

Generators and Bases for Monadic Closures

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Abstract

It is well-known that every regular language admits a unique minimal deterministic acceptor. Establishing an analogous result for non-deterministic acceptors is significantly more difficult, but nonetheless of great practical importance. To tackle this issue, a number of sub-classes of non-deterministic automata have been identified, all admitting canonical minimal representatives. In previous work, we have shown that such representatives can be recovered categorically in two steps. First, one constructs the minimal bialgebra accepting a given regular language, by closing the minimal coalgebra with additional algebraic structure over a monad. Second, one identifies canonical generators for the algebraic part of the bialgebra, to derive an equivalent coalgebra with side effects in a monad. In this paper, we further develop the general theory underlying these two steps. On the one hand, we show that deriving a minimal bialgebra from a minimal coalgebra can be realized by applying a monad on an appropriate category of subobjects. On the other hand, we explore the abstract theory of generators and bases for algebras over a monad.

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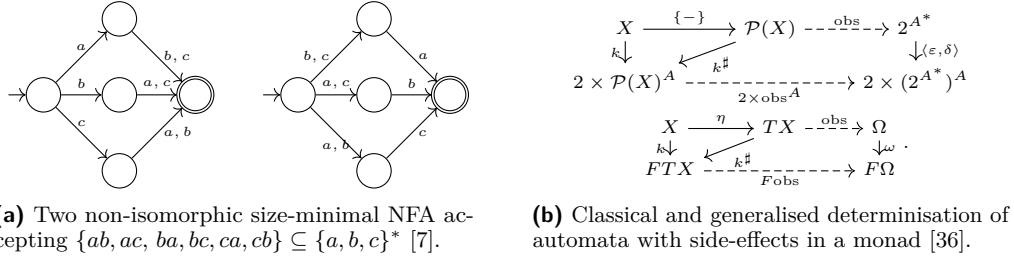
1 Introduction

The existence of a unique minimal *deterministic* finite automaton is an important property of regular languages [30]. Establishing a similar result for *non-deterministic* finite automata is of great importance, as non-deterministic automata can be exponentially more succinct than deterministic ones, but turns out to be surprisingly difficult. The main problem is that a regular language can be accepted by several size-minimal NFAs that are not isomorphic. An example illustrating the situation is displayed in Figure 1a.

To tackle the issue, a number of sub-classes of non-deterministic automata admitting canonical representatives have been identified [15, 16, 44, 29]. One such example is the *canonical residual finite state automaton* (short *canonical RFSA*, also known as *jiromaton*),

¹ This paper is the result of work done prior to the author's affiliation with Amazon Web Services.





■ **Figure 1** Non-isomorphic NFAs and generalised determinisation.

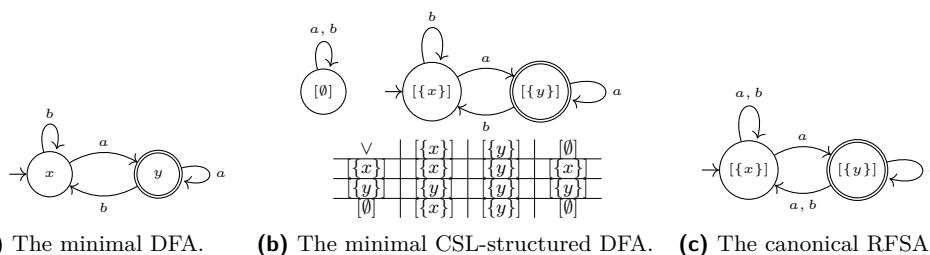
which is minimal among non-deterministic automata accepting joins of residual languages [16]. In previous work [46], we have presented a categorical framework that unifies constructions and correctness proofs of canonical non-deterministic automata and unveils new ones.

The framework adopts the well-known representation of automata as coalgebras [20, 34, 33] and side-effects like non-determinism as monads [26, 27, 28]. For instance, an NFA (without initial states) is represented as a coalgebra (X, k) with side-effects in the powerset monad $(\mathcal{P}, \{-\}, \mu)$, where X is the set of states, $k: X \rightarrow 2 \times \mathcal{P}(X)^A$ combines the function classifying each state as accepting or rejecting with the function giving the set of next states for each input, $\{-\}$ creates singleton sets, and μ takes the union of a set of sets.

To derive canonical non-deterministic acceptors, the framework suggests a procedure that is closely related to the so-called *powerset construction*. As depicted at the top of Figure 1b, the latter converts a non-deterministic finite automaton (X, k) into an equivalent deterministic finite automaton $(\mathcal{P}X, k^\sharp)$, where k^\sharp is obtained by lifting k to the subsets of X , the tuple $\langle \varepsilon, \delta \rangle$ is the automaton of languages, and the morphism obs assigns language semantics to each set of states. As seen at the bottom of Figure 1b, the construction can be generalised by replacing the functor $2 \times (-)^A$ with any (suitable) functor F describing the automaton structure, and \mathcal{P} with a monad T describing the automaton side-effects, to transform a coalgebra $k: X \rightarrow FTX$ with side-effects in T into an equivalent coalgebra $k^\sharp: TX \rightarrow FTX$ [36]. Under this perspective, $\Omega \xrightarrow{\omega} F\Omega$ is the so-called *final coalgebra*, providing a semantic universe that generalises the automaton of languages. The deterministic automata resulting from such determinisation constructions have *additional algebraic structure*: the state space $\mathcal{P}(X)$ defines a free complete join-semilattice (CSL) over X and k^\sharp is a CSL homomorphism. More generally, TX defines a (free) algebra for the monad T , and k^\sharp is a T -algebra homomorphism, thus constituting a so-called *bialgebra* over a *distributive law* relating F and T [9, 38].

Using the powerset construction, a canonical succinct acceptor for a regular language $L \subseteq A^*$ over an alphabet A can be obtained in two steps:

1. One constructs the minimal (pointed) coalgebra M_L for the functor $F = 2 \times (-)^A$ accepting L . For the case $A = \{a, b\}$ and $L = (a + b)^*a$, the coalgebra M_L is depicted in Figure 2a. Generally, it can be obtained via the Myhill-Nerode construction [30]. One then equips the former with additional algebraic structure in a monad T (which is related to F via a typically canonically³ induced distributive law). This can be done by applying the generalised determinisation procedure to M_L , when seen as coalgebra with trivial side-effects in T . By identifying semantically equivalent states one consequently derives the minimal (pointed) bialgebra for L . If $T = \mathcal{P}$ is the powerset monad, the minimal bialgebra for the language $L = (a + b)^*a$ is depicted in Figure 2b.
2. One exploits the algebraic structure underlying the minimal bialgebra for L to “reverse” the generalised determinisation procedure. That is, one identifies a minimal set of *generators* that spans the full algebraic structure, to derive an equivalent succinct automaton with



■ **Figure 2** Three automata accepting the language $(a + b)^*a \subseteq \{a, b\}^*$.

side-effects in T . For example, by choosing the *join-irreducibles*² for the CSL underlying the minimal bialgebra in Figure 2b as generators (in this case, the join-irreducibles are given by all non-zero states), one recovers the canonical acceptor in Figure 2c.

In this paper, we further develop the general theory underlying these two steps. First, we generalise the closure of a subset of an algebraic structure as a functor between categories of subobjects relative to a factorisation system. We then equip the functor with the structure of a monad. We investigate the closure of a particular subclass of subobjects: the ones that arise from the image of a morphism. We show that deriving a minimal bialgebra from a minimal coalgebra can be realized by applying the monad to a subobject in this class. Second, we define a category of algebras with generators, which is in adjunction with the category of Eilenberg-Moore algebras, and, under certain assumptions, monoidal. We generalise the matrix representation theory of vector spaces and discuss bases for bialgebras. We compare our ideas with an approach that generalises bases as coalgebras [19]. We find that a basis in our sense induces a basis in the sense of [19], and identify assumptions under which the reverse is true, too. We characterise generators for finitary varieties in the sense of universal algebra and relate our work to the theory of locally finitely presentable categories.

2 Preliminaries

We assume basic knowledge of category theory (including functors, natural transformations, adjunctions), for an overview see e.g. [8].

We briefly recall the definitions of coalgebras, monads, and Eilenberg-Moore algebras. A *coalgebra* for an endofunctor F on a category \mathcal{C} is a tuple (X, k) consisting of an object X in \mathcal{C} and a morphism $k: X \rightarrow FX$. A homomorphism $f: (X, k_X) \rightarrow (Y, k_Y)$ between coalgebras for F is a morphism $f: X \rightarrow Y$ in \mathcal{C} satisfying $k_Y \circ f = Ff \circ k_X$. The category of coalgebras for F and homomorphisms is denoted by $\text{Coalg}(F)$.

