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# Monads and Quantitative Equational Theories for Nondeterminism and Probability

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## Abstract

The monad of convex sets of probability distributions is a well-known tool for modelling the combination of nondeterministic and probabilistic computational effects. In this work we lift this monad from the category of sets to the category of extended metric spaces, by means of the Hausdorff and Kantorovich metric liftings. Our main result is the presentation of this lifted monad in terms of the quantitative equational theory of convex semilattices, using the framework of quantitative algebras recently introduced by Mardare, Panangaden and Plotkin.

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## 1 Introduction

In the theory of programming languages the categorical concept of *monad* is used to handle computational effects [43, 44]. As main examples, the *powerset monad* ( $\mathcal{P}$ ) and the *probability distribution monad* ( $\mathcal{D}$ ) are used to handle nondeterministic and probabilistic behaviours, respectively. It is of course desirable to handle the combination of these two effects to model, for instance, concurrent randomised protocols where nondeterminism arises from the action of an unpredictable scheduler and probability from the use of randomised procedures such as coin tosses. However, the composite functor  $\mathcal{P} \circ \mathcal{D}$  is not a monad (see, e.g., [52]).

A well-known way to handle this technical issue is to use instead the *convex powerset of distributions monad* ( $\mathcal{C}$ ) which restricts  $\mathcal{P} \circ \mathcal{D}$  by only admitting sets of probability distributions that are closed under the formation of *convex combinations* (see [50, 29, 28, 42, 41, 33, 39] and Section 2). Restricting  $\mathcal{P} \circ \mathcal{D}$  to  $\mathcal{C}$  is not only mathematically convenient, because it leads to a monad, but also natural as convexity captures the possibility of a scheduler to make probabilistic choices, as originally observed by Segala [46]. Suppose indeed that a scheduler can select between two probabilistic behaviours  $\{d_1, d_2\}$  for execution. It is reasonable to assume that said scheduler can also, with the aid of a (biased) coin, choose  $d_1$  with probability  $p$  and  $d_2$  with probability  $1 - p$ . Hence, effectively, the scheduler can choose any behaviour in  $\{p \cdot d_1 + (1 - p) \cdot d_2 \mid p \in [0, 1]\}$ , which is indeed a convex set of distributions.



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In a recent work [13] the authors provide a proof for the following result: the equational theory  $\mathbf{Th}_{CS}$  of convex semilattices is a *presentation* of the **Set** monad  $\mathcal{C}$ . This means (see Section 2 for details) that the category  $\mathbf{A}(\mathbf{Th}_{CS})$  of convex semilattices and their homomorphisms is isomorphic to the category  $\mathbf{EM}(\mathcal{C})$  of Eilenberg-Moore algebras for  $\mathcal{C}$ .

Presentation results of this kind have a number of applications in computer science due to the interplay between the structure (syntax) and the dynamics (behaviour) of systems. For example, it follows from the presentation result of [13] that the free convex semilattice with set of generators  $X$  is isomorphic to  $\mathcal{C}(X)$ . This allows us to manipulate elements of  $\mathcal{C}(X)$  as convex semilattice terms modulo the equations of  $\mathbf{Th}_{CS}$  and, similarly, to perform equational reasoning steps using facts (e.g., from geometry) related to the mathematical structure of  $\mathcal{C}(X)$ . Applications in the field of program semantics and concurrency theory arise by combining coalgebraic reasoning methods, associated with the use of monads as behaviour functors, and algebraic methods, which are made available by presentation theorems. Well known examples include *bisimulation up-to techniques* (e.g., up-to congruence [11]) and the categorical approach to structural operational semantics, introduced by Turi and Plotkin in [51] (see also [35]) and based on the notion of *bialgebras*.

The category **EMet**, having extended metric spaces as objects and non-expansive maps as morphisms, is a natural mathematical setting<sup>1</sup> which can replace the category **Set** when it is desirable to switch from the concept of *program equivalence* to that of *program distance*. This has been a very active topic of research in the last two decades (see, e.g., [45, 27, 15, 23, 16]). In this context, it is necessary to deal with monads on **EMet**. Variants of the **Set** monads  $\mathcal{P}$  and  $\mathcal{D}$  have been proposed on **EMet** (see, e.g., [15, 8] and Section 3), and are technically based on different types of *metric liftings*, due to Hausdorff and Kantorovich.

**Contributions of this work.** In this work we investigate a **EMet** variant of the **Set** monad  $\mathcal{C}$ , which we denote by  $\hat{\mathcal{C}}$ . As a functor,  $\hat{\mathcal{C}} : \mathbf{EMet} \rightarrow \mathbf{EMet}$  maps a metric space  $(X, d)$  to the metric space  $(\mathcal{C}(X), HK(d))$ , the collection of non-empty, finitely generated convex sets of finitely supported probability distributions on  $X$  endowed with the metric  $H(K(d))$ , the Hausdorff lifting of the Kantorovich lifting of the metric  $d$ .

$$\hat{\mathcal{C}} : \mathbf{EMet} \rightarrow \mathbf{EMet} \quad (X, d) \mapsto (\mathcal{C}(X), H(K(d))).$$

As a first contribution, in Section 4 we give a direct proof of the fact that  $\hat{\mathcal{C}}$  is indeed a monad on **EMet**. This result does not seem straightforward to prove. Most notably, establishing the non-expansiveness of the monad multiplication  $\mu^{\hat{\mathcal{C}}}$  requires some detailed calculations.

Our second and main result concerns the presentation of the **EMet** monad  $\hat{\mathcal{C}}$ . Presentations of monads in **Set** are given in terms of categories of algebras (in the sense of universal algebra) and their homomorphisms, but these are not adequate in the metric setting. For this reason we use, instead, the recently introduced apparatus of *quantitative algebras* and *quantitative equational theories* of [36] (see also [37, 7, 5, 4]). This framework generalises that of universal algebra and equational reasoning by dealing with quantitative algebras, which are metric spaces equipped with non-expansive operations over a signature, and quantitative equations of the form  $s =_{\epsilon} t$ , intuitively expressing that the distance between terms  $s$  and  $t$  is less than or equal to  $\epsilon$ . In Section 4 we define the quantitative equational theory  $\mathbf{QTh}_{CS}$  of

<sup>1</sup> The category **EMet** of extended metric spaces carries additional categorical structure compared to the category **Met** of ordinary metric spaces such as, e.g., the existence of coproducts. This structure is often useful in the field of program semantics. All the results obtained in this paper can be easily adapted to hold in the category **Met**.

quantitative convex semilattices, and in Section 5 we prove the presentation result (Theorem 36): the category  $\mathbf{EM}(\hat{\mathcal{C}})$  of Eilenberg-Moore algebras for  $\hat{\mathcal{C}}$  is isomorphic to the category  $\mathbf{QA}(\mathbf{QTh}_{CS})$  of quantitative convex semilattices and their non-expansive homomorphisms.

**Relation with other works.** This work continues the research path opened in the seminal [36] (see also subsequent works [37, 7, 5, 4]) where the authors investigated the connection between the quantitative theories of semilattices ( $\mathbf{QTh}_{SL}$ ) and convex algebras ( $\mathbf{QTh}_{CA}$ ) and the monads  $\hat{\mathcal{P}}$  and  $\hat{\mathcal{D}}$ , which are  $\mathbf{EMet}$  variants of  $\mathcal{P}$  and  $\mathcal{D}$ , respectively. Hence, our work constitutes a natural step forward. From a technical standpoint, there is a difference between our main presentation result and those of [36] regarding  $\mathbf{QTh}_{SL}$  and  $\mathbf{QTh}_{CA}$  (corollaries 9.4 and 10.6 respectively in [36]). Indeed, in [36] the authors only provide representations of the free objects in the categories  $\mathbf{QA}(\mathbf{QTh}_{SL})$  and  $\mathbf{QA}(\mathbf{QTh}_{CA})$ . While this suffices in many applications, we believe that proving a full presentation, in the sense introduced and investigated in this work, provides a more general and useful result, giving a representation for the whole categorical structure and not just for free objects. This said, the technical machinery developed in [36] suffices, with minor additional work<sup>2</sup>, to establish the following presentation results in our sense:  $\mathbf{QA}(\mathbf{QTh}_{SL}) \cong \mathbf{EM}(\hat{\mathcal{P}})$  and  $\mathbf{QA}(\mathbf{QTh}_{CA}) \cong \mathbf{EM}(\hat{\mathcal{D}})$ .

## 2 Monads on Sets and Equational Theories

In this section we present basic definitions and results regarding monads. We assume the reader is familiar with the basic concepts of category theory (see [3] as a reference).

► **Definition 1.** *Given a category  $\mathbf{C}$ , a monad on  $\mathbf{C}$  is a triple  $(\mathcal{M}, \eta, \mu)$  composed of a functor  $\mathcal{M}: \mathbf{C} \rightarrow \mathbf{C}$  together with two natural transformations: a unit  $\eta: id \Rightarrow \mathcal{M}$ , where  $id$  is the identity functor on  $\mathbf{C}$ , and a multiplication  $\mu: \mathcal{M}^2 \Rightarrow \mathcal{M}$ , satisfying the two laws  $\mu \circ \eta\mathcal{M} = \mu \circ \mathcal{M}\eta = id$  and  $\mu \circ \mathcal{M}\mu = \mu \circ \mu\mathcal{M}$ .*

We now introduce three relevant monads on the category  $\mathbf{Set}$  of sets and functions.

► **Definition 2.** *The non-empty finite powerset monad  $(\mathcal{P}, \eta^{\mathcal{P}}, \mu^{\mathcal{P}})$  on  $\mathbf{Set}$  is defined as follows. Given an object  $X$  in  $\mathbf{Set}$ ,  $\mathcal{P}(X) = \{X' \subseteq X \mid X' \neq \emptyset \text{ and } X' \text{ is finite}\}$ . Given an arrow  $f: X \rightarrow Y$ ,  $\mathcal{P}(f): \mathcal{P}(X) \rightarrow \mathcal{P}(Y)$  is defined as  $\mathcal{P}(f)(X') = \bigcup_{x \in X'} f(x)$  for any  $X' \in \mathcal{P}(X)$ . The unit  $\eta_X^{\mathcal{P}}: X \rightarrow \mathcal{P}(X)$  is defined as  $\eta_X^{\mathcal{P}}(x) = \{x\}$ , and the multiplication  $\mu_X^{\mathcal{P}}: \mathcal{P}\mathcal{P}(X) \rightarrow \mathcal{P}(X)$  is defined as  $\mu_X^{\mathcal{P}}(\{X_1, \dots, X_n\}) = \bigcup_{i=1}^n X_i$ .*

A probability distribution on a set  $X$  is a function  $\Delta: X \rightarrow [0, 1]$  such that  $\sum_{x \in X} \Delta(x) = 1$ . The *support* of  $\Delta$  is defined as the set  $supp(\Delta) = \{x \in X \mid \Delta(x) \neq 0\}$ . In this paper we only consider probability distributions with finite support which we often just refer to as distributions. The Dirac distribution  $\delta(x)$  is defined as  $\delta(x)(x') = 1$  if  $x' = x$  and  $\delta(x)(x') = 0$  otherwise. We often denote a distribution having  $supp(\Delta) = \{x_1, x_2\}$  using the expression  $p_1x_1 + p_2x_2$ , with  $p_i = \Delta(x_i)$ . Analogously, we let  $\sum_{i=1}^n p_i x_i$  denote a distribution  $\Delta$  with support  $\{x_1, \dots, x_n\}$  and with  $p_i = \Delta(x_i)$ .

