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Healthiness from Duality

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Abstract

Healthiness is a good old question in program logics that dates back to Dijkstra. It asks for an intrinsic characterization of those predicate transformers which arise as the (backward) interpretation of a certain class of programs. There are several results known for healthiness conditions: for deterministic programs, nondeterministic ones, probabilistic ones, etc. Building upon our previous works on so-called *state-and-effect triangles*, we contribute a unified categorical framework for investigating healthiness conditions. This framework is based on a *dual adjunction* induced by a dualizing object and on our notion of *relative Eilenberg-Moore algebra*. The latter notion seems interesting in its own right in the context of monads, Lawvere theories and enriched categories.

Categories and Subject Descriptors F.3.2 [Semantics of Programming Languages]: Algebraic Approaches to Semantics

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1. Introduction

Predicate Transformer Semantics of Computation Program logics are formal systems for reasoning about programs. They come in different styles: in the *Floyd-Hoare logic* [14] one derives triples of a precondition, a program and a postcondition; *dynamic logics* [11] are logics that have programs as modal operators; type-theoretic presentations would have predicates as *refinement* (or *dependent*) types, allowing smooth extension to higher-order programs; and many program verification tools for imperative programs have programs represented as *control flow graphs*, where predicates are labels to the edges. Whatever presentation style is taken, the basic idea that underlies these variations of program logics is that of *weakest precondition*, dating back to Dijkstra [7]. It asks: *in order to guarantee a given postcondition after the execution of a given program, what precondition does it suffice to assume, before the execution?*

Through weakest preconditions a program gives rise to a (backward) *predicate transformer* that carries a given postcondition to the corresponding weakest precondition. This way of interpreting programs—sometimes called *axiomatic semantics* [34]—is in contrast to (forward) *state transformer semantics* where programs are

understood as functions (possibly with branching or side effects) that carry input states/values to output ones.

Predicate Transformer Semantics and Quantum Mechanics The topic of weakest precondition and predicate transformer semantics is classic in computer science, in decades of foundational and practical studies. Recently, fresh light has been shed on their *structural* aspects: the same kind of interplay between *dynamics* and *observations* for *quantum mechanics* and *quantum logic* appears in predicate transformer semantics, as noted by one of the current authors— together with his colleagues [17, 19, 20]. This enabled them to single out a simple categorical scheme—called *state-and-effect triangles*—that is shared by program semantics and quantum mechanics.

On the program semantics side, the scheme of state-and-effect triangles allows the informal “duality” between state and predicate transformer semantics to be formalized as a categorical duality. Interestingly, the quantum counterpart of this duality is the one between the *Schrödinger* and *Heisenberg* pictures of quantum mechanics. In this sense the idea of weakest precondition dates back before Dijkstra, and before the notion of program.

State-and-effect triangles will be elaborated on in Section 3.1; we note at this stage that the term “effect” in the name refers to a notion in quantum mechanics and should be read as *predicate* in the programming context. In particular, it has little to do with *computational effect*.

In Search of Healthiness The question of *healthiness conditions* is one that is as old as the idea of weakest precondition [7]: it asks for an intrinsic characterization of those predicate transformers which arise as the (backward) interpretation of programs. One basic healthiness result is for *nondeterministic* programs. The result is stated, in elementary terms, as follows.

Theorem 1.1 (healthiness under the “may”-nondeterminism). 1. Let $R \subseteq X \times Y$ be a binary relation; it is thought of as a *nondeterministic computation from X to Y* . This R induces a *predicate transformer* (wp for “weakest precondition”)

$$\begin{aligned} \text{wp}_\diamond(R) : 2^Y &\longrightarrow 2^X, \quad \text{defined by} \\ \text{wp}_\diamond(R)(f)(x) = 1 &\iff \exists y \in Y. (xRy \wedge f(y) = 1), \end{aligned}$$

for each $f : Y \rightarrow 2$ (thought of as a predicate and more specifically as a postcondition) and each $x \in X$.

2. (Healthiness) Let $\varphi : 2^Y \rightarrow 2^X$ be a function. The following are equivalent.
 - (a) The function φ arises in the way prescribed above. That is, there exists $R \subseteq X \times Y$ such that $\varphi = \text{wp}_\diamond(R)$.
 - (b) The map φ is join-preserving, where 2^Y and 2^X are equipped with (the pointwise extensions of) the order $0 < 1$ in 2 .

Here we interpret $0 \in 2$ as false and $1 \in 2$ as true, a convention we adopt throughout the paper.

There are many different instances of healthiness results. For example, the works [21, 27] study *probabilistic* computations in place of nondeterministic ones; the (alternating) combination of nondeterministic and probabilistic branching is studied in [31]; and Dijkstra’s original work [7] deals with the (alternating) combination of nondeterminism and divergence. In fact it is implicit in our notation wp_\diamond that there is a possible “must” variant of Theorem 1.1. In this variant, another predicate transformer wp_\square is defined by

$$\text{wp}_\square(R)(f)(x) = 1 \iff \forall y \in Y. (xRy \Rightarrow f(y) = 1), \quad (1)$$

requiring that every possible poststate must satisfy the postcondition f . The corresponding healthiness result has it that the resulting predicate transformers are characterized by *meet-preservation*.

The goal of the current work is to identify a structural and categorical principle behind healthiness, and hence to provide a common ground for the existing body of healthiness results, also providing a methodology that possibly aids finding new results.

As a concrete instance of this goal, we wish to answer why join-preservation should characterize “may”-nondeterministic predicate transformers wp_\diamond in Theorem 1.1. A first observation would be that the powerset monad \mathcal{P} —that occurs in the alternative description $R: X \rightarrow \mathcal{P}Y$ of a binary relation R —has complete join-semilattices as its Eilenberg-Moore algebras. This alone should not be enough though—the framework needs to account for different modalities, such as \diamond (“may”) vs. \square (“must”) for nondeterminism. (In fact it turns out that this “first observation” is merely a coincidence. See Section 2.1 later.)

Our Contributions We shall answer to the above question of “categorical healthiness condition” by unifying two constructions—of *recipes*—of state-and-effect triangles.

- One recipe [12, 13] is called the *modality* one, whose modeling of situations like in Theorem 1.1 is centered around the notion of *monad*. Firstly, the relevant class of computations (nondeterministic, diverging, probabilistic, etc.) is determined by a monad T , and a computation is then a function of the type $X \rightarrow TY$. Secondly, the set Ω of truth values (such as 2 in Theorem 1.1) carries a T -algebra $\tau: T\Omega \rightarrow \Omega$; it represents a modality such as \diamond and \square .
- The other recipe [18] is referred to as the *dual adjunction* one. It takes a dual adjunction $\mathcal{C} \overset{\perp}{\rightleftarrows} \mathcal{D}^{\text{op}}$ as an ingredient; and uses two *comparison functors*—from a Kleisli category and to an Eilenberg-Moore category—to form a state-and-effect triangle, additionally exploiting \mathcal{D} ’s completeness assumption. One notable feature is that the resulting state-and-effect triangle is automatically “healthy”—this is because comparison functors are full and faithful.

Combining the two recipes we take advantages of both: the former provides a concrete presentation of predicate transformers by a modality; and the latter establishes healthiness. We demonstrate that many known healthiness results are instances of this framework.

The key to combining the two recipes is to interpret a monad T on Set in a category \mathcal{D} that is other than Set . For this purpose—assuming that the dual adjunction in the second recipe is given with a dualizing object—we introduce the notion of *\mathcal{D} -relative T -algebra* and develop its basic theory. Notably the structure map of a \mathcal{D} -relative T -algebra is given by a *monad map* from T to a suitable continuation-like monad (that arises from the aforementioned dual adjunction). This notion seems to be more than a tiny side-product of the current venture: we expect it to play an important role in the *categorical model theory* (see e.g. [1, 28, 30]) where the equivalence between (finitary) monads and *Lawvere theories* is fundamental. See below for further discussions.

Related and Future Work We believe the current results allow rather straightforward generalization (from ordinary, Set -based category theory) to enriched category theory [25]. For example, the use of the $|X|$ -fold product Ω^X can be replaced by the *cotensor* $[X, \Omega]$. Doing so, and identification of this generalization’s relevance in program logics, is left as future work.

The current theoretical developments are heavily influenced by *Lawvere theories*, another categorical formalization of algebraic structures that is (if finitary) equivalent to monads. In particular, our notion of relative algebra is aimed to be a (partial) answer to the oft-heard question: *A Lawvere theory can be interpreted in different categories. Why not a monad?* We intend to establish formal relationships in future work, possibly in an enriched setting. There the line of works on enriched Lawvere theories will be relevant [16, 28]. The first observation in this direction is that: a monad T on Set gives rise to a (possibly large) “Lawvere theory” $\mathcal{Kl}(T)^{\text{op}}$; and then its “algebra” in a category \mathcal{D} (with enough products) is a product-preserving functor $\mathcal{Kl}(T)^{\text{op}} \rightarrow \mathcal{D}$.

What is definitely lacking in the current work (and in our previous work [13, 18]) is syntax for programs/computations and program logics. In this direction the work [9] presents a generic set of inference rules—that is sound and relatively complete—for a certain class of monadic computations.

We are grateful to a referee who brought our attention to recent [15]. Motivated by the modal logic question of equivalences between Kripke frames and modal algebras—possibly equipped with suitable topological structures—they are led to a framework that is close to ours. Their aim is a dual equivalence between a Kleisli category $\mathcal{Kl}(T)$ and a category of algebras \mathcal{D} , and our goal of healthiness (i.e. a full and faithful functor $\mathcal{Kl}(T) \rightarrow \mathcal{D}^{\text{op}}$) comes short of such only by failure of iso-denseness. Some notable differences are as follows. Firstly, in [15] principal examples of a monad T is for nondeterminism, so that a Kleisli arrow is a relation, whereas we have probability and alternation as other leading examples. Secondly, in place of relative algebra (that is our novelty), in [15] they use the notion of algebra that is syntactically presented with operations. Unifying the results as well as the motivations of the two papers is an exciting direction of future research. See also Remark 2.2.

Another closely related work [23] studies healthiness from a domain-theoretic point of view. While it is based on syntactic presentations of algebras (differently from our monadic presentations), notable similarity is found in its emphasis on continuation monads. Its domain-theoretic setting—every construct is DCpo -enriched—will be relevant when we wish to accommodate recursion in our current results, too.

Organization of the Paper We exhibited our leading example in Theorem 1.1. In Section 2 we describe its proof—in a categorical language—and this will motivate our general framework. After recalling the scheme of state-and-effect triangles in Section 3, in Section 4 we unify two known recipes for them to present a new *relative algebra* recipe. The basic theory of relative algebras is developed there, too. Section 5 is devoted to probabilistic instances of our framework. Finally in Section 6 we further extend the generic framework to accommodate *alternating* branching that involve two players typically with conflicting interests.

Some missing proofs are found in the appendix.

Preliminaries and Notations We assume familiarity with basic category theory, from references like [2, 29]. We list some categories that we will use, mostly for fixing notations: the category Set of sets and functions; the category Rel of sets and binary relations; and the categories CL_\vee and CL_\wedge of complete join- and meet-semilattices,

and join- and meet-preserving maps between them, respectively.¹ Given a monad T , its *Eilenberg-Moore* and *Kleisli* categories are denoted by $\mathcal{EM}(T)$ and $\mathcal{Kl}(T)$, respectively. Their definitions are found e.g. in [2, 29].

Let S, T be monads on \mathcal{C} . The standard notion of *monad map* from S to T is defined by a natural transformation $\alpha: S \rightarrow T$ that is compatible with the monad structures. For its explicit requirements see Appendix A.1.

We shall be using various “hom-like” entities such as homsets, exponentials, cotensors and so on; they are denoted by $\mathcal{C}(X, Y)$, Y^X , $[X, Y]$, etc. For those entities we abuse the notations f^* and f_* and use them uniformly for the *precomposition* and *postcomposition* morphisms, such as:

$$f^* = (-) \circ f: Z^Y \rightarrow Z^X \quad \text{and} \quad f_* = f \circ (-): X^Z \rightarrow Y^Z,$$

for $f: X \rightarrow Y$. Another generic notation we will use for those hom-like entities is $(-)^{\sharp}$ for correspondences like

$$f: B \rightarrow A^X \quad // \quad f^{\sharp}: X \rightarrow A^B.$$

An example of such is via the universality of products:

$$\frac{f: B \rightarrow A^X \text{ in a category } \mathcal{D} \text{ with arbitrary products}}{f^{\sharp}: X \rightarrow \mathcal{D}(B, A) \text{ in } \mathbf{Set}}$$

where $A, B \in \mathcal{D}$, $X \in \mathbf{Set}$ and A^X is the $|X|$ -fold product of A .