A *monad* on a category \mathcal{C} is a tuple (T, η, μ) consisting of an endofunctor $T: \mathcal{C} \rightarrow \mathcal{C}$ and natural transformations $\eta: \text{id}_{\mathcal{C}} \Rightarrow T$ and $\mu: T^2 \Rightarrow T$ satisfying $\mu \circ T\mu = \mu \circ \mu_T$ and $\mu \circ \eta_T = \text{id}_T = \mu \circ T\eta$. A morphism $(F, \alpha): (\mathcal{C}, S) \rightarrow (\mathcal{D}, T)$ between a monad S on a category \mathcal{C} and a monad T on a category \mathcal{D} consists of a functor $F: \mathcal{C} \rightarrow \mathcal{D}$ and a natural transformation $\alpha: TF \Rightarrow FS$ satisfying $\alpha \circ \eta^T F = F\eta^S$ and $F\mu^S \circ \alpha S \circ T\alpha = \alpha \circ \mu^T F$ [37]. The composition of two monad morphisms $(F, \alpha): (\mathcal{C}, S) \rightarrow (\mathcal{D}, T)$ and $(G, \beta): (\mathcal{D}, T) \rightarrow (\mathcal{E}, U)$ is the monad morphism $(GF, G\alpha \circ \beta F): (\mathcal{C}, S) \rightarrow (\mathcal{E}, U)$ [37]. Two well-known monads on the category of sets and functions are the *powerset monad* \mathcal{P} and the *free \mathbb{K} -vector space monad* $\mathcal{V}_{\mathbb{K}}$ [46].

² A *join-irreducible* is a non-zero element a satisfying, for all $y, z \in L$ with $a = y \vee z$, that $a = y$ or $a = z$.

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An *Eilenberg-Moore algebra* over a monad T on \mathcal{C} is a tuple (X, h) consisting of an object X in \mathcal{C} and a morphism $h : TX \rightarrow X$ satisfying $h \circ \mu_X = h \circ Th$ and $h \circ \eta_X = \text{id}_X$. A homomorphism $f : (X, h_X) \rightarrow (Y, h_Y)$ between Eilenberg-Moore algebras over T is a morphism $f : X \rightarrow Y$ in \mathcal{C} satisfying $h_Y \circ Tf = f \circ h_X$. The category of Eilenberg-Moore algebras over T is denoted by \mathcal{C}^T . One can show that the category of algebras over \mathcal{P} is isomorphic to the category of complete join-semi lattices, and the category of algebras over $\mathcal{V}_{\mathbb{K}}$ is isomorphic to the category of \mathbb{K} -vector spaces.

We now introduce other notions that are necessary to follow our technical development: distributive laws, bialgebras, and generators and bases for algebras over a monad.

Distributive laws have originally occurred as a way to compose monads [9], but now also exist in a wide range of other forms [38]. For our case it is sufficient to consider distributive laws between a monad and an endofunctor, sometimes called *Eilenberg-Moore laws* [21].

► **Definition 1** (Distributive Law). *A distributive law between a monad T and an endofunctor F on \mathcal{C} is a natural transformation $\lambda : TF \Rightarrow FT$ satisfying $F\eta_X = \lambda_X \circ \eta_{FX}$ and $\lambda_X \circ \mu_{FX} = F\mu_X \circ \lambda_{TX} \circ T\lambda_X$.*

Given a distributive law, one can model the determinisation of a system with dynamics in F and side-effects in T by lifting a FT -coalgebra (X, k) to the F -coalgebra (TX, k^\sharp) , where $k^\sharp := (F\mu_X \circ \lambda_{TX}) \circ Tk$. As one verifies, k^\sharp is a T -algebra homomorphism of type $(TX, \mu_X) \rightarrow (FTX, F\mu_X \circ \lambda_{TX})$. There exists a distributive law for which the lifting k^\sharp is the DFA in CSL obtained from an NFA k via the classical powerset construction [36].

The example illustrates the concept of a bialgebra: the algebraic part (TX, μ_X) and the coalgebraic part (TX, k^\sharp) of a lifted automaton are compatible along the distributive law λ .

► **Definition 2** (Bialgebra). *A λ -bialgebra is a tuple (X, h, k) consisting of a T -algebra (X, h) and an F -coalgebra (X, k) satisfying $Fh \circ \lambda_X \circ Tk = k \circ h$.*

A homomorphism between λ -bialgebras is a morphism between the underlying objects that is simultaneously a T -algebra homomorphism and an F -coalgebra homomorphism. The category of λ -bialgebras and homomorphisms is denoted by $\text{Bialg}(\lambda)$.

The generalised determinisation can be rephrased as a functor exp_T that *expands* a F -coalgebra with side-effects in T into a λ -bialgebra. We will also refer to the functor free_T that arises from exp_T by pre-composition with the canonical embedding of F -coalgebras into FT -coalgebras, therefore assigning to a F -coalgebra the λ -bialgebra it *freely* generates.

► **Lemma 3** ([21]).

- Defining $\text{exp}_T(X, k) := (TX, \mu_X, F\mu_X \circ \lambda_{TX} \circ Tk)$ and $\text{exp}_T(f) := Tf$ yields a functor $\text{exp}_T : \text{Coalg}(F) \rightarrow \text{Bialg}(\lambda)$.
- Defining $\text{free}_T(X, k) := (TX, \mu_X, \lambda_X \circ Tk)$ and $\text{free}_T(f) := Tf$ yields a functor $\text{free}_T : \text{Coalg}(F) \rightarrow \text{Bialg}(\lambda)$ satisfying $\text{free}_T(X, k) = \text{exp}_T(X, F\eta_X \circ k)$.

The last ingredient is a generalisation of generators for structures such as vector spaces.

► **Definition 4** (Generator and Basis [46]). *A generator for a T -algebra (X, h) is a tuple (Y, i, d) consisting of an object Y , a morphism $i : Y \rightarrow X$, and a morphism $d : X \rightarrow TY$ such that $(h \circ Ti) \circ d = \text{id}_X$. A generator is called a *basis* if it additionally satisfies $d \circ (h \circ Ti) = \text{id}_{TY}$.*

A generator for a T -algebra is called a *scoop* by Arbib and Manes [6]. Intuitively, a set Y embedded into an algebraic structure X via i is a generator for the latter if every element $x \in X$ admits a decomposition into a *formal* combination $d(x) \in TY$ of elements of Y that evaluates to x via the interpretation $h \circ Ti$. If the decomposition is moreover *unique*, that is,

$h \circ Ti$ is not only a *surjection* with right-inverse d , but a *bijection* with two-sided inverse d , then a generator is called a basis. Every T -algebra (X, h) is generated by (X, id_X, η_X) and admits a basis iff it is isomorphic to a free algebra.

► **Example 5.**

- A tuple (Y, i, d) is a generator for a \mathcal{P} -algebra $L = (X, h) \simeq (X, \vee^h)$ iff $x = \vee_{y \in d(x)}^h i(y)$ for all $x \in X$, where we write \vee^h for the complete join-semilattice structure induced by h . In the case that $Y \subseteq X$ is a subset, one typically defines $i(y) = y$ for all $y \in Y$. If L satisfies the descending chain condition, which is in particular the case if X is finite, then defining $i(y) = y$ and $d(x) = \{y \in J(L) \mid y \leq x\}$ turns the set of join-irreducibles $J(L)$ into a size-minimal generator $(J(L), i, d)$ for L [46].
- A tuple (Y, i, d) is a generator for a $\mathcal{V}_{\mathbb{K}}$ -algebra $V = (X, h) \simeq (X, +^h, \cdot^h)$ iff $x = \sum_{y \in Y}^h d(x)(y) \cdot^h i(y)$ for all $x \in X$, where we write $+^h$ and \cdot^h for the \mathbb{K} -vector space structure induced by h . As every vector space can be equipped with a basis, every $\mathcal{V}_{\mathbb{K}}$ -algebra V admits a basis. One can show that a basis is a size-minimal generator [46].

A central result in [46] shows that it is enough to find generators for the underlying algebra of a bialgebra to derive an equivalent free bialgebra. This is because the algebraic and coalgebraic components are tightly intertwined via a distributive law.

► **Proposition 6** ([46]). *Let (X, h, k) be a λ -bialgebra and let (Y, i, d) be a generator for the T -algebra (X, h) . Then $h \circ Ti: \exp_T(Y, Fd \circ k \circ i) \rightarrow (X, h, k)$ is a λ -bialgebra homomorphism.*

3 Step 1: Closure

In this section, we further explore the categorical construction of minimal canonical acceptors given in [46]. In particular, we show that deriving a minimal bialgebra from a minimal coalgebra by closing the latter with additional algebraic structure has a direct analogue in universal algebra: taking the closure of a subset of an algebra.

3.1 Factorisation Systems and Subobjects

In the category of sets and functions, every morphism can be factored into a surjection onto its image followed by an injection into the codomain of the morphism. In this section we recall a convenient abstraction of this phenomenon for arbitrary categories. The ideas are well established [13, 32, 25]. We choose to adapt the formalism of [2].

