



A Monad for Randomized Algorithms

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Abstract

In this paper, we introduce a monad of random choice for domains that does not suffer from the main two drawbacks of the probabilistic powerdomain. It is not known whether any Cartesian closed category of domains is closed under the probabilistic powerdomain, but the Cartesian closed category BCD is closed under this monad of random choice. Also, there is no distributive law between the probabilistic powerdomain and any of the nondeterministic powerdomains, but there is a distributive law between the monad of random choice and the lower powerdomain. In order to work with the convex powerdomain, an alteration to the monad of random choice is made, so that the Cartesian closed categories RB and FS are closed under this construction. Then, in these categories, there is a distributive law between this monad and the convex powerdomain. This work is based on the uniform continuous random variables of Goubault-Larrecq and Varacca, which do not form a monad. This paper gives motivation for this model and changes the definition of the Kleisli extension of Goubault-Larrecq and Varacca so that it is monotone, which was the problem with their definition.

Keywords: Probabilistic powerdomain, Cartesian closed category, random variable, distributive law

1 Introduction

Starting with Dana Scott's model of the untyped lambda calculus, domain theory has been largely successful in providing models of computation. The use of domain theory has expanded to provide denotational semantics for many computational effects, such as continuations and nondeterminism, using Moggi's [16] monadic approach. One type of computation that has been problematic to model, however, is probabilistic computation. The most well known monad of probabilistic computation is the probabilistic powerdomain, first defined by Saheb-Djahromi in 1980 [18]. However, this monad has two major flaws [11]. First, there is no distributive law between the probabilistic powerdomain and any of the three nondeterministic powerdomains [24]. According to Beck's Theorem [4], the composition of two monads is a monad if and only if the monads satisfy a distributive law. Thus, to generate

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a monad from the probabilistic powerdomain and any of the monads for nondeterministic choice, new laws must be added, an approach explored independently by Tix [22, 23] and Mislove [12]. Second, it is not known whether any Cartesian closed category of domains is closed under the probabilistic powerdomain. The category of coherent domains is closed under this construction, but it is not Cartesian closed.

To address these flaws, work has been done to develop alternate models of probabilistic computation. Varacca and Winskel [24, 25] constructed what they called *indexed valuation monads*. These monads weaken the laws of probabilistic choice, no longer requiring that $p +_r p = p$, where $p +_r q$ denotes choosing p with probability r and q with probability $1 - r$. In this setting, it is possible to satisfy a distributive law with the nondeterministic powerdomains.

Mislove [13] built upon this work, using an indexed valuation model to define a monad of finite random variables. The Cartesian closed categories RB and FS were shown to be closed under this construction. Later, Goubault-Larrecq and Varacca [9] proposed a model of continuous random variables over the Cartesian closed category BCD, but the model did not form a monad in this category [14]. The model that this paper describes is based upon these continuous random variables, in particular, the uniform continuous random variables. In this construction, computation is allowed to take different branches based on the flips of an unbiased coin.

The contribution of this paper is to redefine the Kleisli extension mapping proposed in Goubault-Larrecq and Varacca’s paper so that the resulting construction forms a monad on the category BCD. We also obtain a distributive law with this monad and the lower powerdomain. Another slight alteration can be made to the model in order to work in the Cartesian closed categories RB and FS, since the convex powerdomain does not necessarily stay in BCD. Then, working in RB and FS, this altered monad is shown to satisfy a distributive law with respect to the convex powerdomain.

The monad laws and the distributive law are both defined by a few commutative diagrams. Verifying that these diagrams do indeed commute is usually straightforward, but it can be very tedious. These details are omitted from this paper for readability and space concerns, but they will be included in the author’s upcoming thesis.

2 Background

2.1 Domain Theory

It will be assumed that the reader has some familiarity with domain theory. For more information, consult [1, 7].

A *poset* is a partially ordered set. A subset of a poset is an *antichain* if no two distinct elements of the poset are comparable.