► **Definition 3.** *The finitely supported probability distribution monad  $(\mathcal{D}, \eta^{\mathcal{D}}, \mu^{\mathcal{D}})$  on  $\mathbf{Set}$  is defined as follows. For objects  $X$  in  $\mathbf{Set}$ ,  $\mathcal{D}(X) = \{\Delta \mid \Delta \text{ is a finitely supported probability distribution on } X\}$ . For arrows  $f: X \rightarrow Y$  in  $\mathbf{Set}$ ,  $\mathcal{D}(f): \mathcal{D}(X) \rightarrow \mathcal{D}(Y)$  is defined as*

<sup>2</sup> The proof structure of our Theorem 36 can be adapted (and in fact much simplified due to the simpler nature of  $\mathbf{QTh}_{SL}$  and  $\mathbf{QTh}_{CA}$  compared to  $\mathbf{QTh}_{CS}$ ) to obtain these isomorphisms of categories. The recent result [7, Thm 4.2] might also provide an alternative proof method.

$\mathcal{D}(f)(\Delta) = (y \mapsto \sum_{x \in f^{-1}(y)} \Delta(x))$ . The unit  $\eta_X^{\mathcal{D}} : X \rightarrow \mathcal{D}(X)$  is defined as  $\eta_X(x) = \delta(x)$ . The multiplication  $\mu_X^{\mathcal{D}} : \mathcal{D}\mathcal{D}(X) \rightarrow \mathcal{D}(X)$  is defined, for  $\sum_{i=1}^n p_i \Delta_i \in \mathcal{D}\mathcal{D}(X)$ , as  $\mu_X^{\mathcal{D}}(\sum_{i=1}^n p_i \Delta_i) = (x \mapsto \sum_{i=1}^n p_i \cdot \Delta_i(x))$ .

► **Remark 4.** Given elements  $\Delta_1, \dots, \Delta_n \in \mathcal{D}(X)$ , the expression  $\sum_{i=1}^n p_i \Delta_i$  denotes an element in  $\mathcal{D}\mathcal{D}(X)$ . The set  $\mathcal{D}(X)$  can be seen as a convex subset of the real vector space  $\mathbb{R}^X$ , so in order to avoid confusion with the notation  $\sum_{i=1}^n p_i \Delta_i$  we will use the following dot-notation  $\sum_{i=1}^n p_i \cdot \Delta_i$  to denote convex combinations of distributions:  $\sum_{i=1}^n p_i \cdot \Delta_i = \mu_X^{\mathcal{D}}(\sum_{i=1}^n p_i \Delta_i) = (x \mapsto \sum_{i=1}^n p_i \cdot \Delta_i(x))$ . Hence,  $\sum_{i=1}^n p_i \Delta_i$  denotes an element of  $\mathcal{D}\mathcal{D}(X)$  (a distribution of distributions), while  $\sum_{i=1}^n p_i \cdot \Delta_i$  denotes an element of  $\mathcal{D}(X)$ .

Given a collection  $S \subseteq \mathcal{D}(X)$  of distributions, we can construct its *convex closure*  $cc(S) = \{\sum_{i=1}^n p_i \cdot \Delta_i \mid n \geq 1, \Delta_i \in S \text{ for all } i, \text{ and } \sum_{i=1}^n p_i = 1\}$ . Note that  $cc(cc(S)) = cc(S)$ . A subset  $S \subseteq \mathcal{D}(X)$  is *convex* if  $S = cc(S)$ . We say that a convex set  $S \subseteq \mathcal{D}(X)$  is *finitely generated* if there exists a finite set  $S' \subseteq \mathcal{D}(X)$  (i.e.,  $S' \in \mathcal{P}\mathcal{D}(X)$ ) such that  $S = cc(S')$ . Given a finitely generated convex set  $S \subseteq \mathcal{D}(X)$ , there exists one minimal (with respect to the inclusion order) finite set  $\text{UB}(S) \in \mathcal{P}\mathcal{D}(X)$  such that  $S = cc(\text{UB}(S))$ . The finite set  $\text{UB}(S)$  is referred to as the *unique base* of  $S$  (see, e.g., [14]). The distributions in  $\text{UB}(S)$  are convex-linear independent, i.e., if  $\text{UB}(S) = \{\Delta_1, \dots, \Delta_n\}$ , then for all  $i$ ,  $\Delta_i \notin cc(\{\Delta_j \mid j \neq i\})$ .

► **Definition 5.** The finitely generated non-empty convex powerset of distributions *monad*  $(\mathcal{C}, \eta^{\mathcal{C}}, \mu^{\mathcal{C}})$  on **Set** is defined as follows. Given an object  $X$  in **Set**,  $\mathcal{C}(X)$  is the collection of non-empty finitely generated convex sets of finitely supported probability distributions on  $X$ , i.e.,  $\mathcal{C}(X) = \{cc(S) \mid S \in \mathcal{P}\mathcal{D}(X)\}$ . Given an arrow  $f : X \rightarrow Y$  in **Set**, the arrow  $\mathcal{C}(f) : \mathcal{C}(X) \rightarrow \mathcal{C}(Y)$  is defined as  $\mathcal{C}(f)(S) = \{\mathcal{D}(f)(\Delta) \mid \Delta \in S\}$ . The unit  $\eta_X^{\mathcal{C}} : X \rightarrow \mathcal{C}(X)$  is defined as  $\eta_X^{\mathcal{C}}(x) = \{\delta(x)\}$ , the singleton (convex) set consisting of the Dirac distribution. The multiplication  $\mu_X^{\mathcal{C}} : \mathcal{C}\mathcal{C}(X) \rightarrow \mathcal{C}(X)$  is defined, for any  $S \in \mathcal{C}\mathcal{C}(X)$ , as  $\mu_X^{\mathcal{C}}(S) = \bigcup_{\Delta \in S} \text{WMS}(\Delta)$ , where, for any  $\Delta \in \mathcal{D}\mathcal{C}(X)$  of the form  $\sum_{i=1}^n p_i S_i$ , with  $S_i \in \mathcal{C}(X)$ , the weighted Minkowski sum operation  $\text{WMS} : \mathcal{D}\mathcal{C}(X) \rightarrow \mathcal{C}(X)$  is defined as  $\text{WMS}(\Delta) = \{\sum_{i=1}^n p_i \cdot \Delta_i \mid \text{for each } 1 \leq i \leq n, \Delta_i \in S_i\}$ .

## 2.1 Equational Theories and Monad Presentations

An important concept regarding monads is that of algebras for a monad.

► **Definition 6.** Let  $(\mathcal{M} : \mathbf{C} \rightarrow \mathbf{C}, \eta, \mu)$  be a monad. An algebra for  $\mathcal{M}$  is a pair  $(A, h)$  where  $A \in \mathbf{C}$  is an object and  $h : \mathcal{M}(A) \rightarrow A$  is a morphism such that:  $h \circ \eta_A = \text{id}_A$  and  $h \circ \mathcal{M}h = h \circ \mu_A$ . Given two  $\mathcal{M}$ -algebras  $(A, h)$  and  $(A', h')$ , a  $\mathcal{M}$ -algebra morphism is an arrow  $f : A \rightarrow A'$  in  $\mathbf{C}$  such that  $f \circ h = h' \circ \mathcal{M}(f)$ . The category of Eilenberg-Moore algebras for  $\mathcal{M}$ , denoted by  $\mathbf{EM}(\mathcal{M})$ , has  $\mathcal{M}$ -algebras as objects and  $\mathcal{M}$ -morphisms as arrows.

The definitions above are purely categorical and, as a consequence, the category  $\mathbf{EM}(\mathcal{M})$  is sometimes hard to work with as an abstract entity. It is therefore very useful when  $\mathbf{EM}(\mathcal{M})$  can be proven isomorphic to a category whose objects and morphisms are well-known and understood. This leads to the concept of *presentation of a monad*. Before introducing it, we recall some basic definitions of universal algebra (see [17] for a standard introduction).

► **Definition 7.** A signature  $\Sigma$  is a set of function symbols each having its own finite arity. We denote with  $\mathcal{T}(X, \Sigma)$  the set of terms built from a set of generators  $X$  with the function symbols of  $\Sigma$ . An equational theory  $\text{Th}$  of type  $\Sigma$  is a set  $\text{Th} \subseteq \mathcal{T}(X, \Sigma) \times \mathcal{T}(X, \Sigma)$  of equations between terms  $\mathcal{T}(X, \Sigma)$  closed under deducibility in the logical apparatus of equational logic. Given a set  $E \subseteq \mathcal{T}(X, \Sigma) \times \mathcal{T}(X, \Sigma)$  of equations, the theory induced by  $E$  is the smallest

equational theory containing  $E$ . The models of a theory  $\mathbf{Th}$  are  $\Sigma$ -algebras of the theory  $\mathbf{Th}$ , i.e., structures  $(A, \{f^A\}_{f \in \Sigma})$  consisting of a set  $A$  and operations  $f^A : A^{\text{ar}(f)} \rightarrow A$ , for each operation symbol  $f \in \Sigma$  having arity  $\text{ar}(f)$ , satisfying all (universally quantified) equations in  $\mathbf{Th}$ . A homomorphism from  $(A, \{f^A\}_{f \in \Sigma})$  to  $(B, \{f^B\}_{f \in \Sigma})$  is a function  $g : A \rightarrow B$  such that  $g(f^A(a_1, \dots, a_n)) = f^B(g(a_1), \dots, g(a_n))$ , for all  $f \in \Sigma$ . We denote with  $\mathbf{A}(\mathbf{Th})$  the category whose objects are models of the theory  $\mathbf{Th}$  and morphisms are homomorphisms.

► **Definition 8** (Presentation of **Set** monads). Let  $\mathcal{M}$  be a monad on **Set**. A presentation of  $\mathcal{M}$  is an equational theory  $\mathbf{Th}$  such that the categories  $\mathbf{EM}(\mathcal{M})$  and  $\mathbf{A}(\mathbf{Th})$  are isomorphic.

In what follows we introduce equational theories that are presentations of the three **Set** monads  $\mathcal{P}$ ,  $\mathcal{D}$  and  $\mathcal{C}$  introduced earlier.

► **Definition 9**. The theory  $\mathbf{Th}_{SL}$  of semilattices is the theory having as signature  $\Sigma_{SL} = \{\oplus\}$  and equations stating that  $\oplus$  is associative, commutative, and idempotent:

$$(A) (x \oplus y) \oplus z = x \oplus (y \oplus z) \quad (C) x \oplus y = y \oplus x \quad (I) x \oplus x = x.$$

► **Definition 10**. The theory  $\mathbf{Th}_{CA}$  of convex algebras has signature  $\Sigma_{CA} = \{+_p\}_{p \in (0,1)}$  and, for all  $p, q \in (0, 1)$ , the equations for probabilistic associativity, commutativity, and idempotency:

$$(A_p) (x +_q y) +_p z = x +_{pq} (y +_{\frac{p(1-q)}{1-pq}} z) \quad (C_p) x +_p y = y +_{1-p} x \quad (I_p) x +_p x = x.$$

► **Definition 11**. The theory  $\mathbf{Th}_{CS}$  of convex semilattices is the theory with signature  $\Sigma_{CS} = (\{\oplus\} \cup \{+_p\}_{p \in (0,1)})$  where  $\oplus$  satisfies the equations of semilattices,  $+_p$  satisfies the equations of convex algebras for every  $p \in (0, 1)$ , and, furthermore, for every  $p \in (0, 1)$  the following distributivity equation (D) is satisfied:  $x +_p (y \oplus z) = (x +_p y) \oplus (x +_p z)$ .

The following proposition collects known results in the literature (see [48, 24, 32, 13]).

► **Proposition 12**.

1. The theory  $\mathbf{Th}_{SL}$  of semilattices is a presentation of  $\mathcal{P}$ , i.e.,  $\mathbf{A}(\mathbf{Th}_{SL}) \cong \mathbf{EM}(\mathcal{P})$ .
2. The theory  $\mathbf{Th}_{CA}$  of convex algebras is a presentation of  $\mathcal{D}$ , i.e.,  $\mathbf{A}(\mathbf{Th}_{CA}) \cong \mathbf{EM}(\mathcal{D})$ .
3. The theory  $\mathbf{Th}_{CS}$  of convex semilattices is a presentation of  $\mathcal{C}$ , i.e.,  $\mathbf{A}(\mathbf{Th}_{CS}) \cong \mathbf{EM}(\mathcal{C})$ .

