Varieties of Data Languages

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Abstract

We establish an Eilenberg-type correspondence for data languages, i.e. languages over an infinite alphabet. More precisely, we prove that there is a bijective correspondence between varieties of languages recognized by orbit-finite nominal monoids and pseudovarieties of such monoids. This is the first result of this kind for data languages. Our approach makes use of nominal Stone duality and a recent category theoretic generalization of Birkhoff-type theorems that we instantiate here for the category of nominal sets. In addition, we prove an axiomatic characterization of weak pseudovarieties as those classes of orbit-finite monoids that can be specified by sequences of nominal equations, which provides a nominal version of a classical theorem of Eilenberg and Schützenberger.

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1 Introduction

In the algebraic theory of formal languages, one studies automata and the languages they represent in terms of associated algebraic structures. This approach has been successfully implemented for numerous types of languages and has proven extremely fruitful because it allows to import powerful algebraic methods into the realm of automata theory. As a prime example, regular languages can be described purely algebraically as the languages recognized by finite monoids, and a celebrated result by McNaughton, Papert, and Schützenberger [13,21] asserts that a regular language is definable in first-order logic if and only if its syntactic monoid is aperiodic (i.e. it satisfies the equation $x^{n+1} = x^n$ for sufficiently large $n$). As an immediate application, this algebraic characterization yields an effective procedure for deciding first-order definability. The first systematic approach to correspondence results of this kind was initiated by Eilenberg [7] who proved that varieties of languages (i.e. classes of regular languages closed under the set-theoretic boolean operations, derivatives, and homomorphic preimages) correspond bijectively to pseudovarieties of monoids (i.e. classes of finite monoids closed under quotients monoids, submonoids, and finite products). Eilenberg’s result thus establishes a generic relation between properties of regular languages and properties of finite monoids.

In addition, Eilenberg and Schützenberger [8] contributed a model-theoretic description of pseudovarieties: they are those classes of finite monoids that can be axiomatized by a sequence $(s_n = t_n)_{n \in \mathbb{N}}$ of equations, interpreted as “$s_n = t_n$ holds for sufficiently large $n$”. For instance, the pseudovariety of aperiodic finite monoids is axiomatized by $(x^{n+1} = x^n)_{n \in \mathbb{N}}$.

The goal of our present paper is to study data languages, i.e. languages over an infinite alphabet, from the perspective of algebraic language theory. Such languages have spurred
significant interest in recent years, driven by practical applications in various areas of computer science, including efficient parsing of XML documents or software verification. Mathematically, data languages are modeled using nominal sets. Over the years, several machine models for handling data languages of different expressive power have been proposed; see [22, 23] for a comprehensive survey. The focus of this paper is on languages recognized by orbit-finite nominal monoids. They form an important subclass of the languages accepted by Francez and Kaminski’s finite memory automata [11] (which are expressively equivalent to orbit-finite automata in the category of nominal sets [5]) and have been characterized by a fragment of monadic second-order logic over data words called rigidly guarded MSO [19]. In addition, Bojańczyk [6] and Colcombet, Ley, and Puppis [19] established nominal versions of the McNaughton-Papert-Schützenberger theorem and showed that the first-order definable data languages are precisely the ones recognizable by aperiodic orbit-finite monoids.

In the light of these results, it is natural to ask whether a generic variety theory akin to Eilenberg’s seminal work can be developed for data languages. As the main contribution of our paper, we answer this positively by establishing nominal generalizations of two key results known from the algebraic theory of regular languages. The first one is a counterpart of Eilenberg’s variety theorem, which is the first result of this kind for data languages: ▶ Nominal Eilenberg Theorem. Varieties of data languages correspond bijectively to pseudovarieties of nominal monoids.

Here, the notion of a pseudovariety of nominal monoids is as expected: a class of orbit-finite nominal monoids closed under quotient monoids, submonoids, and finite products. In contrast, the notion of a variety of data languages requires two extra conditions unfamiliar from other Eilenberg-type correspondences, most notably a technical condition called completeness (Definition 4.13). Like the original Eilenberg theorem, its nominal version gives rise to a generic relation between properties of data languages and properties of nominal monoids. For instance, the aperiodic orbit-finite monoids form a pseudovariety, and the first-order definable data languages form a variety, and thus the equivalence of these concepts can be understood as an instance of the nominal Eilenberg correspondence.

On a conceptual level, our results crucially make use of duality, specifically an extension of Petrişan’s [17] nominal version of Stone duality which gives a dual equivalence between nominal sets and nominal complete atomic boolean algebras. To derive the nominal Eilenberg correspondence, we make two key observations. First, we show that varieties of data languages dualize (under nominal Stone duality) to the concept of an equational theory in the category of nominal sets. Second, we apply a recent categorical generalization of Birkhoff-type variety theorems [16] to show that equational theories correspond to pseudovarieties of nominal monoids. Our approach is summarized by the diagram below:

The idea that Stone-type dualities play a major role in algebraic language theory was firmly established by Gehrke, Grigorieff, and Pin [10]. It is also at the heart of our recent line of work [1–3, 24], which culminated in a uniform category theoretic proof of more than a dozen Eilenberg correspondences for various types of languages. A related, yet more abstract, approach was pursued by Salamánca [20]. The key insight of [20, 24] is that Eilenberg-type correspondences arise by combining a Birkhoff-type correspondence with a Stone-type duality. Our present approach to data languages is an implementation of this principle in the nominal setting. Since the existing categorical frameworks for algebraic language theory
consider algebraic-like base categories (which excludes nominal sets) and the recognition of
languages by finite structures, our Nominal Eilenberg Theorem is not covered by any
previous categorical work and requires new techniques. However, our approach can be seen
as an indication of the robustness of the duality-based methodology for algebraic recognition.

As our second main contribution, we complement the Nominal Eilenberg Theorem with
a model-theoretic description of pseudovarieties of nominal monoids in terms of sequences of
nominal equations, generalizing the classical result of Eilenberg and Schützenberger for
ordinary monoids. Our result applies more generally to the class of weak pseudovarieties of
nominal monoids, which are only required to be closed under support-reflecting (rather than
arbitrary) quotients. We then obtain the

**Nominal Eilenberg-Schützenberger Theorem.** Weak pseudovarieties are exactly the
classes of nominal monoids axiomatizable by sequences of nominal equations.

While our main results apply to languages recognizable by orbit-finite monoids, the
underlying methods are of fairly general nature and can be extended to other recognizing
structures in the category of nominal sets. We illustrate this in Section 5 by deriving a (local)
Eilenberg correspondence for languages accepted by deterministic nominal automata.

## 2 Nominal Sets

We start by recalling basic definitions and facts from the theory of nominal sets [18]. Some
of the concepts considered in this paper are most clearly and conveniently formulated in
the language of category theory, but only very basic knowledge of category theory is required
from the reader. Fix a countably infinite set $\mathbb{A}$ of atoms, and denote by $\operatorname{Perm}(\mathbb{A})$ the group
of finite permutations of $\mathbb{A}$ (i.e. bijections $\pi : \mathbb{A} \to \mathbb{A}$ that move only finitely many elements of $\mathbb{A}$).
A $\operatorname{Perm}(\mathbb{A})$-set is a set $X$ with an operation $\operatorname{Perm}(\mathbb{A}) \times X \to X$, denoted as $(\pi, x) \mapsto \pi \cdot x,
such that $(\sigma \pi) \cdot x = \sigma \cdot (\pi \cdot x)$ and $id \cdot x$ for all $\sigma, \pi \in \operatorname{Perm}(\mathbb{A})$ and $x \in X$. If the group action
is trivial, i.e. $\pi \cdot x = x$ for all $\pi \in \operatorname{Perm}(\mathbb{A})$ and $x \in X$, we call $X$ discrete. For any set $S \subseteq \mathbb{A}$
of atoms, denote by $\operatorname{Perm}_S(\mathbb{A}) \subseteq \operatorname{Perm}(\mathbb{A})$ the subgroup of all finite permutations $\pi$ that fix
$S$, i.e. $\pi(a) = a$ for all $a \in S$. The set $S$ is called a support of an element $x \in X$ if for every
$\pi \in \operatorname{Perm}_S(\mathbb{A})$ one has $\pi \cdot x = x$. The intuition is that $x$ is some kind of syntactic object
(e.g. a string, a tree, a term, or a program) whose free variables are contained in $S$. Thus, a
variable renaming $\pi$ that leaves $S$ fixed does not affect $x$. A nominal set is a $\operatorname{Perm}(\mathbb{A})$-set $X$ such
that every element of $X$ has a finite support. This implies that every element $x \in X$ has
a least support, denoted by $\operatorname{supp}_X(x) \subseteq \mathbb{A}$. A nominal set $X$ is strong if, for every $x \in X$ and
$\pi \in \operatorname{Perm}(\mathbb{A})$, one has $\pi \cdot x = x$ if and only if $\pi(a) = a$ for all $a \in \operatorname{supp}_X(x)$. The orbit of an
element $x$ of a nominal set $X$ is the set $\{ \pi \cdot x : \pi \in \operatorname{Perm}(\mathbb{A}) \}$. The orbits form a partition
of $X$. If $X$ has only finitely many orbits, then $X$ is called orbit-finite. More generally, for any
finite set $S \subseteq \mathbb{A}$ of atoms, the $S$-orbit of an element $x \in X$ is the set $\{ \pi \cdot x : \pi \in \operatorname{Perm}_S(\mathbb{A}) \}$,
and the $S$-orbits form a partition of $X$.

**Lemma 2.1.** Let $S$ be a finite subset of $\mathbb{A}$. Then every orbit-finite nominal set has only
finitely many $S$-orbits.

A map $f : X \to Y$ between nominal sets is equivariant if $f(\pi \cdot x) = \pi \cdot f(x)$ for all $\pi \in \operatorname{Perm}(\mathbb{A})$
and $x \in X$, and finitely supported if there exists a finite set $S \subseteq \mathbb{A}$ such that $f(\pi \cdot x) = \pi \cdot f(x)$
for all $\pi \in \operatorname{Perm}_S(\mathbb{A})$ and $x \in X$. Equivariant maps do not increase supports, i.e. one has
$\operatorname{supp}_Y(f(x)) \subseteq \operatorname{supp}_X(x)$ for all $x \in X$. We write $\operatorname{Nom}_f$ for the category of nominal sets and
finitely supported maps, and $\operatorname{Nom}$ for the (non-full) subcategory of nominal sets and
equivariant maps. We shall use the following standard results about $\operatorname{Nom}$:
(1) **Nom** is complete and cocomplete. Finite limits and all colimits are formed on the level of underlying sets. In particular, finite products of nominal sets are given by cartesian products and coproducts by disjoint union.

(2) For every pair $X, Y$ of nominal sets, the exponential $[X, Y]$ is the nominal set consisting of all finitely supported maps $f : X \to Y$, with the group action given by $(\pi \cdot f)(x) = \pi \cdot f(\pi^{-1} \cdot x)$. Moreover, for every nominal set $X$, the nominal power set $\mathcal{P}X$ is carried by the set of all subsets $X_0 \subseteq X$ with finite support; i.e. for which there exists a finite set $S \subseteq \mathcal{A}$ of atoms such that $\pi \cdot X_0 = X_0$ for $\pi \in \text{Perm}_S(\mathcal{A})$, where $\pi \cdot X_0 = \{ \pi \cdot x : x \in X_0 \}$. In particular, every singleton $\{x\}$ is finitely supported by $\text{supp}_{X}(x)$. The group action on $\mathcal{P}X$ is given by $X_0 \mapsto \pi \cdot X_0$, and we have $\mathcal{P}X \cong [X, 2]$, for the discrete nominal set $2 = \{0, 1\}$.

(3) Quotients and subobjects in **Nom** are represented by epimorphisms (= surjective equivariant maps) and monomorphisms (= injective equivariant maps), respectively. **Nom** has image factorizations, i.e. every equivariant map $f : X \to Y$ has a unique decomposition $f = m \cdot e$ into a quotient $e : X \to I$ followed by a subobject $m : I \to Y$. We call $e$ the *coimage* of $f$.

(4) Orbit-finite nominal sets are closed under quotients, subobjects, and finite products.

(5) For each $n \geq 0$, the nominal set $\mathcal{A}^{\#n} = \{(a_1, \ldots, a_n) : a_i \neq a_j$ for $i \neq j\}$ with group action $\pi \cdot (a_1, \ldots, a_n) = (\pi(a_1), \ldots, \pi(a_n))$ is strong and has a single orbit. More generally, the (orbit-finite) strong nominal sets are up to isomorphism exactly the (finite) coproducts of nominal sets of the form $\mathcal{A}^{\#n}$.

### 3 Pseudovarieties of Nominal Monoids

In this section, we investigate classes of orbit-finite nominal monoids and establish two characterizations of such classes: a categorical one, relating pseudovarieties of nominal monoids to equational theories in the category of nominal sets, and an axiomatic one, describing weak pseudovarieties in terms of sequences of nominal equations. The first of these results is the algebraic foundation of our subsequent treatment of varieties of data languages.