We shall use a somewhat unconventional notation of writing X_x for an (Eilenberg-Moore) T -algebra $x: TX \rightarrow X$. In our arguments the monad T is mostly obvious from the context, and this notional convention turns out to be succinct and informative.

2. Leading Example: Nondeterministic Computation and Join- (or Meet-) Preservation

In this section, as a leading example, we revisit the well-known healthiness result in Theorem 1.1 together with its “must” variant. We shall prove the results in an abstract categorical language, paving the way to the general and axiomatic modeling in Section 3.

2.1 “May”-Nondeterminism

In Section 1, regarding Theorem 1.1, we noted the coincidence between the healthiness condition (join-preservation) and Eilenberg-Moore \mathcal{P} -algebras (complete join-semilattices). This turns out to be a deceptive coincidence—the essence lies rather in a *factorization* of the powerset monad \mathcal{P} by a dual adjunction, as we shall describe.

We have a dual adjunction between \mathbf{Set} and the category \mathbf{CL}_{\vee} of complete join-semilattices and join-preserving maps.

$$\mathbf{Set} \begin{array}{c} \xrightarrow{2^{(-)}} \\ \perp \\ \xleftarrow{[-, 2]_{\vee}} \end{array} (\mathbf{CL}_{\vee})^{\text{op}} \quad (2)$$

It is given by a *dualizing object* 2, in the “homming-in” manner:

$$\begin{aligned} 2^{(-)}: \mathbf{Set} &\rightarrow (\mathbf{CL}_{\vee})^{\text{op}}; X \mapsto 2^X, \\ [-, 2]_{\vee}: (\mathbf{CL}_{\vee})^{\text{op}} &\rightarrow \mathbf{Set}; L \mapsto [L, 2]_{\vee}; \end{aligned}$$

here 2 is the poset $\{0 < 1\}$, the poset 2^X is the $|X|$ -fold product of 2, and $[L, 2]_{\vee} = \mathbf{CL}_{\vee}(L, 2)$ is the set of join-preserving maps. This adjunction yields a monad $X \mapsto [2^X, 2]_{\vee}$ on \mathbf{Set} ; the unit η of the monad $[2^{(-)}, 2]_{\vee}$ is defined by $\eta_X(x) = \lambda f. f(x)$ and the multiplication μ_X is $\mu_X(\Xi) = \lambda f. \Xi(\lambda \xi. \xi(f))$.

The following is the first key observation.

¹ Here a *complete join-semilattice* is a poset with arbitrary joins \vee . It is well-known that in this case arbitrary meets \wedge exist, too; we say “join-” to indicate the notion of homomorphism we are interested in.

Lemma 2.1. *The monad $[2^{(-)}, 2]_{\vee}$ is isomorphic to the powerset monad \mathcal{P} , with an isomorphism $\sigma: \mathcal{P} \cong [2^{(-)}, 2]_{\vee}$ given by $\sigma_X(S) = \lambda f. \bigvee_{x \in S} f(x)$. \square*

The isomorphism in Lemma 2.1 put us in the following situation.

$$\mathcal{Kl}(\mathcal{P}) \xrightarrow[\cong]{\mathcal{Kl}(\sigma)} \mathcal{Kl}([2^{(-)}, 2]_{\vee}) \xrightarrow{K} (\mathbf{CL}_{\vee})^{\text{op}} \quad (3)$$

Here $\mathcal{Kl}(\sigma)$ is the functor induced by the isomorphism σ in Lemma 2.1; and K is the *comparison functor* from the Kleisli adjunction as the “initial” factorization of a monad. See e.g. [2, 29].

The second key observation is that the top composite $K \circ \mathcal{Kl}(\sigma)$ —its action on arrows, precisely—coincides with the predicate transformer wp_{\diamond} in Theorem 1.1. Indeed, identifying a binary relation $R \subseteq X \times Y$ with a function $X \rightarrow \mathcal{P}Y$ and hence with a morphism $X \rightarrow Y$ in $\mathcal{Kl}(\mathcal{P})$, the action of $K \circ \mathcal{Kl}(\sigma)$ can be concretely described as follows. The arrows on the second line are all in \mathbf{Set} .

$$\begin{aligned} \mathcal{Kl}(\mathcal{P}) &\xrightarrow{\mathcal{Kl}(\sigma)} \mathcal{Kl}([2^{(-)}, 2]_{\vee}) \xrightarrow{K} (\mathbf{CL}_{\vee})^{\text{op}} \\ (X \xrightarrow{R} \mathcal{P}Y) &\mapsto (X \xrightarrow{\sigma_Y \circ R} [2^Y, 2]_{\vee}) \mapsto (2^X \xleftarrow{K(\sigma_Y \circ R)} 2^Y) \end{aligned}$$

Unfolding the construction of the comparison functor K , the function $K(\sigma_Y \circ R): 2^Y \rightarrow 2^X$ in the end is presented as follows. Given $f: Y \rightarrow 2$,

$$K(\sigma_Y \circ R)(f) = \lambda x. (\sigma_Y \circ R)(x)(f) = \lambda x. \bigvee \{ f(y) \mid x R y \}.$$

This is nothing but the predicate $\text{wp}_{\diamond}(R)(f): X \rightarrow 2$ as defined in Theorem 1.1. Thus we have established

$$(K \circ \mathcal{Kl}(\sigma))_{X, Y} = (\text{wp}_{\diamond})_{X, Y}: \mathcal{Kl}(\mathcal{P})(X, Y) \rightarrow \mathbf{CL}_{\vee}(2^Y, 2^X)$$

for each X and Y .

The last key observation is that a comparison functor is full and faithful in general. The action $(K \circ \mathcal{Kl}(\sigma))_{X, Y}$ is therefore bijective; hence so is $(\text{wp}_{\diamond})_{X, Y}$. This proves Theorem 1.1.

In the arguments above the key observations have been: 1) factorization of a monad via a *dual adjunction* (Lemma 2.1); 2) a *monad map* σ giving rise to a predicate transformer $\text{wp}_{\diamond} = K \circ \mathcal{Kl}(\sigma)$; and 3) the role of a *comparison functor* K —in particular that its fullness entails healthiness. Our general framework will be centered around these three notions (dual adjunction, monad map and comparison), with our notion of *relative algebra* bonding them together.

Remark 2.2. In the above (and in Theorem 1.1) we established a full and faithful functor $\mathcal{Kl}(\mathcal{P}) \rightarrow (\mathbf{CL}_{\vee})^{\text{op}}$. Cutting down its codomain, together with a well-known isomorphism between $\mathcal{Kl}(\mathcal{P})$ and the category \mathbf{Rel} of sets and relations, gives us a dual equivalence $\mathbf{Rel} \simeq (\mathbf{CABA}_{\vee})^{\text{op}}$. Here \mathbf{CABA}_{\vee} is the category of complete atomic Boolean algebras and join-preserving maps between them. The last dual equivalence is a well-known one, found e.g. in [10, Section II.9] and [22].

Our principal interest in this paper—motivated by healthiness in program logics—is in a full and faithful functor. A dual equivalence, in contrast, is pursued typically in the context of modal logic (specifically for correspondences between modal algebras and relational frames); see e.g. [15]. The relevance of such equivalences in program logics would lie in identification of (not only programs but) appropriate *state spaces* that realize desired predicate transformers. Further investigation is future work.

Remark 2.3. For a join-semilattice L there is a poset isomorphism $L^{\text{op}} \cong [L, 2]_{\vee}$. This isomorphism $L^{\text{op}} \cong [L, 2]_{\vee}$ however tends to oversimplify arguments, often leading to errors in our experience.

- We organize the three categories on the top in the previous diagram (8) as a triangle. This gives rise to the following situation.

$$\begin{array}{ccc} \mathcal{D}^{\text{op}} & \xrightarrow{R} & \mathcal{EM}(T) \\ & \swarrow K & \searrow R \circ K \\ & \mathcal{KL}(T) & \end{array}$$

- A left adjoint to R will complete a state-and-effect triangle. For its existence we assume suitable equalizers in \mathcal{D} (hence coequalizers in \mathcal{D}^{op}) and use a variant of Beck’s monadicity theorem.

A formal statement is as follows.

Theorem 3.1 (the dual adjunction recipe, [18, Theorem 1]). *Assume an adjunction (7) and a monad $T = GF$. Assume further that the category \mathcal{D} has equalizers of reflexive pairs. Then we have a situation*

$$\begin{array}{ccc} \mathcal{D}^{\text{op}} & \xrightarrow{R} & \mathcal{EM}(T) \\ & \lrcorner \top & \\ & \xleftarrow{L} & \\ & \swarrow K & \searrow R \circ K \\ & \mathcal{KL}(T) & \end{array}$$

where $LRK \cong K$. Moreover K is full and faithful.

Proof. The constructions have already been sketched in the above; see [18] for details. That the comparison functor K is full and faithful is standard; see e.g. [2, 29]. \square

Note that the dual adjunction recipe in Theorem 3.1 automatically derives healthiness (that K is full and faithful). This recipe, though powerful, is also restrictive: it obviously cannot be used to derive a non-full predicate transformer semantics. Furthermore, the example in (6) cannot be directly derived using the dual adjunction recipe: to do so we would need a slight generalization of the recipe that accommodates a natural isomorphism $T \cong GF$ —in place of the equality $T = GF$ —in the factorization (7). Our generalized, “combined” recipe later in Section 4 will address these issues.

3.3 The Modality Recipe

Here we review the other previous recipe that we will be based on; it is derived from the framework of *monadic predicate transformers* from [12, 13].³ It is centered around the notion of *modality*—given as an Eilenberg-Moore T -algebra $\tau: T\Omega \rightarrow \Omega$ over the domain Ω of truth values—and interprets functions of the type $X \rightarrow TY$, that is, T -branching computations.

Definition 3.2 (\mathbb{P}^τ). Let $\tau: T\Omega \rightarrow \Omega$ be a T -algebra; it is called a *modality*. It induces a functor $\mathbb{P}^\tau: \mathcal{KL}(T) \rightarrow \mathbf{Set}^{\text{op}}$ that is defined by: $\mathbb{P}^\tau X = \Omega^X$ and

$$\mathbb{P}^\tau (X \xrightarrow{f} Y \text{ (in } \mathcal{KL}(T))) = (\Omega^Y \xrightarrow{\tau^\sharp} \Omega^{TY} \xrightarrow{f^*} \Omega^X) .$$

Recall that f^* denotes precomposition of f . Here τ^\sharp is the extension map that extends $h: Y \rightarrow \Omega$ to a T -algebra morphism $\tau^\sharp(h): TY \rightarrow \Omega$, via the bijective “freeness” correspondence

$$Y \longrightarrow \Omega \text{ in } \mathbf{Set} \quad \parallel \quad \left(\begin{array}{c} TTY \\ \downarrow \mu \\ TY \end{array} \right) \longrightarrow \left(\begin{array}{c} T\Omega \\ \downarrow \tau \\ \Omega \end{array} \right) \text{ in } \mathcal{EM}(T) .$$

Note that $\mathbb{P}^\tau(f)$ can be alternatively described as follows. Given $f: X \rightarrow TY$ (a computation) and $h: Y \rightarrow \Omega$ (a postcondition), the function $\mathbb{P}^\tau(f)(h): X \rightarrow \Omega$ (the weakest precondition) is the composite $X \xrightarrow{f} TY \xrightarrow{Th} T\Omega \xrightarrow{\tau} \Omega$.

³In [12, 13] the framework is **Pos**-based rather than **Set**-based. Here for simplicity we present a **Set**-based framework; our generalization later will account for the **Pos**-based one as an instance.

The functor \mathbb{P}^τ is the backward predicate transformer semantics induced by the modality τ . It sends a state space X to the set Ω^X of predicates over X ; and a computation $f: X \rightarrow TY$ is sent to the (backward) predicate transformer $\mathbb{P}^\tau f: \Omega^Y \rightarrow \Omega^X$. The definition of $\mathbb{P}^\tau f$ requires a T -algebra structure on Ω ; it determines how to interpret T -effects, and hence is called a modality.

Example 3.3. Consider the set $2 = \{0, 1\}$ of the Boolean truth values; as a convention we identify 1 as “true.” There are two \mathcal{P} -algebra structures over 2:

$$\tau_\square = \bigwedge : \mathcal{P}2 \rightarrow 2 \quad \text{and} \quad \tau_\diamond = \bigvee : \mathcal{P}2 \rightarrow 2 ,$$

where \inf and \sup refer to the order $0 < 1$. The former is the “must” modality, whereas the latter is the “may” one.

A modality $\tau: T\Omega \rightarrow \Omega$ gives rise to an instance of the state-and-effect triangle.

