

Distributed Modal Logic

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Abstract

Logic, type theory, and category theory give three equivalent ways of expressing computation. Logical theorems and axioms can be implemented as type systems for programming languages using the Curry-Howard correspondence, providing a novel means for safer code. This paper explores this connection and uses a category theory interpretation of modal logic to present an implementation of modal logic applied to distributed systems.

1 Introduction

Conal Elliot’s functional reactive programming [2] provides a declarative and denotative basis for expressing programs that vary over time. The naive implementation of FRP is prone to space- and time-leaks, which can be fixed in two ways. The first is through category theory: by using an abstraction called an **Arrow**, Hudak et al [5] solve many of these issues. The second is through logic: Jeffery [6] demonstrates that Linear-time Temporal Logic types FRP well, and the additional rules of LTL provide safeguards against these performance issues.

Foner’s “Getting a Quick Fix on Comonads” [3] examined an interpretation of Löb’s theorem in Haskell and determined that it did not properly satisfy the axioms of *S4* modal logic. By finding an appropriate Haskell type class that fit the logic more closely, he was able to derive a rather natural and efficient implementation of *n*-dimensional spreadsheets with relative references. The type class in question is **ComonadApply**, a concept imported from category theory.

Tom Murphy VII’s “Modal types for Mobile Code” presented a novel interpretation of *S5* modal logic applicable to distributed systems. [10] Murphy interprets $\Box A$ to be a continuation yielding an *A* that may be run anywhere on the network, and $\Diamond A$ to be an address to a remote value of type *A*.

Logic and categories both offer compelling resources for software developers to improve their work. Murphy does not mention category theory in his work. Is it possible that a categorical interpretation of his distributed system might provide additional insights or implementation tricks?

2 The Logic

Before diving into the logic presented in Murphy's paper on Lambda 5 [9], let's review the basic concepts of modal logic.

2.1 Modal Logic

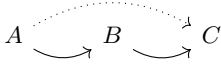


Modal logic is an augmentation of propositional logic that provides a pair of new operators:

- \Box , signifying 'always' or 'necessarily'
- \Diamond , signifying 'at some point in the future' or 'possibly'

The precise semantics of modal logic are determined by which axioms you take. The common axioms are described here:

- N: Necessity: if A is a theorem, then so is $\Box A$.
- K: Distribution $\Box(A \implies B) \implies (\Box A \implies \Box B)$
- T: Reflexivity $\Box A \implies A$
- 4: $\Box A \implies \Box \Box A$
- B: $A \implies \Box \Diamond A$
- 5: $\Diamond A \implies \Box \Diamond A$

The core of modal logic is a tower of these axioms, each added one at a time: K is the combination of N and K axioms, T adds reflexivity, S4 adds the 4 axiom, and S5 adds either the 5 axiom or the B axiom.

Transitivity	Reflexivity	Symmetry
$\Box A \implies \Box \Box A$	$\Box A \implies A$	$\Diamond A \implies \Box \Diamond A$
		

These axioms speak to the specific characteristics of the accessibility relationship. It's easiest to discuss these in terms of the 'possible worlds' model of modal logic, where A means that A is true in this world, $\Box A$ means that A is necessarily true in all worlds, and $\Diamond A$ means that A is true in some possible world. The three major traits of the accessibility relationship are transitivity (if world A can access world B, and world B can access world A, then A can access C), reflexivity (world A can access world A), and symmetry (if world A can access world B, then world B can access world A). As an aside, the reflexivity

and transitivity properties are precisely what is necessary to form a category.

2.2 Propositions as Types

The Curry-Howard correspondence tells us that a logical proposition is equivalent to a type signature in a programming language, a logical proof is equivalent to an expression fitting the type of the sentence, and the evaluation of programs is equivalent to the simplification of proofs. [12] Therefore, the type systems for our programming languages serve as systems to make logical statements about our programs. The more interesting things we can say in our types, the more useful they are in verifying the correctness of our programs. By having these interesting things correspond to a well-behaved formal logic, then we constrain ourselves to making sense. Compile-time verification is particularly appealing: we can't even run the code if it doesn't make logical sense!

