\mathcal{E}} \in \mathrm{K}_{\mathrm{T}^\varsigma}$ *is an external spectral king type.*

Proof. Suppose towards a contradiction that $\kappa_{\mathcal{E}}$ is not a king type, so some $\tau' \in \mathrm{T}^\varsigma$ connects $\kappa_{\mathcal{E}}$ with itself. We must have that $\tau' \in \mathrm{T}^\varsigma_{\mathcal{E}\mathcal{E}}$, so $\tau' = \tau_{\mathcal{E}\mathcal{E}}$ for some $\tau \in \varsigma^{\mathcal{E}\mathcal{E}}$, so τ connects κ with itself — a contradiction. □

Remark 35. *If ς is noble and if $\nu \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma \backslash \mathrm{K}_{\mathrm{T}}$ is an internal worker type, then $\nu_{\mathcal{I}} \in \mathrm{W}_{\mathrm{T}^\varsigma}$ is an internal spectral worker type.*

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

If $\tau \in \varsigma^{\mathcal{II}}$, then $\tau_{\mathcal{II}} \in \mathrm{T}^{\varsigma}_{\mathcal{II}}$ connects $\nu_{\mathcal{I}}$ with itself, so $\nu_{\mathcal{I}}$ is a worker type.

If $\tau \in \varsigma^{\mathcal{EE}}$, then by Remark 28 $\nu \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$. Then by Remark 30 some $\tau \in \varsigma^{\mathcal{IE}}$ connects ν with itself. But then τ is cosmic — a contradiction. □

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

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

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

Definition 78. *Let $\mathfrak{A}^\varsigma$ be a model for T^ς, and let $X^\varsigma = \boldsymbol{in}^{\mathfrak{A}^\varsigma}$ be the set of internal spectral elements. Recall that both X^ς and $\mathfrak{A}^\varsigma \setminus X^\varsigma$ are nonempty. Transform $(\mathfrak{A}^\varsigma \restriction X^\varsigma)$ to a model $\mathfrak{X}^\varsigma$ for Σ by forgetting the interpretation of $\boldsymbol{in}$ and by interpreting $\boldsymbol{e}^{\mathfrak{X}^\varsigma} = X^\varsigma \times X^\varsigma$ as the full relation on X^ς. Call $\mathfrak{X}^\varsigma$ the* galaxy *of the model $\mathfrak{A}^\varsigma$. Note that $\mathfrak{X}^\varsigma$ is a Σ-structure, but is not necessarily a $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$-structure, since some message symbols might be witnessed only by an element outside of X^ς in $\mathfrak{A}^\varsigma$.*

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

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

Define the intended 1-type *of a by: $\pi(a) = \mathrm{tp}_{\boldsymbol{x}}(\sigma(a)) = \mathrm{tp}^{\mathfrak{A}^\varsigma}[a]^{\mathcal{I}} = \mathrm{tp}^{\mathfrak{X}^\varsigma}[a]$.*

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

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

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

($\sigma\pi\boldsymbol{y}$) Let $\pi' \in \mathrm{T}[\pi]$. We have to find some $\tau \in \sigma$ having $\mathrm{tp}_{\boldsymbol{y}}\tau = \pi'$. By Remark 29, $\pi' \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma \cup \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$.

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

Next suppose that $\pi' = \pi$, so π is not a king type. So some $\tau' \in \mathrm{T}$ connects π 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 $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a', b'] = \tau'_{\mathcal{II}}$. So $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a'] = \mathrm{tp}_{\boldsymbol{x}}(\tau'_{\mathcal{II}}) = (\mathrm{tp}_{\boldsymbol{x}}\tau')_{\mathcal{I}} = \pi'_{\mathcal{I}}$ and $\mathrm{tp}^{\mathfrak{A}^\varsigma}[b'] = \mathrm{tp}_{\boldsymbol{y}}(\tau'_{\mathcal{II}}) = (\mathrm{tp}_{\boldsymbol{y}}\tau')_{\mathcal{I}} = \pi'_{\mathcal{I}}$. Let $b \in \{a', b'\} \setminus \{a\}$, which is nonempty. Then $\tau = \mathrm{tp}^{\mathfrak{A}^\varsigma}[a, b]^{\mathcal{II}} \in \sigma$ has $\mathrm{tp}_{\boldsymbol{y}}\tau = \mathrm{tp}^{\mathfrak{A}^\varsigma}[b]^{\mathcal{I}} = (\pi'_{\mathcal{I}})^{\mathcal{I}} = \pi'$.