A **nominal monoid** is a monoid $(M, \cdot, 1_M)$ in the category **Nom**; that is, $M$ is equipped with the structure of a nominal set such that the multiplication $\cdot : M \times M \to M$ is an equivariant map and the unit $1_M \in M$ has empty support, i.e. it corresponds to an equivariant map $1 \to M$, where 1 is the nominal set with one element. We write **nMon** for the category of nominal monoids and equivariant monoid morphisms (usually just called *morphisms*), and **nMon_{\text{of}}** for the full subcategory of orbit-finite nominal monoids. The forgetful functor from **nMon** to **Nom** has a left adjoint assigning to each nominal set $\Sigma$ the free nominal monoid $\Sigma^*$ of all words over $\Sigma$, with monoid multiplication given by concatenation of words, unit $\varepsilon$ (the empty word) and group action $\pi \cdot (a_1 \cdots a_n) = \pi(a_1) \cdots \pi(a_n)$ for $\pi \in \text{Perm}(\mathcal{A})$ and $a_1 \cdots a_n \in \Sigma^*$. The category **nMon** has products (formed on the level of **Nom**), image factorizations, and surjective and injective morphisms represent quotients and submonoids of nominal monoids. A quotient $q : M \to M'$ is called *support-reflecting* if for every $x' \in M'$ there exists an $x \in M$ with $q(x) = x'$ and $\text{supp}_M(x) = \text{supp}_{M'}(x')$. The following result characterizes the quotient monoids of $\Sigma^*$ in terms of unary operations:

**Proposition 3.1 (Unary presentation for nominal monoids).** For every nominal set $\Sigma$ and every surjective equivariant map $e : \Sigma^* \to M$, the following statements are equivalent:

1. $e$ carries a quotient monoid of $\Sigma^*$, i.e. there exists a nominal monoid structure $(M, \cdot, 1_M)$ on $M$ such that $e : \Sigma^* \to (M, \cdot, 1_M)$ is a morphism of nominal monoids;
2. the maps $\Sigma^* \xrightarrow{w} \Sigma^*$ and $\Sigma^* \xrightarrow{w} \Sigma^*$ ($w \in \Sigma^*$) lift along $e$, i.e. there exist (necessarily...
unique) maps \( l_w \) and \( r_w \) making the following squares commute:

\[
\begin{array}{ccc}
\Sigma^* & \xrightarrow{w} & \Sigma^* \\
\downarrow c & & \downarrow c \\
M - l_w & \to & M \\
\end{array}
\quad
\begin{array}{ccc}
\Sigma^* & \xrightarrow{w} & \Sigma^* \\
\downarrow c & & \downarrow c \\
M - r_w & \to & M \\
\end{array}
\quad
\text{for every } w \in \Sigma^*.
\]

In general, the maps \( w \cdot - \) and \(- \cdot w\) are not equivariant, but finitely supported (with support contained in the one of \( w \)). This implies that also \( l_w \) and \( r_w \) in (2) are finitely supported.

### 3.1 Equational Theories

In previous work [16] we studied varieties of objects in a general category and their relation to an abstract form of equations. In the following, we instantiate these concepts to the category of nominal sets to derive a characterization of pseudovarieties of orbit-finite monoids.

- **Definition 3.2.** Let \( \Sigma \) be a nominal set. A \( \Sigma \)-generated nominal monoid is a nominal quotient monoid \( e: \Sigma^* \to M \) of the free monoid \( \Sigma^* \). We denote by \( \Sigma^* \nMon_{\text{of}} \) the poset of \( \Sigma \)-generated orbit-finite nominal monoids, ordered by \( e \leq e' \) iff \( e' \) factorizes through \( e \).

- **Definition 3.3.** A local pseudovariety of \( \Sigma \)-generated nominal monoids is a filter \( \mathcal{F}_\Sigma \subseteq \Sigma^* \nMon_{\text{of}} \) in the poset of \( \Sigma \)-generated orbit-finite nominal monoids; that is, \( \mathcal{F}_\Sigma \) is
  1. (upwards closed) \( e \in \mathcal{F}_\Sigma \) and \( e \leq e' \) implies \( e' \in \mathcal{F}_\Sigma \), and
  2. (downwards directed) for each pair \( e_0, e_1 \in \mathcal{F}_\Sigma \) there exists \( e \in \mathcal{F}_\Sigma \) with \( e \leq e_0, e_1 \).

If we replace (1) by the weaker condition
  1. for each \( e: \Sigma^* \to M \) in \( \mathcal{F}_\Sigma \) and each support-reflecting \( q: M \to N \) one has \( q \cdot e \in \mathcal{F}_\Sigma \),

then \( \mathcal{F}_\Sigma \) is called a weak local pseudovariety of \( \Sigma \)-generated nominal monoids.

- **Remark 3.4.** By Proposition 3.1, the definition of local pseudovariety can be equivalently stated as follows:
  1. \( \mathcal{F}_\Sigma \) is a filter in the poset of orbit-finite quotients of \( \Sigma^* \) in \( \text{Nom} \);
  2. for every \( e \in \mathcal{F}_\Sigma \) and \( w \in \Sigma^* \), the unary operations \( w \cdot - \) and \(- \cdot w \) on \( \Sigma^* \) lift along \( e \).

Let \( \text{Nom}_{\text{of}, s} \) denote the full subcategory of \( \text{Nom} \) on orbit-finite strong nominal sets.

- **Definition 3.5 (Equational Theory).** A (weak) equational theory is a family

\[ \mathcal{T} = (\mathcal{F}_\Sigma \subseteq \Sigma^* \nMon_{\text{of}})_{\Sigma \in \text{Nom}_{\text{of}, s}} \]

of (weak) local pseudovarieties with the following two properties (see the diagrams below):
  1. (Substitution invariance) For each equivariant monoid morphism \( h: \Delta^* \to \Sigma^* \) with \( \Delta, \Sigma \in \text{Nom}_{\text{of}, s} \) and each \( e_\Sigma: \Sigma^* \to M_\Sigma \) in \( \mathcal{F}_\Sigma \), the coimage \( e_\Delta \) of \( e_\Sigma \cdot h \) lies in \( \mathcal{F}_\Delta \).
  2. (Completeness) For each \( \Sigma \in \text{Nom}_{\text{of}, s} \) and each quotient \( e: \Sigma^* \to M_\Sigma \) in \( \mathcal{F}_\Sigma \), there exists \( \Delta \in \text{Nom}_{\text{of}, s} \) and a support-reflecting quotient \( e_\Delta: \Delta^* \to M_\Delta \) in \( \mathcal{F}_\Delta \) with \( M_\Delta = M_\Sigma \).

- **Remark 3.6.** (1) Local pseudovarieties were previously called equations [16]. In fact, in many instances of the framework in op. cit., a filter of quotients can be represented as a single quotient of a free algebra on an object \( \Sigma \), which in turn corresponds to a set of pairs of terms given by the kernel of the quotient, i.e. to the usual syntactic concept of an equation.
2. The restriction to strong nominal sets Σ as generators reflects that the latter are the "free" nominal sets [12], a property crucial for the proof of Theorem 3.8 below. More precisely, letting \( \mathcal{P}_\mathfrak{A} \) denote the set of finite subsets of \( \mathfrak{A} \), the forgetful functor \( U: \text{Nom} \rightarrow \text{Set}^{\mathcal{P}_\mathfrak{A}} \) mapping a nominal set \( X \) to the presheaf \( S \mapsto \{ x \in X \mid \text{supp}_X(x) \subseteq S \} \) has a left adjoint \( F \), and strong nominal sets are exactly the nominal sets of the form \( FP \) for \( P \in \text{Set}^{\mathcal{P}_\mathfrak{A}} \).

3. The somewhat technical completeness property cannot be avoided, i.e. a substitution-invariant family of local pseudovarieties is generally incomplete. Indeed, consider the family

\[ \mathcal{T} = (\mathcal{R}_\Sigma \subseteq \Sigma \downarrow \text{Nom}_{\text{or}})_{\Sigma \in \text{Nom}_{\text{or}}} \]

where \( \mathcal{R}_\Sigma \) consists of all \( \Sigma \)-generated orbit-finite nominal monoids \( e: \Sigma^* \rightarrow M \) such that \( e \) maps each element of \( \Sigma^* \) with a support of size 1 to \( 1_M \).

To see that \( \mathcal{T} \) is a filter, suppose that \( e: \Sigma^* \rightarrow M \) and \( e': \Sigma^* \rightarrow M' \) are two quotients in \( \mathcal{R}_\Sigma \). Form their subdirect product \( q \), viz. the coimage of the morphism \( (e, e'): \Sigma^* \rightarrow M \times M' \). Each \( w \in \Sigma^* \) with a support of size 1 is mapped by \( q \) to \( (e(w), e'(w)) = (1_M, 1_{M'}) = 1_{M \times M'} \). Thus \( q \in \mathcal{R}_\Sigma \) and \( q \leq e, e' \), i.e. \( \mathcal{R}_\Sigma \) is downwards directed. Clearly, \( \mathcal{R}_\Sigma \) is also upwards closed.

For substitution invariance, let \( h: \Delta^* \rightarrow \Sigma^* \) be a morphism and \( e_\Sigma: \Sigma^* \rightarrow M_\Sigma \) a quotient in \( \mathcal{R}_\Sigma \). Then \( e_\Sigma \cdot h \) maps each element with a support of size 1 to \( 1_{M_\Sigma} \) since \( e_\Sigma \) does and the equivariant map \( h \) does not increase supports. Thus, the coimage of \( e_\Sigma \cdot h \) lies in \( \mathcal{R}_\Delta \).

Finally, we show that \( \mathcal{T} \) is not complete. Fix an arbitrary orbit-finite nominal monoid \( M \) containing an element \( m \) with \( |\text{supp}_M(m)| = 1 \). Note that \( m \neq 1_M \) because \( 1_M \) has empty support. Moreover, choose an orbit-finite strong nominal set \( \Sigma \) such that all elements of \( \Sigma \) have least support of size at least 2, and \( M \) can be expressed as a quotient \( e: \Sigma^* \rightarrow M \).

(For instance, one may choose \( \Sigma = \bigsqcup_{n=1}^\infty \Delta^{kn} \) where \( k \) is the number of orbits of \( M \) and \( n = \max\{2, |\text{supp}_M(x)| : x \in M \} \}. \) Since all nonempty words in \( \Sigma^* \) have a least support of size at least 2, one has \( e \in \mathcal{R}_\Sigma \). For every \( \Delta \in \text{Nom}_{\text{or,f}} \) and every quotient \( q: \Delta^* \rightarrow M \) in \( \mathcal{R}_\Delta \), the set \( q^{-1}[\{m\}] \subseteq \Delta^* \) contains no element with least support of size 1, since such elements are mapped by \( q \) to \( 1_M \neq m \). Consequently, \( q \) is not support-reflecting. This shows that \( M \) is not the codomain of any support-reflecting quotient in \( \mathcal{R}_\Delta \).

Definition 3.7 (Pseudovariety and Weak Pseudovariety). A pseudovariety of nominal monoids is a nonempty class \( \mathcal{V} \) of orbit-finite nominal monoids closed under finite products, submonoids, and quotient monoids. That is,

1. For each \( M, N \in \mathcal{V} \) one has \( M \times N \in \mathcal{V} \);
2. For each \( M \in \mathcal{V} \) and each nominal submonoid \( N \rightarrow M \) one has \( N \in \mathcal{V} \);
3. For each \( M \in \mathcal{V} \) and each nominal quotient monoid \( M \rightarrow N \) one has \( N \in \mathcal{V} \).

A weak pseudovariety of nominal monoids is a nonempty class of orbit-finite nominal monoids closed under finite products, submonoids, and support-reflecting quotient monoids.

The following result is a special case of the Generalized Variety Theorem [16, Theorem 3.15]. It asserts that equational theories and pseudovarieties are equivalent concepts. Note that \( \text{(weak)} \) equational theories form a poset ordered by \( \mathcal{T} \leq \mathcal{T}' \) iff \( \mathcal{R}_\Sigma \leq \mathcal{R}_\Sigma' \) for all \( \Sigma \in \text{Nom}_{\text{or,f}} \), where \( \mathcal{R}_\Sigma \leq \mathcal{R}_\Sigma' \) holds iff for every \( e' \in \mathcal{R}_\Sigma' \) there exists an \( e \in \mathcal{R}_\Sigma \) with \( e \leq e' \). Similarly, \( \text{(weak)} \) pseudovarieties of nominal monoids form a poset w.r.t. the inclusion ordering.

Theorem 3.8. (Weak) equational theories and (weak) pseudovarieties of nominal monoids form dually isomorphic complete lattices.

The isomorphism maps a \( \text{(weak)} \) equational theory \( \mathcal{T} \) to the \( \text{(weak)} \) pseudovariety \( \mathcal{V}(\mathcal{T}) \) of all orbit-finite monoids \( M \) such that each morphism \( h: \Sigma^* \rightarrow M \) with \( \Sigma \in \text{Nom}_{\text{or,f}} \) factorizes through some \( e_\Sigma \in \mathcal{R}_\Sigma \). The inverse maps a \( \text{(weak)} \) pseudovariety \( \mathcal{V} \) to the \( \text{(weak)} \) equational theory \( \mathcal{T}(\mathcal{V}) \) where \( \mathcal{T}(\mathcal{V})_{\Sigma} \) consists of all quotients \( e: \Sigma^* \rightarrow M \) with codomain \( M \in \mathcal{V} \).
3.2 The Nominal Eilenberg-Schützenberger Theorem

In addition to their abstract category theoretic characterization in Theorem 3.8, weak pseudovarieties of nominal monoids admit an axiomatic description in terms of sequences of equations, analogous to the classical result of Eilenberg and Schützenberger [8] for pseudovarieties of ordinary monoids. The appropriate concept of equation is as follows:

**Definition 3.9.** (1) An equation is a pair \((s, t) \in X^* \times X^*\), denoted as \(s = t\), where \(X\) is an orbit-finite strong nominal set. A nominal monoid \(M\) satisfies \(s = t\) if for every equivariant map \(h: X \to M\) one has \(\tilde{h}(s) = \tilde{h}(t)\), where \(\tilde{h}: X^* \to M\) denotes the unique extension of \(h\) to an equivariant monoid morphism.