2.3 Lambda 5

Let's evaluate the logical system Lambda 5 as defined by Murphy. [9] It's designed to be used as a type theory for distributed computation. The "many worlds" in this logic are the distinct computers running in a distributed network. Murphy's logic interprets $\Box A$ to mean "Mobile code of type A that can be executed on any computer," and $\Diamond A$ to mean "an address of a remote value of type A ."

Because the relationship between computers on a network is reflexive, transitive, and symmetric, the $S5$ logic is the basis for this system. Furthermore, because constructive proofs are more useful for type theories, the intuitionistic variant $IS5$ is used. Intuitionistic logic dispenses with double negation and the law of excluded middle. In this system, the two operators can no longer be expressed in terms of each other. This makes the B and 5 axioms tricky. Since it's generally not accepted to do $A \implies \Box A$, and the two axioms are able to generate some boxiness given some diamondness, then they *must* be related somehow.

The specific axioms for $IS5$ are given below: [4]

1. $\Box(A \implies B) \implies (\Box A \implies \Box B)$
2. $\Box(A \implies B) \implies (\Diamond A \implies \Diamond B)$
3. $\Diamond \perp \implies \perp$
4. $\Diamond(A \wedge B) \implies (\Diamond A \wedge \Diamond B)$
5. $(\Diamond A \implies \Box B) \implies \Box(A \implies B)$
6. $(\Box A \implies A) \wedge (A \implies \Diamond A)$
7. $(\Diamond \Box A \implies \Box A) \wedge (\Diamond A \implies \Box \Diamond A)$

The operational semantics for the Lambda 5 language involve deterministic sequential machines operating on various worlds, termed w_i . A value can be accessed remotely given a world name w_i and the label for the value.

One of the key examples given is the symmetry axiom, $\Diamond \Box A \implies \Box A$. We can read this as “Given a remote address to a value of mobile code that can run anywhere and produce an A , we can retrieve that code and run it here.” The proof term given in the paper is:

$$\lambda x. \text{letd } w. y = x \text{ in } \text{fetch}[w]y$$

where *letd* is a primitive of the \Diamond elimination rule, which binds a pair of variables w (representing the world that the value originated in) and y (the value at that world) in the expression after *in*. **fetch** is a primitive that takes a value $M : \Box A @ w'$ and runs it in the current world w . The signature $M : \Box A @ w'$ can be read as: M is a continuation that can be executed at any world currently located at w' .

3 Category Theory

Category theory is a branch of abstract mathematics that seeks to provide a unifying meta-language to talk about mathematics. The following sections introduce ideas in category theory that we need in order to provide the link to the modal logic above. This theory will inform our implementation in Haskell.

3.1 Category

A category is an algebraic structure consisting of a collection of objects and morphisms (also known as arrows) between objects. For a first intuition, categories generalize sets, and arrows generalize functions where the domain and range are the same. For \mathcal{C} to be a category, the objects and morphisms must satisfy the following properties:

1. Each object has an identity arrow:

$$\forall a \in \mathcal{C}, \exists f \in \mathcal{C}_{\rightarrow} . f \ a = a$$

$$\begin{array}{c} id \\ \curvearrowright \\ a \end{array}$$

2. Arrows compose associatively

$$\forall a, b, c \in \mathcal{C}. (a \rightarrow b) \rightarrow c = a \rightarrow (b \rightarrow c)$$

$$\begin{array}{ccc} a & \xrightarrow{f \circ g} & c \\ & \searrow f \quad \nearrow g & \\ & b & \end{array}$$

Arrows in category theory correspond with implication in logic and function types in type theory.

The notion of objects and arrows permits the drawing of illustrative diagrams. The associativity property means that any diagram is *commutative*: any path you follow from one object to another using the directed arrows yields the same final result. If we have two paths through a diagram, then we can select the shortest path and be confident that our result is the same.

3.2 Functor

Arrows in a category don't quite generalize functions in the same way that categories generalize sets. For a category \mathcal{C} , the arrows in the category correspond to endomorphisms: functions with the type $f : \forall a \in \mathcal{C}. a \rightarrow a$. Functions like $\lambda x.x^2 : \mathbb{R} \rightarrow \mathbb{R}$ or $Succ : \mathbb{N} \rightarrow \mathbb{N}$ are examples.