### 2.1.1 One Application: Representation of Term Algebras

Having presentations of **Set** monads as categories of algebras of equational theories is mathematically convenient for several reasons. One useful application, especially in the field of program semantics, are representation theorems for free algebras, which are, up to isomorphism, term algebras.

In this section we assume the reader to be familiar with the concept of free object in a category (see, e.g., [3, §10.3]). The free object generated by  $X$  in the category  $\mathbf{EM}(\mathcal{M})$  is the  $\mathcal{M}$ -algebra  $(\mathcal{M}(X), \mu_X^{\mathcal{M}})$ . The free object generated by  $X$  in the category  $\mathbf{A}(\mathbf{Th})$  is the term algebra, i.e., the algebra whose carrier is  $\mathcal{T}(X, \Sigma)_{/\mathbf{Th}}$ , the set of  $\Sigma$ -terms constructed from the set of generators  $X$  taken modulo the equations of the theory  $\mathbf{Th}$ , and with operations defined on equivalences classes, that is,  $f([t_1]_{/\mathbf{Th}}, \dots, [t_n]_{/\mathbf{Th}}) = [f(t_1, \dots, t_n)]_{/\mathbf{Th}}$  for each  $f \in \Sigma$ . These characterisations, together with the fact that free objects are unique up to isomorphism, can be used to derive the following result.

► **Proposition 13**. Let  $\mathcal{M}$  be a monad on **Set** and let  $F : \mathbf{A}(\mathbf{Th}) \cong \mathbf{EM}(\mathcal{M})$  be a presentation of  $\mathcal{M}$  in terms of the equational theory  $\mathbf{Th}$  of type  $\Sigma$ . Then the term algebra  $\mathcal{T}(X, \Sigma)_{/\mathbf{Th}}$  and the free Eilenberg-Moore algebra  $(\mathcal{M}(X), \mu_X^{\mathcal{M}})$  are isomorphic (via  $F$ ).

In other words, a presentation theorem for  $\mathcal{M}$  provides automatically representation results for term algebras via the known semantic behaviour of the multiplication of  $\mathcal{M}$ .

► **Example 14.** The presentation of the monad  $\mathcal{C}$  in terms of the theory of convex semilattices implies that the free convex semilattice generated by  $X$  is isomorphic with the convex semilattice  $(\mathcal{C}X, \oplus, +_p)$  where  $S_1 \oplus S_2 = cc(S_1 \cup S_2)$  (convex union) and  $S_1 +_p S_2 = \text{WMS}(pS_1 + (1-p)S_2)$  (weighted Minkowski sum), for all  $S_1, S_2 \in \mathcal{C}(X)$ . In other words, the set  $\mathcal{T}(X, \Sigma_{CS})_{/\text{Th}_{CS}}$  of convex semilattice terms modulo the equational theory of convex semilattices can be identified with the set  $\mathcal{C}(X)$  of finitely generated convex sets of finitely supported probability distributions on  $X$ . The isomorphism is explicitly given in [14] by the function  $\kappa : \mathcal{C}(X) \rightarrow \mathcal{T}(X, \Sigma_{CS})_{/\text{Th}_{CS}}$  defined as  $\kappa(S) = [\bigoplus_{\Delta \in \text{UB}(S)} (\bigoplus_{x \in \text{supp}(\Delta)} \Delta(x) x)]_{/\text{Th}_{CS}}$ , where  $\bigoplus_{i \in I} x_i$  and  $\bigoplus_{i \in I} p_i x$  are respectively notations for the binary operations  $\oplus$  and  $+_p$  extended to operations of arity  $I$ , for  $I$  finite (see, e.g., [47, 12]). We remark that the equation  $x \oplus y = x \oplus y \oplus (x +_p y)$ , which explicitly expresses closure under taking convex combinations, is derivable from the theory of convex semilattices (see, e.g., [14, Lemma 14]), and that this derivation critically uses the distributivity axiom (D).

### 3 Monads on Met and Quantitative Equational Theories

In Section 2 we have considered monads in the category **Set**. We now shift our focus to monads in the category **EMet** of extended metric spaces and non-expansive functions. The category **EMet** provides a natural mathematical setting for developing the semantics of programs exhibiting quantitative behaviour such as, e.g., probabilistic choice. It is indeed appropriate in this setting to replace the usual notion of program equivalence with the more informative notion of program distance (see, e.g., [45, 27, 15, 23, 16]).

► **Definition 15.** An extended metric space is a pair  $(X, d)$  such that  $X$  is a set and  $d : X \times X \rightarrow \mathbb{R}_{\geq 0} \cup \{\infty\}$  is a function, called the metric, satisfying the following properties:  $d(x, y) = 0$  if and only if  $x = y$ ,  $d(x, y) = d(y, x)$ , and  $d(x, y) \leq d(x, z) + d(z, y)$ , for all  $x, y, z \in X$ . A function  $f : X \rightarrow Y$  between two extended metric spaces  $(X, d_X)$  and  $(Y, d_Y)$  is called non-expansive (a.k.a. 1-Lipschitz) if  $d_Y(f(x_1), f(x_2)) \leq d_X(x_1, x_2)$  for all  $x_1, x_2 \in X$ . We denote with **EMet** the category whose objects are extended metric spaces and whose morphisms are non-expansive maps.

Since we only work with extended metric spaces, in the rest of this paper we will systematically omit the adjective “extended”. Given two metrics  $d_1, d_2$  on  $X$ , we write  $d_1 \sqsubseteq d_2$  if for all  $x, x' \in X$ , it holds that  $d_1(x, x') \leq d_2(x, x')$ . Let  $(Y, d)$  be a metric space,  $X$  a set and  $f : X \rightarrow Y$ . We write  $d\langle f, f \rangle$  for the metric on  $X$  defined as  $d\langle f, f \rangle(x_1, x_2) = d(f(x_1), f(x_2))$ . Let  $d_{\mathbb{R}}$  be the Euclidean metric on  $\mathbb{R}$  defined as  $d_{\mathbb{R}}(r_1, r_2) = |r_1 - r_2|$ . If  $(X, d)$  is a metric space, we simply say that  $f : X \rightarrow [0, 1]$  is non-expansive to mean that  $f : (X, d) \rightarrow ([0, 1], d_{\mathbb{R}})$  is non-expansive. The metric  $d$  of a metric space  $(X, d)$  induces a topology on  $X$  whose open sets are generated by the open balls of the form  $B(x, \epsilon) = \{y \in X \mid d(x, y) < \epsilon\}$ , for  $x \in X$  and  $\epsilon > 0$ . A subset  $Y \subseteq X$  is called compact if each of its open covers has a finite subcover. Every compact set  $Y$  is closed and bounded (i.e., the distance between elements in  $Y$  is bounded by some real number). The collection of non-empty compact subsets of a metric space  $(X, d)$  is denoted by  $\text{Comp}(X, d)$ . Note that every finite subset of  $X$  belongs to  $\text{Comp}(X, d)$ .

The **Set** monads  $\mathcal{P}$  and  $\mathcal{D}$  defined in Section 2 can be extended to monads in **EMet**. These extensions are well-known and are based on metric liftings constructions due to Hausdorff and Kantorovich (see [34] for a standard reference).

► **Definition 16** (Hausdorff Lifting). *Let  $(X, d)$  be a metric space. The Hausdorff lifting of  $d$  is a metric  $H(d)$  on  $\mathbf{Comp}(X, d)$ , the collection of non-empty compact subsets of  $X$ , defined as follows for any pair  $X_1, X_2 \in \mathbf{Comp}(X, d)$ :*

$$H(d)(X_1, X_2) = \max \left\{ \sup_{x_1 \in X_1} \inf_{x_2 \in X_2} d(x_1, x_2), \sup_{x_2 \in X_2} \inf_{x_1 \in X_1} d(x_1, x_2) \right\}.$$

This leads to the well-known *hyperspace monad*  $\mathcal{V}$  on  $\mathbf{EMet}$  ([31], see also [34]).<sup>3</sup>

► **Definition 17.** *The hyperspace monad  $(\mathcal{V}, \eta^{\mathcal{V}}, \mu^{\mathcal{V}})$  on  $\mathbf{EMet}$  is defined as follows. Given an object  $(X, d)$  in  $\mathbf{EMet}$ ,  $\mathcal{V}(X, d) = (\mathbf{Comp}(X, d), H(d))$ , the metric space of non-empty compact subsets of  $X$  equipped with the Hausdorff distance. Given a non-expansive map  $f : (X, d_X) \rightarrow (Y, d_Y)$ ,  $\mathcal{V}(f)(X') = \bigcup_{x \in X'} f(x)$ . The unit  $\eta_{(X,d)}^{\mathcal{V}} : (X, d) \rightarrow \mathcal{V}(X, d)$  is defined as  $\eta_{(X,d)}^{\mathcal{V}}(x) = \{x\}$ , and the multiplication  $\mu_{(X,d)}^{\mathcal{V}} : \mathcal{V}\mathcal{V}(X, d) \rightarrow \mathcal{V}(X, d)$  is defined as  $\mu_{(X,d)}^{\mathcal{V}}(\{X_i\}_{i \in I}) = \bigcup_i X_i$ .*

The restriction of the monad  $\mathcal{V}$  to finite (hence compact) subsets leads to the non-empty finite powerset monad on  $\mathbf{EMet}$ , which we denote with  $\hat{\mathcal{P}}$  to distinguish it from the  $\mathbf{Set}$  monad  $\mathcal{P}$ .

► **Definition 18.** *The non-empty finite powerset monad  $(\hat{\mathcal{P}}, \eta^{\hat{\mathcal{P}}}, \mu^{\hat{\mathcal{P}}})$  on  $\mathbf{EMet}$  is defined as follows. Given an object  $(X, d)$  in  $\mathbf{EMet}$ ,  $\hat{\mathcal{P}}(X, d) = (\mathcal{P}(X), H(d))$ , the collection of finite non-empty subsets of  $X$  equipped with the Hausdorff distance. The action of  $\hat{\mathcal{P}}$  on morphisms, the unit  $\eta^{\hat{\mathcal{P}}}$  and the multiplication  $\mu^{\hat{\mathcal{P}}}$  are defined as for the  $\mathbf{Set}$  monad  $\mathcal{P}$  (or, equivalently, as for the  $\mathcal{V}$  monad on  $\mathbf{EMet}$  restricted to finite sets).*

Next, we introduce the Kantorovich lifting on finitely supported distributions [34].

► **Definition 19** (Kantorovich Lifting). *Let  $(X, d)$  be a metric space. The Kantorovich lifting of  $d$  is a metric  $K(d)$  on  $\mathcal{D}(X)$ , the collection of finitely supported probability distributions on  $X$ , defined as follows for any pair  $\Delta_1, \Delta_2 \in \mathcal{D}(X)$ :*

$$K(d)(\Delta_1, \Delta_2) = \inf_{\omega \in \mathit{Coup}(\Delta_1, \Delta_2)} \left( \sum_{(x_1, x_2) \in X \times X} \omega(x_1, x_2) \cdot d(x_1, x_2) \right)$$

where  $\mathit{Coup}(\Delta_1, \Delta_2)$  is defined as the collection of couplings of  $\Delta_1$  and  $\Delta_2$ , i.e., the collection of probability distributions on the product space  $X \times X$  such that the marginals of  $\omega$  are  $\Delta_1$  and  $\Delta_2$ . Formally,  $\mathit{Coup}(\Delta_1, \Delta_2) = \{\omega \in \mathcal{D}(X \times X) \mid \mathcal{D}(\pi_1)(\omega) = \Delta_1 \text{ and } \mathcal{D}(\pi_2)(\omega) = \Delta_2\}$  where  $\pi_1 : X_1 \times X_2 \rightarrow X_1$  and  $\pi_2 : X_1 \times X_2 \rightarrow X_2$  are the projection functions.

We can now introduce the following version of the finitely supported probability distribution monad on  $\mathbf{EMet}$ , which we denote with  $\hat{\mathcal{D}}$  to distinguish it from the  $\mathbf{Set}$  monad  $\mathcal{D}$ .