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

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

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 $\mathrm{tp}^{\mathfrak{A}^\varsigma}[a', b'] = \tau'_{\mathcal{EE}}$. So for $b = a'$. $\mathrm{tp}^{\mathfrak{A}^\varsigma}[b] = \mathrm{tp}_{\boldsymbol{x}}(\tau'_{\mathcal{EE}}) = (\mathrm{tp}_{\boldsymbol{x}}\tau')_{\mathcal{E}} = \pi'_{\mathcal{E}}$. Then $\tau = \mathrm{tp}^{\mathfrak{A}^\varsigma}[a, b]^{\mathcal{IE}} \in \sigma$ has $\mathrm{tp}_{\boldsymbol{y}}\tau = (\pi'_{\mathcal{E}})^{\mathcal{E}} = \pi'$.

($\sigma\kappa\boldsymbol{y}$) Suppose that $\kappa' \in \mathrm{T}[\pi] \cap \mathrm{K}_{\mathrm{T}}$ and that $\tau, \tau' \in \sigma$ have $\mathrm{tp}_{\boldsymbol{y}}\tau = \mathrm{tp}_{\boldsymbol{y}}\tau' = \kappa'$.

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

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

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

($\sigma\boldsymbol{m}$) Let $\boldsymbol{m} \in \bar{\boldsymbol{m}}$. Since $\mathfrak{A}^\varsigma$ is a model for T^ς, some $b \in A \setminus \{a\}$ has $\boldsymbol{m}(\boldsymbol{x}, \boldsymbol{y}) \in \mathrm{tp}^{\mathfrak{A}^\varsigma}[a, b]$. If $b \in X$, then $\boldsymbol{m}(\boldsymbol{x}, \boldsymbol{y}) \in \mathrm{tp}^{\mathfrak{A}}[a, b]^{\mathcal{II}} \in \sigma$. If $b \in A \setminus X$, then $\boldsymbol{m}(\boldsymbol{x}, \boldsymbol{y}) \in \mathrm{tp}^{\mathfrak{A}}[a, b]^{\mathcal{IE}} \in \sigma$.

□

Lemma 15 (Type characterization)**.** *Let* T *be a type instance, ς be a locally consistent cosmic spectrum over* T*, $\mathfrak{A}^\varsigma$ be a model for the spectral type instance T^ς, X^ς 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 $\pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$ then some $a \in X^\varsigma$ has $\pi(a) = \pi$.*

   If $a \in X^\varsigma$ then $\pi(a) \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$.

   Equivalently $\mathrm{Tp}_{\boldsymbol{x}}\,\varsigma = \{\pi(a) \mid a \in X^\varsigma\}$.

2. *If $\tau \in \varsigma^{\mathcal{II}}$ then some $a \in X^{\varsigma}$ and $b \in X^{\varsigma} \setminus \{a\}$ have $\mathrm{tp}^{\mathfrak{X}^{\varsigma}}[a,b] = \tau$.*

   If $a \in X^{\varsigma}$ and $b \in A^{\varsigma} \setminus X^{\varsigma}$ then $\mathrm{tp}^{\mathfrak{X}^{\varsigma}}[a,b] \in \varsigma^{\mathcal{II}}$.

   Equivalently $\varsigma^{\mathcal{II}} = \left\{\mathrm{tp}^{\mathfrak{X}^{\varsigma}}[a,b] \;\middle|\; a \in X^{\varsigma}, b \in X^{\varsigma} \setminus \{a\}\right\}$.

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 $\varsigma^{\mathcal{IE}} = \{\sigma(a) \mid a \in X^{\varsigma}\} \cap \mathrm{T}^{\mathrm{c}}$.

We will be applying this lemma implicitly.

Proof. 1. If $\pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$ then some $a \in X^{\varsigma}$ has $\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a] = \pi_{\mathcal{I}}$, so $\pi(a) = \mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a]^{\mathcal{I}} = \pi$.