(2) Given a sequence \(E = (s_n = t_n)_{n \in \mathbb{N}}\) of equations (possibly taken over different orbit-finite strong nominal sets \(X\) of generators), a nominal monoid \(M\) eventually satisfies \(E\) if there exists an index \(n_0 \in \mathbb{N}\) such that \(M\) satisfies all the equations \(s_n = t_n\) with \(n \geq n_0\). We denote by \(\mathcal{V}(E)\) the class of all orbit-finite nominal monoids that eventually satisfy \(E\).

**Remark 3.10.** Equations can be presented syntactically as expressions of the form

\[
y_1 : S_1, \ldots, y_n : S_n \vdash u = v,
\]

where \(\pi, \eta \subseteq \mathbb{A}\) are finite sets of atoms, and \(u, v\) are words in \((\text{Perm}(\mathbb{A}) \times Y)^*\). A nominal monoid \(M\) is said to satisfy (1) if for every variable interpretation, i.e., every map \(h: Y \to M\) with \(\text{supp}(h(y_i)) \subseteq S_i\) for \(i = 1, \ldots, n\), one has \(\tilde{h}(u) = \tilde{h}(v)\). Here, \(\tilde{h}: (\text{Perm}(\mathbb{A}) \times Y)^* \to M\) is the unique monoid morphism mapping \((\pi, y_1)\) to \(\pi \cdot h(y_1)\). Every equation can be transformed into an expressively equivalent syntactic equation, and vice versa [15, Lemma B.31].

**Theorem 3.11 (Nominal Eilenberg-Schützenberger Theorem).** A class \(\mathcal{V}\) of orbit-finite nominal monoids forms a weak pseudovariety iff \(\mathcal{V} = \mathcal{V}(E)\) for some sequence \(E\) of equations.

**Proof sketch.** The proof proceeds along the lines of the one for ordinary monoids [8], although some subtle modifications are required. The “if” direction is a routine verification. For the “only if” direction, let \(\mathcal{V}\) be a weak pseudovariety. Using that there are only countably many orbit-finite monoids up to isomorphism, one can construct a sequence \(M_0, M_1, M_2, \ldots\) of nominal monoids in \(\mathcal{V}\) such that each \(M \in \mathcal{V}\) is a quotient of all but finitely many \(M_n\)'s. Let \(X_0, X_1, X_2, \ldots\) be the sequence of all (countably many) strong orbit-finite nominal sets up to isomorphism, and consider the equivariant congruence relation on \(X_n^*\) given by

\[
s \equiv_n t \quad \text{iff} \quad M_n \text{ satisfies the equation } s = t.
\]

One then shows that the congruence \(\equiv_n\) is generated by a finite subset \(W_n \subseteq \equiv_n\) and that \(\mathcal{V} = \mathcal{V}(E)\) for every sequence \(E\) that lists all equations in the countable set \(\bigcup_n W_n\).

**Example 3.12.** An orbit-finite nominal monoid \(M\) is called aperiodic [6, 19] if there exists a natural number \(n \geq 1\) such that \(x^{n+1} = x^n\) for all \(x \in M\). The class of all orbit-finite aperiodic nominal monoids forms a pseudovariety. Taking the set \(Y = \{y\}\) of variables, it is not difficult to see that this pseudovariety is specified by the sequence of syntactic equations

\[
y : S_n \vdash y^{n+1} = y^n \quad (n \in \mathbb{N}),
\]

where \(S_n = \{a_0, a_1, \ldots, a_{n-1}\}\) is the set of the first \(n\) atoms in the countably infinite set \(\mathbb{A} = \{a_0, a_1, a_2 \ldots\}\) of all atoms, and we write \(y\) for \((id, y) \in (\text{Perm}(\mathbb{A}) \times Y)\).
4 Duality and the Nominal Eilenberg Correspondence

In this section, we establish our nominal version of Eilenberg’s variety theorem. It is based on a dual interpretation of the concepts of a (local) pseudovariety of nominal monoids and of an equational theory, introduced in the previous section, under nominal Stone duality.

4.1 Nominal Stone Duality

A classical result from duality theory, known as discrete Stone duality, states that the category of sets is dually equivalent to the category of complete atomic boolean algebras, i.e. complete boolean algebras in which every non-zero element is above some atom. An analogous duality holds for the category \( \text{Nom}_{\text{fs}} \) of nominal sets and finitely supported maps.

- Definition 4.1. A nominal complete atomic boolean algebra (ncaba) \((B, \lor, \land, \lnot, \bot, \top)\) in \(\text{Nom}\) such that every finitely supported subset of \(B\) has a supremum, and for every element \(b \in B \setminus \{\bot\}\) there exists an atom (i.e. a minimal element) \(a \in B\) with \(a \leq b\). Here, the partial order \(\leq\) is defined as usual by \(a \leq b\) if \(a \land b = a\). We denote by \(\text{nCABA}_{\text{fs}}\) the category of ncabas and finitely supported morphisms (i.e. finitely supported maps preserving all the boolean operations and suprema of finitely supported subsets), and by \(\text{nCABA}\) the (non-full) subcategory of ncabas and equivariant morphisms.

- Theorem 4.2 (Nominal Stone Duality). The categories \(\text{nCABA}_{\text{fs}}\) and \(\text{Nom}_{\text{fs}}\) are dually equivalent. The duality restricts to one between the subcategories \(\text{nCABA}\) and \(\text{Nom}\).

The restricted duality is due to Petrişan [17, Prop. 5.3.11].

- Remark 4.3. (1) The equivalence functor \(\text{Nom}_{\text{fs}} \cong \text{nCABA}_{\text{fs}}^{\text{op}}\) maps a nominal set \(X\) to the ncaba \(\mathcal{P}X\) of finitely supported subsets of \(X\) (equipped with the set-theoretic boolean operations), and a finitely supported map \(f: X \to Y\) to the morphism \(f^{-1}: \mathcal{P}Y \to \mathcal{P}X\) taking preimages. The inverse equivalence functor \(\text{nCABA}_{\text{fs}}^{\text{op}} \cong \text{Nom}_{\text{fs}}\) maps an ncaba \(B\) to the equivariant subset \(\text{At}(B)\) of its atoms, with group action restricting the one of \(B\).

(2) The dual equivalence restricts to one between the full subcategories of orbit-finite nominal sets and atom-finite ncabas, i.e. ncabas whose set of atoms is orbit-finite. For atom-finite ncabas the property that every finitely supported subset has a supremum is equivalent to the weaker requirement that for every finite set \(S \subseteq \Delta\), every \(S\)-orbit has a supremum. Indeed, given a finitely supported subset \(X \subseteq B\) (say with finite support \(S \subseteq \Delta\)), put \(X' := \{a \in \text{At}(B) : a \leq x \text{ for some } x \in X\}\). Since \(\leq\) is an equivariant relation, \(X' \subseteq \text{At}(B)\) is a subset with finite support \(S\). Since \(\text{At}(B)\) is orbit-finite and thus has only finitely many \(S\)-orbits by Lemma 2.1, we can express \(X'\) as a finite union \(X' = X'_1 \cup \ldots \cup X'_n\) of \(S\)-orbits. Using that every element of \(B\) is the join of the finitely supported set of all atoms below it, it follows that \(\bigvee X = \bigvee X' = \bigvee X'_1 \lor \ldots \lor \bigvee X'_n\), so \(\bigvee X\) is a finite join of joins of \(S\)-orbits.

4.2 Varieties of Data Languages

For the notion of a language over an alphabet \(\Sigma \in \text{Nom}\) and the corresponding concept of algebraic recognition by nominal monoids, there are two natural choices: consider equivariant subsets \(L \subseteq \Sigma^*\) and their recognition by equivariant monoid morphisms [5, 19], or consider finitely supported subsets \(L \subseteq \Sigma^*\) and their recognition by finitely supported monoid morphisms [6]. For our duality-based approach to data languages, it turns out that we need to work with an intermediate concept: finitely supported languages recognizable by equivariant monoid morphisms (see the discussion in Remark 4.12 below). That is, we work with the following
Definition 4.4. A data language over the alphabet $\Sigma \in \text{Nom}$ is a finitely supported map $L: \Sigma^* \to 2$. It is recognized by an equivariant monoid morphism $e: \Sigma^* \to M$ if there exists a finitely supported map $p: M \to 2$ with $L = p \circ e$. In this case, we also say that $M$ recognizes $L$. A data language is recognizable if it recognized by some orbit-finite nominal monoid.

Remark 4.5. (1) Identifying finitely supported maps into 2 with finitely supported subsets, Definition 4.4 can be restated: an equivariant monoid morphism $e: \Sigma^* \to M$ recognizes a language $L \subseteq \Sigma^*$ if there exists a finitely supported subset $P \subseteq M^*$ with $L = e^{-1}[P]$. (2) If $L$ is an equivariant recognizable language, then $p$ in Definition 4.4 is also equivariant. Therefore, for equivariant languages we recover the notion of recognition of [5, 19]. (3) If $\Sigma$ is a finite set (viewed as an orbit-finite discrete nominal set), a data language is just an ordinary formal language over the alphabet $\Sigma$. Indeed, the free nominal monoid $\Sigma^*$ is discrete, and thus every subset of $\Sigma^*$ is finitely supported. Moreover, every orbit-finite nominal quotient monoid of $\Sigma^*$ is discrete and finite. Hence, the above notion of language recognition coincides with the classical recognition by finite monoids. In particular, for finite $\Sigma$, a recognizable data language is the same as a regular language.

Example 4.6. Examples of recognizable data languages over the alphabet $\Sigma = \mathbb{A}$ include (1) every finite or cofinite subset $L \subseteq \mathbb{A}^*$ (see Remark 4.8 below), (2) $a\mathbb{A}^*$ for a fixed atom $a \in \mathbb{A}$, and (3) $\bigcup_{a \in \mathbb{A}} a\mathbb{A}^*$ for a fixed atom $a \in \mathbb{A}$. The languages (4) $\{a_1 \ldots a_n : a_i \neq a_j \text{ for } i \neq j\}$, (5) $\bigcup_{a \in \mathbb{A}} a\mathbb{A}^* \bullet a\mathbb{A}^*$, and (6) $\mathbb{A}^* \bullet a\mathbb{A}^*$ for a fixed atom $a \in \mathbb{A}$ are not recognizable. The equivariant examples (3)–(5) are taken from [5, 6].

In previous work [1] we have given a categorical account of local varieties of regular languages [10], i.e. sets of regular languages over a fixed finite alphabet $\Sigma$ closed under the set-theoretic boolean operations (finite union, finite intersection, complement) and derivatives. This concept can be generalized to data languages. The derivatives of a data language $L \subseteq \Sigma^*$ with respect to a word $w \in \Sigma^*$ are given by

$$w^{-1}L = \{v \in \Sigma^* : vw \in L\} \quad \text{and} \quad Lw^{-1} = \{v \in \Sigma^* : vw \in L\}.$$ 

Since $\text{supp}(w^{-1}L), \text{supp}(Lw^{-1}) \subseteq \text{supp}(w) \cup \text{supp}(L)$, the derivatives are again data languages.

Definition 4.7 (Local Variety of Data Languages). Let $\Sigma \in \text{Nom}$. A local variety of data languages over $\Sigma$ is an equivariant set $\mathcal{V}_\Sigma \subseteq P\Sigma^*$ of recognizable data languages closed under the set-theoretic boolean operations, unions of $S$-orbits for every finite set $S \subseteq \mathbb{A}$ of atoms (that is, for every $L \in \mathcal{V}_\Sigma$ the language $\bigcup_{\pi \in \text{Perm}_e(\mathbb{A})} \pi \cdot L$ lies in $\mathcal{V}_\Sigma$), and derivatives.

Remark 4.8. (1) If $\Sigma$ is a finite set (viewed as a discrete nominal set), then by Remark 4.5 a local variety $\mathcal{V}_\Sigma$ consists of regular languages, and the closure under unions of $S$-orbits is trivial: since $P\Sigma^*$ is discrete, every $S$-orbit has a single element. Thus, in this case, a local variety of data languages is precisely a local variety of regular languages. (2) However, in general the closedness under unions of $S$-orbits cannot be dropped, as it is neither trivial nor implied by the other conditions. To see this, consider the alphabet $\Sigma = \mathbb{A}$ and the equivariant set $\mathcal{V}_\mathbb{A} \subseteq P\mathbb{A}^*$ of all finite or cofinite subsets of $\mathbb{A}^*$. Note that every finite language $L \subseteq \mathbb{A}^*$ is recognizable: let $n \geq 1$ be an upper bound on the length of words in $L$, and take the orbit-finite monoid $M = \mathbb{A}^{\leq n} \cup \{0\}$ consisting of all words over $\mathbb{A}$ of length at most $n$, and a zero element 0. The multiplication $\bullet$ is defined as follows: given $v, w \in \mathbb{A}^{\leq n}$, if the word $vw$ has length at most $n$, put $v \bullet w = vw$. Otherwise, put $v \bullet w = 0$. Then the equivariant monoid morphism $e: \mathbb{A}^* \to M$ extending $a \mapsto a$ recognizes $L$ since $L = e^{-1}[L]$. It follows that also $\mathbb{A}^* \setminus L = e^{-1}[M \setminus L]$. This shows that every language in $\mathcal{V}_\mathbb{A}$ is recognizable.
Moreover, clearly \( \mathcal{V}_A \) is closed under the set-theoretic boolean operations and derivatives. However, the languages \( \{ a \}, \ a \in A \), form an orbit in \( \mathcal{V}_A \), but their union \( A = \bigcup_{a \in A} \{ a \} \) is not in \( \mathcal{V}_A \). Thus \( \mathcal{V}_A \) is not a local variety of data languages in the sense of Definition 4.7.