Theorem 3.4 (the modality recipe, [12, 13]). *Let $\tau: T\Omega \rightarrow \Omega$ be an Eilenberg-Moore algebra. It gives rise to the following situation, with \mathbb{P}^τ factorized as $\mathbb{P}^\tau \cong [-, \Omega_\tau]_T \circ K$.*

$$\begin{array}{ccc} \mathbf{Set}^{\text{op}} & \xrightarrow{\Omega_\tau^{(-)}} & \mathcal{EM}(T) \\ & \lrcorner \top & \\ & \xleftarrow{[-, \Omega_\tau]_T} & \\ & \swarrow \mathbb{P}^\tau & \searrow K \\ & \mathcal{KL}(T) & \end{array} \quad (9)$$

Here \mathbb{P}^τ is from Definition 3.2, and K is the comparison functor. The dual adjunction on the top is induced by the dualizing object Ω_τ .⁴ Specifically, the functor $[-, \Omega_\tau]_T = \mathcal{EM}(T)(-, \Omega_\tau)$ is the homset functor; and Ω_τ^X for a set X is the X -fold product of the T -algebra Ω_τ . The latter is explicitly given by the transpose of

$$X \xrightarrow{\text{id}^\sharp} \mathbf{Set}(\Omega^X, \Omega) \xrightarrow{T_{\Omega^X, \Omega}} \mathbf{Set}(T(\Omega^X), T\Omega) \xrightarrow{\tau_\#} \mathbf{Set}(T(\Omega^X), \Omega)$$

where id^\sharp is the transpose of the identity $\text{id}: \Omega^X \rightarrow \Omega^X$ and $T_{\Omega^X, \Omega}$ is the action of T on homsets. \square

4. The “Relative Algebra” Recipe for State-and-Effect Triangles

We unify the two recipes (*dual adjunction* and *modality*) to render a general one. It is called the *relative algebra recipe*, because of the role played by our notion of *relative Eilenberg-Moore algebra*.

4.1 Relative Eilenberg-Moore Algebra

We shall introduce the notion of relative Eilenberg-Moore algebra for a monad T on **Set** and a category \mathcal{D} with small products. Notably its carrier object is an object of \mathcal{D} ; hence what we do is arguably to interpret a monad T on **Set** over a different category \mathcal{D} .

Remark 4.1. We expect further generalization is possible. The developments below bear a strong enriched flavor; and we envisage a general framework where a \mathcal{V} -monad T on an SMCC \mathcal{V} is interpreted over an arbitrary \mathcal{V} -enriched category \mathcal{D} . Working out the precise statements is future work.

Let \mathcal{D} be a category with arbitrary products. For each object $A \in \mathcal{D}$ there is a dual adjunction, with A playing the role of a dualizing object.

$$\mathbf{Set} \xleftarrow[\mathcal{D}(-, A)]{A^{(-)}} \mathcal{D}^{\text{op}}, \quad \text{by} \quad \frac{B \longrightarrow A^X \text{ in } \mathcal{D}}{X \longrightarrow \mathcal{D}(B, A) \text{ in } \mathbf{Set}} . \quad (10)$$

⁴Recall our notational convention that an Eilenberg-Moore algebra $\tau: T\Omega \rightarrow \Omega$ is denoted by Ω_τ . See Section 1.

This is much like in (2); recall that A^X denotes the $|X|$ -fold product of $A \in \mathcal{D}$ (i.e. a *cotensor*, in the enriched terms).

This adjunction induces a continuation-like monad $\mathcal{D}(A^{(-)}, A)$.

Definition 4.2 (\mathcal{D} -relative T -algebra). Let T be a monad on \mathbf{Set} , and \mathcal{D} be a category with small products. A \mathcal{D} -relative T -algebra is

$$\text{a pair } (A, \alpha : T \rightarrow \mathcal{D}(A^{(-)}, A))$$

of an object $A \in \mathcal{D}$ and a monad map α from T to the continuation-like monad $\mathcal{D}(A^{(-)}, A)$ from (10).

A *morphism* of \mathcal{D} -relative T -algebras, say from (A, α) to (B, β) , is a morphism $f : A \rightarrow B$ in \mathcal{D} such that the following diagram commutes for each $X \in \mathbf{Set}$.

$$\begin{array}{ccc} A^X & \xrightarrow{\alpha_X^\sharp} & A^{TX} \\ f_* \downarrow & & \downarrow f_* \\ B^X & \xrightarrow{\beta_X^\sharp} & B^{TX} \end{array}$$

Here α_X^\sharp is induced canonically from $\alpha_X : TX \rightarrow \mathcal{D}(A^X, A)$, via the bijective correspondence in (10) (the universality of products).

\mathcal{D} -relative T -algebras, together with their morphisms, form a category $\mathcal{EM}(T; \mathcal{D})$ that we call the \mathcal{D} -relative Eilenberg-Moore category of T . It comes with an obvious forgetful functor to \mathcal{D} :

$$U_{\mathcal{D}} : \mathcal{EM}(T; \mathcal{D}) \longrightarrow \mathcal{D} . \quad (11)$$

There are many questions to be asked about relative algebras, for example if $U_{\mathcal{D}}$ has a left adjoint. These questions are left as future work: they seem to be best studied in conjunction with Lawvere theories, and doing so deviates from the current paper's focus.

We shall still show that relative algebras generalize the usual notion of Eilenberg-Moore algebra. We rely on the following folklore result on: algebras, and monad maps to continuation-like monads. It is used e.g. in [24, 26].

Proposition 4.3. *Let \mathcal{C} be a complete category and T be a monad on \mathcal{C} . For each object $A \in \mathcal{C}$, there is a canonical bijective correspondence between: 1) T -algebras $\hat{\alpha} : TA \rightarrow A$ with A being their carrier objects; and 2) monad maps $\alpha : T \rightarrow A^{\mathcal{C}(-, A)}$.*

The concrete correspondence is given by: $\alpha_X = \langle TX \xrightarrow{Tf} TA \xrightarrow{\hat{\alpha}} A \rangle_{f \in \mathcal{C}(X, A)}$ and $\hat{\alpha} = (TA \xrightarrow{\alpha_A} A^{\mathcal{C}(A, A)} \xrightarrow{\pi_{\text{id}_A}} A)$. Moreover, $f : A \rightarrow B$ is a T -algebra morphism from $(A, \hat{\alpha})$ to $(B, \hat{\beta})$ if and only if the following diagram commutes.

$$\begin{array}{ccc} \mathcal{C}(X, A) & \xrightarrow{\alpha_X^\sharp} & \mathcal{C}(TX, A) \\ \downarrow f_* & & \downarrow f_* \\ \mathcal{C}(X, B) & \xrightarrow{\beta_X^\sharp} & \mathcal{C}(TX, B) \end{array}$$

Here α_X^\sharp is defined analogously to Definition 4.2. \square

This result and Definition 4.2 yields the following. There we also need the isomorphism $\mathbf{Set}(A^X, A) \cong A^{\mathbf{Set}(X, A)}$ that identifies homsets and cotensors. This is available since \mathbf{Set} is self-enriched.

Corollary 4.4. *Let T be a monad on \mathbf{Set} . We have an isomorphism $\mathcal{EM}(T; \mathbf{Set}) \cong \mathcal{EM}(T)$.* \square

Remark 4.5. There is a Lawvere theory-like intuition behind Proposition 4.3 (from which we came up with Definition 4.2). Given an algebra $\hat{\alpha} : TA \rightarrow A$, the corresponding monad map $\alpha_X : TX \rightarrow A^{\mathcal{C}(X, A)}$ is understood as: “given an algebraic/syntactic term $t \in TX$ with variables from X , and a valuation $V : X \rightarrow A$, the element $\alpha_X(t)(V) \in A$ is how t is interpreted under V (interpreting variables) and $\hat{\alpha}$ (interpreting algebraic operations).”

Lawvere theories are interpretation-free—hence “syntactic”—presentations of algebraic structures. They are therefore subject to

interpretation in *any* category \mathcal{D} with finite products; see e.g. [16]. In contrast, monads—although their equivalence to Lawvere theories is well-known, see e.g. [28]—are always tied to their base category. Our notion of \mathcal{D} -relative T -algebra is how to “interpret” the algebraic structure embodied as a monad T (on \mathbf{Set}) on another category \mathcal{D} .⁵

Example 4.6. Let \mathbf{List} denote the list monad on \mathbf{Set} , whose Eilenberg-Moore algebras are monoids. For $\mathcal{D} = \mathbf{Top}$, the category of topological spaces and continuous maps, the category $\mathcal{EM}(\mathbf{List}; \mathbf{Top})$ is exactly the category of *topological monoids*. Similarly for $\mathcal{D} = \mathbf{Pos}$, the category of posets and monotone maps, the category $\mathcal{EM}(\mathbf{List}; \mathbf{Pos})$ is that of *ordered monoids*. The same phenomena can be observed for many other monads T and categories \mathcal{D} .

We exhibit a *change-of-base* result. In the case of Lawvere theories, we can map a \mathcal{D} -model of a theory to a \mathcal{D}' -model along a (finite) product-preserving functor $H : \mathcal{D} \rightarrow \mathcal{D}'$.

Proposition 4.7. *Let $\mathcal{D}, \mathcal{D}'$ be categories with small products and $H : \mathcal{D} \rightarrow \mathcal{D}'$ be a product-preserving functor. Then H canonically lifts to a functor $\bar{H} : \mathcal{EM}(T; \mathcal{D}) \rightarrow \mathcal{EM}(T; \mathcal{D}')$, with*

$$\begin{array}{ccc} \mathcal{EM}(T; \mathcal{D}) & \xrightarrow{\bar{H}} & \mathcal{EM}(T; \mathcal{D}') \\ U_{\mathcal{D}} \downarrow & & \downarrow U_{\mathcal{D}'} \\ \mathcal{D} & \xrightarrow{H} & \mathcal{D}' \end{array} . \quad (12)$$

The functor \bar{H} preserves arbitrary products. Moreover, if H is faithful, so is \bar{H} . \square

4.2 A State-and-Effect Triangle via Relative Algebras

In the “modality” recipe in Section 3.3, the key to a dual adjunction between \mathbf{Set} and $\mathcal{EM}(T)$ was to use a T -algebra as a dualizing object. We shall now extend this from \mathbf{Set} to a general category \mathcal{D} , using a \mathcal{D} -relative T -algebra in place of a T -algebra.

Theorem 4.8 (the relative algebra recipe). *Let $\Omega_{\mathcal{D}} \in \mathcal{D}$ be an object in a complete category \mathcal{D} , and*

$$\bar{\Omega} = (\Omega_{\mathcal{D}}, \tau : T \rightarrow \mathcal{D}(\Omega_{\mathcal{D}}^{(-)}, \Omega_{\mathcal{D}}))$$

be a \mathcal{D} -relative T -algebra. This yields a state-and-effect triangle:

$$\begin{array}{ccc} \mathcal{D}^{\text{op}} & \xrightarrow{[-, \bar{\Omega}]_{\mathcal{D}}} & \mathcal{EM}(T) \\ \mathbb{P}^{\tau} \swarrow & \xrightarrow{\top} & \searrow K \\ \mathcal{Kl}(T) & & \end{array} \quad \text{with } \mathbb{P}^{\tau} \cong [-, \bar{\Omega}]_T \circ K. \quad (13)$$

Here K is the comparison functor. The other three functors are defined as follows.

- $([-, \bar{\Omega}]_{\mathcal{D}})$ For each $D \in \mathcal{D}$, the object $[D, \bar{\Omega}]_{\mathcal{D}}$ is the set $\mathcal{D}(D, \Omega_{\mathcal{D}})$ equipped with a T -algebra structure ζ_D defined by

$$T(\mathcal{D}(D, \Omega_{\mathcal{D}})) \xrightarrow{\tau} \mathcal{D}(\Omega_{\mathcal{D}}^{\mathcal{D}(D, \Omega_{\mathcal{D}})}, \Omega_{\mathcal{D}}) \xrightarrow{(\text{id}^\sharp)^*} \mathcal{D}(D, \Omega_{\mathcal{D}}) . \quad (14)$$

The last arrow precomposes $\text{id}^\sharp : D \rightarrow \Omega_{\mathcal{D}}^{\mathcal{D}(D, \Omega_{\mathcal{D}})}$.

For a \mathcal{D} -morphism $k : D \rightarrow E$, the T -algebra morphism $k^* = [k, \bar{\Omega}]_{\mathcal{D}} : [E, \bar{\Omega}]_{\mathcal{D}} \rightarrow [D, \bar{\Omega}]_{\mathcal{D}}$ is defined by the precomposition map $k^* : \mathcal{D}(E, \Omega_{\mathcal{D}}) \rightarrow \mathcal{D}(D, \Omega_{\mathcal{D}})$ between the carrier sets.

