FUNCTIONAL PEARL

Applicative programming with effects

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Abstract

In this paper, we introduce Applicative functors—an abstract characterisation of an applicative style of effectful programming, weaker than Monads and hence more widespread. Indeed, it is the ubiquity of this programming pattern that drew us to the abstraction. We retrace our steps in this paper, introducing the applicative pattern by diverse examples, then abstracting it to define the Applicative type class and introducing a bracket notation which interprets the normal application syntax in the idiom of an Applicative functor. Further, we develop the properties of applicative functors and the generic operations they support. We close by identifying the categorical structure of applicative functors and examining their relationship both with Monads and with Arrows.

1 Introduction

This is the story of a pattern that popped up time and again in our daily work, programming in Haskell (Peyton Jones, 2003), until the temptation to abstract it became irresistible. Let us illustrate with some examples.

Sequencing commands One often wants to execute a sequence of commands and collect the sequence of their responses, and indeed there is such a function in the Haskell Prelude (here specialised to the IO monad):

\[
\begin{align*}
\text{sequence} &:: \text{[IO } a\text{]} \to \text{IO [a]} \\
\text{sequence } [ ] &\equiv \text{return } [ ] \\
\text{sequence } (c : cs) &\equiv \text{do} \\
&\quad x \leftarrow c \\
&\quad xs \leftarrow \text{sequence } cs \\
&\quad \text{return } (x : xs)
\end{align*}
\]

In the \((c : cs)\) case, we collect the values of some effectful computations, which we then use as the arguments to a pure function \((-\cdot-)\). We could avoid the need for names to wire these values through to their point of usage if we had a kind of ‘effectful application’. Fortunately, exactly such a thing lives in the standard Monad library:
\begin{align*}
\text{Conor McBride and Ross Paterson} \\
\text{ap} : \text{Monad } m \Rightarrow m (a \rightarrow b) \rightarrow m a \rightarrow m b \\
\text{ap } mf \ mx = \begin{aligned} \\
& f \leftarrow mf \\
& x \leftarrow mx \\
& \text{return } (f \ x)
\end{aligned}
\end{align*}

Using this function we could rewrite \text{sequence} as:
\begin{align*}
\text{sequence} :: [\text{IO } a] \rightarrow \text{IO } [a] \\
\text{sequence } [] = \text{return } [] \\
\text{sequence } (c : cs) = \text{return } (\cdot \text{ ap } \cdot c \cdot \text{ ap }) \text{ sequence } cs
\end{align*}

where the return operation, which every Monad must provide, lifts pure values to the effectful world, whilst ap provides ‘application’ within it.

Except for the noise of the \text{return}s and \text{ap}s, this definition is in a fairly standard applicative style, even though effects are present.

Transposing ‘matrices’ Suppose we represent matrices (somewhat approximately) by lists of lists. A common operation on matrices is transposition:
\begin{align*}
\text{transpose} :: [[a]] \rightarrow [[a]] \\
\text{transpose } [] = \text{repeat } [] \\
\text{transpose } (xs : xss) = \text{zipWith } (::) \ xss \ (\text{transpose } xss)
\end{align*}

Now, the binary \text{zipWith} is one of a family of operations that ‘vectorise’ pure functions. As Daniel Fridlender and Mia Indrika (2000) point out, the entire family can be generated from \text{repeat}, which generates an infinite stream from its argument, and \text{zapp}, a kind of ‘zippy’ application:
\begin{align*}
\text{repeat} :: a \rightarrow [a] \\
\text{repeat } x = x : \text{repeat } x \\
\text{zapp} :: [a \rightarrow b] \rightarrow [a] \rightarrow [b] \\
\text{zapp } (f : fs) \ (x : xs) = f \ x : \text{zapp } fs \ xs \\
\text{zapp } = \text{repeat } []
\end{align*}

The general scheme is as follows:
\begin{align*}
\text{zipWith}_n :: (a_1 \rightarrow \cdots \rightarrow a_n \rightarrow b) \rightarrow [a_1] \rightarrow \cdots \rightarrow [a_n] \rightarrow [b] \\
\text{zipWith}_n \ f \ xs_1 \cdots \ xs_n = \text{repeat } f \cdot \text{zapp } xs_1 \cdot \text{zapp } \cdots \cdot \text{zapp } xs_n
\end{align*}