A nonempty subset is *directed* if each pair of its elements has an upper bound also within the subset. A poset is *directed complete* if each of its directed subsets has a least upper bound. A *dcpo* is a directed complete partial order. Maps between

dcpos that are monotone and preserve suprema of directed sets are called *Scott continuous*.

The following is the least fixed-point theorem for Scott continuous functions:

Theorem 2.1 *Let D be a dcpo with a least element \perp . Then every Scott continuous self-map $f : D \rightarrow D$ has a least fixed-point. It is given by $\cup_{n \in \mathbb{N}} f^n(\perp)$.*

Now we define the Scott and Lawson topologies.

Definition 2.2 Let D be a dcpo. A subset U is *Scott closed* if it is a lower set and is closed under directed suprema of subsets.

The Scott closed sets are closed under all intersections and finite unions, so they are the closed sets of a topology, which is called the Scott topology. The Scott continuous functions defined above are precisely the functions that are continuous with respect to this topology.

Definition 2.3 Let D be a dcpo. The *Lawson topology* on D is the smallest topology containing the Scott open sets and all sets of the form $D \setminus \uparrow x$.

If D is a dcpo and $x, y \in D$, then x *approximates* y (denoted $x \ll y$) iff for every directed set S with $y \leq \sup S$, there is some $s \in S$ such that $x \leq s$. Let $\downarrow y = \{x \in D \mid x \ll y\}$. A dcpo D is a *domain* iff $\forall d \in D$, $\downarrow d$ is directed and $\sup \downarrow d = d$. Note that the Lawson topology on a domain is Hausdorff.

Definition 2.4 A domain D is *coherent* if it is compact in the Lawson topology.

2.2 Category Theory

In this paper, we work within Cartesian closed categories as these are necessary to model lambda calculi [2].

Definition 2.5 A category is a *Cartesian closed category (CCC)* if it has a terminal object, products, and exponentials.

We are interested in three particular Cartesian closed categories of domains: BCD, RB, and FS. The maximal Cartesian closed categories of domains were characterized by Jung [10]. Here are descriptions of the Cartesian closed categories of domains we will need. Note that in each case, the morphisms in the category are the Scott-continuous maps.

Definition 2.6 A domain is *bounded complete* if every subset with an upper bound has a least upper bound. Equivalently, a domain is *bounded complete* if every nonempty subset has a greatest lower bound. BCD denotes the category of bounded complete domains and Scott continuous maps.

Definition 2.7 A self-map on a domain D is a *deflation* if it is less than the identity map in the pointwise order and has a finite image.

Definition 2.8 A domain is a *retract of a bifinite domain*, or an *RB-domain*, if there exists a directed family $(f_i)_{i \in I}$ of Scott continuous deflations whose supremum

is the identity map. RB denotes the category of RB-domains and Scott continuous maps.

Definition 2.9 A self-map on a domain D is *finitely separated* from the identity map if there exists a finite set $M \subseteq D$ such that $\forall x \in D, \exists m \in M. f(x) \leq m \leq x$.

Definition 2.10 A domain is a *finitely separated domain*, or an *FS-domain*, if there exists a directed family $(f_i)_{i \in I}$ of Scott continuous self-maps, each finitely separated from the identity map, whose supremum is the identity map. FS denotes the category of FS-domains and Scott continuous maps.

BCD is a subcategory of RB, which is a subcategory of FS. FS is a maximal Cartesian closed category; however, it is a frustrating open question whether RB is a proper subcategory of FS.

Finally, all three of these categories are subcategories of COH, the category of coherent domains and Scott continuous maps, but COH is not Cartesian closed.

2.3 Monads

A monad is a construction from category theory that has proven to be very useful in modeling computational effects.

Definition 2.11 A *monad* on a category C is a triple, (T, η, μ) , where T is an endofunctor and $\eta : \text{Id}_C \rightarrow T, \mu : T^2 \rightarrow T$ are natural transformations such that the following diagrams commute:

$$\begin{array}{ccc}
 TX & \xrightarrow{\eta_{TX}} & T^2X \\
 T\eta_X \downarrow & \searrow \text{id}_{TX} & \downarrow \mu_X \\
 T^2X & \xrightarrow{\mu_X} & TX
 \end{array}
 \qquad
 \begin{array}{ccc}
 T^3X & \xrightarrow{\mu_{TX}} & T^2X \\
 T\mu_X \downarrow & & \downarrow \mu_X \\
 T^2X & \xrightarrow{\mu_X} & TX
 \end{array}$$

The natural transformation η is called the unit of the monad, and μ is the multiplication.