⁵ We speculate that, when a monad T is bounded, our notion of relative T -algebra coincides with the models of the Lawvere theory \mathcal{L}_T induced by T . We note however that relative T -algebras can be defined even for unbounded T . We need this feature, too, since we deal with unbounded monad like the powerset monad \mathcal{P} .

- $([-, \bar{\Omega}]_T)$ Given a T -algebra $A_a = (A, a: TA \rightarrow A)$, the \mathcal{D} -object $[A_a, \bar{\Omega}]_T$ is defined as the equalizer of $a^*, \tau_A^\sharp: \Omega_{\mathcal{D}}^A \rightrightarrows \Omega_{\mathcal{D}}^{TA}$; see the top row of (15) below. Given a morphism $f: A_a \rightarrow B_b$ of T -algebras, a \mathcal{D} -morphism $f^* = [f, \bar{\Omega}]_T: [A_a, \bar{\Omega}]_T \rightarrow [B_b, \bar{\Omega}]_T$ is induced by the universality of an equalizer, as below.

$$\begin{array}{ccc} [A_a, \bar{\Omega}]_T & \xrightarrow{\text{eq}} & \Omega_{\mathcal{D}}^A \xrightarrow{a^*} \Omega_{\mathcal{D}}^{TA} \\ f^* \uparrow & & \uparrow \tau_A^\sharp \\ [B_b, \bar{\Omega}]_T & \xrightarrow{\text{eq}} & \Omega_{\mathcal{D}}^B \xrightarrow{b^*} \Omega_{\mathcal{D}}^{TB} \end{array} \quad \uparrow (Tf)^* \quad (15)$$

- (\mathbb{P}^τ) $\mathbb{P}^\tau: \mathcal{Kl}(T) \rightarrow \mathcal{D}^{\text{op}}$ is given by: $\mathbb{P}^\tau(X) = \Omega_{\mathcal{D}}^X$, and

$$\mathbb{P}^\tau(X \xrightarrow{f} TY \text{ (in } \mathcal{Kl}(T))) = (\Omega_{\mathcal{D}}^Y \xrightarrow{\tau_Y^\sharp} \Omega_{\mathcal{D}}^{TY} \xrightarrow{f^*} \Omega_{\mathcal{D}}^X). \quad \square$$

Remark 4.9. The notations $[A_a, \bar{\Omega}]_T$ and $[D, \bar{\Omega}]_{\mathcal{D}}$ are sort of abusive, because $\bar{\Omega}$ is not a T -algebra or a \mathcal{D} -object. The notations reflect the dual nature of a \mathcal{D} -relative T -algebra, in the sense that is precisely described in the above. Later in Section 4.3 we develop this point (and notations) more systematically.

The third *relative algebra* recipe in Theorem 4.8 combines the previous two recipes. Indeed, the *modality* recipe in Section 3.3 is a special case, much like usual T -algebras are special cases of relative T -algebras (Corollary 4.4). The current generalization allows us to have a category \mathcal{D} —possibly other than **Set**—at the top-left of a state-and-effect triangle. See (9) and (13).

Regarding the relationship to the *dual adjunction* recipe in Section 3.2—that automatically ensures healthiness, see Theorem 3.1—we have the following cornerstone result towards analysis of general healthiness conditions. Note that the assumption $T = GF$ in (7) translates, in the context of Theorem 4.8, to the condition that $\tau: T \rightarrow \mathcal{D}(\Omega_{\mathcal{D}}^{(-)}, \Omega_{\mathcal{D}})$ is the identity.

Theorem 4.10 (categorical (partial) healthiness condition). *Let $X, Y \in \mathbf{Set}$. In the setting of Theorem 4.8:*

- if $\tau_Y: TY \rightarrow \mathcal{D}(\Omega_{\mathcal{D}}^Y, \Omega_{\mathcal{D}})$ is injective, the functor \mathbb{P}^τ 's action $\mathbb{P}_{XY}^\tau: \mathcal{Kl}(T)(X, Y) \rightarrow \mathcal{D}(\Omega_{\mathcal{D}}^Y, \Omega_{\mathcal{D}}^X)$ is injective;
- if τ_Y is surjective, so is \mathbb{P}_{XY}^τ .

It follows that, if $\tau: T \rightarrow \mathcal{D}(\Omega_{\mathcal{D}}^{(-)}, \Omega_{\mathcal{D}})$ is a natural isomorphism, the functor \mathbb{P}^τ is full and faithful. \square

The last corollary accounts for (part of) Theorem 1.1, generalizing the arguments in Section 2.1. The proof of Theorem 4.10 is like the proof of [29, Theorem IV.3.1], giving the correspondence between monic/epic (co)units and fullness/faithfulness of adjoints.

4.3 Relative Algebras over a Concrete Category

We have obtained the third, unified recipe for state-and-effect triangles in Theorem 4.8, together with a general healthiness result (Theorem 4.10). The remaining piece towards the full coverage of healthiness results like Theorem 1.1 is: how specific predicate transformer semantics—specified by a concrete modality (like wp_\diamond via \diamond)—is related to constructs in the general recipe in Theorem 4.8.

To fill this missing piece we shall study a situation where \mathcal{D} is *concrete*, by which we specifically mean that: 1) we have a faithful “forgetful” functor $V: \mathcal{D} \rightarrow \mathbf{Set}$; and 2) the functor V preserves small limits. Examples are: the Eilenberg-Moore category $\mathcal{EM}(T)$ of a monad T on **Set**; the categories **Top** and **Pos**; and other categories of “sets with additional structures.”

By Proposition 4.7 and Corollary 4.4, the functor $V: \mathcal{D} \rightarrow \mathbf{Set}$ lifts to $\bar{V}: \mathcal{EM}(T; \mathcal{D}) \rightarrow \mathcal{EM}(T)$. This gives rise to the following.

$$\mathcal{D} \begin{array}{c} \xleftarrow{U_{\mathcal{D}}} \\ \xrightarrow{V} \end{array} \mathcal{EM}(T; \mathcal{D}) \begin{array}{c} \xrightarrow{\bar{V}} \\ \xleftarrow{U} \end{array} \mathcal{EM}(T) \quad \text{Here } U_{\mathcal{D}} \text{ is from (11).} \quad (16)$$

The diagram (16) is skewed (compared to (12)) to convey the intuition that: an object in $\mathcal{EM}(T; \mathcal{D})$ is a set equipped both with a \mathcal{D} -structure and with a T -algebra structure, in a compatible manner. The developments below are aimed at formalizing this intuition.

Notation 4.11 $(A, A_{\mathcal{D}}, A_{\hat{\alpha}}, \bar{A})$. From now on we adopt a notational convention of writing: A for a set; $A_{\mathcal{D}}$ for an object in \mathcal{D} such that $V(A_{\mathcal{D}}) = A$; $A_{\hat{\alpha}}$ for a T -algebra $\hat{\alpha}: TA \rightarrow A$ (hence $U(A_{\hat{\alpha}}) = A$); and $\bar{A} \in \mathcal{EM}(T; \mathcal{D})$ for a relative T -algebra such that $VU_{\mathcal{D}}\bar{A} = U\bar{V}\bar{A} = A$. See below, and compare it to (16).

$$\begin{array}{ccc} & \bar{A} & \\ & \downarrow U\bar{V} = VU_{\mathcal{D}} & \\ A_{\mathcal{D}} & \xrightarrow{V} & A \xleftarrow{U} A_{\hat{\alpha}} \end{array} \quad (17)$$

This convention, though admittedly confusing at first sight, follows some literature on dualities (such as [6]) and allows us to describe our technical developments in a succinct manner. We emphasize that

fixing A does not fix $A_{\mathcal{D}}$, $A_{\hat{\alpha}}$ or \bar{A} .

The following characterization of \mathcal{D} -relative T -algebras—it assumes that \mathcal{D} is concrete—embodies the intuition that they are “ T -algebras whose algebraic structures are compatible with \mathcal{D} -structures.” This is much like a topological monoid is a monoid whose multiplication is continuous; see Example 4.6.

Proposition 4.12. *Let $A_{\hat{\alpha}} = (A, \hat{\alpha}: TA \rightarrow A)$ be a T -algebra and $A_{\mathcal{D}} \in \mathcal{D}$ be such that $V A_{\mathcal{D}} = A$. The following are equivalent.*

1. *There exists a \mathcal{D} -relative T -algebra \bar{A} such that $\bar{V}(\bar{A}) = A_{\hat{\alpha}}$ and $U_{\mathcal{D}}\bar{A} = A_{\mathcal{D}}$. See below.*

$$\begin{array}{ccc} & \bar{A} & \\ & \downarrow \bar{V} & \\ A_{\mathcal{D}} & \xleftarrow{U_{\mathcal{D}}} & A \xleftarrow{U} A_{\hat{\alpha}} \end{array} \quad (18)$$

2. *The following lifting condition holds: the monad map $\alpha: T \rightarrow \mathbf{Set}(A^{(-)}, A)$ induced by $\hat{\alpha}$ (Proposition 4.3) factors through $V: \mathcal{D}(A_{\mathcal{D}}^{(-)}, A_{\mathcal{D}}) \rightarrow \mathbf{Set}(A^{(-)}, A)$, as in*

$$\begin{array}{ccc} & \mathcal{D}(A_{\mathcal{D}}^X, A_{\mathcal{D}}) & \\ & \downarrow V & \\ TX & \xrightarrow[\alpha_X]{} & \mathbf{Set}(A^X, A) \end{array} \quad (19)$$

The latter is more concretely stated as follows: for each $X \in \mathbf{Set}$ and $t \in TX$, the function $(\alpha_X)(t): A^X \rightarrow A$ lifts to a \mathcal{D} -morphism $(\bar{\alpha}_X)(t): A_{\mathcal{D}}^X \rightarrow A_{\mathcal{D}}$.

If the conditions hold, we say that $A_{\mathcal{D}}$ and $A_{\hat{\alpha}}$ are compatible. \square

This result means: to render $A \in \mathbf{Set}$ into a \mathcal{D} -relative T -algebra, it suffices to find a T -algebra structure and a \mathcal{D} -structure and then to check the above lifting condition. The lifting condition in Proposition 4.12 is a direct generalization of the *monotonicity condition* (precisely its pointwise version) used in [12, 13]; when $\mathcal{D} = \mathbf{Pos}$ we get the original monotonicity condition.

Under a further assumption that T is finitary, we can restrict the required check to finite sets.

Proposition 4.13. *Assume the setting of Proposition 4.12 and T is finitary. $A_{\hat{\alpha}}$ and $A_{\mathcal{D}}$ are compatible if and only if the lifting condition (19) holds for any natural number n in place of X . \square*

It follows that, in case the monad T is induced by some known algebraic specification (Σ, E) , checking the lifting condition can further be restricted to “basic operations” $\sigma \in \Sigma$. For instance, a monoid (Ω, \star, e) and $\Omega_{\mathcal{D}} \in \mathcal{D}$ satisfy the lifting condition if and only if both the multiplication $\star: \Omega \times \Omega \rightarrow \Omega$ and the unit $e: 1 \rightarrow \Omega$ lift to \mathcal{D} -morphisms.

We can exploit the construction in Theorem 4.8 when \mathcal{D} is concrete. Assume we have a functor $V : \mathcal{D} \rightarrow \mathbf{Set}$ that is faithful and limit-preserving. Given a \mathcal{D} -object D , the T -algebra $[D, \bar{\Omega}]_{\mathcal{D}}$ can be understood as a homset $\mathcal{D}(D, \bar{\Omega})$ with the *pointwise* T -algebra structure along Ω_{τ} i.e. we regard it as a subalgebra of the product $\Omega_{\tau}^{V^D}$. Similarly we can see $[A_a, \bar{\Omega}]_T$ as the \mathcal{D} -object whose ‘‘carrier set’’ is $\mathcal{EM}(T)(A_a, \Omega_{\tau})$ with the pointwise \mathcal{D} -structure. It is precisely stated as follows.