► **Definition 20.** *The finitely supported probability distribution monad  $(\hat{\mathcal{D}}, \eta^{\hat{\mathcal{D}}}, \mu^{\hat{\mathcal{D}}})$  on  $\mathbf{EMet}$  is defined as follows. Given an object  $(X, d)$  in  $\mathbf{EMet}$ ,  $\hat{\mathcal{D}}(X, d) = (\mathcal{D}(X), K(d))$ , the collection of finitely supported probability distributions on  $X$  equipped with the Kantorovich distance. The action of  $\hat{\mathcal{D}}$  on morphisms, the unit  $\eta^{\hat{\mathcal{D}}}$ , and the multiplication  $\mu^{\hat{\mathcal{D}}}$  are defined as for the  $\mathbf{Set}$  monad  $\mathcal{D}$ .*

The fact that the above definitions are correct (i.e., that  $\hat{\mathcal{D}}$  is a functor and that  $\eta^{\hat{\mathcal{D}}}$  and  $\mu^{\hat{\mathcal{D}}}$  are non-expansive and satisfy the monad laws) is well-known (see, e.g., [34, 15, 8]).

<sup>3</sup> This monad, defined on the category  $\mathbf{Met}$  of ordinary (i.e., non-extended) metric spaces, is essentially due to Hausdorff [31]. See, e.g., [34] for a detailed exposition.



### 3.1 Quantitative Equational Theories and Quantitative Algebras

We provide here the essential definitions and results of the framework developed by Mardare, Panangaden, and Plotkin in [36] (see also [7, 37, 5, 38]). In what follows, a signature  $\Sigma$  is fixed. Recall that  $\mathcal{T}(X, \Sigma)$  denotes the set of terms constructed from  $X$  using the function symbols in  $\Sigma$ . A substitution is a map of type  $\sigma : X \rightarrow \mathcal{T}(X, \Sigma)$ . As usual, to any interpretation  $\iota : X \rightarrow A$  of the variables into a set corresponds, by homomorphic extension, a unique map  $\iota : \mathcal{T}(X, \Sigma) \rightarrow A$ .

► **Definition 21** (Quantitative Equational Theory). *A quantitative equation is an expression of the form  $t =_\epsilon s$ , where  $t, s \in \mathcal{T}(X, \Sigma)$  and  $\epsilon \in \mathbb{R}_{\geq 0}$ . We denote with  $E(\Sigma)$  the collection of all quantitative equations. We use the letters  $\Gamma, \Theta$  to range over subsets of  $E(\Sigma)$ . A quantitative inference is an element of  $2^{E(\Sigma)} \times E(\Sigma)$ , i.e., a pair  $(\Gamma, t =_\epsilon s)$  where  $\Gamma \subseteq E(\Sigma)$  and  $t =_\epsilon s$  is a quantitative equation. Note that  $\Gamma$  needs not be finite. A deducibility relation is a set of quantitative inferences  $\vdash \subseteq 2^{E(\Sigma)} \times E(\Sigma)$  closed under the following conditions which are stated for arbitrary  $s, t, u \in \mathcal{T}(X, \Sigma)$ ,  $\epsilon, \epsilon' \in \mathbb{R}_{\geq 0}$ ,  $\Gamma, \Theta \subseteq E(\Sigma)$ , and  $f \in \Sigma$ :*

(Notation: we use the infix notation  $\Gamma \vdash t =_\epsilon s$  to mean that  $(\Gamma, t =_\epsilon s) \in \vdash$ )

(Ref)  $\emptyset \vdash t =_0 t$       (Sym)  $\{t =_\epsilon s\} \vdash s =_\epsilon t$       (Triang)  $\{t =_\epsilon u, u =_{\epsilon'} s\} \vdash t =_{\epsilon+\epsilon'} s$

(Max)  $\{t =_\epsilon s\} \vdash t =_{\epsilon'} s$ , where  $\epsilon' > \epsilon$       (Arch)  $\{t =_{\epsilon'} s\}_{\epsilon' > \epsilon} \vdash t =_\epsilon s$

(NExp)  $\{t_i =_\epsilon s_i\}_{i \in 1..ar(f)} \vdash f(t_1, \dots, t_n) =_\epsilon f(s_1, \dots, s_n)$

(Subst) if  $\Gamma \vdash t =_\epsilon s$  then  $\{\sigma(t) =_\epsilon \sigma(s) \mid (t =_\epsilon s) \in \Gamma\} \vdash \sigma(t) =_\epsilon \sigma(s)$ , for all substitutions  $\sigma$

(Cut) if  $\Gamma \vdash \Theta$  and  $\Theta \vdash t =_\epsilon s$  then  $\Gamma \vdash t =_\epsilon s$

(Assum) if  $t =_\epsilon s \in \Gamma$  then  $\Gamma \vdash t =_\epsilon s$ , for all  $\Gamma, t, s, \epsilon$

where in (Cut) the expression  $\Gamma \vdash \Theta$  means that for all  $(t =_\epsilon s) \in \Theta$  it holds that  $\Gamma \vdash t =_\epsilon s$ . Given a set of quantitative inferences  $\mathcal{U} \subseteq 2^{E(\Sigma)} \times E(\Sigma)$ , the quantitative equational theory induced by  $\mathcal{U}$  is the smallest deducibility relation which includes  $\mathcal{U}$ .

The models of quantitative theories are quantitative algebras, which we now introduce.

► **Definition 22** (Quantitative Algebra). *A quantitative algebra of type  $\Sigma$  is a structure  $\mathbb{A} = (A, \{f^A\}_{f \in \Sigma}, d_A)$  where  $(A, d_A)$  is an extended metric space and, for each  $f \in \Sigma$ , the function  $f^A : A^{ar(f)} \rightarrow A$  is a non-expansive map, with  $A^{ar(f)}$  endowed with the sup-metric defined as  $d_{\text{sup}}(\{a_i\}_{i \in ar(f)}, \{b_i\}_{i \in ar(f)}) = \max_{i \in ar(f)}(d(a_i, b_i))$ . A homomorphism between quantitative algebras  $\mathbb{A}$  and  $\mathbb{B}$  of type  $\Sigma$  is a non-expansive function  $g : (A, d_A) \rightarrow (B, d_B)$  which preserves all operations in  $\Sigma$ , i.e.,  $g(f^A(x_1, \dots, x_n)) = f^B(g(x_1), \dots, g(x_n))$ , for all  $x_i \in A$ . We say that  $\mathbb{A}$  satisfies a quantitative inference  $(\{s_i =_{\epsilon_i} t_i\}_{i \in I}, s =_\epsilon t)$ , written  $\{s_i =_{\epsilon_i} t_i\} \models_{\mathbb{A}} s =_\epsilon t$ , if for every interpretation  $\iota : X \rightarrow A$  of the variables  $X$  into elements of  $A$  the following holds: if for all  $i \in I$ ,  $d_A(\iota(s_i), \iota(t_i)) \leq \epsilon_i$ , then  $d_A(\iota(s), \iota(t)) \leq \epsilon$ . We say that  $\mathbb{A}$  is a model of a quantitative theory  $\mathbf{QTh}$  if  $\mathbb{A}$  satisfies every quantitative inference in  $\mathbf{QTh}$ . We denote with  $\mathbf{QA}(\mathbf{QTh})$  the category having as objects the quantitative algebras that are models of  $\mathbf{QTh}$ , and as arrows the non-expansive homomorphisms between quantitative algebras of type  $\Sigma$ .*

Every quantitative algebra of type  $\Sigma$  satisfies the quantitative inferences generating the deducibility relation  $\vdash$  in Definition 21. We refer to [36] for proofs that all the above definitions are indeed well-defined. Two interesting quantitative theories studied in [36] are the following.<sup>4</sup>

<sup>4</sup> We remark that, in [36], the quantitative theory of convex algebras is referred to as the quantitative theory of interpolative barycentric algebras.

► **Definition 23** (Quantitative Semilattices). *The quantitative theory of quantitative semilattices, denoted by  $\mathbf{QTh}_{SL}$ , has type  $\Sigma_{SL}$  (see Definition 9) and is induced by the following quantitative inferences, for all  $\epsilon_1, \epsilon_2 \in \mathbb{R}_{\geq 0}$ :*

$$(A) \ \emptyset \vdash x \oplus (y \oplus z) =_0 (x \oplus y) \oplus z \quad (C) \ \emptyset \vdash x \oplus y =_0 y \oplus x \quad (I) \ \emptyset \vdash x \oplus x =_0 x$$

$$(H) \ \{x_1 =_{\epsilon_1} y_1, x_2 =_{\epsilon_2} y_2\} \vdash x_1 \oplus x_2 =_{\max(\epsilon_1, \epsilon_2)} y_1 \oplus y_2.$$

► **Definition 24** (Quantitative Convex Algebras). *The quantitative theory of quantitative convex algebras, denoted by  $\mathbf{QTh}_{CA}$ , has type  $\Sigma_{CA}$  (see Definition 10) and is induced by the following quantitative inferences, for all  $p, q \in (0, 1)$  and  $\epsilon_1, \epsilon_2 \in \mathbb{R}_{\geq 0}$ :*

$$(A_p) \ \emptyset \vdash (x +_p y) +_p z =_0 x +_{pq} (y +_{\frac{p(1-q)}{1-pq}} z) \quad (C_p) \ \emptyset \vdash x +_p y =_0 y +_{1-p} x$$

$$(I_p) \ \emptyset \vdash x +_p x =_0 x \quad (K) \ \{x_1 =_{\epsilon_1} y_1, x_2 =_{\epsilon_2} y_2\} \vdash x_1 +_p x_2 =_{p \cdot \epsilon_1 + (1-p) \cdot \epsilon_2} y_1 +_p y_2.$$

In other words, the theories  $\mathbf{QTh}_{SL}$  and  $\mathbf{QTh}_{CA}$  are obtained by taking the equational axioms of semilattices and convex algebras respectively (Definitions 9 and 10), replacing the equality ( $=$ ) with ( $=_0$ ), and by introducing the quantitative inferences (H) and (K) respectively.

A general result from [36, §5] states that free objects always exist in  $\mathbf{QA}(\mathbf{QTh})$ , for any  $\mathbf{QTh}$ , and they are isomorphic to term quantitative algebras for  $\mathbf{QTh}$ . Moreover, such free objects are concretely identified for two relevant theories:

► **Theorem 25** ([36, Cor 9.4 and 10.6]). *The following hold:*

- *The free quantitative semilattice in  $\mathbf{QA}(\mathbf{QTh}_{SL})$  generated by a metric space  $(X, d)$  is isomorphic to the metric space  $\hat{\mathcal{P}}(X, d) = (\mathcal{P}(X), H(d))$ .*
- *The free quantitative convex algebra in  $\mathbf{QA}(\mathbf{QTh}_{CA})$  generated by a metric space  $(X, d)$  is isomorphic to the metric space  $\hat{\mathcal{D}}(X, d) = (\mathcal{D}(X), K(d))$ .*

We remark that the above theorem from [36] falls short from a full presentation result stating the isomorphisms of categories  $\mathbf{QA}(\mathbf{QTh}_{SL}) \cong \mathbf{EM}(\hat{\mathcal{P}})$  and  $\mathbf{QA}(\mathbf{QTh}_{CA}) \cong \mathbf{EM}(\hat{\mathcal{D}})$ . This latter more general statement does indeed hold and can be obtained, with some minor extra work, from the technical machinery developed in [36] (see Footnote 2).

## 4 The Monad $\hat{\mathcal{C}}$ on the Category of Metric Spaces

In this section we introduce a  $\mathbf{EMet}$  version of the  $\mathbf{Set}$  monad  $\mathcal{C}$ , and we denote it with  $\hat{\mathcal{C}}$ . The monad  $\hat{\mathcal{C}}$  is obtained by composing the Hausdorff lifting  $H$  and the Kantorovich lifting  $K$  introduced in the previous section.