   If $a \in X^{\varsigma}$ then $\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a] = \pi_{\mathcal{I}}$ for some $\pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$, so $\pi(a) = \mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a]^{\mathcal{I}} = \pi$.

2. If $\tau \in \varsigma^{\mathcal{II}}$ then some $a \in X^{\varsigma}$ and $b \in X^{\varsigma} \setminus \{a\}$ have $\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a,b] = \tau_{\mathcal{II}}$, so $\mathrm{tp}^{\mathfrak{X}^{\varsigma}}[a,b] = \mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a,b]^{\mathcal{II}} = \tau$.

   If $a \in X^{\varsigma}$ and $b \in X^{\varsigma} \setminus \{a\}$ then $\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a,b] = \tau_{\mathcal{II}}$ for some $\tau \in \varsigma^{\mathcal{II}}$, so $\mathrm{tp}^{\mathfrak{X}^{\varsigma}}[a,b] = \tau$.

3. If $\tau \in \varsigma^{\mathcal{IE}}$ then some $a \in X^{\varsigma}$ and $b \in A^{\varsigma} \setminus X^{\varsigma}$ have $\mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a,b] = \tau_{\mathcal{IE}}$, so $\tau = \mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a,b]^{\mathcal{IE}} \in \sigma(a)$.

   Let $a \in X^{\varsigma}$ and let $\tau \in \sigma(a)$ be cosmic. Then $\tau = \mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a,b]^{\mathcal{IE}}$ for some $b \in A^{\varsigma} \setminus X^{\varsigma}$, so $\tau \in \varsigma^{\mathcal{IE}}$.

∎

Definition 79. *A* certificate $\mathcal{S}$ *for the type instance* T *is a nonempty set of locally consistent cosmic spectrums over* T *satisfying the following conditions:*

($\mathcal{S}\mathrm{T}^{\mathrm{c}}$) *If $\tau \in \mathrm{T}^{\mathrm{c}}$ then some $\varsigma \in \mathcal{S}$ has $\tau \in \varsigma^{\mathcal{IE}}$.*

($\mathcal{S}\mathrm{T}^{\mathrm{g}}$) *If $\tau \in \mathrm{T}^{\mathrm{g}}$ then some $\varsigma \in \mathcal{S}$ has $\tau \in \varsigma^{\mathcal{II}}$.*

($\mathcal{S}\nu$) *If $\nu \in \mathrm{N}_{\mathrm{T}}$ and $\varsigma, \varsigma' \in \mathcal{S}$ have $\nu \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$ and $\nu \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma'$, then $\varsigma' = \varsigma$.*

Remark 36. *If $\pi \in \Pi_{\mathrm{T}}$ then some $\varsigma \in \mathcal{S}$ has $\pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$.*

Proof. Let $\pi \in \Pi_{\mathrm{T}}$, so some $\tau \in \mathrm{T}$ has $\mathrm{tp}_{\boldsymbol{x}}\tau = \pi$. If τ is cosmic, by ($\mathcal{S}\mathrm{T}^{\mathrm{c}}$) some $\varsigma \in \mathcal{S}$ has $\tau \in \varsigma^{\mathcal{IE}}$, so $\pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$. If τ is galactic, by ($\mathcal{S}\mathrm{T}^{\mathrm{g}}$) some $\varsigma \in \mathcal{S}$ has $\tau \in \varsigma^{\mathcal{II}}$, so by Remark 28 $\pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$. ∎

Remark 37. *If $\nu \in \mathrm{N}_{\mathrm{T}}$, then a unique $\varsigma \in \mathcal{S}$ has $\nu \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$.*

Proof. Let $\nu \in \mathrm{N}_{\mathrm{T}}$. By Remark 36, some $\varsigma \in \mathcal{S}$ has $\nu \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$. By ($\mathcal{S}\nu$) such $\varsigma \in \mathcal{S}$ is unique. ∎