There is an alternate characterization of a monad that uses a Kleisli extension in place of the multiplication. An endofunctor T is a monad if, for any map $f : X \rightarrow TY$, there is a Kleisli extension $f^\dagger : TX \rightarrow TY$, and the following laws hold:

- (i) $\eta^\dagger = \text{id}$
- (ii) $h^\dagger \circ \eta_D = h$
- (iii) $k^\dagger \circ h^\dagger = (k^\dagger \circ h)^\dagger$

Given the Kleisli extension, the multiplication is defined by $\mu = \text{id}_{TX}^\dagger$. Conversely, given the multiplication and a function $f : X \rightarrow TY$, then $f^\dagger = \mu \circ T(f)$.

2.4 Powerdomains

Nondeterminism is modeled in domain theory by powerdomains which are built by considering nondeterministic choice as an idempotent, commutative, and associative

operation [15]. This is equivalent to the algebraic definition of a semilattice, so the powerdomains are simply free ordered semilattice domains over a domain.

Starting with a poset having a commutative, idempotent operation $+$, assuming $x \leq x+y$ results in a sup-semilattice, assuming $x \geq x+y$ results in a inf-semilattice, and an ordered semilattice will result from not assuming any relation between x and $x+y$. The lower, or Hoare, powerdomain is the free sup-semilattice over a domain, the upper, or Smyth, powerdomain is the free inf-semilattice over a domain, and the convex, or Plotkin, powerdomain is the free ordered semilattice over a domain. These powerdomains have nice topological characterizations which will be used in this paper.

Definition 2.12 For a domain D , the *lower powerdomain* is $\Gamma_0(D)$, the family of nonempty Scott closed subsets of D , ordered by inclusion.

Definition 2.13 A subset S of a topological space X is *saturated* if it is the intersection of the open sets that contain it.

For a poset with the Scott topology, saturated sets are simply the upper sets.

Definition 2.14 For a domain D , the *upper powerdomain* is $SC(D)$, the family of nonempty, saturated, and Scott compact subsets of D , ordered by reverse inclusion.

Definition 2.15 For a domain D , a subset $L \subseteq D$ is a *lens* if L is Scott compact and $L = \bar{L} \cap \uparrow L$, where \bar{L} is the Scott closure of L .

Definition 2.16 The *Egli-Milner order* is defined by:

$$A \sqsubseteq_{EM} B \Leftrightarrow A \subseteq \downarrow B \wedge B \subseteq \uparrow A$$

Definition 2.17 For a coherent domain D , the *convex powerdomain* is $Lens(D)$, the family of nonempty lenses, with the Egli-Milner order.

All three of the above categories, BCD, RB, and FS, are closed under the lower and upper powerdomains, but only RB and FS are closed under the convex powerdomain.

2.5 Randomized Computation

We consider a randomized computation to be any program or algorithm that uses some source of randomness to guide its computation. This includes assigning a random value to a variable or using a conditional expression that branches based on the output of a random process. If the probability distribution of the random source is known, we can view this as probabilistic computation. Abstractly, probabilistic computation is usually represented as a probabilistic choice operator, $p +_r q$, where p is chosen with probability r and q is chosen with probability $1 - r$.

Probabilistic Turing machines were first defined by de Leeuw *et al* in 1956 [5]. These machines are the same as normal Turing machines with an attached random device. This device prints 0's and 1's to a tape, with 1's occurring with probability p and 0's occurring with probability $1 - p$, where $0 < p < 1$. This tape can then

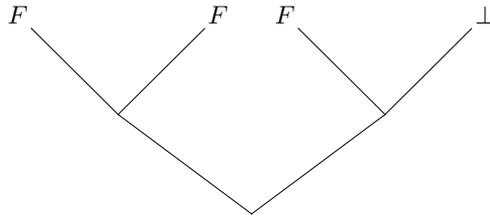


Fig. 1. One possible iteration of a simplified Miller-Rabin test on a composite number.

be used as an input tape for the Turing machine. It was shown that as long as p is computable, then these machines cannot compute anything that a deterministic machine cannot compute. However, it may be possible that a probabilistic machine can compute something faster than any deterministic machine could [8].