► **Proposition 26.** *Let  $(X, d)$  be a metric space and let  $S \in \mathbf{Comp}(\mathcal{D}(X), K(d))$ . Then  $cc(S) \in \mathbf{Comp}(\mathcal{D}(X), K(d))$ , i.e., the convex closure of  $S$  is also compact.*

► **Corollary 27.** *Let  $(X, d)$  be a metric space. If  $S \in \mathcal{C}(X)$  then  $S \in \mathbf{Comp}(\mathcal{D}(X), K(d))$ .*

Corollary 27 implies that, given a metric space  $(X, d)$ , the collection  $\mathcal{C}(X)$  of finitely generated non-empty convex sets of distributions on  $X$  can be endowed with the subspace metric of  $\mathcal{V}(\hat{\mathcal{D}}(X, d))$ , and therefore  $(\mathcal{C}(X), HK(d))$  is a metric space, with  $HK(d) = H(K(d))$ . This observation leads to the following definition.

► **Definition 28** (Monad  $\hat{\mathcal{C}}$ ). *The finitely generated non-empty convex powerset of finitely supported probability distributions monad  $(\hat{\mathcal{C}}, \eta^{\hat{\mathcal{C}}}, \mu^{\hat{\mathcal{C}}})$  on  $\mathbf{EMet}$  is defined as follows. Given an object  $(X, d)$  in  $\mathbf{EMet}$ ,  $\hat{\mathcal{C}}(X, d) = (\mathcal{C}(X), HK(d))$ . The action of  $\hat{\mathcal{C}}$  on morphisms, the monad unit  $\eta^{\hat{\mathcal{C}}}$ , and the monad multiplication  $\mu^{\hat{\mathcal{C}}}$  are defined as for the  $\mathbf{Set}$  monad  $\mathcal{C}$  (Definition 5).*

The rest of this section is devoted to the proof that the above definition is well-specified, i.e., that  $\hat{\mathcal{C}}$  is indeed a monad on **EMet**. First, one needs to verify that  $\hat{\mathcal{C}}$  is a functor on **EMet**. This follows immediately from the definition, Corollary 27, and  $\mathcal{C}$  being a functor on **Set**. It then remains to verify that the unit  $\eta^{\hat{\mathcal{C}}}$  and the multiplication  $\mu^{\hat{\mathcal{C}}}$  of  $\hat{\mathcal{C}}$  are indeed morphisms in **EMet** (i.e., they are non-expansive functions) and that they satisfy the monad laws of Definition 1. The fact that the laws are satisfied follows directly from the definitions  $\mu^{\hat{\mathcal{C}}} = \mu^{\mathcal{C}}$  and  $\eta^{\hat{\mathcal{C}}} = \eta^{\mathcal{C}}$  and the fact that  $\mathcal{C}$  is a monad on **Set** (hence  $\mu^{\mathcal{C}}$  and  $\eta^{\mathcal{C}}$  satisfy the monad laws). Then it only remains to verify that  $\eta^{\hat{\mathcal{C}}}$  and  $\mu^{\hat{\mathcal{C}}}$  are non-expansive. It is straightforward to verify that  $\eta^{\hat{\mathcal{C}}}$  is an isometric (hence non-expansive) embedding of  $(X, d)$  into  $(\mathcal{C}(X), HK(d))$ . Proving that  $\mu^{\hat{\mathcal{C}}}$  is non-expansive, instead, does not seem straightforward and requires some detailed calculations. We state this result as a theorem.

► **Theorem 29.** *Let  $(X, d)$  be a metric space in **EMet**. Then  $\mu_{(X,d)}^{\hat{\mathcal{C}}} : \hat{\mathcal{C}}\hat{\mathcal{C}}(X, d) \rightarrow \hat{\mathcal{C}}(X, d)$  is a non-expansive function, i.e., using functional notation,  $HK(d)\langle\mu^{\hat{\mathcal{C}}}, \mu^{\hat{\mathcal{C}}}\rangle \sqsubseteq HKHK(d)$ .*

#### 4.1 Sketch of the Proof of Theorem 29

The key result to prove is Lemma 32, stating that the weighted Minkowski sum function **WMS** is non-expansive. This is obtained by exploiting a key property of the  $HK$  metric (see Lemma 31) called convexity. It might well be that both these results have already appeared in the literature in some form or another or are known as folklore by specialists. We present here a direct proof.

► **Definition 30 (Convex metric).** *Let  $(X, \{+_p\}_{p \in (0,1)})$  be a convex algebra, i.e., a set  $X$  equipped with operations  $+_p : X \times X \rightarrow X$  satisfying the axioms of Definition 10. Let  $d : X \times X \rightarrow \mathbb{R}_{\geq 0} \cup \{\infty\}$  be a metric on  $X$ . We say that  $d$  is convex if  $d(x_1 +_p x_2, y_1 +_p y_2) \leq d(x_1, y_1) +_p d(x_2, y_2)$  holds for all  $x_1, x_2, y_1, y_2 \in X$  and  $p \in (0, 1)$ , where  $d(x_1, y_1) +_p d(x_2, y_2) = p \cdot d(x_1, y_1) + (1 - p) \cdot d(x_2, y_2)$  with the convention that  $\infty +_p x = x +_q \infty = \infty +_r \infty = \infty$  for all  $p, q, r \in (0, 1)$  and  $x \in X$ .*

It is well known that the Kantorovich metric  $K(d)$  is convex. The following lemma states that also the Hausdorff–Kantorovich metric  $HK(d)$ , defined on the collection  $\mathcal{C}(X)$  of non-empty finitely generated convex sets of distributions, which carries the structure of a convex semilattice (see Example 14) and thus also of a convex algebra, is convex.

► **Lemma 31.** *Let  $(X, d)$  be a metric space. The metric  $HK(d)$  on the convex algebra  $(\mathcal{C}(X), \{+_p\}_{p \in (0,1)})$ , with  $S_1 +_p S_2 = \text{WMS}(pS_1 + (1 - p)S_2)$ , is convex.*

Using the convexity of  $HK$  it is possible to prove that the **WMS** function is non-expansive.

► **Lemma 32.** *Let  $(X, d)$  be a metric space. The function  $\text{WMS} : \hat{\mathcal{D}}(\hat{\mathcal{C}}(X, d)) \rightarrow \hat{\mathcal{C}}(X, d)$  (see Definition 5) is non-expansive, i.e.  $HK(d)\langle\text{WMS}, \text{WMS}\rangle \sqsubseteq KHK(d)$ .*

Lastly, we state the following two useful properties of the Hausdorff lifting.

► **Proposition 33.** *Let  $d, d'$  be two metrics over  $X$  such that  $d \sqsubseteq d'$ . Then  $H(d) \sqsubseteq H(d')$ .*

► **Proposition 34.** *Let  $(X, d_X)$  and  $(Y, d_Y)$  be metric spaces, let  $f : X \rightarrow Y$  with  $d_X = d_Y\langle f, f \rangle$  (i.e.,  $d_X(x_1, x_2) = d_Y(f(x_1), f(x_2))$ ). Then  $H(d_X) = H(d_Y)\langle \mathcal{V}(f), \mathcal{V}(f) \rangle$ .*

**Proof of Theorem 29.** We need to show that  $HK(d)\langle\mu^{\hat{\mathcal{C}}}, \mu^{\hat{\mathcal{C}}}\rangle \sqsubseteq HKHK(d)$ .

Since  $\mathcal{V}$  is a monad on **EMet** (Definition 17),  $\mu^{\mathcal{V}}$  is non-expansive, i.e.,  $H(d)\langle\mu^{\mathcal{V}}, \mu^{\mathcal{V}}\rangle \sqsubseteq HH(d)$ . By applying this to the metric  $K(d)$ , we derive

$$HK(d)\langle\mu^{\mathcal{V}}, \mu^{\mathcal{V}}\rangle \sqsubseteq HHK(d). \quad (1)$$

By definition  $\mu^{\hat{C}} = \mu^{\mathcal{V}} \circ \mathcal{V}(\text{WMS})$  (i.e.,  $S \mapsto \bigcup \{\text{WMS}(\Delta) \mid \Delta \in S\}$ ) and therefore:

$$\begin{aligned} HK(d)\langle \mu^{\hat{C}}, \mu^{\hat{C}} \rangle &= HK(d)\langle \mu^{\mathcal{V}} \circ \mathcal{V}(\text{WMS}), \mu^{\mathcal{V}} \circ \mathcal{V}(\text{WMS}) \rangle \\ &= HK(d)\langle \mu^{\mathcal{V}}, \mu^{\mathcal{V}} \rangle \langle \mathcal{V}(\text{WMS}), \mathcal{V}(\text{WMS}) \rangle \end{aligned}$$

Thus, by (1) we can derive

$$HK(d)\langle \mu^{\hat{C}}, \mu^{\hat{C}} \rangle \sqsubseteq HHK(d)\langle \mathcal{V}(\text{WMS}), \mathcal{V}(\text{WMS}) \rangle. \quad (2)$$

Moreover, by the non-expansiveness of WMS (Lemma 32), we know that

$$HK(d)\langle \text{WMS}, \text{WMS} \rangle \sqsubseteq KHK(d)$$

which implies by the monotonicity of  $H$  (Proposition 33) that

$$H(HK(d)\langle \text{WMS}, \text{WMS} \rangle) \sqsubseteq HKHK(d). \quad (3)$$

By Proposition 34, we can rewrite the left-hand term of (3) as follows

$$H(HK(d)\langle \text{WMS}, \text{WMS} \rangle) = HHK(d)\langle \mathcal{V}(\text{WMS}), \mathcal{V}(\text{WMS}) \rangle$$

and thus we derive from (3):

$$HHK(d)\langle \mathcal{V}(\text{WMS}), \mathcal{V}(\text{WMS}) \rangle \sqsubseteq HKHK(d). \quad (4)$$

Lastly, by (2) and (4):  $HK(d)\langle \mu^{\hat{C}}, \mu^{\hat{C}} \rangle \sqsubseteq HHK(d)\langle \mathcal{V}(\text{WMS}), \mathcal{V}(\text{WMS}) \rangle \sqsubseteq HKHK(d)$ . ◀

## 5 Presentation of the Monad $\hat{C}$

In this section we present the main result of this work and show that the monad  $\hat{C}$  on **EMet**, introduced in Section 4, is presented by quantitative convex semilattices.

► **Definition 35.** *The quantitative equational theory of quantitative convex semilattices, denoted by  $\text{QTh}_{CS}$ , is the quantitative theory over the signature  $\Sigma_{CS} = (\{\oplus\} \cup \{+_p\}_{p \in (0,1)})$  of convex semilattices induced by the following set of quantitative inferences:*

- the quantitative inferences (A), (C), (I) and (H) inducing the quantitative theory of semilattices (see Definition 23),
- the quantitative inferences ( $A_p$ ), ( $C_p$ ), ( $I_p$ ), and (K) inducing the quantitative theory of convex algebras (see Definition 24),
- for every  $p \in (0, 1)$ , the quantitative inference (D)  $\emptyset \vdash x +_p (y \oplus z) =_0 (x +_p y) \oplus (x +_p z)$ .

The following is the main result of this work.

► **Theorem 36.** *The quantitative equational theory  $\text{QTh}_{CS}$  of quantitative convex semilattices is a presentation of the monad  $\hat{C}$ , that is,  $\mathbf{QA}(\text{QTh}_{CS}) \cong \mathbf{EM}(\hat{C})$ .*

As one direct corollary of this general statement we automatically get the following result (cf. with Theorem 25) characterising free quantitative convex semilattices, which, by [36, §5], are in turn isomorphic to term quantitative algebras for  $\text{QTh}_{CS}$ .