Lemma 16 (Certificate extraction)**.** *Let $\mathfrak{A}$ be a model for the type instance* T *over the* $\mathcal{L}^2e\mathrm{E}_{\mathsf{refine}}$*-classified signature* $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$ *such that* $E = \boldsymbol{e}^{\mathfrak{A}}$ *is not full on* A*. For each 2-type* $\tau \in \mathrm{T}$ *let* $a_\tau \neq b_\tau \in A$ *realize* τ*, that is* $\mathrm{tp}^{\mathfrak{A}}[a_\tau, b_\tau] = \tau$*. Let*

$$\mathcal{S} = \left\{ \mathrm{csp}^{\mathfrak{A}}[E[a_\tau]] \,\middle|\, \tau \in \mathrm{T} \right\}.$$

Then $\mathcal{S}$ *is a certificate for* T*. The size of* $\mathcal{S}$ *is quadratic with respect to the size of the type instance.*

Proof. That $\mathcal{S}$ is nonempty follows since E is not full on A. We check the conditions for a certificate:

($\mathcal{S}\mathrm{T}^{\mathrm{c}}$) Let $\tau \in \mathrm{T}^{\mathrm{c}}$ be any cosmic type, let $a_\tau \in A$ be the selected $\boldsymbol{x}$-element for τ and let $\varsigma = \mathrm{csp}^{\mathfrak{A}}[E[a_\tau]]$. Then $b_\tau \in A \setminus E[a_\tau]$ and so $\tau = \mathrm{tp}^{\mathfrak{A}}[a_\tau, b_\tau] \in \varsigma_{\mathcal{I}\mathcal{E}}$.

($\mathcal{S}\mathrm{T}^{\mathrm{g}}$) Let $\tau \in \mathrm{T}^{\mathrm{g}}$ be any galactic type, and consider a_τ and b_τ. Then $(a_\tau, b_\tau) \in E$, so $\tau = \mathrm{tp}^{\mathfrak{A}}[a_\tau, b_\tau] \in \varsigma_{\mathcal{I}\mathcal{I}}$ for $\varsigma = \mathrm{csp}^{\mathfrak{A}}[a_\tau]$.

($\mathcal{S}\nu$) Let $\nu \in \mathrm{N}_{\mathrm{T}}$ be any noble type. Then a unique galaxy X realizes ν. Then if $\varsigma \in \mathcal{S}$ has $\nu \in \mathrm{Tp}_{\boldsymbol{x}}\, \varsigma$, then $\varsigma = \mathrm{csp}^{\mathfrak{A}}[X]$.

□

Theorem 5 (Certificate expansion)**.** *Let* $\mathcal{S}$ *be a certificate for the type instance* T *over the* $\mathcal{L}^2e\mathrm{E}_{\mathsf{refine}}$*-classified signature* $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$*.] 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 have shown the base case $e = 0$, $\mathcal{L}^2e\mathrm{E}_{\mathsf{refine}} = \mathcal{L}^2$ in Theorem 4. Now let $e \geq 1$ and assume the hypothesis for $(e-1)$. We build a model $\mathfrak{A}$ for T. For every $\varsigma \in \mathcal{S}$, let $\mathfrak{A}^\varsigma$ be a model for T^ς in which every worker type is realized at least $3t$ times. Such a model exists. Indeed let $\mathfrak{B}$ be any model for the spectral type instance T^ς of the locally consistent cosmic spectrum ς. By certificate extraction (if $e = 1$ by Lemma 9 or if $e \geq 2$ by Lemma 16), we can extract a certificate from $\mathfrak{B}$ and then by induction hypothesis we can build a model $\mathfrak{A}^\varsigma$ based on the certificate with the desired properties. 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 $\pi(a) = \mathrm{tp}_{\boldsymbol{x}}(\sigma(a))$ 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 $\pi \in \Pi_{\mathrm{T}}$. Consider any noble $\nu \in \mathrm{N}_{\mathrm{T}}$. By Remark 37 a unique $\varsigma \in \mathcal{S}$ has $\nu \in \mathrm{Tp}_{\boldsymbol{x}}\, \varsigma$. Note that ς is noble and $A^\nu \subseteq X^\varsigma$.