Functions that map elements from one set to another, like $\lambda xy.\frac{x}{y} : \mathbb{N} \rightarrow \mathbb{N} \rightarrow \mathbb{Q}$, require a more powerful concept. The categorical equivalent is called a functor. A functor F is a mapping between categories \mathcal{C} and \mathcal{D} . F maps every object and arrow in \mathcal{C} to \mathcal{D} with two laws:

$$\begin{array}{ccc} F(a) \in \mathcal{D} & \xrightarrow{F(f)} & F(b) \\ F \uparrow & & \uparrow F \\ a \in \mathcal{C} & \xrightarrow{f} & b \in \mathcal{C} \end{array}$$

3.2.1 Identity

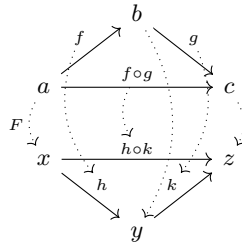
$$\forall a \in \mathcal{C}. id(F a) = F(id a)$$

$$\begin{array}{ccc} a & \xrightarrow{F} & F(a) \\ id \uparrow & \xrightarrow{F(id)} & \uparrow id \\ a & & F(a) \end{array}$$

If a functor maps an object a in \mathcal{C} to b in \mathcal{D} , then the functor must map the identity arrow for a to the identity arrow to b .

3.2.2 Composition

$$\forall f, g : a \rightarrow b \in \mathcal{C}. F(f \circ g) = F(f) \circ F(g)$$



In the above diagram, the functor F maps each object and arrow from the top category \mathcal{C} to the bottom category \mathcal{D} with the dotted lines representing the mappings. The mapping of composition of

arrows must be equal to the composition of the mapping of arrows.

Functors give rise to the category of categories *Cat*, where objects are categories and morphisms are functors between categories.

3.2.3 Correspondence in Type Theory

Functors correspond to type constructors or type functions in type theory, with the added laws of identity and composition. We can gain an intuition on functors by considering examples of generic or parametric types.

In Haskell, functors (specifically, endofunctors on the category *Hask* of Haskell values) are defined as:

```
class Functor f where
    fmap :: (a -> b) -> f a -> f b
```

Containers form easy functors to get an intuition about. A container can be a functor if you can provide an implementation of `fmap` which transforms each `a` in the container to an element of type `b`. Many non-container types are functors, too, like functions with a fixed input value:

```
instance Functor ((->) input) where
    fmap :: (a -> b) -> (input -> a) -> (input -> b)
    fmap f g = \x -> f (g x)
```

as well as continuations:

```
newtype Cont r a = Cont { runCont :: (a -> r) -> r }
```

```
instance Functor (Cont r) where
    fmap f c = Cont (\k -> runCont c (k . f))
```

and stateful computation:

```
newtype State s a = State { runState :: s -> (a, s) }
```

```
instance Functor (State s) where
    fmap f sa = State (\s -> let (a, s') = runState sa s
                              in (f a, s'))
```

The `fmap` operation is about generalizing a function that works on ordinary values to work on a whole Functorful of ordinary values.

3.3 An Entirely Natural Transformation

A natural transformation is a mapping η between two functors F and G on two categories \mathcal{C} and \mathcal{D} that satisfy the following commutative diagram:

$$\begin{array}{ccc} F(X) & \xrightarrow{F(f)} & F(Y) \\ \downarrow \eta_X & & \downarrow \eta_Y \\ G(X) & \xrightarrow{G(f)} & G(Y) \end{array}$$

A natural transformation is a way to convert one functor into another. Similar to how categories+functors form a category, natural transformations and functors between two categories also form a category. The objects in the category are the functors, and the morphisms are the natural transformations.

3.3.1 Code Examples

The essence of a natural transformation is that you shouldn't use any of the information from the objects in the underlying category when mapping the functors. In Haskell, this can be expressed in terms of a rank 2 type:

```
type Nat f g = forall x. f x -> g x
```

The use of the rank 2 type constrains the function from being able to view or inspect the values inside the functors.