► **Corollary 37.** *The free quantitative algebra in  $\mathbf{QA}(\text{QTh}_{CS})$  generated by a metric space  $(X, d)$  is isomorphic to  $\hat{C}(X, d)$ , the metric space of finitely generated convex sets of probability distributions metrized by the Hausdorff–Kantorovich metric  $HK(d)$ .*

We prove Theorem 36 by explicitly defining a pair of functors  $\mathcal{F} : \mathbf{EM}(\hat{\mathcal{C}}) \rightarrow \mathbf{QA}(\mathbf{QTh}_{CS})$  and  $\mathcal{G} : \mathbf{QA}(\mathbf{QTh}_{CS}) \rightarrow \mathbf{EM}(\hat{\mathcal{C}})$  and proving that they are isomorphisms of categories, i.e., that  $\mathcal{G} \circ \mathcal{F} = id_{\mathbf{EM}(\hat{\mathcal{C}})}$  and  $\mathcal{F} \circ \mathcal{G} = id_{\mathbf{QA}(\mathbf{QTh}_{CS})}$ . In the following sections, we exhibit such functors and show that they are well-defined isomorphisms.

► **Remark 38.** A recent result (Theorem 4.2 of [7]), showing that, for any quantitative equational theory, the category of Eilenberg-Moore algebras of the term monad and the category  $\mathbf{QA}(\mathbf{QTh}_{CS})$  are isomorphic, might provide an alternative route to obtain the result of Theorem 36. Our proof technique has the virtue of concretely exhibiting the functors witnessing the isomorphism.

## 5.1 The functor $\mathcal{F} : \mathbf{EM}(\hat{\mathcal{C}}) \rightarrow \mathbf{QA}(\mathbf{QTh}_{CS})$

Recall from Definition 6 that an object in  $\mathbf{EM}(\hat{\mathcal{C}})$  is a structure  $((X, d), \alpha)$  where  $(X, d)$  is a metric space and  $\alpha : (\mathcal{C}(X), HK(d)) \rightarrow (X, d)$  is a non-expansive function satisfying  $\alpha \circ \eta_X^{\hat{\mathcal{C}}} = id_X$  and  $\alpha \circ \hat{\mathcal{C}}\alpha = \alpha \circ \mu_X^{\hat{\mathcal{C}}}$ . A morphism  $f : ((X, d_X), \alpha_X) \rightarrow ((Y, d_Y), \alpha_Y)$  in  $\mathbf{EM}(\hat{\mathcal{C}})$  is a non-expansive function  $f : X \rightarrow Y$  such that  $f \circ \alpha_X = \alpha_Y \circ \hat{\mathcal{C}}(f)$ .

► **Definition 39 (Functor  $\mathcal{F}$ ).** We define  $\mathcal{F} : \mathbf{EM}(\hat{\mathcal{C}}) \rightarrow \mathbf{QA}(\mathbf{QTh}_{CS})$  as follows:

- on objects:  $\mathcal{F}((X, d), \alpha) = (X, \Sigma_{CS}^\alpha, d)$   
with  $\Sigma_{CS}^\alpha = (\{\oplus^\alpha\} \cup \{+_p^\alpha\}_{p \in (0,1)})$  the interpretation of the convex semilattice operations  $\oplus$  and  $+_p$  as  $x_1 \oplus x_2 = \alpha(cc\{\delta(x_1), \delta(x_2)\})$  and  $x_1 +_p^\alpha x_2 = \alpha(\{px_1 + (1-p)x_2\})$ ,
- on morphisms:  $\mathcal{F}(f) = f$ , with  $f : X \rightarrow Y$  seen as a non-expansive map from  $X$  to  $Y$ .

We now prove that the functor  $\mathcal{F}$  is well-defined. First, on objects, we need to show that  $\mathcal{F}((X, d), \alpha)$  is indeed a quantitative algebra satisfying the quantitative inferences of the theory  $\mathbf{QTh}_{CS}$ . To show that  $(X, \Sigma_{CS}^\alpha, d)$  is a quantitative algebra (Definition 22), since  $(X, d)$  is a metric space, we only need to verify that the operations  $\oplus^\alpha$  and  $+_p^\alpha$  are non-expansive.

► **Lemma 40.** The operations  $\oplus^\alpha$  and  $+_p^\alpha$ , for all  $p \in (0, 1)$ , are non-expansive.

**Proof.** Using functional notation we have  $\oplus^\alpha = \alpha \circ cc \circ \mathcal{P}\eta_X^{\hat{\mathcal{D}}} \circ (\lambda x_1, x_2. \{x_1, x_2\})$ . The function  $\alpha$  is non-expansive by assumption.  $\mathcal{P}\eta_X^{\hat{\mathcal{D}}}$  is non-expansive by  $\hat{\mathcal{P}}$  and  $\hat{\mathcal{D}}$  being monads on  $\mathbf{EMet}$ . The functions  $\lambda x_1, x_2. \{x_1, x_2\} : (X, d) \times (X, d) \rightarrow \hat{\mathcal{P}}(X, d)$  and  $cc : \hat{\mathcal{P}}\hat{\mathcal{D}}(X, d) \rightarrow \hat{\mathcal{C}}(X, d)$  are non-expansive as well. Hence  $\oplus^\alpha$  is non-expansive as composition of non-expansive maps. Similarly, we have  $+_p^\alpha = \alpha \circ \eta_{\mathcal{D}(X)}^{\mathcal{P}} \circ (\lambda x_1, x_2. (px_1 + (1-p)x_2))$  and all operations involved are non-expansive. ◀

As  $\mathcal{F}((X, d), \alpha)$  is a quantitative algebra, it satisfies all the quantitative inferences of Definition 21. It only remains to show that the quantitative inferences of the theory  $\mathbf{QTh}_{CS}$  (Definition 35) are also satisfied. For each of the quantitative inferences  $(A, C, I, A_p, C_p, I_p, D)$ , which are of the form  $\emptyset \vdash s =_0 t$ , we need to show that the equality  $s = t$  holds (universally quantified) in  $(X, \Sigma_{CS}^\alpha, d)$ . This amounts to showing that the algebra  $(X, \Sigma_{CS}^\alpha)$  (with the metric  $d$  forgotten) is a model of the equational theory of convex semilattices (Definition 11). This proof has no specific metric-theoretic content and is omitted here. Thus, it only remains to show that the quantitative inferences  $(H)$  and  $(K)$  are satisfied.

► **Lemma 41 (H).**  $\{x_1 =_{\epsilon_1} y_1, x_2 =_{\epsilon_2} y_2\} \models_{\mathcal{F}((X,d),\alpha)} x_1 \oplus x_2 =_{\max(\epsilon_1, \epsilon_2)} y_1 \oplus y_2$ .

**Proof.** The quantitative inference  $(H)$  is equivalent (i.e., mutually derivable in presence of the others deductive rules of Definition 21) with the  $(\mathbf{NExp})$  deductive rule. This means that  $(H)$  holds in  $\mathcal{F}((X, d), \alpha)$  because the operation  $\oplus^\alpha$  is non-expansive (Lemma 40). ◀

► **Lemma 42 (K).**  $x_1 =_{\epsilon_1} y_1, x_2 =_{\epsilon_2} y_2 \vdash_{\mathcal{F}((X,d),\alpha)} x_1 +_p x_2 =_{p \cdot \epsilon_1 + (1-p) \cdot \epsilon_2} y_1 +_p y_2$ .

**Proof.** For arbitrary  $x_1, x_2, y_1, y_2 \in X$ , assume  $d(x_1, y_1) \leq \epsilon_1$  and  $d(x_2, y_2) \leq \epsilon_2$ . Then

$$\begin{aligned} d(x_1 +_p x_2, y_1 +_p y_2) &= d(\alpha(\{px_1 + (1-p)x_2\}), \alpha(\{py_1 + (1-p)y_2\})) \\ &\leq HK(d)(\{px_1 + (1-p)x_2\}, \{py_1 + (1-p)y_2\}) \quad (\alpha \text{ non-exp.}) \\ &= K(d)(px_1 + (1-p)x_2, py_1 + (1-p)y_2) \\ &\leq p \cdot d(x_1, y_1) + (1-p) \cdot d(x_2, y_2) \quad (\text{the metric } K(d) \text{ is convex}) \\ &\leq p \cdot \epsilon_1 + (1-p) \cdot \epsilon_2 \quad \blacktriangleleft \end{aligned}$$

Hence  $\mathcal{F}$  is well-defined on objects. It remains to verify that  $\mathcal{F}$  is well defined on morphisms. Let  $f : ((X, d), \alpha) \rightarrow ((Y, d'), \beta)$  be a morphism in  $\mathbf{EM}(\hat{\mathcal{C}})$ . We need to verify that  $\mathcal{F}(f)$  is a morphism in  $\mathbf{QA}(\mathbf{QTh}_{CS})$ , i.e., a non-expansive homomorphism of convex semilattices (see Definition 22). Since by definition  $\mathcal{F}(f) = f$ , the function  $\mathcal{F}(f)$  is non-expansive. It remains to verify that it is a homomorphism. This proof has no specific metric-theoretic content and we omit it here.

## 5.2 The functor $\mathcal{G} : \mathbf{QA}(\mathbf{QTh}_{CS}) \rightarrow \mathbf{EM}(\hat{\mathcal{C}})$

Recall that an object in  $\mathbf{QA}(\mathbf{QTh}_{CS})$  is a quantitative convex semilattice  $\mathbb{A} = (X, \Sigma_{CS}^{\mathbb{A}}, d)$ , with  $\Sigma_{CS}^{\mathbb{A}} = (\{\oplus^{\mathbb{A}}\} \cup \{+_p^{\mathbb{A}}\}_{p \in (0,1)})$ . Also, recall from Example 14 that there is an isomorphism  $\kappa$  mapping elements of  $\mathcal{C}(X)$  to equivalence classes of convex semilattice terms in  $\mathcal{T}(X, \Sigma_{CS})_{/\mathbf{Th}_{CS}}$ . Let us define  $\nu : \mathcal{C}(X) \rightarrow \mathcal{T}(X, \Sigma_{CS})$  as a choice function, mapping each  $S \in \mathcal{C}(X)$  to one representative of the equivalence class  $\kappa(S)$ . This allows us to uniquely write down each  $S \in \mathcal{C}(X)$  as a convex semilattice term:

$$\nu(S) = \bigoplus_{\Delta \in \mathbf{UB}(S)} \left( +_{x \in \text{supp}(\Delta)} \Delta(x) x \right).$$

With abuse of notation, we have used the letter  $X$  to range both over a set of variables and the carrier of  $\mathbb{A}$ . By interpreting each variable  $x$  with the corresponding element  $x \in X$  of  $\mathbb{A}$ , and by homomorphic extension, we get that each term  $t \in \mathcal{T}(X, \Sigma_{CS})$  can be interpreted as an element  $t^{\mathbb{A}}$  of  $\mathbb{A}$ , and in particular  $(\nu(S))^{\mathbb{A}}$  denotes an element of  $\mathbb{A}$  for each  $S \in \mathcal{C}(X)$ .

► **Definition 43 (Functor  $\mathcal{G}$ ).** We specify  $\mathcal{G} : \mathbf{QA}(\mathbf{QTh}_{CS}) \rightarrow \mathbf{EM}(\hat{\mathcal{C}})$  as follows:

- on objects  $\mathbb{A} = (X, \Sigma_{CS}^{\mathbb{A}}, d)$ , we define  $\mathcal{G}(\mathbb{A}) = ((X, d), \alpha)$ , with  $\alpha : (\mathcal{C}(X), HK(d)) \rightarrow (X, d)$  defined as:  $\alpha(S) = (\nu(S))^{\mathbb{A}}$ ,
- on morphisms (i.e., non-expansive homomorphisms) we define  $\mathcal{G}(f) = f$ .

In order to prove that  $\mathcal{G}$  is well-defined on objects, we have to show that indeed  $((X, d), \alpha)$  is an Eilenberg-Moore algebra for  $\hat{\mathcal{C}}$ , which amounts to proving the following lemma.

► **Lemma 44.** Let  $\mathcal{G}(\mathbb{A}) = ((X, d), \alpha)$ , for  $\mathbb{A} = (X, \Sigma_{CS}^{\mathbb{A}}, d) \in \mathbf{QA}(\mathbf{QTh}_{CS})$ .