In particular, transposition becomes
\begin{align*}
\text{transpose} :: [[a]] \rightarrow [[a]] \\
\text{transpose } [] = \text{repeat } [] \\
\text{transpose } (xs : xss) = \text{repeat } (\cdot \text{ zapp } \cdot xs \cdot \text{ zapp } \cdot \text{ transpose } xss)
\end{align*}

Except for the noise of the \text{repeat}s and \text{zapp}s, this definition is in a fairly standard applicative style, even though we are working with vectors.

\footnote{This function differs from the one in the standard library in its treatment of ragged lists}
**Evaluating expressions** When implementing an evaluator for a language of expressions, it is customary to pass around an environment, giving values to the free variables. Here is a very simple example:

```
data Exp v = Var v | Val Int | Add (Exp v) (Exp v)
```

```
eval :: Exp v → Env v → Int
   eval (Var x) γ = fetch x γ
   eval (Val i) γ = i
   eval (Add p q) γ = eval p γ + eval q γ
```

where `Env v` is some notion of environment and `fetch x` projects the value for the variable `x`.

We can eliminate the clutter of the explicitly threaded environment with a little help from some very old friends, designed for this purpose:

```
eval :: Exp v → Env v → Int
   eval (Var x) = fetch x
   eval (Val i) = K i
   eval (Add p q) = K (+) 'S' eval 'S' eval q
```

where

```
K :: a → env → a
K x γ = x
S :: (env → a → b) → (env → a) → (env → b)
S ef es γ = (ef γ) (es γ)
```

Except for the noise of the `K` and `S` combinators\(^2\), this definition of `eval` is in a fairly standard applicative style, even though we are abstracting an environment.

## 2 The Applicative class

We have seen three examples of this ‘pure function applied to funny arguments’ pattern in apparently quite diverse fields—let us now abstract out what they have in common. In each example, there is a type constructor `f` that embeds the usual notion of value, but supports its own peculiar way of giving meaning to the usual applicative language—its *idiom*. We correspondingly introduce the Applicative class:

```
infixl 4 ⊛
class Applicative f where
   pure :: a → f a
   (⊛) :: f (a → b) → f a → f b
```

This class generalises `S` and `K` from threading an environment to threading an effect. (As we shall see later, these effects include, but are not limited to, monadic effects.)

\(^2\) also known as the `return` and `ap` of the environment Monad
We shall require the following laws for applicative functors:

- **identity**
  \[ \text{pure } \text{id} \odot u = u \]

- **composition**
  \[ \text{pure } (\cdot) \odot u \odot v \odot w = u \odot (v \odot w) \]

- **homomorphism**
  \[ \text{pure } f \odot \text{pure } x = \text{pure } (f \ x) \]

- **interchange**
  \[ u \odot \text{pure } x = \text{pure } (\lambda f \to f \ x) \odot u \]

The idea is that \text{pure} embeds pure computations into the pure fragment of an effectful world—the resulting computations may thus be shunted around freely, as long as the order of the genuinely effectful computations is preserved.

One can easily check that applicative functors are indeed functors, with the following action on functions:

\[
\text{fmap} :: \text{Applicative } f \Rightarrow (a \to b) \to f a \to f b
\]

\[
\text{fmap } f \ u = \text{pure } f \odot u
\]

Moreover, any expression built from the \text{Applicative} combinators can be transformed to a canonical form in which a single pure function is ‘applied’ to the effectful parts in depth-first order:

\[
\text{pure } f \odot u_1 \odot \ldots \odot u_n
\]

This canonical form captures the essence of \text{Applicative} programming: computations have a fixed structure, given by the pure function, and a sequence of subcomputations, given by the effectful arguments. We therefore find it convenient, at least within this paper, to write this form using a special bracket notation:

\[
[f \ u_1 \ldots u_n]
\]

This signals a shift into the idiom of an \text{Applicative} functor, where a \text{pure} function is applied to a sequence of effectful arguments using the appropriate \odot. Our intention is to give an indication that effects are present, whilst retaining readability of code.