If $\kappa \in \mathrm{K_T}$ is any king type, then since κ is noble, there is a unique $\varsigma \in \mathcal{S}$ having $\kappa \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$. By Remark 33, $\kappa_{\mathcal{I}} \in \mathrm{K}_{\mathrm{T}^{\varsigma}}$ 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 $\nu \in \mathrm{N_T} \setminus \mathrm{K_T}$ is any noble type that is not a king type, then by Remark 35 $\nu_{\mathcal{I}} \in \mathrm{W}_{\mathrm{T}^{\varsigma}}$ is an internal worker spectral type for the unique (noble) $\varsigma \in \mathcal{S}$ having $\nu \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$. So $A^{\nu} = \left\{a \in X^{\varsigma} \,\middle|\, \mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a] = \nu_{\mathcal{I}}\right\}$ 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 $\pi \in \mathrm{P_T}$ is any peasant type, let $\mathcal{S}^{\pi} = \{\varsigma \in \mathcal{S} \mid \pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma\}$ be the set of (peasant) cosmic spectrums including π. By Remark 36, $\mathcal{S}^{\pi}$ is nonempty. Then:

$$A^{\pi} = \left\{a \in X^{\varsigma}_{ij} \,\middle|\, \varsigma \in \mathcal{S}^{\pi}, i \in \{0,1,2\}, j \in [1,t], \pi(a) = \pi\right\}.$$

By Lemma 15:

$$A^{\pi} = \left\{a \in X^{\varsigma}_{ij} \,\middle|\, \varsigma \in \mathcal{S}^{\pi}, i \in \{0,1,2\}, j \in [1,t], \mathrm{tp}^{\mathfrak{A}^{\varsigma}}[a] = \pi_{\mathcal{I}}\right\}.$$

Consider the partition $A^{\pi} = A^{\pi}_0 \cup A^{\pi}_1 \cup A^{\pi}_2$, where:

$$A^{\pi}_i = \left\{a \in X^{\varsigma}_{ij} \,\middle|\, \varsigma \in \mathcal{S}^{\pi}, j \in [1,t], \pi(a) = \pi\right\}.$$

Then $|A^{\pi}_i| \geq t$ and whenever $\pi, \pi' \in \Pi_{\mathrm{T}}$ 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 $\kappa' \in \mathrm{K_T}$ be any king type, let $\varsigma' \in \mathcal{S}$ be the unique (noble) cosmic spectrum having $\kappa' \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma'$ 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 $\kappa' = \mathrm{tp}_{\boldsymbol{x}}\sigma'$. 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 $\mathfrak{X}^{\varsigma}$ be the galaxy of b, so $\pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$ and $b \in X^{\varsigma} \neq X^{\varsigma'}$. By construction $\varsigma' \neq \varsigma$, since $\mathfrak{A}$ contains a unique noble galaxy for each noble cosmic spectrum from $\mathcal{S}$ and since ς' is noble. Then $\kappa' \notin \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$. Indeed, if $\kappa' \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$ then since $\kappa' \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma'$, we have a contradiction of ($\mathcal{S}\nu$). Then $\pi \neq \kappa'$, since $\pi \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$. So $\kappa' \in \mathrm{T}[\pi] \cap \mathrm{K_T}$ and by ($\sigma\kappa\boldsymbol{y}$) there is a unique $\tau \in \sigma$ having $\mathrm{tp}_{\boldsymbol{y}}\tau = \kappa'$. If τ is galactic, then $\tau \in \varsigma^{\mathcal{II}}$ by construction, so $\kappa' = \mathrm{tp}_{\boldsymbol{y}}\tau \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$ — a contradiction. So τ must be cosmic. Assign $\mathrm{tp}^{\mathfrak{A}}[b,a] = \tau$. 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 $\kappa \in \mathrm{T}[\kappa'] \cap \mathrm{K_T}$ and by ($\sigma\kappa\boldsymbol{y}$), there is a unique $\tau' \in \sigma(a) = \sigma'$ such that $\mathrm{tp}_{\boldsymbol{y}}\tau' = \kappa'$. We claim that $\tau' = \tau^{-1}$. Indeed, since $\tau \in \sigma$ is cosmic we have $\tau \in \varsigma^{\mathcal{IE}}$, so $\tau^{-1} \in \mathrm{T^c}$, so some $\varsigma'' \in \mathcal{S}$ has $\tau^{-1} \in \varsigma''^{\mathcal{IE}}$ by ($\mathcal{S}\mathrm{T^c}$). So $\kappa = \mathrm{tp}_{\boldsymbol{x}}(\tau^{-1}) \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma''$, 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 $\mathrm{tp}_{\boldsymbol{y}}(\tau^{-1}) = \kappa' \in \mathrm{K_T}$, by ($\sigma\kappa\boldsymbol{y}$) we must have $\tau' = \tau^{-1}$.