A function to convert a `[a]` into a `Vector a` is an easy natural transformation, as is the inverse. There's also a natural transformation `[a]` to `Map Int a`, where the integer keys are the indexes in the list.

A natural transformation is not required to preserve all information. `Maybe` has a natural transformation to `List`:

```
maybeToList :: Nat Maybe []
maybeToList (Just x) = [x]
maybeToList Nothing  = []
```

Note that the type signature does not mention the type of the value in the container. We can expand the type signature to read as:

```
maybeToList :: forall a. [a] -> Maybe a
```

We're asserting that this function must work for all types `a`, and that we can't use any information about the `as` inside in order to implement the function. The reversal of this natural transformation is necessarily lossy:

```
listToMaybe :: Nat [] Maybe
listToMaybe (x:_) = Just x
listToMaybe []    = Nothing
```

3.4 Monad

A monad is an endofunctor (a mapping from \mathcal{C} to \mathcal{C}) that is equipped with two natural transformations:

1. η , or **return**, taking any object from the identity functor $I(\mathcal{C})$ to $F(\mathcal{C})$.
2. μ , or **join**, taking objects from $F(F(\mathcal{C}))$ to $F(\mathcal{C})$.

Monads follow the monoid laws of associativity and identity where the unit is η and \oplus is μ . The identity functor is an easy monad. The natural transformation η is the identity natural transformation. For μ , we can show (by commutativity of the diagram) that taking identity twice is equivalent to taking identity once:

$$\begin{array}{ccccc} & & Id & & \\ & \swarrow & & \searrow & \\ \mathcal{C} & \xrightarrow{Id} & \mathcal{C} & \xrightarrow{Id} & \mathcal{C} \end{array}$$

3.4.1 More Code Examples

Monads can be represented as a type class in Haskell, with the following definition:

```
class Applicative m => Monad m where
    return :: a -> m a
    (>>=)  :: m a -> (a -> m b) -> m b
    join   :: m (m a) -> m a

    ma >>= f = join (fmap f ma)
    join mma = mma >>= \ma -> ma
```

We can provide a default implementation of bind (written here with the infix operator `>>=`) and join written in terms of each other. Lists and optionals form monads.

```
instance Monad [] where
    return a = [a]
    join (xs:xss) = xs ++ join xss
```

The list monad is used for nondeterministic programming and is the basis for list comprehensions in Haskell.

```
instance Monad Maybe where
    return a = Just a
```



```
Just a  >>= f = f a
Nothing >>= _ = Nothing
```

The `Maybe` monad is useful when sequencing actions that might fail, like looking up items in a dictionary.

A monad is a powerful abstraction for sequencing computational effects. Given a value in a monadic structure `m`, we can provide a function that operates on that value and yields more monadic structure. `bind` handles the boilerplate of flattening it back out. Monads are a convenient way to express state, asynchronous computation, and computation that may error.

The use of monads in computer science was initially discovered by Eugenio Moggi [8] and then popularized by Wadler [11] and others for use in functional programming.

3.5 Comonad

A comonad is the categorical dual of a monad. In category theory, all ideas have a dual. The dual of a concept is given by taking the object's diagram reversing all of the arrows. We can arrive at something similar by reversing the arrows of types in type signatures. Flipping the `Monad` function's arrows gives us:

```
return    :: a -> m a
coreturn  :: a <- m a
extract   :: w e -> e

join      :: m (m a) -> m a
cojoin    :: m (m a) <- m a
duplicate :: w e -> w (w e)

bind      :: m a -> (a -> m b) -> m b
cobind    :: m a <- (a <- m b) <- m b
extend    :: w q -> (w q -> e) -> w e
```

Where a monad gives us the ability to take a single value in a structure and generate new structure, a comonad gives us the ability to take a structure of values and yield a single new value. The canonical comonad is the infinite stream data type:

```
data Stream a = a :< Stream a

instance Functor Stream where
    fmap f (a :< sa) = f a :< fmap f sa
```

```
instance Comonad Stream where
    extract (a :< _) = a
    duplicate s@(a :< as) = s :< duplicate as
    extend f = fmap f . duplicate
```

To `duplicate` a stream, we set the value of index i_n to be the entire stream, and the position at i_{n+1} to be the stream starting from i_{n+1} .