► **Definition 7** (Factorisation System). *Let \mathcal{E} and \mathcal{M} be classes of morphisms in a category \mathcal{C} . We call the tuple $(\mathcal{E}, \mathcal{M})$ a factorisation system for \mathcal{C} if the following three conditions hold:*

- (F1) *Each of \mathcal{E} and \mathcal{M} is closed under composition with isomorphisms.*
- (F2) *Each morphism f in \mathcal{C} can be factored as $f = m \circ e$, with $e \in \mathcal{E}$ and $m \in \mathcal{M}$.*
- (F3) *Whenever $g \circ e = m \circ f$ with $e \in \mathcal{E}$ and $m \in \mathcal{M}$, there exists a unique diagonal d , such that $f = d \circ e$ and $g = m \circ d$.*

We use double headed (\rightrightarrows) and hooked (\hookrightarrow) arrows to indicate that a morphism is in \mathcal{E} or \mathcal{M} , respectively. If f factors into e and m , we call the codomain of e , or equivalently, the domain of m , the *image* of f and denote it by $\text{im}(f)$.

One can show that each of \mathcal{E} and \mathcal{M} contains all isomorphisms and is closed under composition [2, Prop. 14.6]. From the uniqueness of the diagonal one can deduce that factorisations are unique up to unique isomorphism [2, Prop. 14.4]. It further follows that \mathcal{E} has the *right cancellation property*, that is $g \circ f \in \mathcal{E}$ and $f \in \mathcal{E}$ implies $g \in \mathcal{E}$. Dually, \mathcal{M} has the *left cancellation property*, that is, $g \circ f \in \mathcal{M}$ and $g \in \mathcal{M}$ implies $f \in \mathcal{M}$ [2, Prop. 14.9].

$$\begin{array}{ccc}
 TX \xrightarrow{Tf} TY & X \xrightarrow{e} \text{im}(f) & TX \xrightarrow{Te} T\text{im}(f) \\
 h_X \downarrow & \searrow f & \swarrow e \circ h_X \downarrow \\
 X \xrightarrow{f} Y & \downarrow m & \text{im}(f) \xrightarrow{m} Y \\
 & & \swarrow h_{\text{im}(f)} \quad \downarrow h_Y \circ Tm
 \end{array}$$

■ **Figure 3** Factorising a T -algebra homomorphism via the factorisation system of a base category.

As intended, in the category of sets and functions, surjective and injective functions, or equivalently, epi- and monomorphisms, constitute a factorisation system [2, Ex. 14.2]. More involved examples can be constructed for e.g. the category of topological spaces or the category of categories [2, Ex. 14.2]. We are particularly interested in factorisation systems for the categories of algebras over a monad and coalgebras over an endofunctor.

The naive categorification of a subset $Y \subseteq X$ is a monomorphism $Y \rightarrow X$. Since in the category of sets epi- and monomorphism constitute a factorisation system, we may generalise subsets to arbitrary categories \mathcal{C} with a factorisation system $(\mathcal{E}, \mathcal{M})$ in the following way:

► **Definition 8 (Subobjects).** A subobject of an object $X \in \mathcal{C}$ is a morphism $m_Y : Y \hookrightarrow X \in \mathcal{M}$. A morphism $f : m_{Y_1} \rightarrow m_{Y_2}$ between subobjects of X consists of a morphism $f : Y_1 \rightarrow Y_2$ such that $m_{Y_2} \circ f = m_{Y_1}$.

The category of (isomorphism classes of) subobjects of X is denoted by $\text{Sub}(X)$.

As \mathcal{M} has the left cancellation property, every morphism between subobjects in fact lies in \mathcal{M} . We work with isomorphism classes of subobjects since factorisations of morphisms are only defined up to unique isomorphism. For epi-mono factorizations, there is at most one morphism between any two subobjects, that is, $\text{Sub}(X)$ is simply a partially ordered set.

3.2 Factorising Algebra Homomorphisms

In this section, we recall that if one is given a category \mathcal{C} with a factorisation system $(\mathcal{E}, \mathcal{M})$ and a monad T on \mathcal{C} that preserves \mathcal{E} (that is, satisfies $T(e) \in \mathcal{E}$ for all $e \in \mathcal{E}$), it is possible to lift the factorisation system of the base category \mathcal{C} to a factorisation system on the category of Eilenberg-Moore algebras \mathcal{C}^T .

The result appears in e.g. [45] and may be extended to algebras over an endofunctor. It can also be stated in its dual version: if an endofunctor on \mathcal{C} preserves \mathcal{M} , it is possible to lift the factorisation system of \mathcal{C} to the category of coalgebras [22, 45].

The induced factorisation system for \mathcal{C}^T consists of those algebra homomorphisms, whose underlying morphism lies in \mathcal{E} or \mathcal{M} , respectively. Clearly in such a system condition (F1) holds. The next result shows that it also satisfies (F3).

► **Lemma 9** ([45, Lem. 3.6]). *Whenever $g \circ e = m \circ f$ for T -algebra homomorphisms f, g, e, m , with $e \in \mathcal{E}$ and $m \in \mathcal{M}$, there exists a unique diagonal T -algebra homomorphism d , such that $f = d \circ e$ and $g = m \circ d$.*

Let us now show that the proposed factorisation system satisfies (F2). Assume we are given a homomorphism f as on the left of Figure 3. Using the factorisation system of the base category \mathcal{C} , we can factorise it, as ordinary morphism, into $e \in \mathcal{E}$ and $m \in \mathcal{M}$. In consequence the outer square of the diagram on the right of Figure 3 commutes. Since by assumption the morphism Te is again in \mathcal{E} , we thus find a unique diagonal $h_{\text{im}(f)}$ in \mathcal{C} that makes the triangles on the right of Figure 3 commute. The result below shows that $h_{\text{im}(f)}$ equips $\text{im}(f)$ with the structure of a T -algebra.

► **Lemma 10** ([45, Prop. 3.7]). *$(\text{im}(f), h_{\text{im}(f)})$ is an Eilenberg-Moore T -algebra.*

$$\begin{array}{ccc}
\mathcal{C}/X & \longrightarrow & \mathcal{C}^T/\mathbb{X} \\
\uparrow & & \downarrow \\
\text{Sub}(X) & \xrightarrow{(\cdot)^{\mathbb{X}}} & \text{Sub}(\mathbb{X})
\end{array}
\qquad
\begin{array}{ccc}
\mathcal{C}/X & \longrightarrow & \mathcal{C}^T/\mathbb{X} \\
\downarrow & & \downarrow \\
\text{Sub}(X) & \xrightarrow{(\cdot)^{\mathbb{X}}} & \text{Sub}(\mathbb{X})
\end{array}$$

(a) Decomposition. (b) Commutativity.

■ **Figure 4** A high-level perspective on the subobject closure functor defined in Proposition 11.

We thus obtain a factorisation of $f : (X, h_X) \rightarrow (Y, h_Y)$ into Eilenberg-Moore T -algebra homomorphisms $e : (X, h_X) \rightarrow (\text{im}(f), h_{\text{im}(f)})$ and $m : (\text{im}(f), h_{\text{im}(f)}) \hookrightarrow (Y, h_Y)$.

3.3 The Subobject Closure Functor

While subobjects in the category of sets generalise subsets, subobjects in the category of algebras generalise subalgebras. By taking the algebraic closure of a subset of an algebra one can thus transition from one category of subobjects to the other.

In this section, we generalise this phenomenon from the category of sets to more general categories. As before, we assume a base category \mathcal{C} with a factorisation system $(\mathcal{E}, \mathcal{M})$ and a monad T on \mathcal{C} that preserves \mathcal{E} . Our aim is to construct, for any T -algebra \mathbb{X} with carrier X , a functor from the subobjects $\text{Sub}(X)$ in \mathcal{C} to the subobjects $\text{Sub}(\mathbb{X})$ in \mathcal{C}^T that assigns to a subobject of X its *closure*, that is, the least T -subalgebra of \mathbb{X} containing it.

Recall the free Eilenberg-Moore algebra adjunction. For any object Y in \mathcal{C} and T -algebra $\mathbb{X} = (X, h)$, it maps a morphism $\varphi : Y \rightarrow X$ to the T -algebra homomorphism $\varphi^\sharp := h \circ T\varphi : (TY, \mu_Y) \rightarrow \mathbb{X}$. In Section 3.1 we have seen that the factorisation system of \mathcal{C} naturally lifts to a factorisation system on the category of T -algebras. In particular, we know that up to isomorphism the homomorphism φ^\sharp admits a factorisation into algebra homomorphisms of the form $\varphi^\sharp = m_{\text{im}(\varphi^\sharp)} \circ e_{\text{im}(\varphi^\sharp)}$. If the morphism φ is given by a subobject m_Y , let $\bar{Y} := (\text{im}(m_Y^\sharp), h_{\text{im}(m_Y^\sharp)})$, then above construction yields a second subobject $m_{\bar{Y}}$:

$$m_Y : Y \rightarrow X \in \mathcal{M} \qquad m_{\bar{Y}} : \bar{Y} \rightarrow \mathbb{X} \in \mathcal{M}.$$

Since for any morphism $f : m_{Y_1} \rightarrow m_{Y_2}$ between subobjects of X one has $m_{\bar{Y}_1} \circ e_{\bar{Y}_1} = m_{\bar{Y}_2} \circ (e_{\bar{Y}_2} \circ Tf)$, there exists a unique homomorphism $\bar{f} : m_{\bar{Y}_1} \rightarrow m_{\bar{Y}_2}$ satisfying $\bar{f} \circ e_{\bar{Y}_1} = e_{\bar{Y}_2} \circ Tf$.