A local variety \( \mathcal{V}_\Sigma \) is generally not a subobject of \( \mathcal{P}\Sigma^* \) in \( \mathsf{nCABA} \), because it is not required to be closed under unions of arbitrary finitely supported subsets and also not necessarily atomic as a boolean algebra. However, if the atomic languages in \( \mathcal{V}_\Sigma \) form an orbit-finite subset and every language in \( \mathcal{V}_\Sigma \) contains some atomic language, then \( \mathcal{V}_\Sigma \) is an atom-finite subobject of \( \mathcal{P}\Sigma^* \), see Remark 4.3(2). In this case, we call \( \mathcal{V}_\Sigma \) an atom-finite local variety.

**Theorem 4.9 (Finite Local Variety Theorem).** The lattice of atom-finite local varieties of data languages over \( \Sigma \) is dually isomorphic to the lattice of \( \Sigma \)-generated orbit-finite monoids.

The isomorphism maps a \( \Sigma \)-generated orbit-finite monoid \( e: \Sigma^* \to M \) to the atom-finite local variety of all data languages recognized by \( e \).

**Proof.** By the duality of \( \mathsf{Nom} \) and \( \mathsf{nCABA} \), orbit-finite equivariant quotients \( e: \Sigma^* \to M \) of \( \Sigma^* \) in \( \mathsf{Nom} \) correspond bijectively to atom-finite subobjects \( \mathcal{V}_\Sigma \hookrightarrow \mathcal{P}\Sigma^* \) in \( \mathsf{nCABA} \), i.e. atom-finite equivariant sets of languages closed under the set-theoretic boolean operations and unions of \( S \)-orbits for every finite \( S \subseteq A \). By Proposition 3.1 and the dual equivalence of \( \mathsf{Nom}_b \) and \( \mathsf{nCABA}_b \), the map \( e \) represents a nominal quotient monoid of \( \Sigma^* \) if and only if \( \mathcal{V}_\Sigma \) is closed under derivatives, i.e. a local variety. The closure under left derivatives is illustrated by the two dual commutative squares below, where the left-hand one lives in \( \mathsf{Nom}_b \) and the right-hand one in \( \mathsf{nCABA}_b \).

\[
\begin{array}{ccc}
\Sigma^* & \xrightarrow{w} & \Sigma^* \\
\downarrow & & \downarrow e \\
M & \leftarrow & \mathcal{V}_\Sigma
\end{array}
\quad
\begin{array}{ccc}
\mathcal{P}\Sigma^* & \xrightarrow{w^{-1}(-)} & \mathcal{P}\Sigma^* \\
\subseteq & & \subseteq \\
\mathcal{V}_\Sigma & \leftarrow & \mathcal{P}\Sigma^*
\end{array}
\]

The elements of \( \mathcal{V}_\Sigma \) are precisely the languages recognized by \( e \). Indeed, the former correspond to the morphisms \( \mathbb{I} \to \mathcal{V}_\Sigma \) in \( \mathsf{nCABA}_b \), where \( \mathbb{I} \) is the free boolean algebra on one generator, the latter to the finitely supported maps \( M \to 2 \) in \( \mathsf{Nom}_b \), and \( \mathbb{I} \) and 2 are dual objects. \( \blacksquare \)

Recall that an **ideal** in a poset is a downwards closed and upwards directed subset. For the lattice of local varieties of data languages over \( \Sigma \) (ordered by inclusion), we obtain

**Lemma 4.10.** The lattice of local varieties of data languages over \( \Sigma \) is isomorphic to the lattice of ideals of atom-finite local varieties over \( \Sigma \).

The isomorphism maps a local variety \( \mathcal{V}_\Sigma \) to the ideal of all atom-finite local subvarieties of \( \mathcal{V}_\Sigma \). Its inverse maps an ideal \( \{ \mathcal{V}_{\Sigma,i} : i \in I \} \) in the poset of atom-finite local varieties to the local variety \( \bigcup_{i \in I} \mathcal{V}_{\Sigma,i} \). In order-theoretic terms, the above lemma states that local varieties of data languages form the ideal completion of the poset of atom-finite local varieties. Using Theorem 4.9, Lemma 4.10, and the fact that ideals are dual to filters, we obtain

**Theorem 4.11 (Local Variety Theorem).** For each \( \Sigma \in \mathsf{Nom} \), the lattice of local varieties of data languages over \( \Sigma \) is dually isomorphic to the lattice of local pseudovarieties of \( \Sigma \)-generated nominal monoids.

**Remark 4.12.** (1) Since data languages are morphisms \( L: \Sigma^* \to 2 \) in \( \mathsf{Nom}_b \), the reader may wonder why we do not entirely work in this category and use monoids with finitely...
supported multiplication and finitely supported monoid morphisms (rather than the equivariant ones) for the recognition of languages. The reason lies on the dual side: in the proof of Theorem 4.9, we used that equivariant injective maps \( \mathcal{V}_\Sigma \to \mathcal{P}\Sigma^* \) can be uniquely identified with equivariant subsets of \( \mathcal{P}\Sigma^* \). In contrast, finitely supported injective maps \( \mathcal{V}_\Sigma \to \mathcal{P}\Sigma^* \) do not correspond to the finitely supported (or any other kind of) subsets of \( \mathcal{P}\Sigma^* \).

(2) Similarly, we cannot restrict ourselves to the category \( \text{Nom} \) and only consider equivariant languages \( L \subseteq \Sigma^* \) rather than finitely supported ones. Indeed, the Finite Local Variety Theorem then fails: the map sending a \( \Sigma \)-generated orbit-finite monoid \( e: \Sigma^* \to M \) to the set of equivariant languages it recognizes is no longer bijective. To see this, consider the nominal monoids \( M = \mathbb{A} \cup \{1\} \) with \( a \bullet b = a \) for \( a, b \in \mathbb{A} \), and \( N = \{0, 1\} \) with \( 0 \bullet 0 = 0 \bullet 1 = 1 \bullet 0 = 0 \).

Then the two surjective morphisms \( e: \mathbb{A}^* \to M \), extending \( a \mapsto a \), and \( f: \mathbb{A}^* \to N \), extending \( a \mapsto 0 \), recognize the same equivariant languages, namely \( \mathbb{A}^*, \mathbb{A}^* \setminus \{e\}, \{e\} \) and \( \emptyset \).

In the following, we consider data languages whose alphabet \( \Sigma \) is an orbit-finite strong nominal set (see Remark 3.6(2)). By dualizing the concept of an equational theory, we obtain

**Definition 4.13 (Variety of data languages).** A variety of data languages is a family

\[ \mathcal{V} = (\mathcal{V}_\Sigma \subseteq \mathcal{P}\Sigma^*)_{\Sigma \in \text{Nom}_{af}} \]

of local varieties of data languages with the following two properties:

1. **Closedness under preimages.** For each equivariant monoid morphism \( h: \Delta^* \to \Sigma^* \) with \( \Sigma, \Delta \in \text{Nom}_{af} \), and each \( L \in \mathcal{V}_\Sigma \), one has \( h^{-1}[L] \in \mathcal{V}_\Delta \).

2. **Completeness.** For each atom-finite local subvariety \( \mathcal{V}_\Sigma' \subseteq \mathcal{V}_\Sigma \), there exists an equivariant monoid morphism \( h: \Sigma^* \to \Delta^* \) and an atom-finite local subvariety \( \mathcal{V}_\Delta' \subseteq \mathcal{V}_\Delta \) such that

   a) the map \( L \mapsto h^{-1}[L] \) defines a bijection between \( \mathcal{V}_\Delta' \) and \( \mathcal{V}_\Sigma' \), and

   b) every atomic language \( L \in \mathcal{V}_\Delta' \) contains a word \( w \in \Delta^* \) with \( \text{supp}_{P, \Delta^*}(L) = \text{supp}_{\Delta^*}(w) \).

**Remark 4.14.** Except for the completeness condition, the above concept is analogous to Eilenberg’s original notion of a variety of regular languages (i.e. a family of local varieties of regular languages closed under preimages of monoid morphisms). In fact, if \( \Sigma \) is a finite alphabet, and thus \( \mathcal{V}_\Sigma \) is just a local variety of regular languages, completeness is trivial: given any finite local subvariety \( \mathcal{V}_\Sigma' \) of \( \mathcal{V}_\Sigma \), choose \( \Delta = \Sigma \), \( \mathcal{V}_\Delta' = \mathcal{V}_\Sigma' \), and \( h = \text{id}: \Sigma^* \to \Delta^* \).

Then (a) is clear, and (b) holds because each \( L \in \mathcal{P}\Sigma^* \) and each \( w \in \Sigma^* \) has empty support.

In general, however, the completeness property cannot be dropped. This follows from Remark 3.6(3) and the observation that the completeness of a variety dualizes to the completeness of the corresponding equational theory (see the proof of Theorem 4.15).

We are ready to state the main result of our paper:

**Theorem 4.15 (Nominal Eilenberg Theorem).** Varieties of data languages and pseudovarieties of nominal monoids form isomorphic complete lattices.

The isomorphism maps a variety \( \mathcal{V} \) of data languages to the pseudovariety \( \mathcal{F} \) of all orbit-finite nominal monoids that recognize only languages from \( \mathcal{V} \). Its inverse maps a pseudovariety \( \mathcal{F} \) to the variety \( \mathcal{V} \) of all data languages recognized by some monoid in \( \mathcal{F} \).

**Proof sketch.** We observe that the concept of a variety is dual to that of an equational theory. Indeed, by the Local Variety Theorem 4.11, a family \( \mathcal{V} = (\mathcal{V}_\Sigma \subseteq \mathcal{P}\Sigma^*)_{\Sigma \in \text{Nom}_{af}} \) of local varieties of data languages bijectively corresponds to a family \( \mathcal{T} = (\mathcal{T}_\Sigma \subseteq \Sigma^* \text{inMon}_{af})_{\Sigma \in \text{Nom}_{af}} \) of local pseudovarieties of nominal monoids. One then shows that (1) \( \mathcal{T} \) is substitution-invariant if and only if \( \mathcal{V} \) is closed under preimages, and (2) \( \mathcal{T} \) is complete if and only if \( \mathcal{V} \) is complete. In particular, \( \mathcal{T} \) is a theory if and only if \( \mathcal{V} \) is a variety of data languages. Since theories correspond to pseudovarieties by Theorem 3.8, this proves the theorem. ✷
5 Adding Expressivity: Regular Data Languages

As recognizing structures for data languages, nominal monoids are of limited expressivity: in particular, they are strictly weaker than deterministic automata in the category of nominal sets [5,6]. Therefore, we now show how to extend our results for monoid-recognizable data languages and establish a local variety theorem for languages accepted by nominal automata.

Definition 5.1. Fix an input alphabet $\Sigma \in \text{Nom}$. A nominal $\Sigma$-automaton $A = (Q, \delta, q_0)$ consists of a nominal set $Q$ of states, an equivariant transition map $\delta: Q \times \Sigma \rightarrow Q$, and an initial state $q_0 \in Q$ with empty support. It is called orbit-finite if $Q$ is orbit-finite. A morphism between nominal automata $A = (Q, \delta, q_0)$ and $A' = (Q', \delta', q'_0)$ is an equivariant map $h: Q \rightarrow Q'$ such that $\delta(h(q), a) = h(\delta(q, a))$ for all $q \in Q$ and $a \in \Sigma$, and $h(q_0) = q'_0$.

The initial nominal $\Sigma$-automaton is given by $I = (\Sigma^*, \delta, \varepsilon)$ with transition map $\delta(w, a) = wa$ for $w \in \Sigma^*$ and $a \in \Sigma$. It is characterized by the universal property that for every nominal $\Sigma$-automaton $A = (Q, \delta, q_0)$, there exists a unique morphism $e_A : I \rightarrow A$, sending a word $w \in \Sigma^*$ to the state reached from $q_0$ after reading $w$. The automaton $A$ is called reachable if $e_A$ is surjective. A data language $L \subseteq \Sigma^*$ is accepted by $A$ if there exists a finitely supported subset $F \subseteq Q$ with $L = e^{-1}_A[F]$. This corresponds to the usual notion of acceptance of an automaton with final states $F$: the language $L$ consists of all words $w \in \Sigma^*$ such that $A$ reaches a state in $F$ after reading $w$. A data language $L \subseteq \Sigma^*$ is called regular if there exists an orbit-finite nominal automaton accepting it. In analogy to Proposition 3.1, we get

Proposition 5.2 (Unary presentation for nominal automata). For every surjective equivariant map $e : \Sigma^* \rightarrow Q$, the following statements are equivalent:

1. there exists a nominal automaton $A = (Q, \delta, q_0)$ with states $Q$ such that $e = e_A$;
2. the maps $\Sigma^* \rightarrow \Sigma^* (w \in \Sigma^*)$ lift along $e$, i.e. there exist (necessarily unique) maps $r_w : Q \rightarrow Q$ such that $e \cdot (\cdot \cdot w) = r_w \cdot e$ for all $w \in \Sigma^*$.

Define a local pseudovariety of nominal $\Sigma$-automata to be a class $\mathcal{V}_\Sigma$ of orbit-finite reachable nominal $\Sigma$-automata such that (1) $\mathcal{V}_\Sigma$ is closed under quotients (represented by surjective automata morphisms), and (2) for every pair $A, B \in \mathcal{V}_\Sigma$, the reachable part of the product $A \times B$ lies in $\mathcal{V}_\Sigma$. Here, the product of two nominal automata $A = (Q, \delta, q_0)$ and $B = (Q', \delta', q'_0)$ is given by $A \times B = (Q \times Q', \delta, (q_0, q'_0))$ with $\delta((q, q'), a) = (\delta(q, a), \delta'(q', a))$ for $(q, q') \in Q \times Q'$ and $a \in \Sigma$, and the reachable part $R$ of $A \times B$ is the coinage $e : \Sigma^* \rightarrow R$ of the unique morphism $e_{A \times B} : \Sigma^* \rightarrow A \times B$. Note that a local pseudovariety corresponds precisely to a filter in the poset $\Sigma^* \downarrow \text{NomAut}_\Sigma$ of orbit-finite reachable nominal $\Sigma$-automata. The dual version of this concept is the one of a local variety of regular data languages over $\Sigma$: an equivariant set $\mathcal{V}_\Sigma \subseteq \mathcal{P}\Sigma^*$ of such languages closed under the set-theoretic boolean operations, unions of $S$-orbits for every finite set $S \subseteq \mathcal{A}$ of atoms, and right derivatives. The following theorem, and its proof, are completely analogous to Theorem 4.11:

Theorem 5.3 (Local Variety Theorem for Regular Data Languages). For each $\Sigma \in \text{Nom}$, the lattice of local varieties of regular data languages over $\Sigma$ is dually isomorphic to the lattice of local pseudovarieties of nominal $\Sigma$-automata.