1.  $(X, \alpha)$  is an Eilenberg-Moore algebra for  $\mathcal{C}$  in  $\mathbf{Set}$ , i.e.,  $\alpha \circ \eta^{\mathcal{C}} = id$  and  $\alpha \circ \mathcal{C}\alpha = \alpha \circ \mu^{\mathcal{C}}$ .
2.  $\alpha$  is a morphism in  $\mathbf{EMet}$ , i.e.,  $\alpha$  is a non-expansive map:  $d\langle \alpha, \alpha \rangle \sqsubseteq HK(d)$ .

**Proof.** The proof of the first point does not have any specific metric-theoretic content and is omitted here. For the second point, let  $S, T \in \mathcal{C}(X)$ . By the definition of  $\alpha$ , we have  $d(\alpha(S), \alpha(T)) = d((\nu(S))^{\mathbb{A}}, (\nu(T))^{\mathbb{A}})$ . As stated in Lemma 45 below, it is possible to derive in  $\mathbf{QTh}_{CS}$  the quantitative inference

$$\bigcup_{(\Delta, \Theta) \in \mathbf{UB}(S) \times \mathbf{UB}(T)} \left( \bigcup_{(x,y) \in \text{supp}(\Delta) \times \text{supp}(\Theta)} \{x =_{d(x,y)} y\} \right) \vdash \nu(S) =_{HK(d)(S,T)} \nu(T)$$

which, since  $\mathbb{A}$  is a model of  $\mathbf{QTh}_{CS}$ , is thereby satisfied by  $\mathbb{A}$ . Since all the premises of the inference hold in  $\mathbb{A}$ , we conclude that  $d((\nu(S))^{\mathbb{A}}, (\nu(T))^{\mathbb{A}}) \leq HK(d)(S, T)$  and, therefore,  $d(\alpha, \alpha) \sqsubseteq HK(d)$  holds, as desired.  $\blacktriangleleft$

The following technical lemma is critically used in the proof of Lemma 44(2) above. Note that its statement is purely syntactic as it deals with derivability in the deductive apparatus of quantitative equational theories (Definition 21).

► **Lemma 45.** *Let  $(X, d)$  be a metric space and let  $S, T \in \mathcal{C}(X)$ . Then we have in  $\mathbf{QTh}_{CS}$ :*

$$\bigcup_{(\Delta, \Theta) \in \mathbf{UB}(S) \times \mathbf{UB}(T)} \left( \bigcup_{(x, y) \in \mathit{supp}(\Delta) \times \mathit{supp}(\Theta)} \{x =_{d(x, y)} y\} \right) \vdash \nu(S) =_{HK(d)(S, T)} \nu(T)$$

**Proof Sketch.** First, we derive the following useful quantitative inference dealing with the case of  $S = \{\Delta\}$  and  $T = \{\Theta\}$  being singletons, so that  $HK(d)(S, T) = K(d)(\Delta, \Theta)$ . Let  $(X, d)$  be a metric space and let  $\Delta, \Theta \in \mathcal{D}(X)$ . Then the following is derivable in  $\mathbf{QTh}_{CS}$ :

$$\bigcup_{(x, y) \in \mathit{supp}(\Delta) \times \mathit{supp}(\Theta)} \{x =_{d(x, y)} y\} \vdash \nu(\{\Delta\}) =_{K(d)(\Delta, \Theta)} \nu(\{\Theta\}).$$

To construct this derivation we take an optimal coupling  $\omega$  of  $\Delta$  and  $\Theta$  (see Definition 19) witnessing the Kantorovich distance  $K(d)(\Delta, \Theta)$  and then use the information provided by  $\omega$  to construct a syntactic derivation where only the quantitative inferences ( $A_p$ ,  $C_p$ ,  $I_p$  and  $K$ ) of the quantitative theory of convex algebras are used. The construction of this derivation follows analogously to the completeness result for quantitative convex algebras from [36].

Secondly, we calculate the  $HK(d)(S, T)$  distance between  $S$  and  $T$ .

$$HK(d)(S, T) = \max \left\{ \sup_{\Delta \in S} \inf_{\Theta \in T} K(d)(\Delta, \Theta) \ , \ \sup_{\Theta \in T} \inf_{\Delta \in S} K(d)(\Delta, \Theta) \right\}.$$

By compactness arguments, the inf and sup are always attained. Hence this calculation involves distances  $K(d)(\Delta_i, \Theta_j)$  between a finite number of elements  $\Delta_i \in S$  and  $\Theta_j \in T$ , for  $0 \leq i \leq n$  and  $0 \leq j \leq m$ . Since the equation  $x \oplus y = x \oplus y \oplus (x +_p y)$  holds in all convex semilattices, we can derive in the theory of convex semilattices the equalities:  $\nu(S) = \nu(S) \oplus \nu(\{\Delta_1\}) \oplus \dots \oplus \nu(\{\Delta_n\})$  and  $\nu(T) = \nu(T) \oplus \nu(\{\Theta_1\}) \oplus \dots \oplus \nu(\{\Theta_m\})$ . For each of the pairs  $(\Delta_i, \Theta_j)$  appearing in the expressions above we can derive, as described above, the quantitative equation  $\nu(\{\Delta_i\}) =_{K(d)(\Delta_i, \Theta_j)} \nu(\{\Theta_j\})$ . The calculation of  $HK(d)(S, T)$  can then be mimicked syntactically to derive the quantitative equation  $\nu(S) =_{HK(d)(S, T)} \nu(T)$  by only using the quantitative inferences ( $A$ ,  $C$ ,  $I$  and  $H$ ) of quantitative semilattices. This follows analogously to the completeness result for quantitative semilattices from [36].  $\blacktriangleleft$

It remains to verify that the functor  $\mathcal{G}$  is well-defined on morphisms. To see this, take  $f : X \rightarrow Y$  a non-expansive homomorphism of quantitative algebras  $\mathbb{A} = (X, \Sigma_{CS}^{\mathbb{A}}, d)$  and  $\mathbb{B} = (Y, \Sigma_{CS}^{\mathbb{B}}, d')$  in  $\mathbf{QA}(\mathbf{QTh}_{CS})$ . Then  $f$  is an arrow in  $\mathbf{EMet}$ , being non-expansive. We therefore only need to show that  $f$  is also a morphism of Eilenberg-Moore algebras (see Definition 6) i.e., that  $f \circ \alpha = \beta \circ \hat{C}(f)$ . The verification of this equality involves no specific metric-theoretic considerations, and is therefore omitted.

### 5.3 The isomorphism

It remains to prove that the functors  $\mathcal{F} : \mathbf{EM}(\hat{C}) \rightarrow \mathbf{QA}(\mathbf{QTh}_{CS})$  and  $\mathcal{G} : \mathbf{EM}(\hat{C}) \rightarrow \mathbf{QA}(\mathbf{QTh}_{CS})$  define an isomorphism between the categories  $\mathbf{EM}(\hat{C})$  and  $\mathbf{QA}(\mathbf{QTh}_{CS})$ . This means proving that  $\mathcal{G} \circ \mathcal{F} = id_{\mathbf{EM}(\hat{C})}$  and  $\mathcal{F} \circ \mathcal{G} = id_{\mathbf{QA}(\mathbf{QTh}_{CS})}$ . On morphisms, by definition

we have  $\mathcal{G} \circ \mathcal{F}(f) = f = \mathcal{F} \circ \mathcal{G}(f)$ . Hence the identities trivially hold true. The proofs regarding the identities on objects require only routine verifications, unfolding definitions, not involving any specific metric-theoretic content and therefore we omit them here.

## 6 Conclusions

We have introduced the **EMet** monad  $\hat{\mathcal{C}}$  of finitely generated non-empty convex sets of distributions equipped with the Hausdorff-Kantorovich distance, and we have proved that  $\hat{\mathcal{C}}$  is presented by the quantitative equational theory  $\mathbf{QTh}_{CS}$  of quantitative convex semilattices. This result provides the basis for a foundational understanding of equational reasoning about program distances in processes combining nondeterminism and probabilities, as in bisimulation and trace metrics [22, 25, 26, 49, 6, 18]. This opens several directions for future research.

For instance, one interesting line of research is to examine the axiomatizations of bisimulation equivalences and metrics for nondeterministic and probabilistic programs (or process algebras) that have been proposed in the literature [40, 9, 21, 1, 2, 20]. The quantitative equational framework of quantitative convex semilattices provides a novel tool for comparing and further developing the existing works.

It is also important to explore variants of the **EMet** monad  $\hat{\mathcal{C}}$  such as, for instance, the one that also includes the empty set. These are needed to model program observations such as termination. Following the ideas presented in [13], these variants can be explored via the lift monad  $(\cdot + 1)$  and its quotients described by equational theories over the signature of convex semilattices extended with a new constant symbol. A systematic study of these quotients is a promising direction for future work. Applications to up-to techniques for bisimulation metrics [19, 10] could then be pursued as well.

Lastly, it is natural to ask if the monad  $\hat{\mathcal{C}}$ , and its presentation, can be obtained as a general categorical composition of the hyperspace monad  $\mathcal{V}$  and the distribution monad  $\hat{\mathcal{D}}$ . Recently, Goy and Petrisan [30] have used the notion of weak distributive law to provide a positive answer for the corresponding monads in the category **Set**. Investigating whether this machinery is also applicable to the category **EMet** is an interesting topic for future work.

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## References

- 1 Suzana Andova. Process algebra with probabilistic choice. In *Formal Methods for Real-Time and Probabilistic Systems, 5th International AMAST Workshop, ARTS'99, Bamberg, Germany, May 26-28, 1999. Proceedings*, pages 111–129, 1999. doi:10.1007/3-540-48778-6\_7.
- 2 Suzana Andova and Sonja Georgievska. On compositionality, efficiency, and applicability of abstraction in probabilistic systems. In Mogens Nielsen, Antonín Kucera, Peter Bro Miltersen, Catuscia Palamidessi, Petr Tuma, and Frank D. Valencia, editors, *SOFSEM 2009: Theory and Practice of Computer Science, 35th Conference on Current Trends in Theory and Practice of Computer Science, Spindleruv Mlýn, Czech Republic, January 24-30, 2009. Proceedings*, volume 5404 of *Lecture Notes in Computer Science*, pages 67–78. Springer, 2009. doi:10.1007/978-3-540-95891-8\_10.
- 3 Steve Awodey. *Category Theory*. Oxford University Press, 2010.
- 4 Giorgio Bacci, Giovanni Bacci, Kim G. Larsen, and Radu Mardare. Complete axiomatization for the total variation distance of Markov chains. In Sam Staton, editor, *Proceedings of the Thirty-Fourth Conference on the Mathematical Foundations of Programming Semantics, MFPS 2018, Dalhousie University, Halifax, Canada, June 6-9, 2018*, volume 341 of *Electronic Notes in Theoretical Computer Science*, pages 27–39. Elsevier, 2018. doi:10.1016/j.entcs.2018.03.014.