The following result shows that above constructions are compositional.

► **Proposition 11.** *Assigning $m_Y \mapsto m_{\bar{Y}}$ and $f \mapsto \bar{f}$ yields a functor $\overline{(\cdot)}^{\mathbb{X}} : \text{Sub}(X) \rightarrow \text{Sub}(\mathbb{X})$.*

Mapping an algebra homomorphism with codomain \mathbb{X} to the \mathcal{M} -part of its factorisation extends to a functor from the slice category over \mathbb{X} (in which we here and in the following identify isomorphic objects) to the category of subobjects of \mathbb{X} . Similarly, one observes that the free Eilenberg-Moore algebra adjunction gives rise to a functor from the slice category over X to the slice category over \mathbb{X} . Finally, it is clear that there exists a functor from the category of subobjects of X to the slice category over X . The functor defined in Proposition 11 can thus be recognised as the composition in Figure 4a.

3.4 The Subobject Closure Monad

In this section, we show that the functor in Proposition 11 induces a monad on the category of subobjects $\text{Sub}(X)$. As before, we assume a base category \mathcal{C} with a factorisation system $(\mathcal{E}, \mathcal{M})$ and a monad $T = (T, \eta, \mu)$ on \mathcal{C} that preserves \mathcal{E} .

$$\begin{array}{ccc}
 \begin{array}{ccc}
 Y & \xrightarrow{1} & Y \\
 e_{\overline{Y}} \circ \eta_Y \downarrow & \swarrow \eta_{m_Y}^{\mathbb{X}} & \downarrow m_Y \\
 \overline{Y} & \xrightarrow{m_{\overline{Y}}} & X
 \end{array} &
 \begin{array}{ccc}
 T^2 Y & \xrightarrow{e_{\overline{Y}} \circ T e_{\overline{Y}}} & \overline{Y} \\
 e_{\overline{Y}} \circ \mu_Y \downarrow & \swarrow \mu_{m_Y}^{\mathbb{X}} & \downarrow m_{\overline{Y}} \\
 \overline{Y} & \xrightarrow{m_{\overline{Y}}} & X
 \end{array} &
 \begin{array}{ccc}
 (\text{Sub}(A), \overline{(\cdot)}^A) & \xrightarrow{(f_*, \alpha_f)} & (\text{Sub}(B), \overline{(\cdot)}^B) \\
 (U_A, \alpha_A) \searrow & & \swarrow (U_B, \alpha_B) \\
 & (\mathcal{C}, T) &
 \end{array}
 \end{array}$$

(a) Induced unit $\eta^{\mathbb{X}}$ and multiplication $\mu^{\mathbb{X}}$ of the monad in Theorem 13. (b) Commutativity of the monad morphisms in Lemma 14 and Lemma 15.

■ **Figure 5** Structure and properties of the monad in Theorem 13.

We begin by establishing the following two technical identities, which assume a T -algebra $\mathbb{X} = (X, h)$ and a subobject $m_Y : Y \rightarrow X \in \mathcal{M}$.

► **Lemma 12.** $m_{\overline{Y}} \circ e_{\overline{Y}} \circ \eta_Y = m_Y$ and $m_{\overline{Y}} \circ e_{\overline{Y}} \circ \mu_Y = m_{\overline{Y}} \circ e_{\overline{Y}} \circ T e_{\overline{Y}}$.

In consequence, we can define candidates for the monad unit $\eta^{\mathbb{X}}$ and the monad multiplication $\mu^{\mathbb{X}}$, respectively, as the unique diagonals in Figure 5a. By construction both morphisms are homomorphisms of subobjects: $\eta_{m_Y}^{\mathbb{X}} : m_Y \rightarrow m_{\overline{Y}}$ and $\mu_{m_Y}^{\mathbb{X}} : m_{\overline{Y}} \rightarrow m_{\overline{Y}}$. The remaining proofs of naturality and the monad laws are covered below. By a slight abuse of notation, we write $\overline{(\cdot)}^{\mathbb{X}}$ for the endofunctor on $\text{Sub}(X)$ that arises by post-composition of the functor in Proposition 11 with the canonical forgetful functor from $\text{Sub}(\mathbb{X})$ to $\text{Sub}(X)$.

► **Theorem 13.** $(\overline{(\cdot)}^{\mathbb{X}}, \eta^{\mathbb{X}}, \mu^{\mathbb{X}})$ is a monad on $\text{Sub}(X)$.

We will now show that the mapping of an algebra \mathbb{X} to the monad $\overline{(\cdot)}^{\mathbb{X}}$ in Theorem 13 extends to algebra homomorphisms. To this end, for any algebra homomorphism $f : \mathbb{A} \rightarrow \mathbb{B}$ in \mathcal{M} , let $f_* : \text{Sub}(A) \rightarrow \text{Sub}(B)$ be the induced functor defined by $f_*(m_X) = f \circ m_X$ and $f_*(g) = g$. The result below shows that f_* can be extended to a morphism between monads.

► **Lemma 14.** For any $f : \mathbb{A} \rightarrow \mathbb{B} \in \mathcal{M}$, there exists a monad morphism $(f_*, \alpha) : (\text{Sub}(A), \overline{(\cdot)}^A) \rightarrow (\text{Sub}(B), \overline{(\cdot)}^B)$.

The next statement establishes that the canonical forgetful functor $U : \text{Sub}(X) \rightarrow \mathcal{C}$ defined by $U(m_Y) = Y$ and $U(f) = f$ extends to a morphism between monads.

► **Lemma 15.** There exists a monad morphism $(U, \alpha) : (\text{Sub}(X), \overline{(\cdot)}^{\mathbb{X}}) \rightarrow (\mathcal{C}, T)$.

We conclude with the observation that the monad morphism defined in Lemma 14 commutes with the monad morphisms defined in Lemma 15.

► **Lemma 16.** Figure 5b commutes for any algebra homomorphism $f : \mathbb{A} \rightarrow \mathbb{B} \in \mathcal{M}$.

3.5 Closing an Image

In this section we investigate the closure of a particular class of subobjects: the ones that arise by taking the image of a morphism. We then show that deriving a minimal bialgebra from a minimal coalgebra by equipping the latter with additional algebraic structure can be realized as the closure of a subobject in this class.

As before, we assume a category \mathcal{C} with a factorisation system $(\mathcal{E}, \mathcal{M})$ and a monad T on \mathcal{C} that preserves \mathcal{E} . Suppose that $\mathbb{X} = (X, h_X)$ is a T -algebra and $f : Y \rightarrow X$ a morphism in \mathcal{C} . On the one hand, there exists a factorisation of f in \mathcal{C} :

$$f = Y \xrightarrow{e_{\text{im}(f)}} \text{im}(f) \xrightarrow{m_{\text{im}(f)}} X.$$

On the other hand, there exists a factorisation of the lifting $f^\sharp = h_X \circ Tf$ in the category of Eilenberg-Moore algebras \mathcal{C}^T :

$$f^\sharp = (TY, \mu_Y) \xrightarrow{e_{\text{im}(f^\sharp)}} (\text{im}(f^\sharp), h_{\text{im}(f^\sharp)}) \xrightarrow{m_{\text{im}(f^\sharp)}} (X, h_X).$$

The next result shows that, up to isomorphism, the closure of the subobject $m_{\text{im}(f)}$ with respect to the algebra \mathbb{X} is given by the subobject $m_{\text{im}(f^\sharp)}$.

► **Lemma 17.** $\overline{m_{\text{im}(f)}}^{\mathbb{X}} = m_{\text{im}(f^\sharp)}$ in $\text{Sub}(\mathbb{X})$.

The following example shows that closing a minimal Moore automaton with additional algebraic structure can be realised by applying a monad of the type in Theorem 13.

► **Example 18 (Closure of Minimal Moore Automata).** Let F be the set endofunctor with $FX = B \times X^A$, for fixed sets A and B . As F preserves monomorphisms, the canonical epi-mono factorisation system of the category of sets lifts to the category $\text{Coalg}(F)$, which consists of unpointed Moore automata with input A and output B .

For any language $L : A^* \rightarrow B$, there exists a size-minimal Moore automaton M_L that accepts L . It can be recovered as the epi-mono factorisation of the final F -coalgebra homomorphism $\text{obs} : A^* \rightarrow \Omega$, that is, $M_L = m_{\text{im}(\text{obs})}$. In more detail, Ω is carried by B^{A^*} , obs satisfies $\text{obs}(w)(v) = L(wv)$, and A^* is equipped with the F -coalgebra structure $\langle \varepsilon, \delta \rangle : A^* \rightarrow B \times (A^*)^A$ defined by $\varepsilon(w) = L(w)$ and $\delta(w)(a) = wa$ [41].