Randomized computation first gained prominence when Rabin [6] introduced a randomized algorithm for finding the nearest pair in a set of n points. This algorithm had a linear average runtime, faster than the $n \log n$ runtime of the fastest known deterministic algorithm. More well known are the algorithms of Solovay and Strassen [21] and Rabin [17] for determining if a number is prime. These algorithms run in polynomial time (with a small error probability), and they were discovered over 20 years before the AKS primality test [3], the first known deterministic algorithm for recognizing prime numbers in polynomial time.

3 The Functor

This work is inspired by a model of uniform continuous random variables first proposed by Goubault-Larrecq and Varacca [9]. In their paper, it was shown that the category of bounded complete domains (BCD) is closed under a similar construction. However, their assertion that the construction forms a monad in BCD was incorrect, since the proposed Kleisli extension failed to be monotone, thus not Scott continuous.

The basic idea of a random variable model is to separate the random choices from the domain itself. In the probabilistic powerdomain, the probability distributions are placed on the underlying domain. In a model of random variables, random bits are generated by coin flips, and then a random variable is defined from these random outcomes to the underlying domain. In the probabilistic powerdomain, for an element d , making a choice between d and d is the same as just d , since the probabilities are the same. In the model described here, there is a distinction between choosing d or d and d itself, even though the probabilities are the same. In the first case, a random bit is still chosen, so programmatically, this is distinct from the latter case where no such choice is made.

3.1 Motivation for the Functor

One of most well known randomized algorithms is the Miller-Rabin primality test. To test whether a given number n is prime, a random number is chosen between 2

probability associated with the word is $\frac{1}{2^n}$, where n is the length of the word. For example, the probability of 10, which represents getting heads and then tails, is $\frac{1}{4}$.

Definition 3.1 An *antichain* of $\{0, 1\}^\omega$ is a subset of words such that no two distinct words are comparable (no word is a prefix of another word). An antichain M is *full* if $\forall w \in \{0, 1\}^\omega, \exists z \in M, z \leq w$. Put another way, $\{0, 1\}^\omega \subseteq \uparrow M$, or $M \sqsubseteq_{EM} \{0, 1\}^\omega$. Denote the nonempty, full antichains by $FAC(\{0, 1\}^\omega)$.

Using coin flips in a program results in a branching of computation that can be represented as a binary tree. The final possible outcomes will be located at the leaves of this tree, which must form an antichain. This antichain is required to be full since for any coin flip, it is possible to get either heads or tails, and both outcomes must be accounted for.

Definition 3.2 For a category of domains, the random choice functor, RC , is defined on objects by

$$RC(D) = \{(M, f) \mid M \in FAC(\{0, 1\}^\omega), f : M \rightarrow D\}$$

where f is Scott continuous (giving M the subspace topology from the Scott topology of $\{0, 1\}^\omega$). For a morphism, $a : D \rightarrow D'$, and $(M, f) \in RC(D)$, we define

$$RC(a)(M, f) = (M, a \circ f)$$

We order $RC(D)$ by $(M, f) \sqsubseteq (N, g)$ iff $M \sqsubseteq_{EM} N$ and $w \leq z \Rightarrow f(w) \sqsubseteq g(z), \forall w \in M, z \in N$. Since the antichains are required to be full, $M \sqsubseteq_{EM} N$ is equivalent to $M \subseteq \downarrow N$, or dually, $N \subseteq \uparrow M$. Another characterization for the order on functions is $\forall z \in N, f \circ \pi_M(z) \sqsubseteq g(z)$, where $\pi_M(z)$ sends z to the unique element of M below z .