3.6 Adjunctions

An adjunction is a pair of functors which generalize the notion of a Galois connection. From the category \mathcal{C} , the functor R *lifts* an object to the category \mathcal{D} by providing some free structure. The functor L then *loses* some information about an object in \mathcal{D} to map the object back to \mathcal{C} . This isn't necessarily an isomorphism, as forgetting composed with lifting $R \circ L$ loses some information and can't map the object back. However, lifting followed by forgetting $L \circ R$ is equivalent to the *Id* functor, and $R \circ L \circ R$ is equivalent to R .

In this case, we write $L \dashv R$ to say that L is left adjoint to R and that R is right adjoint to L . An interesting property of an adjunction is that every adjunction gives rise to both a monad through $R \circ L$ and a comonad through $L \circ R$.

3.6.1 A Common Adjunction: Pair and Function

The Haskell tuple `(r, a)` (also known as *Prod_r a*) and function `r -> a` (also known as *Exp_r a*) are both functors, and it is the case that *Prod* \dashv *Exp*.

```
instance Functor ((,) r) where
    fmap f (r, a) = (r, f a)

instance Functor ((->) r) where
    fmap f k = f . k

class (Functor g, Functor f) => Adjunction f g | f -> g, g -> f where
    unit   :: a -> g (f a)
    counit :: f (g a) -> a
    left   :: (f a -> b) -> a -> g b
    right  :: (a -> g b) -> f a -> b

instance Adjunction ((,) r) ((->) r) where
```

```
unit a          = \r -> (r, a)
counit (r, f) = f r
```

We can specialize the type of `unit` to this specific adjunction, which illustrates the monad/comonad:

```
unit  :: a -> r -> (r, a)
counit :: (r, r -> a) -> a
```

Indeed, we can write a generic instance of the `Monad` type class in Haskell that works with any composition of two functors which form an adjunction. If we flip the composition, then we can write a `comonad` instance as well. This is witnessed below:

```
newtype Compose f g a = Compose { decompose :: f (g a) }

instance (Adjunction f g, Applicative f, Applicative g) => Monad (Compose g f) where
    return = Compose . unit
    m >>= f = Compose . fmap (right (decompose . f)) . decompose $ m

instance (Adjunction f g) => Comonad (Compose f g) where
    extract = counit . decompose
    extend f = Compose . fmap (left (f . Compose)) . decompose
```

If this is the case, then `Compose ((,) r) ((->) r)` should be a `comonad`, and `Compose ((->) r) ((,) r)` should be a `monad`. If we expand the types, we'll see that:

```
Compose ((->) r) ((,) r)
= (->) r ((,) r a)
= r -> (r, a)
```

```
Compose ((,) r) ((->) r)
= (,) r ((->) r a)
= (r, r -> a)
```

Indeed, the monad formed by the adjunction of the two functors is the `State` monad! The `comonad` is known as the `Store` `comonad`, and is less common in practice.

4 Link to Modal Logic

Now that we've gathered all of our toys from logic and category theory, it's time to figure out how they're related. The type signatures of the functions in the `Monad` and `Comonad` classes look awfully familiar to the axioms for the \Diamond and \Box constructs. Let's see if there's more to that.

4.1 Diamonad

The \Diamond operator in modal logic looks like it corresponds to the monad in category theory. Let's consider the natural transformations $\eta : I(A) \rightarrow M(A)$ and $\mu : M(M(A)) \rightarrow M(A)$. Can we prove these?

η is simple enough. It corresponds with the \Diamond introduction rule $A \vdash \Diamond A$: “If A is true, then A is possibly true.” μ , likewise, is the $\Diamond 4$ axiom.