Any algebra structure $h : TB \rightarrow B$ over a set monad T induces a canonical³ distributive law λ between T and F with $FX = B \times X^A$. It is well-known that λ -bialgebras are algebras over the monad T_λ on $\text{Coalg}(F)$ defined by $T_\lambda(X, k) = (TX, \lambda_X \circ Tk)$ and $T_\lambda f = Tf$ [40]. One such T_λ -algebra is the final F -coalgebra Ω , when equipped with a canonical T -algebra structure induced by finality [21, Prop. 3].

The functor T_λ preserves epimorphisms in the category $\text{Coalg}(F)$, if T preserves epimorphisms in the category of sets. The latter is the case for every set functor. By Theorem 13, there thus exists a well-defined monad $\overline{(\cdot)}$ on $\text{Sub}(\Omega)$.

By construction, the minimal Moore automaton M_L lives in $\text{Sub}(\Omega)$. Reviewing the constructions in [46] shows that the minimal λ -bialgebra \mathbb{M}_L for L is given by the image of the lifting of obs , that is, $\mathbb{M}_L = m_{\text{im}(\text{obs}^\sharp)}$. From Lemma 17 it thus follows $\mathbb{M}_L = \overline{M}_L$. In other words, the minimal λ -bialgebra for L can be obtained from the minimal F -coalgebra for L by closing the latter with respect to the T_λ -algebra structure of Ω .

For an example of the monad unit, observe how the minimal coalgebra in Figure 2a embeds into the minimal bialgebra in Figure 2b.

The situation can be further generalised. We assume that i) \mathcal{C} is a category with an $(\mathcal{E}, \mathcal{M})$ -factorisation system; ii) λ is a distributive law between a monad T on \mathcal{C} that preserves \mathcal{E} and an endofunctor F on \mathcal{C} that preserves \mathcal{M} ; iii) $(\Omega, h_\Omega, k_\Omega)$ is a final λ -bialgebra.

► **Theorem 19.** *There exists a functor $\overline{(\cdot)} : \text{Sub}(\Omega, k_\Omega) \rightarrow \text{Sub}(\Omega, h_\Omega, k_\Omega)$ that yields a monad on $\text{Sub}(\Omega, k_\Omega)$ and satisfies $\overline{m_{\text{im}(\text{obs}_{(X,k)}})} \cong m_{\text{im}(\text{obs}_{\text{free}_T(X,k)}})$ in $\text{Sub}(\Omega, h_\Omega, k_\Omega)$, for any F -coalgebra (X, k) .*

³ Given an algebra $h : TB \rightarrow B$ for a set monad T , one can define a distributive law λ between T and F with $FX = B \times X^A$ by $\lambda_X := (h \times \text{st}) \circ \langle T\pi_1, T\pi_2 \rangle : TFX \rightarrow FTX$ [18]. (We write st for the usual strength function $\text{st} : T(X^A) \rightarrow (TX)^A$ defined by $\text{st}(U)(a) = T(\text{ev}_a)(U)$, where $\text{ev}_a(f) = f(a)$.)

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To recover Example 18 as a special case of Theorem 19, one instantiates the latter for the set endofunctor F with $FX = B \times X^A$ and the canonical F -coalgebra with carrier A^* .

Finally, using analogous functors to the ones present in Figure 4a, we observe that, as a consequence of Lemma 17, the diagram in Figure 4b commutes.

4 Step 2: Generators and Bases

One of the central notions of linear algebra is the *basis*: a subset of a vector space is called basis, if every vector can be uniquely written as a linear combination of basis elements.

Part of the importance of bases stems from the convenient consequences that follow from their existence. For example, linear transformations between vector spaces admit matrix representations relative to pairs of bases [23], which can be used for efficient calculations. The idea of a basis however is not restricted to the theory of vector spaces: other algebraic theories have analogous notions of bases – and generators, by waiving the uniqueness constraint –, for instance modules, semi-lattices, Boolean algebras, convex sets, and many more. In fact, the theory of bases for vector spaces is special only in the sense that every vector space admits a basis, which is not the case for e.g. modules.

In this section, we use the abstraction of generators and bases given in Definition 4 to lift results from one theory to the others. For example, one may wonder if there exists a matrix representation theory for convex sets that is analogous to the one of vector spaces.

4.1 Categorification

This section introduces a notion of morphism between algebras with a generator or a basis.

► **Definition 20.** *The category $\text{GAlg}(T)$ of algebras with a generator over a monad T is defined as: objects are pairs $(\mathbb{X}_\alpha, \alpha)$, where $\mathbb{X}_\alpha = (X_\alpha, h_\alpha)$ is a T -algebra with generator $\alpha = (Y_\alpha, i_\alpha, d_\alpha)$; a morphism $(f, p) : (\mathbb{X}_\alpha, \alpha) \rightarrow (\mathbb{X}_\beta, \beta)$ consists of a T -algebra homomorphism $f : \mathbb{X}_\alpha \rightarrow \mathbb{X}_\beta$ and a Kleisli-morphism $p : Y_\alpha \rightarrow TY_\beta$, such that the diagram below commutes:*

$$\begin{array}{ccccc} X_\alpha & \xrightarrow{d_\alpha} & TY_\alpha & \xrightarrow{i_\alpha^\#} & X_\alpha \\ f \downarrow & & \downarrow p^\# & & \downarrow f \\ X_\beta & \xrightarrow{d_\beta} & TY_\beta & \xrightarrow{i_\beta^\#} & X_\beta \end{array} \quad (1)$$

Given $(f, p) : (\mathbb{X}_\alpha, \alpha) \rightarrow (\mathbb{X}_\beta, \beta)$ and $(g, q) : (\mathbb{X}_\beta, \beta) \rightarrow (\mathbb{X}_\gamma, \gamma)$, their composition is defined componentwise as $(g, q) \circ (f, p) := (g \circ f, q \cdot p)$, where $q \cdot p := \mu_{Y_\gamma} \circ Tq \circ p$ denotes the usual Kleisli-composition.

The category $\text{BAlg}(T)$ of algebras with a basis is defined as full subcategory of $\text{GAlg}(T)$.

Let $F : \mathcal{C}^T \rightarrow \text{GAlg}(T)$ be the functor with $F(\mathbb{X}) := (\mathbb{X}, (X, \text{id}_X, \eta_X))$ and $F(f : \mathbb{X} \rightarrow \mathbb{Y}) := (f, \eta_Y \circ f)$, and $U : \text{GAlg}(T) \rightarrow \mathcal{C}^T$ the forgetful functor defined as the projection on the first component. Then F and U are in an adjoint relation:

► **Lemma 21.** $F \dashv U : \text{GAlg}(T) \rightleftarrows \mathcal{C}^T$.

4.2 Products

In this section we show that, under certain assumptions, the monoidal product of a category naturally extends to a monoidal product of algebras with bases within that category. As a natural example we obtain the tensor-product of vector spaces with fixed bases.

We assume basic familiarity with monoidal categories. A monoidal monad T on a monoidal category $(\mathcal{C}, \otimes, I)$ is a monad which is equipped with natural transformations $T_{X,Y} : TX \otimes TY \rightarrow T(X \otimes Y)$ and $T_0 : I \rightarrow TI$, satisfying certain coherence conditions (see e.g. [35]). One can show that, given such additional data, the monoidal structure of \mathcal{C} induces a monoidal category $(\mathcal{C}^T, \boxtimes, (TI, \mu_I))$, if two appropriately defined⁴ assumptions (A1) and (A2) are satisfied [35, Cor. 2.5.6]. The two monoidal products \otimes and \boxtimes are related via the natural embedding $q_{\mathbb{X}_\alpha, \mathbb{X}_\beta} \circ \eta_{X_\alpha \otimes X_\beta}$, in the following referred to as $\iota_{\mathbb{X}_\alpha, \mathbb{X}_\beta}$. One can prove that the product $TY_\alpha \boxtimes TY_\beta$ is given by $T(Y_\alpha \otimes Y_\beta)$ and the coequaliser q_{TY_α, TY_β} by $\mu_{Y_\alpha \otimes Y_\beta} \circ T(T_{Y_\alpha, Y_\beta})$, where we abbreviate the free algebra (TY, μ_Y) as TY [35].

With the previous remarks in mind, we are able to claim the following.

► **Lemma 22.** *Let T be a monoidal monad on $(\mathcal{C}, \otimes, I)$ satisfying (A1) and (A2). Let $\alpha = (Y_\alpha, i_\alpha, d_\alpha)$ and $\beta = (Y_\beta, i_\beta, d_\beta)$ be generators (bases) for T -algebras \mathbb{X}_α and \mathbb{X}_β . Then $\alpha \boxtimes \beta = (Y_\alpha \otimes Y_\beta, \iota_{\mathbb{X}_\alpha, \mathbb{X}_\beta} \circ (i_\alpha \otimes i_\beta), (d_\alpha \boxtimes d_\beta))$ is a generator (basis) for the T -algebra $\mathbb{X}_\alpha \boxtimes \mathbb{X}_\beta$.*

► **Corollary 23.** *Let T be a monoidal monad on $(\mathcal{C}, \otimes, I)$ such that (A1) and (A2) are satisfied. The definitions $(\mathbb{X}_\alpha, \alpha) \boxtimes (\mathbb{X}_\beta, \beta) := (\mathbb{X}_\alpha \boxtimes \mathbb{X}_\beta, \alpha \boxtimes \beta)$ and $(f, p) \boxtimes (g, q) := (f \boxtimes g, T_{Y_{\alpha'}, Y_{\beta'}} \circ (p \boxtimes q))$ yield monoidal structures with unit $((TI, \mu_I), (I, \eta_I, \text{id}_{TI}))$ on $\text{GAlg}(T)$ and $\text{BAlg}(T)$.*

We conclude by instantiating above construction to the setting of vector spaces.