Proposition 4.14. *In the situation of Theorem 4.8 we have $U \circ [D, \bar{\Omega}]_{\mathcal{D}} = \mathcal{D}(D, \bar{\Omega})$.*

Furthermore, assume we have a limit-preserving functor $V : \mathcal{D} \rightarrow \mathbf{Set}$ and let $\bar{V}(\bar{\Omega}) = \Omega_{\tau}$. Then $[D, \bar{\Omega}]_{\mathcal{D}}$ is a T -subalgebra of $\Omega_{\tau}^{V^D}$ —meaning that the algebraic structure of the former is a pointwise extension of τ —and we have $V \circ [-, \bar{\Omega}]_T \cong \mathcal{EM}(T)(-, \Omega_{\tau})$. \square

In the latter setting of Proposition 4.14 where \mathcal{D} is ‘‘concrete’’ with $V : \mathcal{D} \rightarrow \mathbf{Set}$, let $\bar{\Omega} = (\Omega_{\mathcal{D}}, \bar{\tau}) \in \mathcal{EM}(T; \mathcal{D})$ and $\bar{V}\bar{\Omega} = \Omega_{\tau} = (\Omega, \tau : T\Omega \rightarrow \Omega)$ be its underlying T -algebra. These data give rise to two different predicate transformer semantics: one is $\mathbb{P}^{\bar{\tau}} : \mathcal{KL}(T) \rightarrow \mathcal{D}^{\text{op}}$ from the relative algebra $\bar{\Omega}$ via the relative algebra recipe (Theorem 4.8); and the other is $\mathbb{P}^{\tau} : \mathcal{KL}(T) \rightarrow \mathbf{Set}^{\text{op}}$ from the (ordinary) T -algebra Ω_{τ} via the modality recipe (Theorem 3.4). Between these we have the following correspondence, as we announced in the beginning of Section 4.3.

Proposition 4.15. *In the situation of Theorem 4.8, additionally assume that $V : \mathcal{D} \rightarrow \mathbf{Set}$ is a faithful and limit-preserving functor. Then, in terms of the above notations we have $\mathbb{P}^{\tau} \cong V \circ \mathbb{P}^{\bar{\tau}}$.*

$$\begin{array}{ccc} \mathcal{D}^{\text{op}} & \xrightarrow{V} & \mathbf{Set}^{\text{op}} \\ \uparrow \mathbb{P}^{\bar{\tau}} & \mathcal{KL}(T) & \uparrow \mathbb{P}^{\tau} \end{array} \quad (20)$$

We have required $V : \mathcal{D} \rightarrow \mathbf{Set}$ to be limit-preserving; in fact it mostly suffices to assume *product-preservation*. In that case the only thing that fails is the isomorphism $V \circ [-, \bar{\Omega}]_T \cong \mathcal{EM}(T)(-, \Omega_{\tau})$ in Proposition 4.14, which is the result that connects the top-right corner of the two (*relative algebra* and *modality*) triangles. Proposition 4.15 is only concerned about the top-left and bottom corners, and survives under V that preserves only products.

4.4 Finitary Predicate Transformers

The categorical results so far for healthiness (Theorem 4.8 and 4.10) are not enough for some instances of healthiness results, as we will see in the examples of Section 5. Specifically, besides the *structural* aspects covered by those results, we need to take account of *sizes*.

Throughout Section 4.4 we adopt the setting in Proposition 4.15, i.e. the relative algebra recipe with a faithful and limit-preserving $V : \mathcal{D} \rightarrow \mathbf{Set}$. In particular we have a \mathcal{D} -relative T -algebra $\bar{\Omega} = (\Omega_{\mathcal{D}}, \bar{\tau})$, and $\Omega_{\bar{\tau}} = \bar{V}\bar{\Omega}$ as its underlying T -algebra. Recall the correspondence between $\hat{\tau} : T\Omega \rightarrow \Omega$ and a monad map τ (Proposition 4.3).

The key observation is the following lemma.

Lemma 4.16. *Let X be a set and $t \in TX$. If T is finitary, the map $(\tau_X)(t) : \Omega^X \rightarrow \Omega$ factors through a precomposition map $s^* : \Omega^X \rightarrow \Omega^{X'}$ for some finite subset $s : X' \rightarrow X$ of X i.e. there exists $\varphi' : \Omega^{X'} \rightarrow \Omega$ such that $(\tau_X)(t) = \varphi' \circ s^*$. \square*

We formulate a size restriction on predicate transformers.

Definition 4.17 (finitary predicate transformer). A predicate transformer $\varphi : \Omega^Y \rightarrow \Omega^X$ is *finitary* if for each $x \in X$ there exists a finite subset $s : Y' \rightarrow Y$ such that $\pi_x \circ \varphi$ factors through the

precomposition s^* . See below.

$$\begin{array}{ccc} \Omega^{Y'} & & \\ s^* \uparrow & \searrow \exists \varphi' & \\ \Omega^Y & \xrightarrow{\varphi} \Omega^X & \xrightarrow{\pi_x} \Omega \end{array} \quad (21)$$

Corollary 4.18. *Let T be finitary. For each $f : X \rightarrow Y$ in $\mathcal{KL}(T)$, the predicate transformer $\mathbb{P}^{\tau}(f) : \Omega^Y \rightarrow \Omega^X$ is finitary. \square*

Theorem 4.19 (healthiness, in a finitary setting). *Let T be a monad and $\bar{\Omega} = (\Omega_{\mathcal{D}}, \bar{\tau} : T \rightarrow \mathcal{D}(\Omega_{\mathcal{D}}^{(-)}, \Omega_{\mathcal{D}}))$ be a \mathcal{D} -relative T -algebra. Assume T is finitary, and that $\bar{\tau}_X$ is surjective—much like in Theorem 4.10—but for each finite set X . Then, for each map $\varphi : \Omega^Y \rightarrow \Omega^X$, the following are equivalent (healthiness).*

- There exists $f : X \rightarrow Y$ in $\mathcal{KL}(T)$ such that $\mathbb{P}^{\tau}(f) = \varphi$.
- φ is finitary (Definition 4.17) and lifts to \mathcal{D} . The latter means there exists $\bar{\varphi} : \Omega_{\mathcal{D}}^Y \rightarrow \Omega_{\mathcal{D}}^X$ such that $\bar{\varphi} = \varphi$. \square

In particular, in case a monad T is finitary, every predicate transformer $\mathbb{P}^{\tau}(f) : \Omega^Y \rightarrow \Omega^X$ that arises from a ‘‘computation’’ $f : X \rightarrow TY$ is finitary in the sense of Definition 4.17. We will see that this is indeed the case for the (sub)distribution monads (Sections 5.2–5.3); these monads are finitary because we restrict to (sub)distributions with a finite support.

We end with a topological interpretation of Definition 4.17.

Proposition 4.20. *Let Ω be a finite set with the discrete topology. A predicate transformer $\varphi : \Omega^Y \rightarrow \Omega^X$ is finitary if and only if φ is continuous with respect to the product topology of Ω^Y and Ω^X . \square*

5. (Purely) Probabilistic Examples

The term *probabilistic computation* in the literature often refers to one with an alternation of probabilistic and nondeterministic branching, the latter modeling (totally unknown) environments’ behaviors, or a (demonic) *scheduler*. This will be an example of our extended alternating framework of Section 6. Here we deal with computations with purely probabilistic branching.

5.1 Monads and Modalities for Probabilistic Branching

One of the following monads replaces \mathcal{P} in Section 2. We impose the restriction of countable supports.

Definition 5.1 (the (sub)distribution monad $\mathcal{D}_{=1}, \mathcal{D}_{\leq 1}$). *The distribution monad $\mathcal{D}_{=1}$ on \mathbf{Set} is such that: $\mathcal{D}_{=1}X = \{p : X \rightarrow [0, 1] \mid \sum_{x \in X} p(x) = 1, \text{ and } p(x) = 0 \text{ for all but finitely many } x \in X\}$; $\mathcal{D}_{=1}f(p)(y) = \sum_{x \in f^{-1}(y)} p(x)$ on arrows; its unit is the Dirac distribution $\eta_X^{\mathcal{D}_{=1}}(x)(y) = 1$ (if $y = x$) and 0 otherwise; and $\mu_X^{\mathcal{D}_{=1}}(\Phi)(x) = \sum_{p \in \mathcal{D}_{=1}X} \Phi(p) \cdot p(x)$.*

The subdistribution monad $\mathcal{D}_{\leq 1}$ is a variant defined by $\mathcal{D}_{\leq 1}X = \{p \text{ w/ finite supp.} \mid \sum_{x \in X} p(x) \leq 1\}$.

$\mathcal{D}_{=1}$ -algebras are often called *convex spaces*, with convex subsets in \mathbb{R}^n as typical examples. $\mathcal{D}_{=1}$ -algebra morphisms are *convex linear maps*, accordingly. Since any (finite) convex combination can be expressed by a repetition of suitable binary convex combinations $x \oplus_p y = (1-p)x + py$, a $\mathcal{D}_{=1}$ -algebra structure is totally determined by how binary convex combinations are interpreted.

Remark 5.2. Not all convex spaces are represented as convex subsets of \mathbb{R} -vector spaces: a two-point set $\{x, y\}$ is a convex space by defining $(1-p)x + py$ as x (if $p = 0$) and y (otherwise). In general we have a monad map $\mathcal{D}_{=1} \rightarrow \mathcal{P}_{\omega}$ to the finite powerset monad \mathcal{P}_{ω} that takes the *support* of a distribution; consequently each join-semilattice (i.e. \mathcal{P}_{ω} -algebras) yields a convex space. See [8] for more on convex spaces.

A $\mathcal{D}_{\leq 1}$ -algebra $x: \mathcal{D}_{\leq 1}X \rightarrow X$ is in turn called a *convex cone*, with the point $x(0) \in X$ (where 0 is the *zero* subdistribution) assuming the special role of the *apex* of a cone. Indeed it is straightforward to see that a convex cone is a “pointed convex space.”

Let us turn to *modalities*—i.e. $\mathcal{D}_{=1}$ - and $\mathcal{D}_{\leq 1}$ -algebras—that would induce predicate transformer semantics by the *modality* recipe (Theorem 3.4). We adopt $\Omega = [0, 1]$, the unit interval, with the intuition that “probabilistic predicates” are $[0, 1]$ -valued random variables whose values express the likelihood of truth.

Definition 5.3 (modalities for $\mathcal{D}_{=1}, \mathcal{D}_{\leq 1}$). For $\mathcal{D}_{=1}$ we use $\tau: \mathcal{D}_{=1}[0, 1] \rightarrow [0, 1]$; it uses the usual convex structure of $[0, 1]$.

For $\mathcal{D}_{\leq 1}$ we have a continuum of modalities: for each real number $r \in [0, 1]$ a modality $\tau_r: \mathcal{D}_{\leq 1}[0, 1] \rightarrow [0, 1]$ is given by $\tau_r(p) = \sum_{x \in [0, 1]} xp(x) + r(1 - \sum_x p(x))$.

We will in particular use the two extremes $\tau_{\text{total}} = \tau_0$ and $\tau_{\text{partial}} = \tau_1$; they are called the *total* and *partial* modalities for $\mathcal{D}_{\leq 1}$, respectively. In the latter *divergence*—whose probability is expressed by $1 - \sum_x p(x)$ —is deemed to yield truth. Hence τ_{total} and τ_{partial} are analogues of \diamond and \square in the nondeterministic setting (Section 2).

5.2 Healthiness for: Possibly Diverging Probabilistic Computations and the Total Modality

We shall first focus on the subdistribution monad $\mathcal{D}_{\leq 1}$ and the total modality τ_{total} . These data give rise to predicate transformer semantics—in the form of a state-and-effect triangle (9)—via the *modality* recipe (Theorem 3.4). In particular we obtain a functor $\mathbb{P}^{\tau_{\text{total}}}: \mathcal{Kl}(\mathcal{D}_{\leq 1}) \rightarrow \mathbf{Set}^{\text{op}}$ for interpreting a function $X \rightarrow \mathcal{D}_{\leq 1}Y$; the latter is identified with a *probabilistic computation* from X to Y that is possibly diverging (accounted for by subprobabilities).

Our goal is a healthiness result in this setting, towards which we rely on our *relative algebra* recipe. As we noted the original Theorem 4.8 is not enough; we use its finitary variant (Theorem 4.19), providing its ingredient (a relative algebra $\overline{\Omega}$) by means of the lifting result (Proposition 4.12).

It turns out that the category \mathcal{D} in the relative algebra recipe is given by so-called *generalized effect modules*. They have been used in the context of categorical quantum logics [19] and the more general theory of effectuses [5].

Definition 5.4 (**GEMod**). A *partial commutative monoid* (PCM) is a set M with a partial binary *sum* \oplus and a *zero* element $0 \in M$ that are subject to: $(x \oplus y) \oplus z \simeq x \oplus (y \oplus z)$, $x \oplus 0 \simeq x$ and $x \oplus y \simeq y \oplus x$, where \simeq is the Kleene equality. A *generalized effect algebra* is a PCM $(M, \oplus, 0)$ that is *positive* ($x \oplus y = 0 \Rightarrow x = y = 0$) and *cancellative* ($x \oplus y = x \oplus z \Rightarrow y = z$).

A *generalized effect module* is a generalized effect algebra M with a scalar multiplication $\cdot: [0, 1] \times M \rightarrow M$ that satisfies $(r \oplus s) \cdot x \simeq (r \cdot x) \oplus (s \cdot x)$, $r \cdot (x \oplus y) \simeq (r \cdot x) \oplus (r \cdot y)$, $1 \cdot x = x$ and $r \cdot (s \cdot x) = (r \cdot s) \cdot x$. Here for $r, s \in [0, 1]$ the partial sum $r \oplus s = r + s$ is defined when $r + s \leq 1$.