Next, every $\tau \in \sigma' = \sigma(a)$ is realized. If τ is galactic, then some $b \in X^{\varsigma} \setminus \{a\}$ has $\mathrm{tp}^{\mathfrak{X}^{\varsigma}}[a,b] = \tau$, so τ is realized within the galaxy of a. If τ is cosmic, then τ^{-1} is cosmic and by $(\mathcal{S}\mathrm{T}^{\mathrm{c}})$ some $\varsigma \in \mathcal{S}$ has $\tau^{-1} \in \varsigma^{\mathcal{IE}}$. 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 $\mathrm{tp}_{\boldsymbol{y}}(\tau^{-1}) = \kappa' \in \mathrm{K}_{\mathrm{T}}$, so $\tau^{-1} \in \sigma(b)$ is the unique having $\mathrm{tp}_{\boldsymbol{y}}(\tau^{-1}) = \kappa'$, so we had assigned $\mathrm{tp}^{\mathfrak{A}}[b,a] = \tau^{-1}$.

Realization of workers Let $\pi \in \mathrm{W}_{\mathrm{T}}$ be any worker type and let $a \in A_i^{\pi}$ be any element having intended 1-type π. Let $i' = (i + 1 \bmod 3) \in \{0,1,2\}$ be the index of the next copy of elements. 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 τ is galactic, then it is realized between a and some other element in the galaxy of a. If $\mathrm{tp}_{\boldsymbol{y}}\tau \in \mathrm{K}_{\mathrm{T}}$ is a king type, then we have already seen that it is realized during the realization of kings.

So only the case where τ is galactic and $\pi' = \mathrm{tp}_{\boldsymbol{y}}\tau \in \mathrm{W}_{\mathrm{T}}$ is a worker type remains. Let $\mathrm{U} = \left\{\eta \in \sigma \;\middle|\; \mathrm{tp}_{\boldsymbol{y}}\eta = \pi'\right\}$ be the set of all 2-types parallel to τ in σ. Note that $|\mathrm{U}| \le t$. We simultaneously find distinct b_η from the *next copy* of elements for the assignments $\mathrm{tp}^{\mathfrak{A}}[a,b_\eta] = \eta$: Since $\left|A_{i'}^{\pi'}\right| \ge t$, 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 π' is a peasant type, this is immediate by our remark right after we defined $A_{i'}^{\pi'}$.

Next, suppose that $\pi' \in \mathrm{N}_{\mathrm{T}}$ is a noble worker type. We claim that $\pi' \notin \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$. Suppose that $\pi' \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$. Since $\tau \in \sigma$ is cosmic, we have that $\tau \in \varsigma^{\mathcal{IE}}$. Since $\mathrm{tp}_{\boldsymbol{y}}\tau = \pi'$, we have $\pi' \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$. By Remark 30, some (cosmic) $\tau' \in \varsigma^{\mathcal{IE}}$ connects π' with itself — a contradiction. So $\pi' \notin \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$, 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 $\tau \in \mathrm{T}^{\mathrm{g}}$ has $\mathrm{tp}_{\boldsymbol{x}}\tau = \pi$ and $\mathrm{tp}_{\boldsymbol{y}}\tau = \pi'$. Let $\pi = \pi(a)$ and $\pi' = \pi(b)$ and let $\mathfrak{X}^{\varsigma}$ be the galaxy of a.

First suppose that π' is noble. If $\pi' \in \mathrm{Tp}_{\boldsymbol{x}}\,\varsigma$, then ς is noble, so b and a come from the same galaxy — a contradiction. Otherwise $\pi' \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$ and by Remark 30 some $\tau \in \varsigma^{\mathcal{IE}}$ has $\mathrm{tp}_{\boldsymbol{x}}\tau = \pi$ and $\mathrm{tp}_{\boldsymbol{y}}\tau = \pi'$.