Theorem 3.3 *If D is a bounded complete domain, then so is $RC(D)$.*

4 The RC Monad

To show that the functor RC forms a monad, the unit and Kleisli extension (or multiplication) of the monad must be exhibited. For a domain D and $d \in D$, the unit, $\eta : D \rightarrow RC(D)$ is defined by

$$\eta(d) = (\epsilon, \chi_d)$$

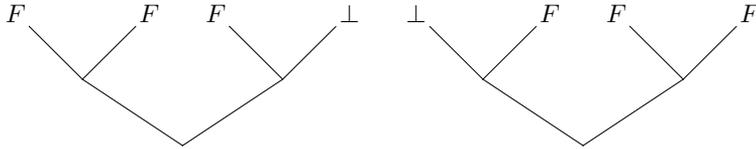
where ϵ is the antichain only containing the empty word, and χ_d is the constant function whose value is d .

4.1 Motivation for the Kleisli extension

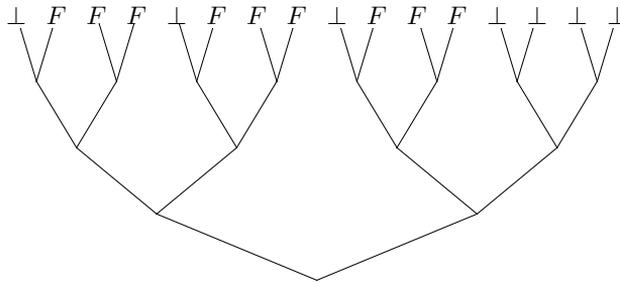
The Kleisli extension of a monad T can be hard to think about intuitively since we normally do not work with functions from D to $T(E)$. However, the Kleisli extension is important in lifting binary operations on the underlying structures

to binary operations on the monadic structures. If we have a binary operation $*$: $D \times E \rightarrow F$, the Kleisli extension lifts this operation to $*^\dagger$: $T(D) \times T(E) \rightarrow T(F)$. This is achieved by setting $*^\dagger = (\lambda a.T(\lambda b.a * b))^\dagger$.

Suppose that we have a Miller-Rabin test performed on two composite numbers with the following possible outcomes:



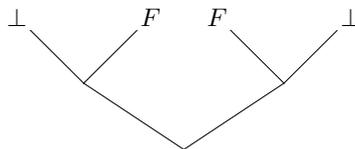
How should the binary operation **or** be lifted? It may seem natural to perform the two tests one after the other, resulting in:



The probability of error in this case is $\frac{7}{16}$, assuming we use a fair coin. However, this method has two main flaws.

- (i) How do we handle the infinite case? If the first random test can use infinitely many coin flips, then the second test will never even start.
- (ii) The Kleisli extension that results in this behavior is not monotone. Therefore, it does not form a monad in a category we want.

Instead, consider feeding the result of each coin flip to both tests concurrently. For two coin flips, our example would look like:



To properly compare it with the sequential case, we should use the same maximum number of coin flips. Feeding all four coin flips to both Miller-Rabin tests results in:

where $\text{Min}(W)$ gives the minimal words of W . The second component of the Kleisli extension gives a function from the first component into E . For a given z in the first component, this is defined by:

$$((\pi_2 \circ h^\dagger)(M, f))(z) = g(\pi_N(z)) \text{ where } (N, g) = h \circ f \circ \pi_M(z)$$

Since the first component given by the Kleisli extension is bigger than M , the function f may not be defined on z . Therefore, $\pi_M(z)$ is used followed by $h \circ f$ to pick a randomized algorithm $(N, g) \in RC(E)$. Similarly, g may not be defined on z , but there is a unique element of N , $\pi_N(z)$, where it is defined.

Proposition 4.2 h^\dagger is monotone.