- 5 Giorgio Bacci, Giovanni Bacci, Kim G. Larsen, and Radu Mardare. A complete quantitative deduction system for the bisimilarity distance on Markov chains. *Logical Methods in Computer Science*, 14(4), 2018. doi:10.23638/LMCS-14(4:15)2018.
- 6 Giorgio Bacci, Giovanni Bacci, Kim G. Larsen, Radu Mardare, Qiyi Tang, and Franck van Breugel. Computing probabilistic bisimilarity distances for probabilistic automata. In *30th International Conference on Concurrency Theory, CONCUR 2019, August 27-30, 2019, Amsterdam, the Netherlands*, pages 9:1–9:17, 2019. doi:10.4230/LIPIcs.CONCUR.2019.9.
- 7 Giorgio Bacci, Radu Mardare, Prakash Panangaden, and Gordon D. Plotkin. An algebraic theory of Markov Processes. In Anuj Dawar and Erich Grädel, editors, *Proceedings of the 33rd Annual ACM/IEEE Symposium on Logic in Computer Science, LICS 2018, Oxford, UK, July 09-12, 2018*, pages 679–688. ACM, 2018. doi:10.1145/3209108.3209177.
- 8 Paolo Baldan, Filippo Bonchi, Henning Kerstan, and Barbara König. Coalgebraic behavioral metrics. *Logical Methods in Computer Science*, 14(3), 2018. doi:10.23638/LMCS-14(3:20)2018.
- 9 E. Bandini and R. Segala. Axiomatizations for probabilistic bisimulation. In *Proc. of the 28th Int. Coll. on Automata, Languages and Programming (ICALP 2001)*, volume 2076 of *LNCS*, pages 370–381. Springer, 2001.
- 10 Filippo Bonchi, Barbara König, and Daniela Petrisan. Up-to techniques for behavioural metrics via fibrations. In *29th International Conference on Concurrency Theory, CONCUR 2018, September 4-7, 2018, Beijing, China*, pages 17:1–17:17, 2018. doi:10.4230/LIPIcs.CONCUR.2018.17.
- 11 Filippo Bonchi, Daniela Petrisan, Damien Pous, and Jurriaan Rot. A general account of coinduction up-to. *Acta Inf.*, 54(2):127–190, 2017. doi:10.1007/s00236-016-0271-4.
- 12 Filippo Bonchi, Alexandra Silva, and Ana Sokolova. The Power of Convex Algebras. In *CONCUR 2017*, volume 85, pages 23:1–23:18. LIPIcs, 2017. doi:10.4230/LIPIcs.CONCUR.2017.23.
- 13 Filippo Bonchi, Ana Sokolova, and Valeria Vignudelli. The theory of traces for systems with nondeterminism and probability. In *34th Annual ACM/IEEE Symposium on Logic in Computer Science, LICS 2019, Vancouver, BC, Canada, June 24-27, 2019*, pages 1–14, 2019. doi:10.1109/LICS.2019.8785673.
- 14 Filippo Bonchi, Ana Sokolova, and Valeria Vignudelli. Presenting convex sets of probability distributions by convex semilattices and unique bases, 2020. arXiv:2005.01670.
- 15 Franck van Breugel. The metric monad for probabilistic nondeterminism. <http://www.cse.yorku.ca/~franck/research/drafts/monad.pdf>, 2005.
- 16 Franck van Breugel and James Worrell. Towards quantitative verification of probabilistic transition systems. In Fernando Orejas, Paul G. Spirakis, and Jan van Leeuwen, editors, *Automata, Languages and Programming, 28th International Colloquium, ICALP 2001, Crete, Greece, July 8-12, 2001, Proceedings*, volume 2076 of *Lecture Notes in Computer Science*, pages 421–432. Springer, 2001. doi:10.1007/3-540-48224-5\_35.
- 17 Stanley Burris and H. P. Sankappanavar. *A Course in Universal Algebra*. Springer-Verlag Graduate Texts in Mathematics, 1981.
- 18 Valentina Castiglioni. Trace and testing metrics on nondeterministic probabilistic processes. In *Proc. Express/SOS 2018.*, pages 19–36, 2018. doi:10.4204/EPTCS.276.4.
- 19 Konstantinos Chatzikokolakis, Catuscia Palamidessi, and Valeria Vignudelli. Up-to techniques for generalized bisimulation metrics. In *27th International Conference on Concurrency Theory, CONCUR 2016, August 23-26, 2016, Québec City, Canada*, pages 35:1–35:14, 2016. doi:10.4230/LIPIcs.CONCUR.2016.35.
- 20 Pedro R. D’Argenio, Daniel Gebler, and Matias David Lee. Axiomatizing bisimulation equivalences and metrics from probabilistic SOS rules. In *Foundations of Software Science and Computation Structures - 17th International Conference, FOSSACS 2014, Held as Part of the European Joint Conferences on Theory and Practice of Software, ETAPS 2014, Grenoble, France, April 5-13, 2014, Proceedings*, pages 289–303, 2014. doi:10.1007/978-3-642-54830-7\_19.

- 21 Y. Deng and C. Palamidessi. Axiomatizations for probabilistic finite-state behaviors. *Theoretical Computer Science*, 373:92–114, 2007.
- 22 Yuxin Deng, Tom Chothia, Catuscia Palamidessi, and Jun Pang. Metrics for action-labelled quantitative transition systems. *Electron. Notes Theor. Comput. Sci.*, 153(2):79–96, 2006. doi:10.1016/j.entcs.2005.10.033.
- 23 Josee Desharnais, Radha Jagadeesan, Vineet Gupta, and Prakash Panangaden. The metric analogue of weak bisimulation for probabilistic processes. In *Proc. LICS'02*, pages 413–422. IEEE Computer Society, 2002. doi:10.1109/LICS.2002.1029849.
- 24 E. Doberkat. Eilenberg-moore algebras for stochastic relations. *Information and Computation*, 204(12):1756–1781, 2006. Erratum and Addendum: Eilenberg-Moore algebras for stochastic relations. *Information and Computation*, Volume 206, Issue 12, December 2008, Pages 1476–1484.
- 25 Daniel Gebler, Kim G. Larsen, and Simone Tini. Compositional bisimulation metric reasoning with probabilistic process calculi. *Logical Methods in Computer Science*, 12(4), 2016. doi:10.2168/LMCS-12(4:12)2016.
- 26 Daniel Gebler and Simone Tini. SOS specifications for uniformly continuous operators. *J. Comput. Syst. Sci.*, 92:113–151, 2018. doi:10.1016/j.jcss.2017.09.011.
- 27 A. Giacalone, C.-C. Jou, and S.A. Smolka. Algebraic reasoning for probabilistic concurrent systems. In *Proc. PROCOMET'90*, pages 443–458. North-Holland, 1990.
- 28 Jean Goubault-Larrecq. Continuous previsions. In Jacques Duparc and Thomas A. Henzinger, editors, *Computer Science Logic, 21st International Workshop, CSL 2007, 16th Annual Conference of the EACSL, Lausanne, Switzerland, September 11-15, 2007, Proceedings*, volume 4646 of *Lecture Notes in Computer Science*, pages 542–557. Springer, 2007. doi:10.1007/978-3-540-74915-8\_40.
- 29 Jean Goubault-Larrecq. Prevision domains and convex powercones. In Roberto M. Amadio, editor, *Foundations of Software Science and Computational Structures, 11th International Conference, FOSSACS 2008, Held as Part of the Joint European Conferences on Theory and Practice of Software, ETAPS 2008, Budapest, Hungary, March 29 - April 6, 2008. Proceedings*, volume 4962 of *Lecture Notes in Computer Science*, pages 318–333. Springer, 2008. doi:10.1007/978-3-540-78499-9\_23.
- 30 Alexandre Goy and Daniela Petrisan. Combining probabilistic and non-deterministic choice via weak distributive laws. In Holger Hermanns, Lijun Zhang, Naoki Kobayashi, and Dale Miller, editors, *LICS '20: 35th Annual ACM/IEEE Symposium on Logic in Computer Science, Saarbrücken, Germany, July 8-11, 2020*, pages 454–464. ACM, 2020. doi:10.1145/3373718.3394795.
- 31 Felix Hausdorff. Grundzuge der mengenlehre. *German. Veit und Co. (cit. page 5)*, 1914.
- 32 B. Jacobs. Convexity, duality and effects. In *Theoretical computer science*, volume 323 of *IFIP Adv. Inf. Commun. Technol.*, pages 1–19. Springer, Berlin, 2010. doi:10.1007/978-3-642-15240-5\_1.
- 33 Bart Jacobs. Coalgebraic trace semantics for combined possibilistic and probabilistic systems. *Electr. Notes Theor. Comput. Sci.*, 203(5):131–152, 2008.
- 34 Alexander Kechris. *Classical Descriptive Set Theory*. Springer-Verlag, 1995.
- 35 Bartek Klin. Bialgebras for structural operational semantics: An introduction. *Theor. Comput. Sci.*, 412(38):5043–5069, 2011. doi:10.1016/j.tcs.2011.03.023.
- 36 Radu Mardare, Prakash Panangaden, and Gordon D. Plotkin. Quantitative algebraic reasoning. In Martin Grohe, Eric Koskinen, and Natarajan Shankar, editors, *Proceedings of the 31st Annual ACM/IEEE Symposium on Logic in Computer Science, LICS '16, New York, NY, USA, July 5-8, 2016*, pages 700–709. ACM, 2016. doi:10.1145/2933575.2934518.
- 37 Radu Mardare, Prakash Panangaden, and Gordon D. Plotkin. On the axiomatizability of quantitative algebras. In *32nd Annual ACM/IEEE Symposium on Logic in Computer Science, LICS 2017, Reykjavik, Iceland, June 20-23, 2017*, pages 1–12. IEEE Computer Society, 2017. doi:10.1109/LICS.2017.8005102.

- 38 Radu Mardare, Prakash Panangaden, and Gordon D. Plotkin. Free complete Wasserstein algebras. *Logical Methods in Computer Science*, 14(3), 2018. doi:10.23638/LMCS-14(3:19)2018.
- 39 Matteo Mio. Upper-expectation bisimilarity and lukasiewicz  $\mu$ -calculus. In Anca Muscholl, editor, *Foundations of Software Science and Computation Structures - 17th International Conference, FOSSACS 2014, Held as Part of the European Joint Conferences on Theory and Practice of Software, ETAPS 2014, Grenoble, France, April 5-13, 2014, Proceedings*, volume 8412 of *Lecture Notes in Computer Science*, pages 335–350. Springer, 2014. doi:10.1007/978-3-642-54830-7\_22.
- 40 M. Mislove, J. Ouaknine, and J. Worrell. Axioms for probability and nondeterminism. In *Proc. of the 10th Int. Workshop on Expressiveness in Concurrency (EXPRESS 2003)*, volume 96 of *ENTCS*, pages 7–28. Elsevier, 2003.
- 41 Michael W. Mislove. Nondeterminism and probabilistic choice: Obeying the laws. In *CONCUR 2000*, pages 350–364. LNCS 1877, 2000. doi:10.1007/3-540-44618-4\_26.
- 42 Michael W. Mislove. On combining probability and nondeterminism. *Electron. Notes Theor. Comput. Sci.*, 162:261–265, 2006. doi:10.1016/j.entcs.2005.12.113.
- 43 Eugenio Moggi. Computational lambda-calculus and monads. In *Fourth Annual IEEE Symposium on Logic in Computer Science*, pages 14–23, 1989.
- 44 Eugenio Moggi. Notions of computation and monads. *Information and Computation*, 93(1):55–92, 1991.
- 45 Prakash Panangaden. *Labelled Markov Processes*. Imperial College Press, 2009.
- 46 R. Segala. *Modeling and verification of randomized distributed real-time systems*. PhD thesis, MIT, 1995.
- 47 M.H. Stone. Postulates for the barycentric calculus. *Ann. Mat. Pura Appl. (4)*, 29:25–30, 1949. doi:10.1007/BF02413910.
- 48 T. Świrszcz. Monadic functors and convexity. *Bull. Acad. Polon. Sci. Sér. Sci. Math. Astronom. Phys.*, 22:39–42, 1974.
- 49 Qiyi Tang and Franck van Breugel. Deciding probabilistic bisimilarity distance one for probabilistic automata. In *29th International Conference on Concurrency Theory, CONCUR 2018, September 4-7, 2018, Beijing, China*, pages 9:1–9:17, 2018. doi:10.4230/LIPIcs.CONCUR.2018.9.
- 50 Regina Tix, Klaus Keimel, and Gordon D. Plotkin. Semantic domains for combining probability and non-determinism. *Electron. Notes Theor. Comput. Sci.*, 222:3–99, 2009. doi:10.1016/j.entcs.2009.01.002.
- 51 Daniele Turi and Gordon D. Plotkin. Towards a mathematical operational semantics. In *Proc. LICS 1997*, pages 280–291, 1997. doi:10.1109/LICS.1997.614955.
- 52 D. Varacca and G. Winskel. Distributing probability over non-determinism. *Mathematical Structures in Computer Science*, 16:87–113, 2006.