► **Example 24 (Tensor Product of Vector Spaces).** Recall the free \mathbb{K} -vector space monad $\mathcal{V}_{\mathbb{K}}$ defined by $\mathcal{V}_{\mathbb{K}}(X) = X \rightarrow \mathbb{K}$ and $\mathcal{V}_{\mathbb{K}}(\varphi)(y) = \sum_{x \in f^{-1}(y)} \varphi(x)$. Its unit is given by $\eta_X(x)(y) = [x = y]$ and its multiplication by $\mu_X(\Phi)(x) = \sum_{\varphi \in \mathbb{K}^X} \Phi(\varphi) \cdot \varphi(x)$.

The category of sets is monoidal (in fact, cartesian) with respect to the cartesian product \times and the singleton set $\{*\}$. The monad $\mathcal{V}_{\mathbb{K}}$ is monoidal when equipped with $(\mathcal{V}_{\mathbb{K}})_{X,Y}(\varphi, \psi)(x, y) := \varphi(x) \cdot \psi(y)$ and $(\mathcal{V}_{\mathbb{K}})_0(*)(*) := 1_{\mathbb{K}}$ [31]. The category of $\mathcal{V}_{\mathbb{K}}$ -algebras is isomorphic to the category of \mathbb{K} -vector spaces, and satisfies (A1) and (A2). The monoidal structure induced by $\mathcal{V}_{\mathbb{K}}$ is the usual tensor product \otimes with the unit field $\mathcal{V}_{\mathbb{K}}(\{*\}) \simeq \mathbb{K}$.

Lemma 22 captures the well-known fact that the dimension of the tensor product of two vector spaces is the product of the respective dimensions. The structure maps of the product generator map (y_α, y_β) to the vector $i(y_\alpha) \otimes i(y_\beta)$, and x to $(d_\alpha \otimes d_\beta)(x)$, where

$$d_\alpha \otimes d_\beta = \overline{d_\alpha \times d_\beta} : \mathbb{X}_\alpha \otimes \mathbb{X}_\beta \rightarrow (\mathcal{V}_{\mathbb{K}}(Y_\alpha), \mu_{Y_\alpha}) \otimes (\mathcal{V}_{\mathbb{K}}(Y_\beta), \mu_{Y_\beta}) \simeq (\mathcal{V}_{\mathbb{K}}(Y_\alpha \times Y_\beta), \mu_{Y_\alpha \otimes Y_\beta})$$

is the unique linear extension of the bilinear map defined by

$$(d_\alpha \times d_\beta)(x_\alpha, x_\beta)(y_\alpha, y_\beta) := d_\alpha(x_\alpha)(y_\alpha) \cdot d_\beta(x_\beta)(y_\beta).$$

4.3 Kleisli Representation Theory

In this section we use our category-theoretical definition of a basis to derive a representation theory for homomorphisms between algebras over monads that is analogous to the matrix representation theory for linear transformations between vector spaces.

In more detail, recall that a linear transformation $L : V \rightarrow W$ between k -vector spaces with finite bases $\alpha = \{v_1, \dots, v_n\}$ and $\beta = \{w_1, \dots, w_m\}$, respectively, admits a matrix representation $L_{\alpha\beta} \in \text{Mat}_k(m, n)$ with $L(v_j) = \sum_i (L_{\alpha\beta})_{i,j} w_i$, such that for any vector v in

⁴ (A1) For any two algebras $\mathbb{X}_\alpha = (X_\alpha, h_\alpha)$ and $\mathbb{X}_\beta = (X_\beta, h_\beta)$ the coequaliser $q_{\mathbb{X}_\alpha, \mathbb{X}_\beta}$ of the algebra homomorphisms $T(h_\alpha \otimes h_\beta)$ and $\mu_{X_\alpha \otimes X_\beta} \circ T(T_{X_\alpha, X_\beta})$ of type $(T(TX_\alpha \otimes TX_\beta), \mu_{TX_\alpha \otimes TX_\beta}) \rightarrow (T(X_\alpha \otimes X_\beta), \mu_{X_\alpha \otimes X_\beta})$ exists (we denote its codomain by $\mathbb{X}_\alpha \boxtimes \mathbb{X}_\beta := (X_\alpha \boxtimes X_\beta, h_{\alpha \boxtimes \beta})$). (A2) Left and right-tensoring with the induced functor \boxtimes preserves reflexive coequalisers.

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$$A = L_{\alpha'\alpha'} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, \quad L_{\alpha\alpha} = \begin{pmatrix} 3 & 2 \\ -5 & -3 \end{pmatrix}, \quad P = \begin{pmatrix} -1 & 1 \\ 2 & -1 \end{pmatrix}, \quad P^{-1} = \begin{pmatrix} 1 & 1 \\ 2 & 1 \end{pmatrix}$$

■ **Figure 6** The basis representation of the counter-clockwise rotation by 90 degree $L : \mathbb{R}^2 \rightarrow \mathbb{R}^2$, $L(v) = Av$ with respect to $\alpha = \{(1, 2), (1, 1)\}$ and $\alpha' = \{(1, 0), (0, 1)\}$ satisfies $L_{\alpha'\alpha'} = P^{-1}L_{\alpha\alpha}P$.

V the coordinate vectors $L(v)_\beta \in k^m$ and $v_\alpha \in k^n$ satisfy the equality $L(v)_\beta = L_{\alpha\beta}v_\alpha$. A great amount of linear algebra is concerned with finding bases such that the corresponding matrix representation is in an efficient shape, for instance diagonalised. The following definitions generalise the situation by substituting Kleisli morphisms for matrices.

► **Definition 25.** Let $\alpha = (Y_\alpha, i_\alpha, d_\alpha)$ and $\beta = (Y_\beta, i_\beta, d_\beta)$ be bases for T -algebras $\mathbb{X}_\alpha = (X_\alpha, h_\alpha)$ and $\mathbb{X}_\beta = (X_\beta, h_\beta)$, respectively. The basis representation $f_{\alpha\beta}$ of a T -algebra homomorphism $f : \mathbb{X}_\alpha \rightarrow \mathbb{X}_\beta$ with respect to α and β is defined by

$$f_{\alpha\beta} := Y_\alpha \xrightarrow{i_\alpha} X_\alpha \xrightarrow{f} X_\beta \xrightarrow{d_\beta} TY_\beta. \quad (2)$$

Conversely, the morphism $p^{\alpha\beta}$ associated with a Kleisli morphism $p : Y_\alpha \rightarrow TY_\beta$ with respect to α and β is defined by

$$p^{\alpha\beta} := X_\alpha \xrightarrow{d_\alpha} TY_\alpha \xrightarrow{Tp} T^2Y_\beta \xrightarrow{\mu_{Y_\beta}} TY_\beta \xrightarrow{Ti_\beta} TX_\beta \xrightarrow{h_\beta} X_\beta. \quad (3)$$

The associated morphism is the linear transformation between vector spaces induced by some matrix of the right type. The following result confirms this intuition.

► **Lemma 26.** The function (3) is a T -algebra homomorphism $p^{\alpha\beta} : \mathbb{X}_\alpha \rightarrow \mathbb{X}_\beta$.

The next result establishes a generalisation of the observation that for fixed bases, constructing a matrix representation of a linear transformation and associating a linear transformation to a matrix of the right type are mutually inverse operations.

► **Lemma 27.** The operations (2) and (3) are mutually inverse.

At the beginning of this section we recalled the soundness identity $L(v)_\beta = L_{\alpha\beta}v_\alpha$ for the matrix representation $L_{\alpha\beta}$ of a linear transformation L . The next result is a natural generalisation of this statement.

► **Lemma 28.** $f_{\alpha\beta}$ is the unique Kleisli-morphism such that $f_{\alpha\beta} \cdot d_\alpha = d_\beta \circ f$. Conversely, $p^{\alpha\beta}$ is the unique T -algebra homomorphism such that $p \cdot d_\alpha = d_\beta \circ p^{\alpha\beta}$.

The next result establishes the compositionality of the operations (2) and (3). For example, the matrix representation of the composition of two linear transformations is given by the multiplication of the matrix representations of the individual linear transformations.

► **Lemma 29.** $g_{\beta\gamma} \cdot f_{\alpha\beta} = (g \circ f)_{\alpha\gamma}$ and $q^{\beta\gamma} \circ p^{\alpha\beta} = (q \cdot p)^{\alpha\gamma}$.

The previous statements may be summarised as functors between appropriately defined⁵ categories $\text{Alg}_B(T)$ and $\text{Kl}_B(T)$.