The category of general effect modules (with a straightforward notion of their morphism, see [4]) is denoted by **GEMod**.

An example of a generalized effect module is the set $\mathcal{D}_{\leq 1}X$ of subdistributions over X . Here $p \oplus q \in \mathcal{D}_{\leq 1}X$ is given by $(p \oplus q)(x) = p(x) + q(x)$, which is well-defined clearly only if $\sum_{x \in X} p(x) + q(x) \leq 1$. The set $\mathcal{D}_{\leq 1}X$ comes with an obvious scalar multiplication, too. The unit interval $[0, 1]$ is another example; so is its products $[0, 1]^X$. See [4] for details.

For our purpose of healthiness conditions, we have to study the monad map induced by the $\mathcal{D}_{\leq 1}$ -algebra τ_{total} . It shall also be denoted by τ_{total} . The following is easy.

Lemma 5.5. *The monad map $\tau_{\text{total}}: \mathcal{D}_{\leq 1} \rightarrow \mathbf{Set}([0, 1]^{(-)}, [0, 1])$ is concretely given by: $(\tau_{\text{total}})_X(p)(f) = \sum_{x \in X} f(x)p(x)$.*

1. *It lifts to $\tau_{\text{total}}: \mathcal{D}_{\leq 1} \rightarrow \mathbf{GEMod}([0, 1]^{(-)}, [0, 1])$, that is, the map $(\tau_{\text{total}})_X(p): [0, 1]^X \rightarrow [0, 1]$ for each X and $p \in \mathcal{D}_{\leq 1}X$ preserves 0 , \oplus and scalar multiplication.*
2. *Furthermore $(\tau_{\text{total}})_Y: \mathcal{D}_{\leq 1}Y \rightarrow \mathbf{GEMod}([0, 1]^Y, [0, 1])$ is an isomorphism for each finite set Y .* \square

From the last lemma the following healthiness result follows immediately, via our general results. Specifically: Lemma 5.5.1 discharges the condition of Proposition 4.12 and provides the ingredient for the relative algebra recipe; we then exploit Lemma 5.5.2 and that $\mathcal{D}_{\leq 1}$ is finitary in applying Theorem 4.19.

Theorem 5.6 (healthiness for $\mathcal{D}_{\leq 1}$ and τ_{total}). *For a function $\varphi: [0, 1]^Y \rightarrow [0, 1]^X$ the following are equivalent: 1) there is $f: X \rightarrow \mathcal{D}_{\leq 1}Y$ such that $\varphi = \mathbb{P}^{\tau_{\text{total}}}(f)$; 2) φ is finitary (Definition 4.17) and is a morphism of generalized effect modules, meaning that 0 , \oplus and scalar multiplications are preserved by φ .* \square

5.3 Healthiness for Other Variations

For the other two variations of monads and modalities we can use the same arguments as in Section 5.2.

For the combination of $\mathcal{D}_{\leq 1}$ and the other modality τ_{partial} , we use the same category **GEMod** as an ingredient \mathcal{D} ; the difference is that the induced monad map τ_{partial} is “dualized.”

Theorem 5.7 (healthiness for $\mathcal{D}_{\leq 1}$ and τ_{partial}). *For a function $\varphi: [0, 1]^Y \rightarrow [0, 1]^X$ the following are equivalent: 1) there is $f: X \rightarrow \mathcal{D}_{\leq 1}Y$ such that $\varphi = \mathbb{P}^{\tau_{\text{partial}}}(f)$; 2) φ is finitary and is a morphism of generalized effect modules. Here $[0, 1]$ is regarded as a generalized effect module in the way dual to usual: its zero element is 1 , the partial sum \oplus is defined by $x \oplus y = x + y - 1$ (if the right hand side is in $[0, 1]$) and scalar multiplication \circ is defined by $r \circ x = r \cdot x + (1 - r)$.* \square

For the (not sub-) distribution monad $\mathcal{D}_{=1}$ and the modality τ in Definition 5.3, we use the category **EMod** of *effect modules* in place of **GEMod**.

Definition 5.8 (**EMod**). An *effect module* M is a generalized effect module that additionally has a *top element* 1 . It is required to be the greatest with respect to the canonical order \leq on M , defined by $x \leq y$ if $y = x \oplus z$ for some $z \in M$. Effect modules and their morphisms—functions that preserve $0, 1, \oplus$ and scalar multiplication—form a category denoted by **EMod**.

Theorem 5.9 (healthiness for $\mathcal{D}_{=1}$ and τ). *For a predicate transformer function $\varphi: [0, 1]^Y \rightarrow [0, 1]^X$ the following are equivalent: 1) there is $f: X \rightarrow \mathcal{D}_{=1}Y$ such that $\varphi = \mathbb{P}^{\tau}(f)$; 2) φ is finitary and is a morphism of effect modules, meaning that $0, 1, \oplus$ and scalar multiplication are preserved by φ .* \square

6. Alternating Branching

In this last section we further extend our general framework to accommodate *alternating* branching, in which two players in conflicting interests interplay. Its instances are pervasive in computer science, such as: *games*, i.e. a two-player variant of automata, in which two players alternate in choosing next states (see e.g. [33]); and various modeling of *probabilistic systems* where it is common to include additional nondeterministic branching for modeling demonic behaviors of the environments (or *schedulers*). See e.g. [32].

In [13] the *modality* recipe (Theorem 3.4) is extended to alternating branching; the central observation is a compositional treatment of two branching layers, using a monad T on **Set** (for one) and a monad R on **EM(T)** (for the other). See (22) later. It turns out

that the same idea works for our current generalized *relative algebra* recipe (Theorem 4.8).

After the general framework we will describe some examples. A notable one is (a variant of) *probabilistic predicate transformers* [31].

6.1 The Relative Algebra Recipe for Alternation

Definition 6.1 ($R \star T$). Let T be a monad on \mathbf{Set} and R be a monad on $\mathcal{EM}(T)$. Then a monad $R \star T$ is defined by the composite of the canonical adjunction $F \dashv U : \mathcal{EM}(T) \rightarrow \mathbf{Set}$ and the monad R .

$$R \star T = URF \quad \left(\mathbf{Set} \begin{array}{c} \xrightarrow{F} \\ \perp \\ \xleftarrow{U} \end{array} \mathcal{EM}(T) \right)^R \quad (22)$$

Example 6.2. One example is given by $T = \mathcal{P}$ on \mathbf{Set} and $R = \text{Up}$, the *up-closed powerset monad*, on $\mathcal{EM}(\mathcal{P}) \cong \mathbf{CL}_V$. It is given by $\text{Up}(L, \leq) = (\{S \subseteq L \mid S \text{ is up-closed}\}, \supseteq)$; note that the inclusion order is reversed. This combination is for alternating branching where both layers are nondeterministic.

Another is given by $T = \mathcal{D}_{=1}$ on \mathbf{Set} and $R = \text{Cv}$, the *nonempty convex powerset monad*, on $\mathcal{EM}(\mathcal{D}_{=1}) \cong \mathbf{Conv}$ (the category of convex spaces and convex-linear maps). The latter is given by

$$\text{Cv}X = \{S \subseteq X \mid S \text{ is nonempty and convex-closed, i.e.}$$

$$x_1, \dots, x_n \in S \text{ and } \lambda_1 + \dots + \lambda_n = 1 \text{ implies } \sum_i \lambda_i x_i \in S\}.$$

This is for alternating probabilistic and nondeterministic branching.

It is important that these R are not monads on \mathbf{Set} per se; they involve T -algebra structures.

Remark 6.3. We have comparison functors $K : \mathcal{KL}(R \star T) \rightarrow \mathcal{KL}(R)$ and $L : \mathcal{EM}(R) \rightarrow \mathcal{EM}(R \star T)$ as follows.

$$\begin{array}{ccc} \mathcal{KL}(R \star T) & \xrightarrow{K} & \mathcal{KL}(R) \\ & \searrow \downarrow \dashv \downarrow & \nearrow \dashv \downarrow \\ & \mathcal{EM}(T) & \\ & \uparrow \dashv \downarrow & \nearrow \dashv \downarrow \\ R \star T & \left(\mathbf{Set} \right) & \mathcal{EM}(R) \xrightarrow{L} \mathcal{EM}(R \star T) \end{array} \quad (23)$$

We aim at reproducing the *relative algebra* recipe (Theorem 4.8) for the current alternating setting. The first ingredient for the recipe was a dual adjunction $\mathbf{Set} \xleftarrow{\perp} \mathcal{D}^{\text{op}}$ from which we derived a continuation-like monad $\mathcal{D}(\Omega_D^{(-)}, \Omega_D)$. For the alternating version of the recipe, in view of (22) it is natural to use a dual adjunction $\mathcal{EM}(T) \xleftarrow{\perp} \mathcal{D}^{\text{op}}$ (where $\mathcal{EM}(T)$ replaced \mathbf{Set} in the non-alternating counterpart). Interestingly, for such an ingredient $\mathcal{EM}(T) \xleftarrow{\perp} \mathcal{D}^{\text{op}}$ we can exploit (the original, non-alternating version of) *relative algebra* recipe itself. See (13) in Theorem 4.8; this yields a continuation-like monad $[[-, \bar{\Omega}]_T, \bar{\Omega}]_{\mathcal{D}}$ over $\mathcal{EM}(T)$.

Then it is clear that the next key ingredient in the original recipe—namely a monad map $\tau : T \rightarrow \mathcal{D}(\Omega_D^{(-)}, \Omega_D)$ —has a monad map $\rho : R \rightarrow [[-, \bar{\Omega}]_T, \bar{\Omega}]_{\mathcal{D}}$ as its alternating counterpart.

Given such data we obtain predicate transformer semantics.

Definition 6.4 ($\mathbb{P}^\rho, \mathbb{P}^{(\tau, \rho)}$). Let T be a monad on \mathbf{Set} , \mathcal{D} be a complete category and $\bar{\Omega} = (\Omega_{\mathcal{D}}, \tau)$ be a \mathcal{D} -relative T -algebra. Moreover let R be a monad on $\mathcal{EM}(T)$ and $\rho : R \rightarrow [[-, \bar{\Omega}]_T, \bar{\Omega}]_{\mathcal{D}}$ be a monad map. Here $[[-, \bar{\Omega}]_T, \bar{\Omega}]_{\mathcal{D}}$ is the monad that arises from the dual adjunction $\mathcal{EM}(T) \xleftarrow{\perp} \mathcal{D}^{\text{op}}$ induced by $\bar{\Omega}$ as in Theorem 4.8.

We define a functor $\mathbb{P}^\rho : \mathcal{KL}(R) \rightarrow \mathcal{D}^{\text{op}}$ by: $\mathbb{P}^\rho A_a = A_a$ and

$$\mathbb{P}^\rho(A_a \xrightarrow{f} B_b \text{ in } \mathcal{KL}(R)) = ([B_b, \bar{\Omega}]_T \xrightarrow{\rho^\sharp} [RB_b, \bar{\Omega}]_T \xrightarrow{f^\star} [A_a, \bar{\Omega}]_T).$$

Furthermore, by precomposing the comparison functor $K : \mathcal{KL}(R \star T) \rightarrow \mathcal{KL}(R)$, we have another functor:

$$\mathbb{P}^{(\tau, \rho)} = \mathbb{P}^\rho \circ K : \mathcal{KL}(R \star T) \rightarrow \mathcal{D}^{\text{op}}. \quad (24)$$

The last functor $\mathbb{P}^{(\tau, \rho)}$ is what we want: it interprets a function $X \rightarrow (R \star T)Y$ —a computation from X to Y , with alternation of T - and R -branching—in the category \mathcal{D} , in a backward manner.

The following extends Theorem 4.10.

Theorem 6.5 (alternating healthiness condition). *Assume the setting of Definition 6.4, and let X and Y be sets. If the map*

$$U\rho_{FY} : URFY \rightarrow U[[FY, \bar{\Omega}]_T, \bar{\Omega}]_{\mathcal{D}} \cong \mathcal{D}(\Omega_{\mathcal{D}}^Y, \Omega_{\mathcal{D}})$$

is surjective (injective), then the action $\mathbb{P}_{XY}^{(\tau, \rho)} : \mathcal{KL}(R \star T)(X, (R \star T)Y) \rightarrow \mathcal{D}(\Omega^Y, \Omega^X)$ of $\mathbb{P}^{(\tau, \rho)}$ is surjective (injective). \square

Let us now assume that \mathcal{D} is concrete, and develop an alternating counterpart of Section 4.3.