Given Haskell extended with multi-parameter type classes, enthusiasts for overloading may replace ‘[’ and ‘]’ by appropriately defined identifiers \texttt{I} and \texttt{I} with appropriate parentheses.

The \text{IO} monad, and indeed any \text{Monad}, can be made \text{Applicative} by taking \text{pure} = \text{return} and (\odot) = \text{ap}. (We could alternatively use the variant of \text{ap} that performs the computations in the opposite order, but we shall keep to the left-to-right order in this paper.) Here is a direct implementation of the instance derived from the (\to) \text{env} monad:

\[
\text{instance Applicative } ((\to) \text{ env}) \text{ where}
\]

\[
\text{pure } x = \lambda \gamma \to x \quad -- \ K
\]

\[
\text{ef} \odot \text{ex} = \lambda \gamma \to (\text{ef } \gamma) \ (\text{ex } \gamma) \quad -- \ S
\]

With these instances, \text{sequence} and \text{eval} become:

\[
\text{sequence} :: [\text{IO } a] \to \text{IO } [a]
\]

\[
\text{sequence } [] = [[[]]]
\]

\[\text{Hint: Define an overloaded function apply } u \ v_l \ldots \ v_n \ l = u \odot v_l \odot \ldots \odot v_n\]
sequence \( (c : cs) = [(:) c (\text{sequence } cs)] \)

eval :: Exp v \rightarrow Env v \rightarrow \text{Int}

eval (\text{Var } x) = \text{fetch } x

eval (\text{Val } i) = [i]

eval (\text{Add } p q) = [ (+) (\text{eval } p) (\text{eval } q)]

If we want to do the same for our transpose example, we shall have to avoid the library’s ‘list of successes’ (Wadler, 1985) monad and take instead an instance Applicative \([\ ]\) that supports ‘vectorisation’, where \text{pure} = \text{repeat} and \text{(⊛)} = \text{zapp}, yielding

\[
\begin{align*}
\text{transpose} :: \text{[[} a \text{]]} &\rightarrow \text{[[} a \text{]]} \\
\text{transpose} \ [\ ] &\equiv [[[]]] \\
\text{transpose} (xs : xss) &\equiv [(:) xs \text{ transpose } xss] 
\end{align*}
\]

In fact, \text{repeat} and \text{zapp} are not the return and \text{ap} of any Monad.

### 3 Traversing data structures

Have you noticed that \text{sequence} and \text{transpose} now look rather alike? The details that distinguish the two programs are inferred by the compiler from their types. Both are instances of the \textit{applicative distributor} for lists:

\[
\begin{align*}
\text{dist} :: \text{Applicative } f \Rightarrow [f a] \rightarrow f [a] \\
\text{dist} [\ ] &\equiv [[[]]] \\
\text{dist} (v : vs) &\equiv [(:) v \text{ dist } vs] 
\end{align*}
\]

Distribution is often used together with ‘map’. For example, given the monadic ‘failure-propagation’ applicative functor for \textit{Maybe}, we can map some failure-prone operation (a function in \( a \rightarrow \text{Maybe } b \)) across a list of inputs in such a way that any individual failure causes failure overall.

\[
\begin{align*}
\text{flakyMap} :: (a \rightarrow \text{Maybe } b) \rightarrow [a] \rightarrow \text{Maybe } [b] \\
\text{flakyMap } f ss &\equiv \text{dist } (\text{fmap } f ss)
\end{align*}
\]

As you can see, \text{flakyMap} traverses \( ss \) twice—once to apply \( f \), and again to collect the results. More generally, it is preferable to define this applicative mapping operation directly, with a single traversal:

\[
\begin{align*}
\text{traverse} :: \text{Applicative } f \Rightarrow (a \rightarrow f b) \rightarrow [a] \rightarrow f [b] \\
\text{traverse } f [\ ] &\equiv [[[]]] \\
\text{traverse } f (x : xs) &\equiv [(:) f x \text{ traverse } f xs]
\end{align*}
\]