⁵ Let $\text{Alg}_B(T)$ be the category in which objects are given by pairs $(\mathbb{X}_\alpha, \alpha)$, where \mathbb{X}_α is a T -algebra with basis $\alpha = (Y_\alpha, i_\alpha, d_\alpha)$, and a morphism $f : (\mathbb{X}_\alpha, \alpha) \rightarrow (\mathbb{X}_\beta, \beta)$ consists of a T -algebra homomorphism $f : \mathbb{X}_\alpha \rightarrow \mathbb{X}_\beta$. Let $\text{Kl}_B(T)$ be the category in which objects are the same ones as for $\text{Alg}_B(T)$, and a morphism $p : (\mathbb{X}_\alpha, \alpha) \rightarrow (\mathbb{X}_\beta, \beta)$ consists of a Kleisli-morphism $p : Y_\alpha \rightarrow TY_\beta$.

► **Corollary 30.** *There exist isomorphisms of categories $\text{BAlg}(T) \simeq \text{Alg}_B(T) \simeq \text{Kl}_B(T)$.*

Assume we are given bases α, α' and β, β' for T -algebras (X_α, h_α) and (X_β, h_β) , respectively. The following result clarifies how the representations $f_{\alpha\beta}$ and $f_{\alpha'\beta'}$ are related.

► **Proposition 31.** *There exist Kleisli isomorphisms p and q such that $f_{\alpha'\beta'} = q \cdot f_{\alpha\beta} \cdot p$.*

Above result simplifies if one restricts to an endomorphism: the basis representations are *similar*. This generalises the situation for vector spaces, cf. Figure 6.

► **Proposition 32.** *There exists a Kleisli isomorphism p with Kleisli inverse p^{-1} such that $f_{\alpha'\alpha'} = p^{-1} \cdot f_{\alpha\alpha} \cdot p$.*

4.4 Bases for Bialgebras

This section is concerned with generators and bases for *bialgebras*. It is well-known [40] that an Eilenberg-Moore law λ between a monad T and an endofunctor F induces simultaneously i) a monad $T_\lambda = (T_\lambda, \mu, \eta)$ on $\text{Coalg}(F)$ by $T_\lambda(X, k) = (TX, \lambda_X \circ Tk)$ and $T_\lambda f = Tf$; and ii) an endofunctor F_λ on \mathcal{C}^T by $F_\lambda(X, h) = (FX, Fh \circ \lambda_X)$ and $F_\lambda f = Ff$, such that the algebras over T_λ , the coalgebras of F_λ , and λ -bialgebras coincide. We will consider generators and bases for T_λ -algebras, or equivalently, λ -bialgebras.

By Definition 4, a generator for a λ -bialgebra (X, h, k) consists of a F -coalgebra (Y, k_Y) and morphisms $i : Y \rightarrow X$, $d : X \rightarrow TY$, such that the three squares on the left of (4) commute:

$$\begin{array}{ccccc}
 Y & \xrightarrow{i} & X & & X & \xrightarrow{d} & TY & & TY & \xrightarrow{Ti} & TX & & TX & \xrightarrow{h} & X \\
 k_Y \downarrow & & \downarrow k & & k \downarrow & & \downarrow \lambda_Y \circ Tk_Y & & d \uparrow & & \downarrow h & & Ti \uparrow & & \downarrow d \\
 FY & \xrightarrow{Fi} & FX & & FX & \xrightarrow{Fd} & FTY & & X & \xrightarrow{\text{id}_X} & X & & TY & \xrightarrow{\text{id}_{TY}} & TY
 \end{array} \quad (4)$$

A basis for a bialgebra is a generator such that the diagram on the right of (4) commutes.

By forgetting the F -coalgebra structure, every generator for a bialgebra is in particular a generator for its underlying T -algebra. By Proposition 6 there exists a λ -bialgebra homomorphism $i^\sharp := h \circ Ti : \exp_T(Y, Fd \circ k \circ i) \rightarrow (X, h, k)$. The next result establishes that there exists a second equivalent free bialgebra with a different coalgebra structure.

► **Lemma 33.** *Let (Y, k_Y, i, d) be a generator for (X, h, k) . Then $i^\sharp : TY \rightarrow X$ is a λ -bialgebra homomorphism $i^\sharp : \text{free}_T(Y, k_Y) \rightarrow (X, h, k)$.*

If one moves from generators to bases for bialgebras, both structures coincide.

► **Lemma 34.** *Let (Y, k_Y, i, d) be a basis for (X, h, k) , then $\text{free}_T(Y, k_Y) = \exp_T(Y, Fd \circ k \circ i)$.*

► **Example 35 (Canonical RFSA).** Recall the minimal pointed bialgebra (X, h, k) for the language $L = (a+b)^*a$ depicted in Figure 2b. Let $(J(\mathbb{X}), i, d)$ be the generator for $\mathbb{X} = (X, h)$ defined as follows: the carrier $J(\mathbb{X})$ consists of the join-irreducibles for \mathbb{X} , the embedding satisfies $i(y) = y$, and the decomposition is given by $d(x) = \{y \in J(\mathbb{X}) \mid y \leq x\}$. We used $(J(\mathbb{X}), i, d)$ to recover the canonical RFSA for L depicted in Figure 2c as the coalgebra $(J(\mathbb{X}), Fd \circ k \circ i)$. Examining the graphs shows that k restricts to the join-irreducibles $J(\mathbb{X})$, suggesting $\alpha = (J(\mathbb{X}), k, i, d)$ as a possible generator for the full bialgebra. However, the a -action on $[\{y\}]$ implies the non-commutativity of the second diagram on the left of (4). The issue can be fixed by modifying d via $d([\{y\}]) := \{[\{y\}]\}$. In consequence $\text{free}(J(\mathbb{X}), k)$ and $\exp(J(\mathbb{X}), Fd \circ k \circ i)$ coincide (even though the assumptions of Lemma 34 are not satisfied).

We close this section by observing that a basis for the underlying algebra of a bialgebra is sufficient for constructing a generator for the full bialgebra.

► **Lemma 36.** *Let (X, h, k) be a λ -bialgebra and (Y, i, d) a basis for the T -algebra (X, h) . Then $(TY, F\mu_Y \circ \lambda_{TY} \circ T(Fd \circ k \circ i), h \circ Ti, \eta_{TY} \circ d)$ is a generator for (X, h, k) .*

4.5 Bases as Coalgebras

In this section, we compare our approach to an alternative perspective on the generalisation of bases. More specifically, we are interested in the work of Jacobs [19], where a basis is defined as a coalgebra for the comonad on the category of Eilenberg-Moore algebras induced by the free algebra adjunction. Explicitly, a basis for a T -algebra (X, h) , in the sense of [19], consists of a T -coalgebra (X, k) such that the following three diagrams commute:

$$\begin{array}{ccc}
 TX \xrightarrow{Tk} T^2X & X \xrightarrow{k} TX & X \xrightarrow{k} TX \\
 h\downarrow & \text{id}_X \searrow & k\downarrow \\
 X \xrightarrow{k} TX & & X \xrightarrow{k} TX \\
 & & \downarrow T\eta_X \\
 & & TX \xrightarrow{Tk} T^2X
 \end{array} \quad (5)$$

The next result shows that a basis as in Definition 4 induces a basis in the sense of [19].

► **Lemma 37.** *Let (Y, i, d) be a basis for a T -algebra (X, h) , then (5) commutes for $k := Ti \circ d$.*

Conversely, assume (X, k) is a T -coalgebra structure satisfying (5) and $i_k : Y_k \rightarrow X$ an equaliser of k and η_X . If the underlying category is the usual category of sets, the equaliser of any two functions exists. If Y_k non-empty, one can show that the equaliser is preserved under T , that is, Ti_k is an equaliser of Tk and $T\eta_X$ [19]. By (5) we have $Tk \circ k = T\eta_X \circ k$. Thus there exists a unique morphism $d_k : X \rightarrow TY_k$ such that $Ti_k \circ d_k = k$, which can be shown to be the inverse of $h \circ Ti_k$ [19]. In other words, $G(X, k) := (Y_k, i_k, d_k)$ is a basis for (X, h) in the sense of Definition 4. In the following let $F(Y, i, d) := (X, Ti \circ d)$ for an arbitrary basis of (X, h) .

► **Lemma 38.** *Let (Y, i, d) be a basis for a T -algebra (X, h) and $k := Ti \circ d$. Then $\eta_X \circ i = k \circ i$ and $Tk \circ (\eta_X \circ i) = T\eta_X \circ (\eta_X \circ i)$.*

► **Corollary 39.** *Let $\alpha := (Y, i, d)$ be a basis for a set-based T -algebra (X, h) and $k := Ti \circ d$. Let $i_k : Y_k \rightarrow X$ be an equaliser of k and η_X , and Y_k non-empty, then $(\text{id}_{(X, h)})_{\alpha, GF\alpha} : Y \rightarrow TY_k$ is the unique morphism ψ making the diagram below commute:*

$$\begin{array}{ccccc}
 & & \eta_X \circ i & & \\
 & & \curvearrowright & & \\
 Y & \xrightarrow{\psi} & TY_k & \xrightarrow{Ti_k} & TX \\
 & & & & \downarrow T\eta_X \\
 & & & & T^2X
 \end{array}$$

4.6 Signatures, Equations, and Finitary Monads

Most of the algebras over set monads one usually considers generators for constitute finitary varieties in the sense of universal algebra. In this section, we will briefly explore the consequences for generators that arise from this observation. The constructions are well-known; we include them for completeness.