Proof. $(M, f) \leq (N, g)$ means that $N \subseteq \uparrow M$ (thus, $\uparrow N \subseteq \uparrow M$) and $w \leq z \Rightarrow f(w) \leq g(z)$ for any $w \in M, z \in N$.

$$\begin{aligned} \uparrow \pi_1 \circ h^\dagger(M, f) &= \uparrow \bigcup_{w \in M} \text{Min}(\uparrow w \cap \uparrow \pi_1 \circ h \circ f(w)) \\ &= \bigcup_{w \in M} \uparrow \text{Min}(\uparrow w \cap \uparrow \pi_1 \circ h \circ f(w)) \\ &= \bigcup_{w \in M} (\uparrow w \cap \uparrow \pi_1 \circ h \circ f(w)) \end{aligned}$$

The same applies to (N, g) , so we just need to show that

$$\bigcup_{z \in N} (\uparrow z \cap \uparrow \pi_1 \circ h \circ g(z)) \subseteq \bigcup_{w \in M} (\uparrow w \cap \uparrow \pi_1 \circ h \circ f(w))$$

For each $z \in N$, there is a $w \in M$ that is below z . In this case, $\uparrow z \subseteq \uparrow w$ and $\uparrow(\pi_1 \circ h \circ g(z)) \subseteq \uparrow(\pi_1 \circ h \circ f(w))$ since $g(z) \geq f(w)$ and h is monotone. Thus, $(\uparrow z \cap \uparrow(\pi_1 \circ h \circ g(z))) \subseteq (\uparrow w \cap \uparrow(\pi_1 \circ h \circ f(w)))$.

Now we check the functions. For $w \in (\pi_1 \circ h^\dagger(M, f))$ and $z \in (\pi_1 \circ h^\dagger(N, g))$ with $w \leq z$, we must show that $(\pi_2 \circ h^\dagger(M, f))(w) \leq (\pi_2 \circ h^\dagger(N, g))(z)$.

Let $\pi_M(w)$ equal the unique word in M below w . Since $w \leq z$, $\pi_M(w) \leq \pi_N(z)$, and $f \circ \pi_M(w) \leq g \circ \pi_N(z)$. Since h is monotone, $h \circ f \circ \pi_M(w) \leq h \circ g \circ \pi_N(z)$.

Again, since $w \leq z$, $\pi_{\pi_1 \circ h \circ f \circ \pi_M}(w) \leq \pi_{\pi_1 \circ h \circ g \circ \pi_N}(z)$, and we have

$$\begin{aligned} (\pi_2 \circ h^\dagger(M, f))(w) &= (\pi_2 \circ h \circ f \circ \pi_M(w))(\pi_{\pi_1 \circ h \circ f \circ \pi_M}(w)(w)) \\ &\leq (\pi_2 \circ h \circ g \circ \pi_N(z))(\pi_{\pi_1 \circ h \circ g \circ \pi_N}(z)(z)) \\ &= (\pi_2 \circ h^\dagger(N, g))(z) \end{aligned}$$

□

Proposition 4.3 h^\dagger is Scott continuous.

Theorem 4.4 The functor RC forms a monad in the category BCD .

5 Distributive Laws and Extending the Monad

One of the downsides with the probabilistic powerdomain is that it does not satisfy a distributive law with any of the nondeterministic powerdomains. However, we can show that our monad RC does satisfy a distributive law with respect to the lower powerdomain in the category BCD .

For two monads, (S, η^S, μ^S) and (T, η^T, μ^T) , over the same category, the functor TS is not necessarily a monad. According to Beck's Theorem [4], the composition of two monads, S and T , is a monad if and only if there is a distributive law between them. A distributive law consists of a natural transformation $\lambda : ST \rightarrow TS$ that satisfies the following equations:

- (i) $\lambda \circ S\eta^T = \eta^T S$
- (ii) $\lambda \circ \eta^S T = T\eta^S$
- (iii) $\lambda \circ S\mu^T = \mu^T S \circ T\lambda \circ \lambda T$
- (iv) $\lambda \circ \mu^S T = T\mu^S \circ \lambda S \circ S\lambda$