6 Conclusions and Future Work

We have demonstrated that two cornerstones of the algebraic theory of regular languages, Eilenberg’s variety theorem and Eilenberg and Schützenberger’s axiomatic characterization of pseudovarieties, can be generalized to data languages recognizable by orbit-finite monoids.
Our results are the first of this type for data languages, and thus the present work makes
a contribution towards developing a fully fledged algebraic theory of such languages. In
a broader sense, the approach taken in this paper can be seen as a further illustration
of the power of duality in formal language theory: we believe that without the guidance
given by nominal Stone duality, it would have been significantly harder to even come up
with the suitable notion of a variety of data languages that makes the nominal Eilenberg
 correspondence work. The duality-based approach thus adds much conceptual clarity and
simplicity. There remain several research questions and interesting directions for future work.

As indicated in Section 5, the techniques used in our paper can be adapted without much
effort to languages recognized by nominal algebraic structures other than monoids, including
deterministic nominal automata. As a first step, we aim to extend the local variety theorem
for regular data languages (Theorem 5.3) to a full Eilenberg correspondence. It remains an
important goal to further extend our results to more powerful classes of data languages.

Our proof of the (local) Eilenberg correspondence rests on the observation that a local
variety of data languages can be expressed as the directed union of its atom-finite subvarieties.
From a category theoretic perspective, this suggests that local varieties are formed within the
\( \text{Ind}\)-completion (i.e. the free completion under directed colimits) of the category of atom-finite
nominal complete atomic boolean algebras. We conjecture that this completion can be
expressed as a category of nominal boolean algebras with joins of \( S \)-orbits for each finite set
\( S \) of atoms. On the dual side, we expect that the \( \text{Pro}\)-completion (i.e. the free completion
under codirected limits) of the category of orbit-finite nominal sets consists of some form
of nominal Stone spaces. The approach of working with free completions should lead to
a topological version of nominal Stone duality similar to the one established by Gabbay,
Litak, and Petrişan [9]. More importantly, it might pave the way to the introduction of
pro-(orbit-)finite methods for the theory of data languages.

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A Appendix: Omitted Proofs and Details

In this appendix, we provide full proofs of all our results and technical details omitted due to space restrictions.

Properties of nominal sets

We review some additional concepts from the theory of nominal sets that we shall use in subsequent proofs.

▶ Definition A.1. A supported set is a set $X$ together with a map $\text{supp}_X : X \to \mathcal{P}_f \mathbb{A}$, where $\mathcal{P}_f \mathbb{A}$ is the set of finite subsets of $\mathbb{A}$. A morphism between supported sets $X$ and $Y$ is a function $f : X \to Y$ with $\text{supp}_Y(f(x)) \subseteq \text{supp}_X(x)$ for all $x \in X$. We denote by $\text{SuppSet}$ the category of supported sets and their morphisms.

Note that every nominal set $X$ is a supported set w.r.t. its least-support function $\text{supp}_X$, and that every equivariant map is a morphism of supported sets. The following result is a reformulation of [14, Prop. 5.10]:

▶ Lemma A.2 ([15], Lemma B.25). The forgetful functor from $\text{Nom}$ to $\text{SuppSet}$ has a left adjoint.

The left adjoint $F : \text{SuppSet} \to \text{Nom}$ is constructed as follows. Given a finite set $I$, let $\mathbb{A}^I = \prod_{i \in I} \mathbb{A}$ denote the $I$-fold power of $\mathbb{A}$, and consider the strong nominal set

$\mathbb{A}^#I = \{ a \in \mathbb{A}^I : a : I \to \mathbb{A} \text{ injective} \},$

with group action given by $(\pi \cdot a)(i) := \pi(a(i))$ for every $\pi \in \text{Perm}(\mathbb{A})$. Then $F$ sends a supported set $X$ to the nominal set $FX = \bigsqcup_{x \in X} \mathbb{A}^{\text{supp}_X(x)}$, and the universal map $\eta_X : X \to FX$ maps an element $x \in X$ to the inclusion map $\text{supp}_X(x) \hookrightarrow \mathbb{A}$ in $\mathbb{A}^{\text{supp}_X(x)}$.

▶ Lemma A.3 ([15], Lemma B.27). (1) For each nominal set $Z$, there exists a strong nominal set $X$ and a surjective equivariant map $e : X \to Z$ preserving least supports, i.e. with $\text{supp}_Z(e(x)) = \text{supp}_X(x)$ for all $x \in X$.

(2) Every strong nominal set is isomorphic to $FY$ for some $Y \in \text{SuppSet}$.

It follows from the proof that in the case where $Z$ above is orbit-finite, one may choose $X$ to be orbit-finite (in fact, with the same number of orbits as $Z$). In particular:

▶ Corollary A.4 (Pitts [18], Exercise 5.1). Every nominal set which has only a single orbit is a quotient of the nominal set $\mathbb{A}^#n = \{(a_1, \ldots, a_n) \in \mathbb{A}^n : a_i \neq a_j \text{ for } i \neq j\}$ for some $n \geq 0$.

▶ Lemma A.5. Every orbit-finite nominal set contains only finitely many elements of any given support.

Proof. This is a consequence of the following facts:

- Every nominal set is the disjoint union of its orbits.
- Every single-orbit nominal set is a quotient of the nominal set $\mathbb{A}^#n$ (see Corollary A.4).
- Every $\mathbb{A}^#n$ satisfies the desired property and every equivariant map $f : X \to Y$ satisfies $\text{supp}_Y(f(x)) \subseteq \text{supp}_X(x)$ for every $x \in X$. ◀
Proof of Lemma 2.1

Clearly the nominal set \( \Lambda^n \) has only finitely many \( S \)-orbits: two tuples \((a_1, \ldots, a_n)\) and \((b_1, \ldots, b_n)\) in \( \Lambda^n \) lie in the same \( S \)-orbit if and only if for every \( i = 1, \ldots, n \) one has \( a_i = b_i \). Thus, by Corollary A.4, every nominal set with a single orbit has finitely many \( S \)-orbits (using that equivariant maps preserve \( S \)-orbits). Since every orbit-finite nominal set is the finite coproduct of its orbits, this proves the claim. ▷

Proof of Proposition 3.1

The proof is analogous to the corresponding statement for ordinary monoids. Given a nominal quotient monoid \( e: \Sigma^* \to (M, \cdot, 1_M) \) as in (1), choose \( b_n = e(w) \cdot - \) and \( r_n = - \cdot e(w) \).

Conversely, if (2) holds, there is a unique monoid structure \((M, \cdot, 1_M)\) on \( M \) making \( e \) a monoid morphism in \( \Set \). It is uniquely defined by

\[
e v \cdot ew := e(vw) \text{ for } v, w \in \Sigma^* \quad \text{and} \quad 1_M := e(\varepsilon).
\]

Condition (2) makes sure that \( \cdot \) is well-defined, i.e. independent of the choice of \( v \) and \( w \). Moreover, the multiplication \( \cdot \) is equivariant since, for every \( \pi \in \Perm(\Lambda) \),

\[
\pi \cdot (ev \cdot ew) = \pi \cdot e(vw) = e(\pi \cdot (vw)) = e((\pi v)(\pi w)) = e(\pi v) \cdot e(\pi w) = (\pi \cdot e(v)) \cdot (\pi \cdot e(w)),
\]

using that \( e \) and the monoid multiplication on \( \Sigma^* \) are equivariant. ▷

Proof of Theorem 3.8

This theorem can be derived as an instance of the Generalized Variety Theorem established in our previous work [16, Theorem 3.15], which relates varieties of objects in a category \( \mathcal{A} \) with a categorical notion of equational theory. For the convenience of the reader, we briefly recall this result. For the statement of the theorem one fixes the following parameters:

- a category \( \mathcal{A} \) with a proper factorization system \((\mathcal{E}, \mathcal{M})\);
- a full subcategory \( \mathcal{A}_0 \subseteq \mathcal{A} \);
- a class \( \Lambda \) of cardinal numbers;
- a class \( \mathcal{F} \subseteq \mathcal{A} \) of objects.

Recall that a factorization system \((\mathcal{E}, \mathcal{M})\) is proper if all morphisms in \( \mathcal{E} \) are epic and all morphisms in \( \mathcal{M} \) are monic. The idea is that \( \mathcal{A} \) is some category of algebraic structures, \( \mathcal{A}_0 \) is the subcategory in which varieties are formed, \( \Lambda \) specifies the arities of products under which varieties are closed, and \( \mathcal{F} \) is the class of algebras over which equations are formed (thus, \( \mathcal{F} \) is usually some class of free algebras). Quotients and subobjects in \( \mathcal{A} \) are taken w.r.t. the classes \( \mathcal{E} \) and \( \mathcal{M} \). An object \( A \in \mathcal{A} \) is called \( \mathcal{F} \)-generated if there exists a quotient \( e: X \to A \) for some \( X \in \mathcal{F} \). An object \( X \in \mathcal{A} \) is projective w.r.t. a morphism \( e: A \to B \) if for every morphism \( f: X \to B \) there exists a morphism \( g: X \to A \) with \( e \cdot g = h \). We define the subclass \( \mathcal{E}_\mathcal{F} \subseteq \mathcal{E} \) by

\[
\mathcal{E}_\mathcal{F} = \{ e \in \mathcal{E} : \text{every } X \in \mathcal{F} \text{ is projective w.r.t. } e \}.
\]

Our data is required to satisfy the following assumptions:

(A1) \( \mathcal{A} \) has \( \Lambda \)-products, i.e. for every \( \lambda \in \Lambda \) and every family \((A_i)_{i<\lambda}\) of objects in \( \mathcal{A} \), the product \( \prod_{i<\lambda} A_i \) exists.
(A2) \( \mathcal{A}_0 \) is closed under isomorphisms, \( \Lambda \)-products and \( \mathcal{X} \)-generated subobjects. The last statement means that for every subobject \( m: A \rightarrow B \) in \( \mathcal{M} \) where \( B \in \mathcal{A}_0 \) and \( A \) is \( \mathcal{X} \)-generated, one has \( A \in \mathcal{A}_0 \).

(A3) Every object of \( \mathcal{A}_0 \) is an \( \mathcal{E}_X \)-quotient of some object of \( \mathcal{X} \), that is, for every object \( A \in \mathcal{A}_0 \) there exists some \( e: X \rightarrow A \) in \( \mathcal{E}_X \) with domain \( X \in \mathcal{X} \).

\[ \text{Definition A.6. A (weak) variety is a full subcategory } \mathcal{V} \subseteq \mathcal{A}_0 \text{ closed under (} \mathcal{E}_X \text{-)quotients, subobjects, and } \Lambda \text{-products. More precisely,} \]

(1) for every (\( \mathcal{E}_X \))-quotient \( e: A \rightarrow B \) in \( \mathcal{A}_0 \) with \( A \in \mathcal{V} \) one has \( B \in \mathcal{V} \),

(2) for every \( \mathcal{M} \)-morphism \( m: A \rightarrow B \) in \( \mathcal{A}_0 \) with \( B \in \mathcal{V} \) one has \( A \in \mathcal{V} \), and

(3) for every family of objects \( A_i \) \((i < \lambda)\) in \( \mathcal{V} \) with \( \lambda \in \Lambda \) one has \( \prod_{i < \lambda} A_i \in \mathcal{V} \).

Given an object \( X \in \mathcal{X} \), we denote by \( X \downarrow \mathcal{A}_0 \) the poset of all quotients \( e: X \rightarrow A \) with codomain \( A \in \mathcal{A}_0 \), ordered by \( e \leq e' \) iff \( e' \) factorizes through \( e \). A subset \( \mathcal{T}_X \subseteq X \downarrow \mathcal{A}_0 \) is called a (weak) equation if it is downwards \( \Lambda \)-directed, i.e., every subset of \( S \subseteq \mathcal{T}_X \) with \( |S| \in \Lambda \) has a lower bound in \( \mathcal{T}_X \), and closed under (\( \mathcal{E}_X \))-quotients, i.e., for every quotient \( e: X \rightarrow E \) in \( \mathcal{T}_X \) and every (\( \mathcal{E}_X \))-quotient \( q: E \rightarrow E' \) in \( \mathcal{A}_0 \), one has \( q \cdot e \in \mathcal{T}_X \). An object \( A \in \mathcal{A}_0 \) satisfies the (weak) equation \( \mathcal{T}_X \) if every morphism \( h: X \rightarrow A \) factorizes through some quotient in \( \mathcal{T}_X \).

\[ \text{Definition A.7. A (weak) equational theory is a family} \]

of (weak) equations with the following properties (illustrated by the diagrams below):

(1) Substitution invariance. For every morphism \( h: X \rightarrow Y \) with \( X, Y \in \mathcal{X} \) and every \( e_Y: Y \rightarrow E_Y \) in \( \mathcal{T}_Y \), the coimage \( e_X: X \rightarrow E_X \) of \( e_Y \cdot h \) lies in \( \mathcal{T}_X \).