Let Σ be a set, whose elements we think of as *operations*, and $\text{ar} : \Sigma \rightarrow \mathbb{N}$ a function that assigns to an operation its *arity*. Any such *signature* induces a set endofunctor H_Σ defined on a set as the coproduct $H_\Sigma X = \coprod_{\sigma \in \Sigma} X^{\text{ar}(\sigma)}$, and consequently, a set monad \mathbb{S}_Σ that assigns to a set V of variables the initial algebra $S_\Sigma V = \mu X.(V + H_\Sigma X)$, i.e. the set of

Σ -terms generated by V (see e.g. [39]). One can show that the categories of H_Σ -algebras and \mathbb{S}_Σ -algebras are isomorphic. A \mathbb{S}_Σ -algebra \mathbb{X} satisfies a set of equations $E \subseteq S_\Sigma V \times S_\Sigma V$, if for all $(s, t) \in E$ and valuations $v : V \rightarrow X$ it holds $v^\sharp(s) = v^\sharp(t)$, where $v^\sharp : (S_\Sigma V, \mu_V) \rightarrow \mathbb{X}$ is the unique extension of v to a \mathbb{S}_Σ -algebra homomorphism [4]. The set of \mathbb{S}_Σ -algebras that satisfy E is denoted by $\text{Alg}(\Sigma, E)$. As one verifies, the forgetful functor $U : \text{Alg}(\Sigma, E) \rightarrow \text{Set}$ admits a left-adjoint $F : \text{Set} \rightarrow \text{Alg}(\Sigma, E)$, thus resulting in a set monad $T_{\Sigma, E}$ with underlying endofunctor $U \circ F$ that preserves directed colimits. The functor U can be shown to be monadic, that is, the comparison functor $K : \text{Alg}(\Sigma, E) \rightarrow \text{Set}^{T_{\Sigma, E}}$ is an isomorphism [24]. In other words, the category of Eilenberg-Moore algebras over $T_{\Sigma, E}$ and the finitary variety of algebras over Σ and E coincide. In fact, set monads preserving directed colimits (sometimes called *finitary* monads [4]) and finitary varieties are in *bijection*.

The following result characterises generators for algebras over $T_{\Sigma, E}$. It can be seen as a unifying proof for observations analogous to the one in Example 5.

► **Lemma 40.** *A morphism $i : Y \rightarrow X$ is part of a generator for a $T_{\Sigma, E}$ -algebra \mathbb{X} iff every element $x \in X$ can be expressed as a Σ -term in $i[Y]$ modulo E , that is, there is a term $d(x) \in S_\Sigma Y$ such that $i^\sharp(\llbracket d(x) \rrbracket_E) = x$.*

4.7 Finitely Generated Objects

In this section, we relate our abstract definition of a generator to the theory of *locally finitely presentable* categories, in particular, to the notions of *finitely generated* and *finitely presentable* objects, which are categorical abstractions of finitely generated algebraic structures.

For intuition, recall that an element $x \in X$ of a partially ordered set is *compact*, if for each directed set $D \subseteq X$ with $x \leq \bigvee D$, there exists some $d \in D$ satisfying $x \leq d$. An *algebraic lattice* is a partially ordered set that has all joins, and every element is a join of compact elements. The naive categorification of compact elements is equivalent to the following definition: a object Y in \mathcal{C} is *finitely presentable (generated)*, if $\text{Hom}_{\mathcal{C}}(Y, -) : \mathcal{C} \rightarrow \text{Set}$ preserves filtered colimits (of monomorphisms). Consequently, one can categorify algebraic lattices as *locally finitely presentable (lfp)* categories, which are cocomplete and admit a set of finitely presentable objects, such that every object is a filtered colimit of that set [4].

In [3, Theor. 3.5] it is shown that an algebra \mathbb{X} over a finitary monad T on an lfp category \mathcal{C} is a finitely generated object of \mathcal{C}^T iff there exists a finitely presentable object Y of \mathcal{C} and a morphism $i : Y \rightarrow X$, such that $i^\sharp : (TY, \mu_Y) \rightarrow \mathbb{X}$ is a strong⁶ epimorphism in \mathcal{C}^T . Below, we give a variant of this statement where instead the carrier of i^\sharp is a split⁷ epimorphism in \mathcal{C} , which is the case iff \mathbb{X} admits a generator in the sense of Definition 4.

► **Proposition 41.** *Let \mathcal{C} be a lfp category in which strong epimorphisms split and T a finitary monad on \mathcal{C} preserving epimorphisms. Then an algebra \mathbb{X} over T is a finitely generated object of \mathcal{C}^T iff it is generated by a finitely presentable object Y in \mathcal{C} in the sense of Definition 4.*

⁶ An epimorphism $e : A \rightarrow B$ is said to be *strong*, if for any monomorphism $m : C \rightarrow D$ and any morphisms $f : A \rightarrow C$ and $g : B \rightarrow D$ such that $g \circ e = m \circ f$, there exists a diagonal monomorphism $d : B \rightarrow C$ such that $f = d \circ e$ and $g = m \circ d$.

⁷ A morphism $e : A \rightarrow B$ is called *split*, if there exists a morphism $s : B \rightarrow A$ such that $e \circ s = \text{id}_B$. Any morphism that is split is necessarily a strong epimorphism.

5 Related Work

A central motivation for this paper has been our broad interest in active learning algorithms for state-based models [5]. One of the challenges in learning non-deterministic models is the common lack of a unique minimal acceptor for a given language [16]. The problem has been independently approached for different variants of non-determinism, often with the common idea of finding a subclass admitting a unique representative [17, 10]. Unifying perspectives were given by van Heerdt [43, 41, 42] and Myers et al. [29]. One of the central notions in the work of van Heerdt is the concept of a scoop, originally introduced by Arbib and Manes [6].

In [46] we have presented a categorical framework that recovers minimal non-deterministic representatives in two steps. The framework is based on ideas closely related to the ones in [29], adopts scoops under the name generators, and strengthens the former to the notion of a basis. In a first step, it constructs a minimal bialgebra by closing a minimal coalgebra with additional algebraic structure over a monad. In a second step, it identifies generators for the algebraic part of the bialgebra, to derive an equivalent coalgebra with side effects in a monad. In this paper, we generalise the first step as application of a monad on an appropriate category of subobjects with respect to a $(\mathcal{E}, \mathcal{M})$ -factorisation system, and explore the second step by further developing the abstract theory of generators and bases.

Categorical factorisation systems are well-established [13, 32, 25]. Among others, they have been used for a general view on the minimisation and determinisation of state-based systems [2, 1, 45]. In Section 3 we use the formalism of [2]. In Section 3.1 we have shown that under certain assumptions factorisation systems can be lifted to the categories of algebras and coalgebras. We later realised that the constructions had recently been published in [45].

The notion of a basis for an algebra over an arbitrary monad has been subject of previous interest. Jacobs, for instance, defines a basis as a coalgebra for the comonad on the category of algebras induced by the free algebra adjunction [19]. In Section 4.5 we show that a basis in our sense always induces a basis in their sense, and, conversely, it is possible to recover a basis in our sense from a basis in their sense, if certain assumptions about the existence and preservation of equalisers are given. As equalisers do not necessarily exist and are not necessarily preserved, our approach carries additional data and thus can be seen as finer.

6 Discussion and Future Work

We have generalised the closure of a subset of an algebraic structure as a monad between categories of subobjects relative to a factorisation system. We have identified the closure of a minimal coalgebra as an instance of the closure of subobjects that arise by taking the image of a morphism. We have extended the notion of a generator to a category of algebras with generators, and explored its characteristics. We have generalised the matrix representation theory of vector spaces and discussed bases for bialgebras. We compared our ideas with a coalgebraic generalisation of bases, explored the case in which a monad is induced by a variety, and related our notion to finitely generated objects in finitely presentable categories.

In [46] we have shown that generators and bases in our sense are central ingredients in the definitions of minimal canonical acceptors. Many such acceptors admit double-reversal characterisations [14, 15, 29, 44]. Duality based characterisations as the former have been shown to be closely related to minimisation procedures with respect to factorisation systems [12, 11, 45]. In the future, it would be interesting to further explore the connection between the minimality of generators on the one side, and the minimality of an acceptor with respect to a factorisation system on the other side.

Another interesting question is whether the construction that underlies our definition of a monad in Theorem 13 could be introduced at a more general level of an arbitrary adjunction between categories with suitable factorisation systems, such that the adjunction between the base category \mathcal{C} and the category of Eilenberg-Moore algebras \mathcal{C}^T is a special case.

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