5.1 Distributive Law With the Lower Powerdomain

Let Γ_L be the lower powerdomain functor. Suppose $(M, f) \in RC \circ \Gamma_L(D)$, so that f is a function from M to $\Gamma_L(D)$. Now define the natural transformation $\lambda : RC \circ \Gamma_L(D) \rightarrow \Gamma_L \circ RC(D)$ by:

$$\lambda(M, f) = \downarrow \{(M, g) \mid g(w) \in f(w), \forall w \in M\}$$

Proposition 5.1 *There is a distributive law between the monad of random choice and the lower powerdomain, using the natural transformation λ .*

5.2 Extending the Monad

The above construction is a monad in the category BCD . However, only two of the nondeterministic powerdomains (the upper and lower) leave BCD invariant. BCD is not closed under the convex powerdomain, but the Cartesian closed categories RB and FS , which contain BCD , are. The monad RC is not believed to stay within these categories, since we see no way to construct the deflations needed to show that an object is in one or the other of these categories. In BCD , infima can be used, but outside of BCD , infima are not guaranteed. One way to repair this is to not only define our functions on antichains, but instead to define them on the Scott closure, or lower set, of these antichains. This way, there is no need for infima to project down to smaller trees, since the function is already defined on the lower set.

In our first monad, antichains are used, representing the possible outcomes of a random computation. Now we change this monad to include not only antichains of words, but also the prefixes of these words. These prefixes represent intermediate stages of computation where more random bits are still needed.

Definition 5.2 A Scott closed set M in $\{0, 1\}^\infty$ is *full* if for all words, w , in M , $w * 0 \in M \Leftrightarrow w * 1 \in M$. Denote the family of nonempty, full Scott closed subsets

of $\{0, 1\}^\infty$ by $\Gamma_f(\{0, 1\}^\infty)$.

$\Gamma_f(\{0, 1\}^\infty)$, ordered by inclusion, is a subposet of the lower powerdomain of $\{0, 1\}^\infty$. If a poset is a dcpo, domain, or bounded complete domain, then so is the lower powerdomain of that poset. The supremum of some nonempty subset $\{M_i\}$ is simply the closure of the union, $\overline{\bigcup_i M_i}$.

Definition 5.3 For a category of domains, the functor RC' is now defined on objects by

$$RC'(D) = \{(M, f) \mid M \in \Gamma_f(\{0, 1\}^\infty), f : M \rightarrow D \text{ is Scott continuous}\}$$

For $a : D \rightarrow D'$ and $(M, f) \in RC'(D)$, we define

$$RC'(a)(M, f) = (M, a \circ f)$$

$RC'(D)$ is given an order such that $(M, f) \sqsubseteq (N, g)$ iff $M \subseteq N$ and $f(w) \leq g(w), \forall w \in M$.

Theorem 5.4 RC' is an endofunctor in the categories RB and FS .

For the monad construction, the unit is the same as before:

$$\eta(d) = (\epsilon, \chi_d)$$

For a continuous function $h : D \rightarrow RC'(E)$ and some (M, f) in $RC'(D)$, the Kleisli extension is defined by

$$\pi_1 \circ h^\dagger(M, f) = M \cup \left(\bigcup_{w \in M} (\uparrow w \cap (\pi_1 \circ h \circ f(w))) \right)$$

$$((\pi_2 \circ h^\dagger)(M, f))(z) = g(\pi_N(z))$$

where $(N, g) = h \circ f \circ \pi_M(z)$.

Theorem 5.5 The functor RC' forms a monad in the categories RB and FS .

5.3 Distributive Law With the Convex Powerdomain

Let Γ_C denote the convex powerdomain functor. Recall that the convex powerdomain of a coherent domain D consists of $Lens(D)$, the nonempty lenses of D . For a nonempty compact $K \subseteq D$, define the lens closure of K by $\langle K \rangle = \overline{K} \cap \uparrow K$. The lens closure $\langle K \rangle$ is the smallest lens containing K .

Suppose $U \in \Gamma_C \circ RC'(D)$, so that U is a lens of random choices of X . Define the natural transformation, $\lambda : \Gamma_C \circ RC'(D) \rightarrow RC' \circ \Gamma_C(D)$ by:

$$\lambda(U) = \left(\overline{\bigcup_{(M,f) \in U} M}, w \mapsto \left\langle \bigcup_{(M,f) \in U} f \circ \pi_M(w) \right\rangle \right)$$

Proposition 5.6 There is a distributive law between the monad of random choice and the convex powerdomain, using the natural transformation λ .