(2) \( \mathcal{E}_X \)-completeness. For every \( Y \in \mathcal{X} \) and every quotient \( e: Y \rightarrow E_Y \) in \( \mathcal{T}_Y \), there exists an \( X \in \mathcal{X} \) and a quotient \( e_X: X \rightarrow E_X \) in \( \mathcal{T}_X \cap \mathcal{E}_X \) with \( E_X = E_Y \).

\[ \text{Remark A.8. We warn the reader about a clash of terminology: in our previous work [15], weak equations, weak equational theories and weak varieties were called equations, equational theories and varieties (without the adjective “weak”). Our present non-weak notion of an equation, an equational theory, and variety in Definition A.6/A.7 was not considered in [15].} \]

\[ \text{Remark A.9. (1) To every weak equational theory } \mathcal{T} \text{ one can associate the variety} \]

\[ \mathcal{V}(\mathcal{T}) = \{ A \in \mathcal{A}_0 : A \text{ satisfies } \mathcal{T}_X \text{ for every } X \in \mathcal{X} \} \].

Equivalently, by [15, Lemma A.2] the variety \( \mathcal{V}(\mathcal{T}) \) consists of all objects \( A \in \mathcal{A}_0 \) such that, for some \( X \in \mathcal{X} \), there exists a quotient \( e: X \rightarrow A \) in \( \mathcal{T}_X \) with codomain \( A \).

(2) Conversely, to every weak variety \( \mathcal{V} \) one can associate a weak equational theory \( \mathcal{T}(\mathcal{V}) \) where \( [\mathcal{T}(\mathcal{V})]_X \) consists of all quotients \( e: X \rightarrow A \) with \( A \in \mathcal{V} \).

Given two weak equations \( \mathcal{T}_X \) and \( \mathcal{T}_X' \) over \( X \in \mathcal{X} \), we put \( \mathcal{T}_X \leq \mathcal{T}_X' \) if every quotient in \( \mathcal{T}_X \) factorizes through some quotient in \( \mathcal{T}_X' \). Weak theories form a poset with respect to the order \( \mathcal{T} \leq \mathcal{T}' \) iff \( \mathcal{T}_X \leq \mathcal{T}_X' \) for all \( X \in \mathcal{X} \). Similarly, weak varieties form a poset – in fact, a complete lattice – ordered by inclusion. Then, we obtain the following correspondence:
Theorem A.10 ([16], Theorem 3.15). The complete lattices of weak equational theories and weak varieties are dually isomorphic. The isomorphism is given the maps

\[ T \mapsto \mathcal{V}(T) \quad \text{and} \quad \mathcal{V} \mapsto \mathcal{T}^{-1}(\mathcal{V}).\]

Clearly, the above isomorphism restricts to one between equational theories and varieties. Thus, we obtain

Corollary A.11. The complete lattices of equational theories and varieties are dually isomorphic.

Let us now instantiate these results to the setting of orbit-finite nominal monoids. That is, we choose the parameters of the above categorical setting as follows:

- \( \mathcal{A} = \text{nMon}; \)
- \( \mathcal{B} = (\text{surjective morphisms}, \text{injective morphisms}); \)
- \( \mathcal{A}_0 = \text{nMon}_0; \)
- \( \Lambda = \text{all finite cardinal numbers}; \)
- \( \mathcal{X} = \text{all free nominal monoids } \Sigma^* \text{ with } \Sigma \text{ an orbit-finite strong nominal set}. \)

The class \( \mathcal{E}_\mathcal{X} \) can be characterized as follows:

Lemma A.12 ([15], Lemma B.28). A quotient \( e: M \twoheadrightarrow N \) belongs to \( \mathcal{E}_\mathcal{X} \) if and only if \( e \) is support-reflecting.

It is now easy to verify that the assumptions (A1)–(A3) are satisfied. For (A1) use that products of nominal monoids are formed on the level of their underlying nominal sets. For (A2), use that finite products and equivariant subsets of orbit-finite nominal sets are again orbit-finite. For (A3), let \( M \) be an orbit-finite nominal monoid. By Lemma A.3, we can express the underlying nominal set of \( M \) as a quotient \( e: \Sigma \twoheadrightarrow M \) in \( \text{Nom} \) of an orbit-finite strong nominal set \( \Sigma \), where \( e \) preserves least supports. Then the unique extension \( \hat{e}: \Sigma^* \twoheadrightarrow M \) to an equivariant monoid morphism is support-reflecting. Indeed, given \( m \in M \), choose \( a \in \Sigma \) with \( e(a) = m \). Then \( \hat{e}(a) = m \) and \( \text{supp}_{\Sigma^*}(a) = \text{supp}_\Sigma(a) = \text{supp}_M(e(a)) = \text{supp}_M(m) \).

Finally, observe that the above general concepts of a variety and of an equational theory specialize to the ones of a pseudovariety of nominal monoids and of an equational theory of nominal monoids, respectively. Thus, Theorem 3.8 is an instance of Theorem A.10 and Corollary A.11.

Proof of Theorem 3.11

The key ingredient of the proof is an observation about congruences. A congruence on a nominal monoid \( M \) is an equivariant equivalence relation \( \equiv \subseteq M \times M \) such that, for \( m, n \in M \),

\[ m \equiv n \quad \text{implies} \quad pmq \equiv pnq \text{ for all } p, q \in M. \]

There is an isomorphism of complete lattices

\[ \text{congruences on } M \quad \cong \quad \text{nominal quotients monoids of } M \]

mapping a congruence \( \equiv \) to the quotient monoid \( e: M \twoheadrightarrow M/\equiv \), where \( M/\equiv \) is the monoid of all \( \equiv \)-congruence classes (with multiplication \([m] \bullet [n] = [mn]\) for \( m, n \in M \) and unit
on the free nominal monoid $A$.

A congruence $\equiv$ on $M$ is called orbit-finite if the corresponding quotient monoid $M/\equiv$ is orbit-finite, and finitely generated if there is a finite subset $W \subseteq \equiv$ such that $\equiv$ is the least congruence on $M$ containing $W$.

**Theorem A.13 (Homomorphism Theorem).** Given two equivariant monoid morphisms $e : M \to N$ and $h : M \to P$ with $e$ surjective, there exists a morphism $g : N \to P$ with $g \cdot e = h$ if and only if the kernel of $e$ is contained in the kernel of $h$.

**Lemma A.14.** Let $X$ be an orbit-finite nominal set. Then every orbit-finite congruence on the free nominal monoid $X^*$ is finitely generated.

**Proof.** Let $\equiv$ be an orbit-finite congruence on $X^*$. Since $X^*/\equiv$ is orbit-finite, there exists a natural number $k > 0$ such that each congruence class contains a word of length $< k$.

Moreover, there exists a natural number $n$ such that every word of length $\leq k$ in $X^*$ has a support of size $\leq n$. This follows from the fact that (a) the least support of a word $a_1 \cdots a_m \in \Sigma^*$ is given by $\text{supp}_X(a_1 \cdots a_m) = \bigcup_{i=1}^m \text{supp}_X(a_i)$, and (b) the size of least supports of elements of $X$ has an upper bound because $X$ is orbit-finite and for elements $x, x' \in X$ in the same orbit we have $|\text{supp}_X(x)| = |\text{supp}_X(x')|$.

We now fix a list of $2n$ pairwise distinct atoms $a_1, \ldots, a_{2n} \in A$, and consider the subset $W \subseteq \equiv$ defined by

$$W := \{ (s, t) : s \equiv t, |s| < k, |t| \leq k, \text{supp}(s), \text{supp}(t) \subseteq \{a_1, \ldots, a_{2n}\} \}.$$  

Here $|\cdot|$ denotes the length of a word. The set $W$ is finite because $X$ contains only finitely many elements with support $\{a_1, \ldots, a_{2n}\}$, see Lemma A.5. Let $\sim$ be the congruence on $X^*$ generated by $W$ (i.e. the intersection of all congruences containing $W$). We claim that $\sim = \equiv$, which proves that $\equiv$ is finitely generated.

1. For every pair $s, t \in X^*$ with $s \equiv t$, $|s| < k$ and $|t| \leq k$, one has $s \sim t$. Indeed, since $s$ and $t$ have supports of size $\leq n$, there exist pairwise distinct atoms $b_1, \ldots, b_{2n}$ such that $\text{supp}(s), \text{supp}(t) \subseteq \{b_1, \ldots, b_{2n}\}$. Choose a finite permutation $\pi \in \text{Perm}(A)$ with $\pi(b_i) = a_i$ for $i = 1, \ldots, 2n$. Then the pair $((\pi \cdot s, \pi \cdot t))$ lies in $W$; indeed, we have
   
   (a) $\pi \cdot s \equiv \pi \cdot t$ because $s \equiv t$ and $\equiv$ is equivalent;
   (b) $|\pi \cdot s| < k$ and $|\pi \cdot t| \leq k$ because $|s| < k$ and $|t| \leq k$ and $\pi \cdot (-)$ preserves the length of words;
   (c) $\text{supp}(\pi \cdot s), \text{supp}(\pi \cdot t) \subseteq \{a_1, \ldots, a_{2n}\}$ because $\text{supp}(s), \text{supp}(t) \subseteq \{b_1, \ldots, b_{2n}\}$.

Since $(s, t) = \pi^{-1} \cdot ((\pi \cdot s, \pi \cdot t))$ and $(\pi \cdot s, \pi \cdot t) \in W$, we conclude that the pair $(s, t)$ lies in the congruence generated by $W$, i.e. $s \sim t$.

2. We claim that for every word $s \in X^*$, there exists a word $t \in X^*$ of length $< k$ with $s \sim t$. The proof is by induction on $|s|$. If $|s| < k$, one may take $t = s$. Thus let $|s| \geq k$. Since $k > 0$, we have that $s = xs'$ for some $x \in X$ and $s' \in X^*$. Since $|s'| < |s|$, we have that $s' \sim t'$ for some word $t' \in X^*$ of length $< k$ by induction. This implies $s = xs' \sim xt'$ because $\sim$ is a congruence. By the choice of the number $k$, there exists a word $t \in X^*$ of length $< k$ with $|t| \equiv xt'$. Since $|t| < k$ and $|xt'| \leq k$, we have $t \sim xt'$ by Part (1). Therefore, $s \sim xt' \sim t$, as required.

3. We are ready to prove that $\sim = \equiv$. The inclusion $\subseteq$ is obvious. Conversely, suppose that $s \equiv t$. By Part (2), there are words $s'$ and $t'$ of length $< k$ with $s \sim s'$ and $t \sim t'$. Since $s \sim t$, we get $s' \equiv s \equiv t \equiv t'$. Part (1) then shows that $s' \sim t'$. Thus, we conclude $s \sim s' \sim t' \sim t$.  

\[\square\]
Varieties of Data Languages

**Remark A.15.** As an important consequence of the previous lemma, we note that there are only countably many orbit-finite nominal monoids up to isomorphism. This is because (1) every orbit-finite nominal monoid is a quotient of $X^*$ for some orbit-finite set $X$, (2) up to isomorphism, there are only countably many orbit-finite sets $X$ (this follows from [18, Theorem 5.13]; see also [4, Lemma A.1]), and (3) $X^*$ is countably infinite, and thus has only countably many orbit-finite quotient monoids by Lemma A.14 and the coincidence between quotients and congruences.

We are ready to prove Theorem 3.11.

**Proof of the “if” direction**

Let $E = (s_n = t_n)_{n \in \mathbb{N}}$ be a sequence of nominal equations, where $s_n, t_n \in X_n^*$ for a strong orbit-finite nominal set $X_n$. We need to show that $\mathcal{V}(E)$ forms a weak pseudovariety.

**Closedness under finite products.** Let $M, N \in \mathcal{V}(E)$. Then there exists $n_0 \in \mathbb{N}$ such that both $M$ and $N$ satisfy the equations $s_n = t_n$ for $n \geq n_0$. Let $h: X_n \to M \times N$ be an equivariant map, and denote by $\pi_M: M \times N \to M$ and $\pi_N: M \times N \to N$ the projections. Then, for every $n \geq n_0$,

$$\pi_M \circ \hat{h} = \pi_M \cdot h \circ s_n = \pi_M \cdot \hat{h} \circ t_n = \pi_M \cdot \hat{h}$$

and analogously $\pi_N \circ \hat{h} = \pi_N \cdot h \circ t_n$. This implies $\hat{h}(s_n) = \hat{h}(t_n)$. Thus $M \times N$ satisfies $s_n = t_n$ for $n \geq n_0$, whence $M \times N \in \mathcal{V}(E)$.

**Closedness under submonoids.** Let $M \in \mathcal{V}(E)$ and let $m: N \to M$ be a nominal submonoid of $M$. Choose $n_0 \in \mathbb{N}$ such that $M$ satisfies all equations $s_n = t_n$ with $n \geq n_0$. Then, for each equivariant map $h: X_n \to N$ and $n \geq n_0$, one has

$$m \cdot \hat{h}(s_n) = m \cdot \hat{h}(t_n) = m \cdot \hat{h}(t_n).$$

Since $m$ is monomorphic, this implies that $\hat{h}(s_n) = \hat{h}(t_n)$. Thus, $N$ satisfies $s_n = t_n$ for $n \geq n_0$, whence $N \in \mathcal{V}(E)$.

**Closedness under quotient monoids.** Let $M \in \mathcal{V}(E)$ and let $e: M \to N$ be a support-reflecting surjective equivariant monoid morphism. Choose $n_0 \in \mathbb{N}$ such that $M$ satisfies all equations $s_n = t_n$ with $n \geq n_0$. Given an equivariant map $h: X_n \to N$, since $e$ is support-reflecting, there exists an equivariant map $g: X_n \to M$ with $h = e \cdot g$, see Lemma A.12. It follows that, for each $n \geq n_0$,

$$\hat{h}(s_n) = e \cdot \hat{g}(s_n) = e \cdot \hat{g}(t_n) = e \cdot \hat{g}(t_n) = \hat{h}(t_n).$$

Thus $N$ satisfies $s_n = t_n$ for $n \geq n_0$, whence $N \in \mathcal{V}(E)$.