This is just the way you would implement the ordinary \text{fmap} for lists, but with the right-hand sides wrapped in \([\cdot \cdot \cdot]\), shifting them into the idiom. Just like \text{fmap}, \text{traverse} is a useful gadget to have for many data structures, hence we introduce the type class \textit{Traversable}, capturing functorial data structures through which we can thread an applicative computation:
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\begin{verbatim}
class Traversable t where
  traverse :: Applicative f ⇒ (a → f b) → t a → f (t b)
  dist   :: Applicative f ⇒ t (f a) → f (t a)
  dist  = traverse id

Of course, we can recover an ordinary ‘map’ operator by taking f to be the identity—
the simple applicative functor (corresponding to the identity monad) in which all
computations are pure:

\textbf{newtype} Id a = An { an :: a }

Haskell’s \textbf{newtype} declarations allow us to shunt the syntax of types around without
changing the run-time notion of value or incurring any run-time cost. The
‘labelled field’ notation defines the projection an :: Id a → a at the same time as the
constructor An :: a → Id a. The usual applicative functor has the usual application:

\begin{verbatim}
instance Applicative Id where
  pure = An
  An f ⊗ An x = An (f x)
\end{verbatim}

So, with the \textbf{newtype} signalling which Applicative functor to thread, we have

\[ \text{fmap} f = \text{an} \cdot \text{traverse} (\text{An} \cdot f) \]

Meertens (1998) defined generic dist-like operators, families of functions of type
\( t (f a) \rightarrow f (t a) \) for every regular functor \( t \) (that is, ‘ordinary’ uniform datatype
constructors with one parameter, constructed by recursive sums of products). His
conditions on \( f \) are satisfied by applicative functors, so the regular type constructors
can all be made instances of \textbf{Traversable}. The rule-of-thumb for \textbf{traverse} is ‘like \textbf{fmap}
but with \([ \cdots ]\) on the right’. For example, here is the definition for trees:

\begin{verbatim}
instance Traversable Tree where
  traverse f Leaf = Leaf
  traverse f (Node l x r) = Node (traverse f l) (f x) (traverse f r)
\end{verbatim}

This construction even works for non-regular types. However, not every \textbf{Functor}
is \textbf{Traversable}. For example, the functor \((→)\) \textbf{env} cannot in general be \textbf{Traversable}.
To see why, take env = Integer and try to distribute the \textbf{Maybe} functor!

Although Meertens did suggest that threading monads might always work, his
primary motivation was to generalise reduction or ‘crush’ operators, such as flattening
trees and summing lists. We shall turn to these in the next section.

4 Monoids are phantom Applicative functors

The data that one may sensibly accumulate have the structure of a \textbf{Monoid}:

\begin{verbatim}
class Monoid o where
  ∅ :: o
  (∪) :: o → o → o
\end{verbatim}
such that ‘⊕’ is an associative operation with identity ∅. The functional programming world is full of monoids—numeric types (with respect to zero and plus, or one and times), lists with respect to [ ] and + +, and many others—so generic technology for working with them could well prove to be useful. Fortunately, every monoid induces an applicative functor, albeit in a slightly peculiar way:

```haskell
newtype Accy o a = Acc { acc :: o }

Accy o a is a phantom type (Leijen & Meijer, 1999)—its representation is independent of a—but it does yield the applicative functor of accumulating computations:

```haskell
instance Monoid o ⇒ Applicative (Accy o) where
  pure _ = Acc ∅
  Acc o₁ ⊕ Acc o₂ = Acc (o₁ ⊕ o₂)
```

Now reduction or ‘crushing’ is just a special kind of traversal, in the same way as with any other applicative functor, just as Meertens suggested:

```haskell
accumulate :: (Traversable t, Monoid o) ⇒ (a → o) → t a → o
accumulate f = acc · traverse (Acc · f)
reduce :: (Traversable t, Monoid o) ⇒ t o → o
reduce = accumulate id
```

Operations like flattening and concatenation become straightforward:

```haskell
flatten :: Tree a → [a]  concat :: [ [a] ] → [a]  flatten = accumulate (::[:])  concat = reduce
```

We can extract even more work from instance inference if we use the type system to distinguish different monoids available for a given datatype. Here, we use the disjunctive structure of Bool to test for the presence of an element satisfying a given predicate:

```haskell
newtype Mighty = Might { might :: Bool }

instance Monoid Mighty where
  ∅ = Might False
  Might x ⊕ Might y = Might (x ∨ y)
any :: Traversable t ⇒ (a → Bool) → t a → Bool
any p = might · accumulate (Might · p)
```

Now any · (≡) behaves just as the elem function for lists, but it can also tell whether a variable from v occurs free in an Exp v. Of course, Bool also has a conjunctive Musty structure, which is just as easy to exploit.

5 Applicative versus Monad?

We have seen that every Monad can be made Applicative via return and ap. Indeed, two of our three introductory examples of applicative functors involved the IO monad and the environment monad (→) env. However the Applicative structure we
defined on lists is not monadic, and nor is $\text{Accy } o$ (unless $o$ is the trivial one-point monoid): return can deliver $\emptyset$, but if you try to define

$$\text{(?>=)} : \text{Accy } o \ a \to (a \to \text{Accy } o \ b) \to \text{Accy } o \ b$$

you’ll find it tricky to extract an $a$ from the first argument to supply to the second—all you get is an $o$. The $\otimes$ for $\text{Accy } o$ is not the $\text{ap}$ of a monad.

So now we know: there are strictly more $\text{Applicative}$ functors than $\text{Monad}$s. Should we just throw the $\text{Monad}$ class away and use $\text{Applicative}$ instead? Of course not! The reason there are fewer monads is just that the $\text{Monad}$ structure is more powerful. Intuitively, the $\text{(?>=)} : m \ a \to (a \to m \ b) \to m \ b$ of some $\text{Monad}$ $m$ allows the value returned by one computation to influence the choice of another, whereas $\otimes$ keeps the structure of a computation fixed, just sequencing the effects. For example, one may write

$$\text{miffy} :: \text{Monad } m \Rightarrow m \, \text{Bool} \to m \, \text{a} \to m \, \text{a} \to m \, \text{a}$$

$$\text{miffy } mb \ mt \ me = \text{do}$$

$$b \leftarrow mb$$

$$\text{if } b \text{ then } mt \text{ else } me$$

so that the value of $mb$ will choose between the computations $mt$ and $me$, performing only one, whilst

$$\text{iffy} :: \text{Applicative } f \Rightarrow f \, \text{Bool} \to f \, \text{a} \to f \, \text{a} \to f \, \text{a}$$

$$\text{iffy } fb \ ft \ fe = [\text{cond } fb \ ft \ fe] \text{ where}$$

$$\text{cond } b \ t \ e = \text{if } b \text{ then } t \text{ else } e$$

performs the effects of all three computations, using the value of $fb$ to choose only between the values of $ft$ and $fe$. This can be a bad thing: for example,

$$\text{iffy } [\text{True}] [\text{t}] \text{ Nothing} = \text{Nothing}$$

because the ‘else’ computation fails, even though its value is not needed, but

$$\text{miffy } [\text{True}] [\text{t}] \text{ Nothing} = [\text{t}]$$

However, if you are working with miffy, it is probably because the condition is an expression with effectful components, so the idiom syntax provides quite a convenient extension to the monadic toolkit:

$$\text{miffy } [\text{(<=)} \text{getSpeed getSpeedLimit}] \text{ stepOnIt checkMirror}$$

The moral is this: if you’ve got an $\text{Applicative}$ functor, that’s good; if you’ve also got a $\text{Monad}$, that’s even better! And the dual of the moral is this: if you need a $\text{Monad}$, that’s fine; if you only need an $\text{Applicative}$ functor, that’s even better!

One situation where the full power of monads is not always required is parsing, for which Röjemo (1995) proposed a interface including the equivalents of $\text{pure}$ and ‘$\otimes$’ as an alternative to monadic parsers (Hutton & Meijer, 1998). Several ingenious non-monadic implementations have been developed by Swierstra and colleagues (Swierstra & Duponcheel, 1996; Baars et al., 2004). Because the structure of these
parsers is independent of the results of parsing, these implementations are able to analyse the grammar lazily and generate very efficient parsers.

*Composing applicative functors* The weakness of applicative functors makes them easier to construct from components. In particular, although only certain pairs of monads are composable (Barr & Wells, 1984), the *Applicative* class is *closed under composition*,