We can additionally prove the type of `bind` $:: \text{Monad } m \Rightarrow m \ a \rightarrow (a \rightarrow m \ b) \rightarrow m \ b$ by taking advantage of the distribution of \Diamond over implication.

$$\frac{\frac{\frac{A \Rightarrow \Diamond B}{\Diamond(A \Rightarrow \Diamond B)} \Diamond_I}{\frac{\Diamond A}{\Diamond A \Rightarrow \Diamond \Diamond B} \text{Distribution}} \frac{\Diamond \Diamond B}{\Diamond B} \mu$$

4.2 Comonad

The fundamental operations for a comonad are `duplicate` ($\Box A \Rightarrow \Box \Box A$), which is precisely the axiom that gives rise to $S4$ modal logic, and `extract` ($\Box A \Rightarrow A$), which is the \Box elimination rule. Comonads, as functors, also implement `fmap`, and the interaction of `fmap`, `duplicate`, and `extract` must follow the following laws:

$$\text{extract} \circ \text{duplicate} = \text{id} \tag{1}$$

$$\text{fmap } \text{extract} \circ \text{duplicate} = \text{id} \tag{2}$$

$$\text{duplicate} \circ \text{duplicate} = \text{fmap } \text{duplicate} \circ \text{duplicate} \tag{3}$$

In $S4$ modal logic, a plain comonad is close to the \Box operator, but we don't have $\Box(a \Rightarrow b) \Rightarrow (\Box a \Rightarrow \Box b)$. The Haskell type class `ComonadApply` equips a `Comonad` with exactly that function, allowing it to satisfy the $S4$ axioms.

As Foner observed [3], all comonads in Haskell have a property known as *functorial strength*. Given some `f a` and a `b`, you can `strong b = fmap (\a -> (a, b))` to lift the `b` value into the `Functor`. This corresponds to a proposition of the form $B \Rightarrow \Box A \Rightarrow \Box(A \wedge B)$, which is impermissible in the logic. We'll need to take special care when writing our implementation to avoid this.

4.3 To IS5 and Beyond

The modal logic used in the Lambda 5 system uses $IS5$ as a basis, not $S4$. Extending $S4$ to $S5$ adds the following axiom:

$$\Diamond A \implies \Box \Diamond A$$

This additional axiom expresses the idea that, if A is possible, then the possibility of A is necessary. This makes a category theory interpretation somewhat tricky. One of the necessary features of both \Box and a comonad is that we don't have $A \implies \Box A$ or $f : \forall w. \text{Comonad } w \implies a \rightarrow w a$. In this case, we're relying on some structure of the monad that permits us to push comonadic structure beneath.

In order to extend this interpretation to $S5$, we can't take just any old monad and comonad for our interpretation. We'll need to delve deeper.

4.4 Double the Adjunction, Double the Functor

Suppose we have two categories \mathcal{C} and \mathcal{D} with a triple of functors L, U, R , where $L \dashv U$ and $U \dashv R$, and (as a natural consequence of the composition of adjunctions) $L \dashv U \dashv R$.

$$\begin{array}{ccc} & \xrightarrow{R} & \\ \mathcal{C} & \xleftarrow{U} & \mathcal{D} \\ & \xleftarrow{L} & \end{array}$$

This gives rise to a monad $M = U \circ L$ and a comonad $W = U \circ R$ on \mathcal{C} . Since adjunctions compose, the combination $M \dashv W$ is an adjunction. By assigning M to \Diamond and W to \Box , we've arrived at the axiom we require: $\Diamond \dashv \Box$. [1] Asserting that in Haskell gives us `Adjunction dia box` with a function `unit :: a -> box (dia a)`, which satisfies our requirement.

Our task is to now find the appropriate functors and categories to provide a suitable implementation of Lambda 5.

5 Implementing in Haskell

For the complete implementation, see the `Logic.Modal` Haskell module. The theory has presented us with a neat implementation plan. We can arrive at an $S5$ modal logic categorically. First, we'll define a type class that represents the axioms of $S5$ modal logic:

```
class Modal dia box where
  axiomK :: box (a -> b) -> box a -> box b
  axiomT :: box a -> a
  axiom5 :: dia a -> box (dia a)
```

Adjunctions (among other related abstractions) are defined in the Haskell package `adjunction` maintained by Edward Kmett. [7] The type class we'

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