**Proof of the “only if” direction**

Let $\mathcal{V}$ be a weak pseudovariety of nominal monoids. We need to find a sequence $E$ of equations with $\mathcal{V} = \mathcal{V}(E)$.

1. First, we prove that there exists a sequence of monoids $M_0, M_1, M_2, \ldots \in \mathcal{V}$ such that every $M \in \mathcal{V}$ is a support-reflecting quotient of $M_n$ for all but finitely many $n$. To see this, let $S_0, S_1, S_2, \ldots$ be the countably many elements of $\mathcal{V}$ up to isomorphism (see Remark A.15), and put

$$M_n = S_0 \times S_1 \times \cdots \times S_n \quad \text{for } n \geq 0.$$
For each $M \in \mathcal{V}$ one has $M \cong S_m$ for some $m \geq 0$. Then, for $n \geq m$, we obtain the surjective morphism $M_n \twoheadrightarrow M$ given by the projection

$$M_n = S_0 \times S_1 \times \cdots \times S_n \xrightarrow{\pi_{n,m}} S_m \cong M.$$ 

Note that $\pi_{n,m}$ is support-reflecting: for each $s \in S_m$ one has

$$\pi_{n,m}(1,\ldots,1,s,1,\ldots,1) = s,$$

and since the unit 1 of each nominal monoid has empty support, one has $\text{supp}_{M_n}(1,\ldots,1,s,1,\ldots,1) = \text{supp}_{S_m} s$. Thus, we have shown that $M$ is a support-reflecting quotient of $M_n$ for each $n \geq m$.

(2) Let $X_0, X_1, X_2, \ldots$ be a sequence that enumerates all orbit-finite strong nominal sets (up to isomorphism); cf. Remark A.15. For each $n \geq 0$, consider the following congruence $\equiv_n$ on $X_n^*$:

$$s \equiv_n t \iff h(s) = h(t) \text{ for all morphisms } h: X_n^* \rightarrow M_n.$$ 

In other words, $\equiv_n$ is the set of all equations over $X_n$ satisfied by $M_n$. We claim that

$$X_n^*/\equiv_n \in \mathcal{V} \text{ for all } n \in \mathbb{N}.$$ 

To see this, note first that there are only finitely many morphisms $X_n^* \rightarrow M_n$: such a morphism bijectively corresponds to an equivariant map $X_n \rightarrow M_n$, which in turn corresponds to a map of supported sets $Y_n \rightarrow M_n$, where $Y_n$ is a finite supported set with $X_n \cong F(Y_n)$ (see Lemma A.2 and A.3). Since $M_n$ contains only finitely many elements of any given support by Lemma A.5, there exist only finitely many such maps.

Letting $h_0, \ldots, h_p$ denote the morphisms from $X_n^*$ to $M_n$, the induced morphism

$$(h_i)_{1 \leq i \leq p}: X_n^* \rightarrow \prod_{i \leq p} M_n$$

has kernel $\equiv_n$. Thus, we can conclude that $X_n^*/\equiv_n$ is a submonoid of the finite product $\prod_i M_n$, and therefore it lies in $\mathcal{V}$.

(3) Since $X_n^*/\equiv_n \in \mathcal{V}$ by part (2) above, $\equiv_n$ is an orbit-finite congruence on $X_n^*$ for each $n \geq 0$. Therefore, by Lemma A.14, there exists a finite generating subset $W_n$ of $\equiv_n$. We may assume that $W_n$ is nonempty, so that $\bigcup_n W_n$ is a countably infinite set of equations. Let $E = \langle s_k = t_k \rangle_{k \in \mathbb{N}}$ be a sequence that enumerates all equations in $\bigcup_n W_n$. We claim that $\mathcal{V} = \mathcal{V}(E)$.

To prove “$\subseteq$”, let $M \in \mathcal{V}$. By Part (1), there exists $m \geq 0$ such that $M$ is a support-reflecting quotient of $M_n$ for each $n \geq m$. Since $M_n$ satisfies all equations in $W_n$, it follows that also $M$ satisfies them for $n \geq m$ (using that satisfaction of equations is preserved by support-reflecting quotients, as shown in the “only if” direction of our proof). Thus $M$ satisfies all equations in $\bigcup_{n \geq m} W_n$, i.e. it eventually satisfies $E$.

For the proof of “$\supseteq$”, let $M \in \mathcal{V}(E)$. Note that there are infinitely many $n \in \mathbb{N}$ such that a support-reflecting quotient $h: X_n^* \rightarrow M$ exists (indeed, one may take any orbit-finite strong nominal set $X_n$ of the form $\Delta^{k_0} + \cdots + \Delta^{k_{m-1}} + \Delta^k$, where $m$ is the number of orbits of $M$, $k_i$ is the size of the least support of any element of the $i$th orbit, and $k$ is any natural number with $k \geq k_0$). In particular, since $M$ satisfies all but finitely many of the equations in $E$, one can choose $n \in \mathbb{N}$ such that (a) $M$ satisfies the equations in $W_n$, and (b) a support-reflecting quotient $h: X_n^* \rightarrow M$ exists. Then

$$h(s) = h(t) \text{ for all } (s,t) \in W_n,$$
that is, $W_n$ is contained in the kernel of $h$. Since $W_n$ generates $\equiv_n$, it follows that also $\equiv_n$ is contained in the kernel of $h$. The Homomorphism Theorem A.13 then yields a morphism $e: X^*_n/\equiv_n \to M$ with $h = e \cdot q$, where $q$ is the quotient corresponding to $\equiv_n$:

\[
\begin{array}{c}
X^*_n \xrightarrow{q} X^*_n/\equiv_n \\
\downarrow h \quad \downarrow e \\
M
\end{array}
\]

Note that $e$ is support-reflecting because $h$ is. Since $X^*_n/\equiv_n \in \mathcal{V}$ by part (2) and $\mathcal{V}$ is closed under support-reflecting quotients, we conclude that $M \in \mathcal{V}$. ▶

**Details for Example 3.12**

We show that an orbit-finite nominal monoid $M$ is aperiodic if and only if it eventually satisfies the equations

\[
y : S_n \vdash y^{n+1} = y^n \quad (n \in \mathbb{N}),
\]

where $S_n = \{a_0, a_1, \ldots, a_{n-1}\}$ is the set of the first $n$ atoms in the countably infinite set $\mathcal{A} = \{a_0, a_1, a_2, \ldots\}$ of all atoms, and we write $y$ for $(\text{id}, y) \in \text{Perm} (\mathcal{A}) \times Y$.

For the “if” direction, suppose that $M$ is aperiodic, i.e. there exists a natural number $m \geq 1$ such that $x^{n+1} = x^n$ for every $x \in M$. This implies that $x^{n+1} = x^n$ for all $n \geq m$ and $x \in M$. In particular, this holds for all elements $x$ with support $S_n$, i.e. (2) is satisfied for all $n \geq m$.

For the “only if” direction, suppose that $M$ eventually satisfies the equations (2). Choose $n \in \mathbb{N}$ such that $M$ satisfies the equation $y : S_n \vdash y^{n+1} = y^n$ and every element of $M$ has a support of size $n$. Given any element $x \in M$, choose a finite permutation $\pi \in \text{Perm}(\mathcal{A})$ that maps a support of $x$ to $S_n$. The $\pi \cdot x$ is as element with support $S_n$, and thus $(\pi \cdot x)^{n+1} = (\pi \cdot x)^n$ holds. This implies $x^{n+1} = x^n$ because the monoid multiplication on $M$ is equivariant. Thus, $M$ is aperiodic.

**Proof of Theorem 4.2**

Recall that $\text{Nom}_{fs}$ denotes the category of nominal sets and finitely supported maps and $\text{nCABA}_{fs}$ the category of ncabas and finitely supported boolean homomorphisms preserving suprema of finitely supported subsets. We know from Petrişan [17, Prop. 5.3.11] that the categories $\text{nCABA}$ and $\text{Nom}$ are dually equivalent with the equivalence functors being the restrictions of the ones in Remark 4.3. Thus, in order to obtain the desired result we prove the following

▶ **Proposition A.16.** The dual equivalence $\text{Nom}_{fs} \xrightarrow{\sim} \text{nCABA}_{fs}$ extends to a dual equivalence $\text{Nom}_{fs}^{op} \xrightarrow{\sim} \text{nCABA}_{fs}^{op}$ given by $X \mapsto \mathcal{P}X$ and $f \mapsto f^{-1}$.

**Proof.** We first show that the above functor $\text{Nom}_{fs}^{op} \to \text{nCABA}_{fs}^{op}$ is well-defined, that is, for every finitely supported map $f: Y \to X$ the map $f^{-1}: \mathcal{P}X \to \mathcal{P}Y$ is also finitely supported. Let $S \subseteq \mathcal{A}$ be a finite support of $f$. Then for every $X_0 \in \mathcal{P}X$ and $\pi \in \text{Perm}_S(\mathcal{A})$ one has
\[ \pi \cdot f^{-1}[X_0] = f^{-1}[\pi \cdot X_0] \] since, for all \( y \in Y \),

\[
y \in \pi \cdot f^{-1}[X_0] \iff \pi^{-1} \cdot y \in f^{-1}[X_0] \\
\iff f(\pi^{-1} \cdot y) \in X_0 \\
\iff \pi^{-1} \cdot f(y) \in X_0 \\
\iff f(y) \in \pi \cdot X_0 \\
\iff y \in f^{-1}[\pi \cdot X_0]
\]

This proves that \( f^{-1} \) has support \( S \).

It remains to verify that the functor \( \text{Nom}^\text{op}_\mathbb{A} \to \text{nCABA}_\mathbb{A} \) is (1) essentially surjective on objects, (2) faithful and (3) full. Point (1) is clear because on objects the functor coincides with the equivalence functor \( \text{Nom} \cong \text{nCABA}^\text{op} \). For (2), suppose that \( f \neq g : Y \to X \) are two distinct finitely supported maps. Choose \( y \in Y \) with \( f(y) \neq g(y) \). Since the singleton \( \{ f(y) \} \) is finitely supported, we may apply \( f^{-1} \) and \( g^{-1} \) to it, and we clearly have \( f^{-1}(\{ f(y) \}) \neq g^{-1}(\{ f(y) \}) \). Thus \( f^{-1} \neq g^{-1} \). For (3), let \( g : PX \to PY \) be a morphism in \( \text{nCABA}_\mathbb{A} \) with finite support \( S \subseteq \mathbb{A} \). Then the sets \( g(\{ x \}) \subseteq Y \) \((x \in X)\) form a partition of \( Y \) since \( g \) is a homomorphism of boolean algebras, i.e. for every \( y \in Y \) there exists a unique \( x_y \in X \) with \( y \in g(\{ x_y \}) \). Consider the map \( f : Y \to X \) defined by \( f(y) := x_y \). We claim that \( f \) has support \( S \). To see this, let \( \pi \in \text{Perm}_s(\mathbb{A}) \). Then we have \( \pi \cdot g(\{ x \}) = g(\{ \pi \cdot x \}) \) for every \( x \in X \). Since \( f(y) = x_y \) where \( y \in g(\{ x_y \}) \) we know \( \pi \cdot g(\{ x_y \}) = g(\{ \pi \cdot x_y \}) \), hence, \( f(\pi \cdot y) = \pi \cdot x_y = f(y) \) as desired.

Finally, we show that \( g = f^{-1} \). By the definition of \( f \) the two maps agree on singleton sets \( \{ x \} \). It follows that they agree on all finitely supported subsets of \( X \): every such set can be expressed as the finitely supported union of its singleton subsets, and both \( g \) and \( f^{-1} \) preserve that union.

\[ \text{Details for Example 4.6} \]

(1) See Remark 4.8.
(2) We prove that the language \( L = a\mathbb{A}^* \) (for a fixed atom \( a \in \mathbb{A} \)) is recognizable. Consider the orbit-finite monoid \( M = \{1\} + \mathbb{A} \) with multiplication given by

\[ b \cdot c = b \quad \text{for all } b, c \in \mathbb{A}. \]

Let \( e : \mathbb{A}^* \to M \) be the unique morphism given by \( b \mapsto b \). Thus \( e \) maps \( \varepsilon \) to 1 and every word \( bw \ (w \in \Sigma^*, b \in \mathbb{A}) \) to \( b \). It follows that

\[ L = e^{-1}\{a\}. \]

Since \( \{a\} \) is a finitely supported subset of \( \mathbb{A} \), this shows that \( e \) recognizes \( L \).
(3)–(5) are equivariant languages and were treated in [5, 19].
(6) We prove that the language \( L = \mathbb{A}^* a \mathbb{A}^* \) (for a fixed atom \( a \in \mathbb{A} \)) is not recognizable. Suppose for the contrary that there exists an equivariant monoid morphism \( e : \mathbb{A}^* \to M \) into an orbit-finite monoid \( M \) that recognizes \( L \). We claim that

\[ \text{supp}(e(w)) = \text{supp}(w) \quad \text{for every } w \in \mathbb{A}^* \setminus L. \]

Since \( \mathbb{A}^* \) contains words of arbitrarily large finite support, this implies that also \( M \) contains elements of arbitrarily large finite support, contradicting the assumption that \( M \) is orbit-finite.
To prove the above equation, note that $\text{supp}(e(w)) \subseteq \text{supp}(w)$ holds by equivariance of $e$. For the reverse inclusion, let $w \in \mathbb{A}^* \setminus L$ and $b \in \text{supp}(w)$, i.e. $w$ contains the letter $b$ but not the letter $a$. Suppose for the sake of contradiction that $b \notin \text{supp}(e(w))$. Then $a, b \notin \text{supp}(e(w))$ and thus

$$e(w) = (a) \cdot e(w) = e((a) \cdot w),$$

where $(a) \in \text{Perm}(\mathbb{A})$ denotes the permutation that swaps $a$ and $b$ and leaves all other atoms fixed. But we have $w \notin L$ and $(a) \cdot w \in L$, which implies that $e(w) \neq e((a) \cdot w)$.