```
newtype (f ◦ g) a = Comp { comp :: (f (g a)) }
```

just by lifting the inner *Applicative* operations to the outer layer:

```
instance (Applicative f, Applicative g) ⇒ Applicative (f ◦ g) where
  pure x = Comp [(pure x)]
  Comp fs ⊛ Comp xs = Comp [(⊛) fs xs]
```

As a consequence, the composition of two monads may not be a monad, but it is certainly applicative. For example, both `Maybe ◦ IO` and `IO ◦ Maybe` are applicative: `IO ◦ Maybe` is an applicative functor in which computations have a notion of ‘failure’ and ‘prioritised choice’, even if their ‘real world’ side-effects cannot be undone. Note that `IO` and `Maybe` may also be composed as monads (though not vice versa), but the applicative functor determined by the composed monad differs from the composed applicative functor: the binding power of the monad allows the second `IO` action to be aborted if the first returns a failure.

We began this section by observing that `Accy o` is not a monad. However, given `Monoid o`, it can be defined as the composition of two applicative functors derived from monads—which two, we leave as an exercise.

*Accumulating exceptions* The following type may be used to model exceptions:

```
data Except err a = OK a | Failed err
```

A *Monad* instance for this type must abort the computation on the first error, as there is then no value to pass to the second argument of ‘≫=’. However with the *Applicative* interface we can continue in the face of errors:

```
instance Monoid err ⇒ Applicative (Except err) where
  pure = OK
  OK f ⊛ OK x = OK (f x)  
  OK f ⊛ Failed err = Failed err
  Failed err ⊛ OK x = Failed err
  Failed err1 ⊛ Failed err2 = Failed (err1 ⊕ err2)
```

This could be used to collect errors by using the list monoid (Coutts, 2002), or to summarise them in some way.

6 Applicative functors and Arrows

To handle situations where monads were inapplicable, Hughes (2000) defined an interface that he called *arrows*, defined by the following class with nine axioms:
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\begin{verbatim}
class Arrow (↝) where
  arr :: (a → b) → (a ↝ b)
  (≫) :: (a ↝ b) → (b ↝ c) → (a ↝ c)
  first :: (a ↝ b) → ((a, c) ↝ (b, c))
\end{verbatim}

Examples include ordinary ‘→’, Kleisli arrows of monads and comonads, and stream processors. Equivalent structures called Freyd-categories had been independently developed to structure denotational semantics (Power & Robinson, 1997).

There are similarities to the Applicative interface, with \texttt{arr} generalising \texttt{pure}. The ‘≫’ operation arranges for the result of the first computation to be fed to the second; as with ‘⊛’, the plumbing is independent of the data flowing through it.

By fixing the first argument of an arrow type, we obtain an applicative functor, generalising the environment functor we saw earlier:

\begin{verbatim}
newtype EnvArrow (↝) env a = Env (env ↝ a)
instance Arrow (↝) ⇒ Applicative (EnvArrow (↝) env) where
  pure x = Env (arr (const x))
  Env u ⊛ Env v = Env (u △ v) ⊘ arr (λ(f, x) → f x))
    where u △ v = arr dup ≫ first u ≫ arr swap ≫ first v ≫ arr swap
  dup a = (a, a)
  swap (a, b) = (b, a)
\end{verbatim}

In the other direction, each applicative functor defines an arrow constructor that adds static information to an existing arrow:

\begin{verbatim}
newtype StaticArrow f (↝) a b = Static (f (a ↝ b))
instance (Applicative f, Arrow (↝)) ⇒ Arrow (StaticArrow f (↝)) where
  arr f = Static [arr f]
  Static f ⊘ Static g = Static [⊛] f g
  first (Static f) = Static [first f]
\end{verbatim}

To date, most applications of the extra generality provided by arrows over monads have been either various forms of process, in which components may consume multiple inputs, or computing static properties of components. Indeed one of Hughes’s motivations was the parsers of Swierstra and Duponcheel (1996). It may turn out that applicative functors are more convenient for applications of the second class.

\section{Applicative functors, categorically}

The \texttt{Applicative} class features the asymmetrical operation ‘⊛’, but there is an equivalent symmetrical definition:

\begin{verbatim}
class Functor f ⇒ Monoidal f where
  unit :: f ()
  (⊛) :: f a → f b → f (a, b)
\end{verbatim}

These operations are clearly definable for any \texttt{Applicative} functor:
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unit :: Applicative f ⇒ f ()
unit = [()]

(⋆) :: Applicative f ⇒ f a → f b → f (a, b)
fa ⋆ fb = [(, ) fa fb]

Moreover, we can recover the Applicative interface from Monoidal as follows:

pure :: Monoidal f ⇒ a → f a
pure x = fmap (\_ → x) unit

(⊗) :: Monoidal f ⇒ f (a → b) → f a → f b
mf ⊗ mx = fmap (\_ → \_ → \_) (mf ⋆ mx)

The laws of Applicative given in Section 2 are equivalent to the usual Functor laws, plus the following laws of Monoidal:

\textbf{naturality of }⋆\quad \text{fmap } (f × g) (u ⋆ v) = \text{fmap } f u ⋆ \text{fmap } g v

\textbf{left identity}\quad \text{fmap } \text{snd} (\text{unit } ⋆ v) = v

\textbf{right identity}\quad \text{fmap } \text{fst} (u ⋆ \text{unit}) = u

\textbf{associativity}\quad \text{fmap } \text{assoc} (u ⋆ (v ⋆ w)) = (u ⋆ v) ⋆ w

for the functions

(a → b) → (c → d) → (a, c) → (b, d)

(f × g) (x, y) = (f × g) (x, y)

assoc :: (a, (b, c)) → ((a, b), c)

assoc (a, (b, c)) = ((a, b), c)

Fans of category theory will recognise the above laws as the properties of a lax monoidal functor for the monoidal structure given by products. However the functor composition and naturality equations are actually stronger than their categorical counterparts. This is because we are working in a higher-order language, in which function expressions may include variables from the environment, as in the above definition of pure for Monoidal functors. In the first-order language of category theory, such data flow must be explicitly plumbed using functors with tensorial strength, an arrow:

\[ t_A : A × F B → F (A × B) \]

satisfying standard equations. The natural transformation \( m \) corresponding to ‘⋆’ must also respect the strength:

\[ (A × B) × (F C × F D) \cong (A × F C) × (B × F D) \]

\[ (A × B) \times m \]

\[ (A × B) × F (C × D) \]

\[ t \times t \]

\[ F ((A × B) × (C × D)) \cong F ((A × C) × (B × D)) \]

Note that \( B \) and \( F C \) swap places in the above diagram: strong naturality implies commutativity with pure computations.
Thus in categorical terms applicative functors are *strong lax monoidal functors*. Every strong monad determines two of them, as the definition is symmetrical. The *Monoidal* laws and the above definition of *pure* imply that pure computations commute past effects:

$$\text{fmap swap (pure } x \star u) = u \star \text{pure } x$$

The proof (an exercise) makes essential use of higher-order functions.

8 Conclusions

We have identified *Applicative* functors, an abstract notion of effectful computation lying between *Arrow* and *Monad* in strength. Every *Monad* is an *Applicative* functor, but significantly, the *Applicative* class is closed under composition, allowing computations such as accumulation in a *Monoid* to be characterised in this way.

Given the wide variety of *Applicative* functors, it becomes increasingly useful to abstract *Traversable* functors—container structures through which *Applicative* actions may be threaded. Combining these abstractions yields a small but highly generic toolkit whose power we have barely begun to explore. We use these tools by writing types that not merely structure the *storage* of data, but also the *properties* of data that we intend to exploit.

Library modules based on these classes are included in the libraries shared by all Haskell implementations.

The explosion of categorical structure in functional programming: monads, comonads, arrows and now applicative functors should not, we suggest, be a cause for alarm. Why should we not profit from whatever structure we can sniff out, abstract and re-use? The challenge is to avoid a chaotic proliferation of peculiar and incompatible notations. If we want to rationalise the notational impact of all these structures, perhaps we should try to recycle the notation we already possess. Our $[\! [ f \ u_1 \ldots u_n ] \!]$ notation does minimal damage, showing when the existing syntax for applicative programming should be interpreted with an effectful twist.

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