Next suppose that π' is peasant. Then by Remark 31 $\pi' \in \mathrm{Tp}_{\boldsymbol{y}}\,\varsigma$ and so by Remark 30 some $\tau \in \varsigma^{\mathcal{IE}}$ has $\mathrm{tp}_{\boldsymbol{x}}\tau = \pi$ and $\mathrm{tp}_{\boldsymbol{y}}\tau = \pi'$.

□

Proposition 12. *The type realizability problem for $\mathcal{L}^2 e\mathrm{E}_{\mathsf{refine}}$ coincides with the finite type realizability problem and is in* NPTIME.

Proof. We use induction on e. If $e = 0$, this is Proposition 11. Suppose that $e \ge 1$ and assume the induction hypothesis. Let T be a type instance over the classified signature $\langle \Sigma, \bar{\boldsymbol{m}} \rangle$ over $\mathcal{L}^2 e\mathrm{E}_{\mathsf{refine}}$ and let $\boldsymbol{e}$ be the coarsest equivalence symbol in Σ.

First by induction in nondeterministic polynomial time check if T has a model $\mathfrak{A}$ where $\boldsymbol{e}^{\mathfrak{A}} = A \times A$ is full on $\mathfrak{A}$. This is reducible to $\mathcal{L}^2(e-1)\mathrm{E}_{\mathsf{refine}}$ by considering only the 2-types from T that contain the literal $\boldsymbol{e}(\boldsymbol{x}, \boldsymbol{y})$. If we did not find a model where the interpretation of $\boldsymbol{e}$ is full on its domain, then guess a polynomial certificate for T. Check that each cosmic spectrum of the certificate is locally consistent by induction hypothesis in nondeterministic polynomial time. The full version coincides with the finite version since the model constructed in Theorem 5 is finite. □

Corollary 5. *For any $e \geq 1$, the logic $\mathcal{L}^2e\mathrm{E}_{\mathsf{refine}}$ has the finite model property and its (finite) satisfiability problem is in* NExpTime.

By Proposition 1 and Proposition 3, the same holds for $\mathcal{L}^2e\mathrm{E}_{\mathsf{global}}$ and $\mathcal{L}^2e\mathrm{E}_{\mathsf{local}}$.

Corollary 6. *The logic $\mathcal{L}^2\mathrm{E}_{\mathsf{refine}}$ has the finite model property and its (finite) satisfiability problem is in* N2ExpTime.

By Proposition 2 and Proposition 4, the same holds for $\mathcal{L}^2\mathrm{E}_{\mathsf{global}}$ and $\mathcal{L}^2e\mathrm{E}_{\mathsf{local}}$.

Bibliography

[1] H.D. Ebbinghaus and J. Flum. *Finite Model Theory.* Perspectives in Mathematical Logic. Springer Berlin Heidelberg, 1999.

[2] Erich Grädel and Martin Otto. On logics with two variables. *Theoretical computer science*, 224(1):73–113, 1999.

[3] Dana 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] Peter van Emde Boas. The convenience of tilings. *Lecture Notes in Pure and Applied Mathematics*, pages 331–363, 1997.

[7] Leopold 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] Michael Mortimer. On languages with two variables. *Mathematical Logic Quarterly*, 21(1):135–140, 1975.

[10] Erich Grädel, Phokion G Kolaitis, and Moshe Y Vardi. On the decision problem for two-variable first-order logic. *Bulletin of symbolic logic*, 3(01):53–69, 1997.

[11] Emanuel Kieroński. Results on the guarded fragment with equivalence or transitive relations. In *Computer Science Logic*, pages 309–324. Springer, 2005.

[12] Emanuel Kieroński, Jakub Michaliszyn, Ian Pratt-Hartmann, and Lidia Tendera. Two-variable first-order logic with equivalence closure. *SIAM Journal on Computing*, 43(3):1012–1063, 2014.

[13] Emanuel Kieronski and Martin 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.

[14] Ian Pratt-Hartmann. The two-variable fragment with counting and equivalence. *Mathematical Logic Quarterly*, 61(6):474–515, 2015.