6 Relation to Scott's Stochastic Lambda Calculus

Dana Scott developed an operational semantics of the lambda calculus using the power set of the natural numbers, $\mathcal{P}(\mathbb{N})$. As terms of the lambda calculus, elements of $\mathcal{P}(\mathbb{N})$ can be applied to one another and λ -abstraction is achieved through the use of enumerations similar to Gödel numbering.

Scott then added randomness to his model, resulting in his stochastic lambda calculus [20]. He does this by adding random variables.

Definition 6.1 A *random variable* in Scott's model is a function $X : [0, 1] \rightarrow \mathcal{P}(\mathbb{N})$ where $\{t \in [0, 1] \mid n \in X(t)\}$ is Lebesgue measurable for all n in $\mathcal{P}(\mathbb{N})$.

This is similar to the monad of random choice presented in this paper. We start with a base domain D , which could be $\mathcal{P}(\mathbb{N})$, and then have a function from an antichain of $\{0, 1\}^\infty$ into D . We can really treat this as a function from the Cantor space, $\{0, 1\}^\omega$ to D . For some (M, f) , define $\bar{f} : \{0, 1\}^\omega \rightarrow D$ by $\bar{f}(z) = f(\pi_M(z))$.

Now that random variables are added to the lambda calculus, there must be a way to define application of one random variable to another. In a sense, this is lifting the application operation from $\mathcal{P}(\mathbb{N}) \times \mathcal{P}(\mathbb{N})$ to $([0, 1] \rightarrow \mathcal{P}(\mathbb{N})) \times ([0, 1] \rightarrow \mathcal{P}(\mathbb{N}))$, which, as stated above, is the role of the Kleisli extension of the monad. Scott defines the application as follows:

Definition 6.2 Given two random variables $X, Y : [0, 1] \rightarrow \mathcal{P}(\mathbb{N})$, the *application operation* is defined by

$$X(Y)(t) = X(t)(Y(t))$$

These random variables can be thought of as using an oracle that randomly gives a element of $[0, 1]$, and then the function of the random variable uses this number to output an element of $\mathcal{P}(\mathbb{N})$. Notice that in the above definition for application, both random variables receive the same t . Thus, the oracle is consulted only once instead of giving a different random number to each random variable. This exactly mimics the concurrent operation of our Kleisli extension. But instead of an oracle giving an entire real number at once (which has infinite information), the oracle gives one bit at a time.

7 Summary and Future Work

In this paper, we have presented two monads for randomized computation in Cartesian closed categories of domains. Computational motivation is given for the structure of these monads. In a program, random choice results in the branching of computation, so the possible outcomes form a tree. Our first monad separates random choice from the underlying domain and confines it to the leaves of a binary tree. This is the main difference between our construction and the probabilistic powerdomain. We have shown that this monad captures the randomized behavior found in algorithms such as the Miller-Rabin primality test. We have given a new Kleisli extension that satisfies the monad laws and presented a distributive law with the lower powerdomain, all within the category BCD. In order to work with the

convex powerdomain, we needed to move into the category RB or FS. A slight change was needed for our construction to stay within these categories, and a distributive law was given between this extended monad and the convex powerdomain.

There is much work to be done concerning these monads. Some work has already been completed that is beyond the scope of this paper. Another alteration can be made to the monad to obtain a distributive law with the upper powerdomain. Furthermore, an operational version of the monad has been developed and implemented in functional programming languages such as Scala and Haskell. The proof that the monad laws hold for this operational version has been formally verified using Isabelle. Finally, Randomized PCF (rPCF), a programming language that adds random choice to PCF [19], has been designed, and the Miller-Rabin algorithm has been implemented within the language. An operational and denotational semantics for rPCF have been developed using the monad presented in this paper. This is a proof of concept to show how this monad can be used to augment other languages with random choice.

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