**Proof of Lemma 4.10**

For a given set $W \subseteq \mathcal{P} \Sigma^*$ of recognizable languages we denote by $\langle W \rangle \subseteq \mathcal{P} \Sigma^*$ the subobject of $\mathcal{P} \Sigma^*$ in $\text{ncABA}$ generated by $W$, obtained by closing $W$ under the group action, boolean operations, and unions of finitely supported subsets. Note that if $W$ is closed under derivatives, then so is $\langle W \rangle$, i.e. $\langle W \rangle$ is then a local variety. This follows from the following identities:

$$w^{-1}(K \cup L) = w^{-1}K \cup w^{-1}L,$$

$$w^{-1}(K \cap L) = w^{-1}K \cap w^{-1}L,$$

$$w^{-1}(\Sigma^* \setminus L) = \Sigma^* \setminus w^{-1}L,$$

$$w^{-1}(\bigcup_{j \in J} L_j) = \bigcup_{j \in J} L_j,$$

$$w^{-1}(\pi \cdot L) = \pi \cdot ((\pi^{-1} \cdot w)L),$$

for all $w \in \Sigma^*$, languages $K, L, L_j \subseteq \Sigma^*$ and $\pi \in \text{Perm}(\mathbb{A})$.

(1) Given an ideal of atom-finite local varieties $\mathcal{V}_{\Sigma,i} \subseteq \mathcal{P} \Sigma^*$ ($i \in I$), the directed union $\mathcal{V}_{\Sigma} = \bigcup_i \mathcal{V}_{\Sigma,i}$ is a local variety. Indeed, to see that $\mathcal{V}_{\Sigma}$ is closed under unions of $S$-orbits for every finite $S \subseteq \mathbb{A}$, suppose that $W \subseteq \mathcal{V}_{\Sigma}$ is an $S$-orbit. Then $W \subseteq \mathcal{V}_{\Sigma,i}$ for some $i$ because every $\mathcal{V}_{\Sigma,i}$ is an equivariant subset of $\mathcal{P} \Sigma^*$. Since $\mathcal{V}_{\Sigma,i}$ is closed under unions $S$-orbits, we get $\bigcup W \in \mathcal{V}_{\Sigma,i} \subseteq \mathcal{V}_{\Sigma}$. To show that $\mathcal{V}_{\Sigma}$ is closed under finite union, let $K, L \in \mathcal{V}_{\Sigma}$. Then, since the $\mathcal{V}_{\Sigma,i}$ form a directed set, there exists $i \in I$ with $K, L \in \mathcal{V}_{\Sigma,i}$. Thus $K \cup L \in \mathcal{V}_{\Sigma,i} \subseteq \mathcal{V}_{\Sigma}$ because $\mathcal{V}_{\Sigma,i}$ is closed under finite union. That $\mathcal{V}_{\Sigma}$ is closed under the remaining boolean operations, derivatives, and the group action is shown in the same way.

(2) Given a local variety $\mathcal{V}_{\Sigma} \subseteq \mathcal{P} \Sigma^*$, form the family $\mathcal{V}_{\Sigma,i} \subseteq \mathcal{P} \Sigma^*$ ($i \in I$) of all atom-finite local subvarieties of $\mathcal{V}_{\Sigma}$. We claim that this family forms an ideal. Clearly, it is downwards closed. To show that it is upwards directed, it suffices to verify that for every $i, j \in I$ the local variety $\langle \mathcal{V}_{\Sigma,i} \cup \mathcal{V}_{\Sigma,j} \rangle$ is atom-finite. Let $e_i : \Sigma^* \twoheadrightarrow M_i$ and $e_j : \Sigma^* \twoheadrightarrow M_j$ be the $\Sigma$-generated orbit-finite quotient monoids corresponding to $\mathcal{V}_{\Sigma,i}$ and $\mathcal{V}_{\Sigma,j}$ by the Finite Local Variety Theorem 4.9. Form their subdirect product, i.e. the coimage $e : \Sigma^* \twoheadrightarrow M$ of the map $(e_i, e_j) : \Sigma^* \twoheadrightarrow M_i \times M_j$. Then $e$ is the infimum of $e_i$ and $e_j$ in the lattice of quotients (in $\text{Nom}$) of $\Sigma^*$. Thus $e$ dualizes to $\langle \mathcal{V}_{\Sigma,i} \cup \mathcal{V}_{\Sigma,j} \rangle$, the supremum of $\mathcal{V}_{\Sigma,i}$ and $\mathcal{V}_{\Sigma,j}$ in the lattice of subobjects of $\mathcal{P} \Sigma^*$ in $\text{ncABA}$. Moreover, since $M$ is orbit-finite, $\langle \mathcal{V}_{\Sigma,i} \cup \mathcal{V}_{\Sigma,j} \rangle$ is atom-finite.

(3) It remains to show that the constructions of (1) and (2) are mutually inverse. First, given an ideal of atom-finite local varieties $\mathcal{V}_{\Sigma,i} \subseteq \mathcal{P} \Sigma^*$ ($i \in I$) and an atom-finite local subvariety $\mathcal{W}_{\Sigma} \subseteq \bigcup_i \mathcal{V}_{\Sigma,i}$ we need to prove that $\mathcal{W}_{\Sigma} = \mathcal{V}_{\Sigma,i}$ for some $i$. Let $L_1, \ldots, L_n$ be the finitely many atoms of $\mathcal{W}_{\Sigma}$ up to application of the group action. By the ideal property, we may assume that $L_1, \ldots, L_n \in \mathcal{V}_{\Sigma,j}$ for some $j \in I$. Since every element $L$ of the ncaba $\mathcal{W}_{\Sigma}$ can be expressed as the union of all atoms below it, and the set of these atoms is a finite union
of $S$-orbits for some finite $S \subseteq \Delta$ (cf. Remark 4.3), one has $W_{\Sigma} = \langle L_1, \ldots, L_n \rangle \subseteq V_{\Sigma,i}$ and thus $W_{\Sigma} = V_{\Sigma,i}$ for some $i$ by down-closure.

(4) Conversely, let $V_{\Sigma} \subseteq \mathcal{P}\Sigma^*$ be a local variety and let $V_{\Sigma,i}$ $(i \in I)$ be the ideal of its atom-finite local subvarieties. Clearly, we have $\bigcup_i V_{\Sigma,i} \subseteq V_{\Sigma}$, so we only need to show $V_{\Sigma} \subseteq \bigcup_i V_{\Sigma,i}$. For every $L \in V_{\Sigma}$, since $L$ is recognizable, there exists an orbit-finite quotient monoid $e: \Sigma^* \twoheadrightarrow M$ recognizing $L$. By the Finite Local Variety Theorem 4.9, the quotient $e$ dualizes to an atom-finite local variety $W_{\Sigma} \subseteq \mathcal{P}\Sigma^*$ containing $L$. Then $V_{\Sigma,i} := W_{\Sigma} \cap V_{\Sigma}$ is an atom-finite local subvariety of $V_{\Sigma}$ containing $L$, i.e. $L \in V_{\Sigma,i} \subseteq \bigcup_i V_{\Sigma,i}$.

\section*{Proof of Theorem 4.15}

The proof boils down to the observation that varieties can be interpreted as the dual concept of an equational theory. By the Local Variety Theorem, a collection $V = (V_{\Sigma} \subseteq \mathcal{P}\Sigma^*)_{\Sigma \in \text{Nom}^{\text{st}}}$ of local varieties of data languages corresponds bijectively to a collection $\mathcal{F} = (\mathcal{F}_X \subseteq X^*\text{-Mon}^{\text{st}})_{X \in \text{Nom}^{\text{st}}}$ of local pseudovarieties of nominal monoids. We claim that

(1) $\mathcal{F}$ is substitution-invariant if and only if $V$ is closed under preimages, and

(2) $\mathcal{F}$ is complete if and only if $V$ is complete.

In particular, $\mathcal{F}$ is an equational theory if and only if $V$ is variety. Together with Theorem 3.8, this proves the theorem.

\textbf{Proof of (1).} By the Finite Local Variety Theorem 4.9 and Lemma 4.10, the substitution invariance of $\mathcal{F}$ dualizes to the statement that for every atom-finite local subvariety $V_{\Sigma}^*$ of $V_{\Sigma}$ and every $h: \Delta^* \rightarrow \Sigma^*$, there exists an atom-finite local subvariety $V_{\Sigma}^*$ of $V_{\Sigma}$ that contains the preimage $h^{-1}[L]$ for each $L \in V_{\Sigma}^*$.

\[\begin{array}{ccc}
\Delta^* & \xrightarrow{h} & \Sigma^* \\
eq \downarrow & \quad & \downarrow \neq \\
M_{\Delta} & \rightarrow & M_{\Sigma}
\end{array}\quad \begin{array}{ccc}
\mathcal{P}\Delta^* & \leftarrow \leftarrow & \mathcal{P}\Sigma^* \\
eg \downarrow & \quad & \neg \downarrow \\
V_{\Delta} & \leftarrow & V_{\Sigma}
\end{array}\]

By Lemma 4.10, every language in $V_{\Sigma}$ is contained in some atom-finite subvariety $V_{\Sigma}^*$. Hence, the commutativity of the right-hand diagram above implies that $V$ is closed under preimages. Conversely, suppose that $V$ is closed under preimages, and let $V_{\Sigma}$ be an atom-finite local subvariety of $V_{\Sigma}$. Thus, there are atomic languages $L_1, \ldots, L_n \in V_{\Sigma}$ such that every other atomic language in $V_{\Sigma}$ is of the form $\pi \cdot L_i$ for some $\pi \in \text{Perm}(\Delta)$ and $i \in \{1, \ldots, n\}$. By closure of $V$ under preimages, one has $h^{-1}[L_i] \in V_{\Sigma}$ for all $i$. Choose an atom-finite local subvariety $V_{\Delta,i}$ of $V_{\Sigma}$ containing $L_i$. Since the atom-finite local subvarieties of $V_{\Gamma}$ form an ideal (i.e. are upwards directed), we can choose an atom-finite local subvariety $V_{\Delta}$ containing all $V_{\Delta,i}$’s. Thus $h^{-1}[L_i] \in V_{\Delta}$ for all $i$. By Remark 4.3, every language $L \in V_{\Sigma}$ can be expressed as a finite union $L = K_0 \cup \ldots \cup K_m$, where every $K_i$ is the union of an $S$-orbit in $V_{\Sigma}$. Since the equivariant map $h^{-1}$ maps $S$-orbits to $S$-orbits, and $V_{\Delta}$ is closed under finite unions and unions of $S$-orbits, it follows that $h^{-1}[L] = h^{-1}[K_1] \cup \ldots \cup h^{-1}[K_m]$ lies in $V_{\Delta}$.

\textbf{Proof of (2).} Suppose that $\mathcal{F}$ is complete, let $V_{\Sigma}$ be an atom-finite local subvariety of $V_{\Sigma}$, and let $e_{\Sigma}: \Sigma^* \rightarrow M_{\Sigma}$ be its dual quotient in $\mathcal{F}_{\Sigma}$. Then there exists $\Delta \in \text{Nom}^{\text{st}}$ and a support-reflecting quotient $e_{\Delta}: \Delta^* \rightarrow M_{\Delta}$ in $\mathcal{F}_{\Delta}$ with $M_{\Delta} \cong M_{\Sigma}$. By projectivity (see Lemma A.12), we can choose an equivariant monoid morphism $h: \Sigma^* \rightarrow \Delta^*$ with $e_{\Delta} \cdot h = e_{\Sigma}$. Letting $V_{\Delta}$ denote the atom-finite local subvariety of $V_{\Delta}$ dual to $e_{\Delta}$, we thus obtain the two
The right-hand diagram shows that the map $L \mapsto h^{-1}[L]$ from $V'_\Delta$ to $V'_\Sigma$ is bijective. Moreover, by Theorem 4.9, $M_\Delta$ is (up to isomorphism) carried by the set of atomic languages in $V'_\Delta$, and $e_\Delta$ is the morphism mapping every word $w \in \Delta^*$ to the unique atomic language in $V'_\Delta$ containing $w$. That $e_\Delta$ is support-reflecting thus means precisely that every atomic language $L \in V'_\Delta$ contains a word $w \in L$ with $\text{supp}_{P\Delta^*}(L) = \text{supp}_{\Delta^*}(w)$. This shows that $\mathcal{V}$ is complete.

Conversely, suppose that $\mathcal{V}$ is complete, and let $e_\Sigma: \Sigma^* \to M_\Sigma$ be a quotient in $\mathcal{F}_\Sigma$. Then, for its dual atom-finite local subvariety $V'_\Sigma$ of $V_\Sigma$, we have that there exists a morphism $h: \Sigma^* \to \Delta^*$ and an atom-finite local subvariety $V'_\Delta$ of $V_\Delta$ satisfying the conditions (a) and (b) from Definition 4.13(2). Condition (a) means precisely that we have the right-hand commutative square above. Thus, letting $e_\Delta: \Delta^* \to M_\Delta$ denote the quotient in $\mathcal{F}_\Delta$ that dually corresponds to $V'_\Delta$, we obtain the left-hand diagram above. Moreover, condition (b) states that $e_\Delta$ is support-reflecting. Thus $\mathcal{F}$ is complete. ◀