Theorem 6.6. *Suppose we have a monad T on \mathbf{Set} , a complete category \mathcal{D} with a faithful and limit-preserving functor $V : \mathcal{D} \rightarrow \mathbf{Set}$, and a \mathcal{D} -relative T -algebra $\bar{\Omega} = (\Omega_{\mathcal{D}}, \bar{\tau})$. Moreover assume we have a monad R on $\mathcal{EM}(T)$ and an R -algebra structure $\hat{\rho} : R\Omega_{\tau} \rightarrow \Omega_{\tau}$ on Ω_{τ} . Then the following are equivalent.*

1. *The monad map $\rho : R \rightarrow \Omega_{\tau}^{\mathcal{EM}(T)(-, \Omega_{\tau})}$ that corresponds to $\hat{\rho}$ (Proposition 4.3) lifts to a monad map $\bar{\rho} : R \rightarrow [[-, \bar{\Omega}]_T, \bar{\Omega}]_{\mathcal{D}}$, equipped with a suitable \mathcal{D} -structure.*
2. *(Lifting condition) For each T -algebra A_a , the extension map $\rho_{A_a}^\sharp : \mathcal{EM}(T)(A_a, \Omega_{\tau}) \rightarrow \mathcal{EM}(T)(RA_a, \Omega_{\tau})$, which maps a T -algebra morphism $f : A_a \rightarrow \Omega_{\tau}$ to $\hat{\rho} \circ Rf : RA_a \rightarrow \Omega_{\tau}$, lifts (along V) to a \mathcal{D} -morphism $\bar{\rho}^\sharp : [A_a, \bar{\Omega}]_T \rightarrow [RA_a, \bar{\Omega}]_T$. That is, there exists $\bar{\rho}^\sharp$ such that $V\bar{\rho}^\sharp = \rho^\sharp$.*
3. *(Pointwise lifting condition) For each A_a and $x \in URA_a$, the map $(\rho^\sharp)_x = \pi_x \circ \rho^\sharp : \mathcal{EM}(A_a, \Omega_{\tau}) \rightarrow \Omega$ lifts to a \mathcal{D} -morphism $(\bar{\rho}^\sharp)_x : [A_a, \bar{\Omega}]_T \rightarrow \Omega_{\mathcal{D}}$. Here π_x is defined by the following composite:*

$$\pi_x = (\mathcal{EM}(T)(RA_a, \Omega_{\tau}) \xrightarrow{U} \mathbf{Set}(URA_a, \Omega) \xrightarrow{\text{ev}_x} \Omega) \text{ in } \mathbf{Set}$$

and ev_x evaluates a function $h : URA_a \rightarrow \Omega$ by x . \square

In the above we implicitly used the isomorphism $V[A_a, \bar{\Omega}]_T \cong \mathcal{EM}(T)(A_a, \bar{\Omega})$ given in Proposition 4.14.

6.2 Examples

We list healthiness results for some alternating situations. We indicate how we exploit the general framework above; the details are omitted for space reasons.

Nondeterminism and Divergence In Dijkstra's original work [7] the first healthiness result is presented for computations with alternation between *divergence* and *nondeterminism*. They are described by functions of the type $X \rightarrow (\mathcal{P}_+ \star \mathcal{L})Y$, where: $\mathcal{L}X = 1 + X$ is the *lift* monad on \mathbf{Set} (modeling potential divergence); and \mathcal{P}_+ is the *nonempty powerset* monad on $\mathcal{EM}(\mathcal{L}) \cong \mathbf{Set}_*$, the category of *pointed sets*. The latter monad is given specifically by $\mathcal{P}_+(X, x) = (\{S \subseteq X \mid S \neq \emptyset\}, \{x\})$.

Suitable modalities τ and ρ are found to capture the setting of [7]. For the category \mathcal{D} for predicate transformers we introduce the notion of *strict complete meet-semilattice*. It is a poset with the least element 0 and arbitrary but nonempty meets.

Theorem 6.7 (healthiness for nondeterminism and divergence). *For a function $\varphi : 2^Y \rightarrow 2^X$ the following are equivalent: 1) there is $f : X \rightarrow (\mathcal{P}_+ \star \mathcal{L})Y$ such that $\varphi = \mathbb{P}^{(\rho, \tau)}(f)$; 2) φ preserves 0 and nonempty meets.* \square

Alternating Nondeterminism Alternation of two layers of nondeterminism is found e.g. in *games*. In program logic point of view— one player *ensures* a postcondition, no matter the other player’s move is—such computation is best modeled as a function $X \rightarrow (\text{Up} \star \mathcal{P})Y$. Here Up is the monad on $\mathcal{EM}(\mathcal{P}) \cong \mathbf{CL}_V$ from Example 6.2. There are modalities τ and ρ suited to capture the above game-theoretic intuitions; see [13]. Here we choose a combination in which: the opponent moves first, and the protagonist follows. Towards healthiness we take posets and monotone functions in \mathcal{D} .

Theorem 6.8 (healthiness for alternating nondeterminism). *For a function $\varphi: 2^Y \rightarrow 2^X$ the following are equivalent: 1) there is $f: X \rightarrow (\text{Up} \star \mathcal{P})Y$ s.t. $\varphi = \mathbb{P}^{(\rho, \tau)}(f)$; 2) φ is monotone.* \square

Nondeterminism and Probability Finally we study a common setting in the study of probabilistic systems where: a demonic nondeterministic choice occurs first, followed by an angelic probabilistic choice. This is modeled by a function $X \rightarrow (\text{Cv} \star \mathcal{D}_{=1})Y$, where Cv on $\mathcal{EM}(\mathcal{D}_{=1}) \cong \mathbf{Conv}$ is from Example 6.2. Predicate transformer semantics of such computations has $[0, 1]$ as the domain of truth values; and suitable modalities τ and ρ are found much like in [13]. The outcome is (a slight variation of) *probabilistic predicate transformers* in [31].

For healthiness we use the category of: effect algebras (Definition 5.8) and what we call *regular-sublinear maps* between them. The latter are subject to: (*subadditivity*) if $x \perp y$ then $f(x) \perp f(y)$ and we have $f(x) \otimes f(y) \leq f(x \otimes y)$; (*scaling*) $f(\lambda x) = \lambda f(x)$; and (*translation*) $f(x \otimes \lambda 1) = f(x) \otimes \lambda 1$ if $x \perp \lambda 1$. It deviates from *sublinear maps* [31] in that we require $=$ in (translation).

In the following we assume Y ’s finiteness; this is like in [31].

Theorem 6.9 (healthiness for nondeterminism and probability). *Assume Y is finite. For a function $\varphi: [0, 1]^Y \rightarrow [0, 1]^X$ the following are equivalent: 1) there is $f: X \rightarrow (\text{Cv} \star \mathcal{D}_{=1})Y$ such that $\varphi = \mathbb{P}^{(\rho, \tau)}(f)$; 2) φ is regular-sublinear.* \square

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References

- [1] J. Adámek and J. Rosický. *Locally Presentable and Accessible Categories*, volume 189 of *London Math. Soc. Lect. Note Series*. Cambridge Univ. Press, 1994.
- [2] M. Barr and C. Wells. *Toposes, Triples and Theories*. Springer, Berlin, 1985. Available online.
- [3] M. M. Bonsangue, editor. *Coalgebraic Methods in Computer Science - 12th IFIP WG 1.3 International Workshop, CMCS 2014, Colocated with ETAPS 2014, Grenoble, France, April 5-6, 2014, Revised Selected Papers*, volume 8446 of *Lecture Notes in Computer Science*, 2014. Springer. ISBN 978-3-662-44123-7. URL <http://dx.doi.org/10.1007/978-3-662-44124-4>.
- [4] K. Cho. Total and partial computation in categorical quantum foundations. In C. Heunen, P. Selinger, and J. Vicary, editors, *Proceedings 12th International Workshop on Quantum Physics and Logic, QPL 2015, Oxford, UK, July 15-17, 2015.*, volume 195 of *EPTCS*, pages 116–135, 2015. URL <http://dx.doi.org/10.4204/EPTCS.195.9>.
- [5] K. Cho, B. Jacobs, B. Westerbaan, and A. Westerbaan. An introduction to effectus theory. *CoRR*, abs/1512.05813, 2015. URL <http://arxiv.org/abs/1512.05813>.
- [6] D. M. Clark and B. Davey. *Natural Dualities for the Working Algebraist*. Cambridge Studies in Advanced Mathematics. Cambridge Univ. Press, 1998.
- [7] E. W. Dijkstra. *A Discipline of Programming*. Prentice Hall, 1976.
- [8] T. Fritz. Convex spaces i: Definition and examples. *arXiv preprint arXiv:0903.5522*, 2009.
- [9] S. Goncharov and L. Schröder. A relatively complete generic Hoare logic for order-enriched effects. In *Proc. 28th Annual Symposium on Logic in Computer Science (LICS 2013)*, pages 273–282. IEEE, 2013.
- [10] P. R. Halmos. *Algebraic Logic*. American Mathematical Society, 2006.
- [11] D. Harel, J. Tiuryn, and D. Kozen. *Dynamic Logic*. MIT Press, Cambridge, MA, USA, 2000. ISBN 0262082896.
- [12] I. Hasuo. Generic weakest precondition semantics from monads enriched with order. In Bonsangue [3], pages 10–32. ISBN 978-3-662-44123-7. URL <http://dx.doi.org/10.1007/978-3-662-44124-4>.
- [13] I. Hasuo. Generic weakest precondition semantics from monads enriched with order. *Theor. Comput. Sci.*, 604:2–29, 2015. URL <http://dx.doi.org/10.1016/j.tcs.2015.03.047>.
- [14] C. A. R. Hoare. An axiomatic basis for computer programming. *Commun. ACM*, 12:576–580, 583, 1969.
- [15] D. Hofmann and P. Nora. Dualities for modal algebras from the point of view of triples. *Algebra Universalis*, 73(3):297–320, 2015. ISSN 1420-8911. URL <http://dx.doi.org/10.1007/s00012-015-0324-5>.
- [16] M. Hyland and J. Power. The category theoretic understanding of universal algebra: Lawvere theories and monads. *Electronic Notes in Theoretical Computer Science*, 172:437–458, 2007.
- [17] B. Jacobs. Dijkstra monads in monadic computation. In Bonsangue [3], pages 135–150. ISBN 978-3-662-44123-7. URL <http://dx.doi.org/10.1007/978-3-662-44124-4>.
- [18] B. Jacobs. A recipe for state-and-effect triangles. In L. S. Moss and P. Sobocinski, editors, *6th Conference on Algebra and Coalgebra in Computer Science, CALCO 2015, June 24-26, 2015, Nijmegen, The Netherlands*, volume 35 of *LIPICs*, pages 116–129. Schloss Dagstuhl - Leibniz-Zentrum fuer Informatik, 2015. ISBN 978-3-939897-84-2. URL <http://dx.doi.org/10.4230/LIPICs.CALCO.2015.116>.
- [19] B. Jacobs. New directions in categorical logic, for classical, probabilistic and quantum logic. *Logical Methods in Computer Science*, 11(3), 2015. URL [http://dx.doi.org/10.2168/LMCS-11\(3:24\)2015](http://dx.doi.org/10.2168/LMCS-11(3:24)2015).
- [20] B. Jacobs. Dijkstra and Hoare monads in monadic computation. *Theoretical Computer Science*, 604:30–45, 2015.
- [21] C. Jones. *Probabilistic Non-Determinism*. PhD thesis, Univ. Edinburgh, 1990.
- [22] B. Jónsson and A. Tarski. Boolean algebras with operators I. *Amer. Journ. Math.*, 73:891–939, 1951.
- [23] K. Keimel. Healthiness conditions for predicate transformers. *Electr. Notes Theor. Comput. Sci.*, 319:255–270, 2015. URL <http://dx.doi.org/10.1016/j.entcs.2015.12.016>.
- [24] G. M. Kelly. A unified treatment of transfinite constructions for free algebras, free monoids, colimits, associated sheaves, and so on. *Bulletin of the Australian Mathematical Society*, 20:1–83, 1980.
- [25] G. M. Kelly. *Basic Concepts of Enriched Category Theory*. Number 64 in LMS. Cambridge Univ. Press, 1982. Available online: <http://www.tac.mta.ca/tac/reprints/articles/10/tr10abs.html>.
- [26] G. M. Kelly and A. J. Power. Adjunctions whose counits are coequalizers, and presentations of finitary enriched monads. *Journal of Pure and Applied Algebra*, 89(1–2):163–179, 1993.
- [27] D. Kozen. Semantics of probabilistic programs. *J. Comput. Syst. Sci.*, 22(3):328–350, 1981.
- [28] S. Lack and J. Power. Gabriel-Ulmer duality and Lawvere theories enriched over a general base. *J. Funct. Program.*, 19(3-4):265–286, 2009. URL <http://dx.doi.org/10.1017/S0956796809007254>.

- [29] S. Mac Lane. *Categories for the Working Mathematician*. Springer, Berlin, 2nd edition, 1998.
- [30] M. Makkai and R. Paré. Accessible categories: the foundations of categorical model theory. *Contemp. Math.*, 104, 1989.
- [31] C. Morgan, A. McIver, and K. Seidel. Probabilistic predicate transformers. *ACM Trans. Program. Lang. Syst.*, 18(3):325–353, 1996.
- [32] A. Sokolova. *Coalgebraic Analysis of Probabilistic Systems*. PhD thesis, Techn. Univ. Eindhoven, 2005.
- [33] T. Wilke. Alternating tree automata, parity games, and modal μ -calculus. *Bull. Belg. Math. Soc. Simon Stevin*, 8(2):359–391, 2001.
- [34] G. Winskel. *The Formal Semantics of Programming Languages*. MIT Press, 1993.

A. Omitted Proofs and Details

A.1 Explicit Definition of Monad Maps

Definition A.1. Let S, T be monads on \mathcal{C} . A *monad map* from S to T is a natural transformation $\alpha: S \rightarrow T$ that makes the following diagram commute.

$$\begin{array}{ccccc} X & \xrightarrow{\eta_X^S} & SX & \xrightarrow{SSX \xrightarrow{S\alpha_X} STX \xrightarrow{\alpha_{TX}} TTX} & TTX \\ & \searrow \eta_X^T & \downarrow \alpha_X & \downarrow \mu_X^S & \downarrow \mu_X^T \\ & & TX & \xrightarrow{\alpha_X} & TX \end{array} \quad (25)$$

Here $\eta^{(-)}$ and $\mu^{(-)}$ are the unit and the multiplication of monads.

A.2 Proof of Lemma 2.1

Proof. Let the monad $[2^{(-)}, 2]_{\vee}$ be denoted by T in the current proof, for brevity.

We need to check that σ_X is join-preserving for each X . Indeed, for each $S \subseteq X$, we have $\bigvee_{x \in S} (\bigvee_{f \in \mathcal{F}} f(x)) = \bigvee_{f \in \mathcal{F}} (\bigvee_{x \in S} f(x))$ for any family $\mathcal{F} \subseteq 2^X$. It is easy to check that σ is natural, and that it is compatible with monad units. Compatibility with monad multiplications requires the following diagram to commute.

$$\begin{array}{ccc} \mathcal{P}\mathcal{P}X & \xrightarrow{\mathcal{P}\sigma_X} & \mathcal{P}TX & \xrightarrow{\sigma_{TX}} & TTX \\ \downarrow \cup & & \downarrow \cup & & \downarrow \mu_X \\ \mathcal{P}X & \xrightarrow{\sigma_X} & TX & & TX \end{array}$$

Indeed, for each $S \in \mathcal{P}\mathcal{P}X$ we have

$$\begin{aligned} \mu \circ \sigma_{TX} \circ \mathcal{P}\sigma_X(S) &= \mu \circ \sigma_{TX}(\{\sigma_X(S) \mid S \in \mathcal{S}\}) \\ &= \mu \left(\lambda \varphi. \bigvee_{S \in \mathcal{S}} \varphi \circ \sigma_X(S) \right) \\ &= \lambda f'. \left(\lambda \varphi. \bigvee_{S \in \mathcal{S}} \varphi \circ \sigma_X(S) \right) (\lambda \xi. \xi(f')) \\ &= \lambda f'. \bigvee_{S \in \mathcal{S}} \sigma_X(S)(f') \\ &= \lambda f'. \bigvee_{S \in \mathcal{S}} \bigvee_{x \in S} f'(x) \\ &= \sigma_X \left(\bigcup \mathcal{S} \right). \end{aligned}$$

Finally we check that σ_X is bijective. Its inverse is given by

$$(\sigma_X)^{-1}(\xi) = \{x \in X \mid \xi(\delta_x) = 1\},$$

where $\delta_x: X \rightarrow 2$ is given by: $\delta_x(x) = 1$, and $\delta_x(y) = 0$ if $x \neq y$. \square

A.3 Proof of Theorem 3.4

Proof. For any set X we have $[KX, \Omega_\tau]_T \cong \Omega^X$ since KX is the free T -algebra over X . It is natural in $X \in \mathcal{K}\ell(T)$. Indeed, for $f: X \rightarrow TY$, the diagram

$$\begin{array}{ccc} [TX, \Omega_\tau]_T & \xleftarrow{(Kf)^*} & [TY, \Omega_\tau]_T \\ \downarrow \cong & & \downarrow \cong \\ \Omega^X & \xleftarrow{f^*} \Omega^{TY} & \xleftarrow{\tau^\#} \Omega^Y \end{array}$$

commutes by direct calculation. \square

A.4 Proof of Proposition 4.7

Proof. Since the functor H is product preserving, the canonical map $\theta: H(A^X) \rightarrow (HA)^X$ in \mathcal{D}' , defined by the transpose of

$$X \xrightarrow{\text{id}^\#} \mathcal{D}(A^X, A) \xrightarrow{H} \mathcal{D}'(H(A^X), HA), \quad (26)$$

is an isomorphism. Using this isomorphism θ , we define a natural transformation ψ^A by $\psi_X^A = (\theta^{-1})^* \circ H$, that is,

$$\mathcal{D}(A^X, A) \xrightarrow{H} \mathcal{D}'(H(A^X), HA) \xrightarrow{(\theta^{-1})^*} \mathcal{D}'((HA)^X, HA) .$$

This ψ is seen to be a monad map by some diagram chasing. We define a functor \overline{H} by

$$\overline{H}(A, \alpha) = (HA, \psi \circ \alpha) , \quad \text{and}$$

$$\overline{H}((A, \alpha) \xrightarrow{f} (B, \beta)) = ((HA, \psi \circ \alpha) \xrightarrow{Hf} (HB, \psi \circ \beta)) .$$

It is a routine to check that Hf is indeed a morphism of \mathcal{D}' -relative T -algebra, and that \overline{H} makes the diagram in (12) commute.

That \overline{H} preserves products is easily checked by direct calculations. That \overline{H} is faithful, given that H is so, follows immediately from (12). \square

A.5 Proof of Theorem 4.8

Proof. We will denote Ω_D^X and $\mathcal{D}(M, \Omega_D)$ by X^* and M^* respectively in this proof.

We check the adjointness of $[-, \overline{\Omega}]_T$ and $[-, \overline{\Omega}]_{\mathcal{D}}$. It is enough to show that, for a T -algebra A_a , an object $M \in \mathcal{D}$ and $f: M \rightarrow A^*$ in \mathcal{D} , the commutativity of the two diagrams in (27) are equivalent:

$$\begin{array}{ccc} M & \xrightarrow{f} & A^* & & TA & \xrightarrow{Tf^\#} & T(M^*) & (27) \\ f \downarrow & & \downarrow \tau^\# & & a \downarrow & & \downarrow \zeta_M & \\ A^* & \xrightarrow{a^*} & (TA)^* & & A & \xrightarrow{f^\#} & M^* \end{array}$$

Since commutativity of the left diagram in (27) is equivalent to that of the left diagram in (28), it is enough to show the diagram in (29) commutes.

$$\begin{array}{ccc} TA & \xrightarrow{\tau} & A^{**} & & A^* & \xleftarrow{f} & M & (28) \\ a \downarrow & & \downarrow f^* & & (f^\#)^* \uparrow & & \swarrow \eta & \\ A & \xrightarrow{f^\#} & M^* & & M^{**} & \xleftarrow{\eta} & \end{array}$$

$$\begin{array}{ccc} TA & \xrightarrow{\tau} & A^{**} & \xrightarrow{f^*} & M^* & (29) \\ Tf^\# \downarrow & & (f^\#)^{**} \downarrow & & \swarrow \eta^* & \\ T(M^*) & \xrightarrow{\tau} & M^{***} & \end{array}$$

The left square commutes by the naturality, and the right triangle commutes since the right diagram in (28) does by the adjointness. \square

A.6 Proof of Theorem 4.10

Proof. It is easy to check the functor \mathbb{P}^τ coincides with the composite

$$\mathcal{Kl}(T) \xrightarrow{\mathcal{Kl}(\tau)} \mathcal{Kl}(\mathcal{D}(\Omega_D^{(-)}, \Omega_D)) \xrightarrow{K} \mathcal{D}^{\text{op}} , \quad (30)$$

where K is the comparison functor and $\mathcal{Kl}(\tau)$ denotes the functor defined by

$$\mathcal{Kl}(\tau)(X) = X , \quad \text{and}$$

$$\mathcal{Kl}(\tau)(X \xrightarrow{f} Y \text{ (in } \mathcal{Kl}(T))) = (X \xrightarrow{f} TY \xrightarrow{\tau} \mathcal{D}(\Omega_D^Y, \Omega_D) \text{ (in } \mathbf{Set})) .$$

Since K is full and faithful, it is enough to show the action $\mathcal{Kl}(\tau): \mathcal{Kl}(T)(X, Y) \rightarrow \mathcal{Kl}(\mathcal{D}(\Omega_D^{(-)}, \Omega_D))(X, Y)$ is surjective (resp. injective). By the definition of $\mathcal{Kl}(\tau)$, this action is the post-composition map by τ .

$$\tau_*: \mathbf{Set}(X, TY) \rightarrow \mathbf{Set}(X, \mathcal{D}(\Omega_D^Y, \Omega_D)) \quad (31)$$

Here we use the identification $\mathcal{Kl}(T)(X, Y) = \mathbf{Set}(X, TY)$ and $\mathcal{Kl}(\mathcal{D}(\Omega_D^{(-)}, \Omega_D))(X, Y) = \mathbf{Set}(X, \mathcal{D}(\Omega_D^Y, \Omega_D))$. When τ is injective, the postcomposition τ_* is injective by the definition of mono. When τ is surjective, it is split epi (by the axiom of choice) hence so is τ_* . \square

A.7 Proof of Lemma 4.16

Proof. Since T is finitary, $t: 1 \rightarrow TX$ factor through some finite subset $s: X' \rightarrow X$ as $t = Ts \circ t'$. Then we get a desired factorization as follows:

$$\begin{array}{ccccc} & & TX' & & \Omega^{TX'} \xleftarrow{\tau_{X'}^\#} \Omega^n \\ & \nearrow t' & \downarrow Ts & \nearrow (t')^* & \uparrow s^* \\ 1 & \xrightarrow{t} & TX & \xleftarrow{t^*} & \Omega^{TX} \xleftarrow{\tau_X^\#} \Omega^X \end{array}$$

A.8 Proof of Theorem 4.19

Proof. We can assume $X = 1$.

Only if: It follows from Corollary 4.18.

If: The statement is obviously true for $Y = \emptyset$, so we assume $Y \neq \emptyset$. Since φ is finitary, we can decompose φ as $\varphi = \varphi' \circ s^*$ for some finite subset $s: Y' \rightarrow Y$ and $\varphi': \Omega^{Y'} \rightarrow \Omega$. We can assume Y' is nonempty. Fix a retraction $r: Y \rightarrow Y'$. We have $\varphi' = \varphi \circ r^*$, then φ' also lifts to an \mathcal{D} -morphism $\overline{\varphi}'$. By the surjectiveness of $\sigma_{Y'}$, there exists some $t' \in TY'$ with $\sigma_{Y'}(t') = f'$. Take $t = Ts(t')$, then we have $\sigma_X(t) = \varphi$, which concludes the proof. \square

A.9 Proof of Theorem 4.20

We use the following lemma on elementary topology. It easily follows from the compactness of Ω^X .

Lemma A.2. For a finite discrete space Ω and an arbitrary set X , each clopen set $C \subseteq \Omega^X$ is written as $(s^*)^{-1}(S)$ for some finite subset $s: X' \rightarrow X$ and some subset S of $\Omega^{X'}$.

Proof of Proposition 4.20. We can assume $X = 1$.

If: assume φ is continuous. For each $z \in \Omega$, the inverse image $\varphi^{-1}(z)$ is clopen, so it can be described as $(\iota_z^*)^{-1}(S_z)$ for some finite subset $\iota_z: Y_z \rightarrow Y$ and $S_z \subseteq \Omega^{Y_z}$. Then $\iota: Y' = \bigcup_{z \in \Omega} Y_z \rightarrow Y$ is still finite and φ factors through ι^* .

Only if: assume φ is finitary; we have $s: n \rightarrow Y$ and $\varphi': \Omega^n \rightarrow \Omega$ such that $\varphi' \circ s^* = \varphi$. The map s^* is obviously continuous, and so is φ' since its domain Ω^n is (finite) discrete. Therefore their composite φ is continuous. \square