Chapter 11: Computations in a functor context III
Monad transformers

Sergei Winitzki

Academy by the Bay

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Computations within a functor context: Combining monads

Programs often need to combine monadic effects

- "Effect" $\equiv$ what else happens in $A \Rightarrow M^B$ besides computing B from A
- Examples of effects for some standard monads:
  - ▶ `Option` – computation will have no result or a single result
  - ▶ `List` – computation will have zero, one, or multiple results
  - ▶ `Either` – computation may fail to obtain its result, reports error
  - ▶ `Reader` – computation needs to read an external context value
  - ▶ `Writer` – some value will be appended to a (monoidal) accumulator
  - ▶ `Future` – computation will be scheduled to run later
- How to combine several effects in the same functor block (`for`/`yield`)?

```scala
// This is not valid Scala!
val result = for { i ← 1 to n
    j ← Future { q(i) }
    k ← maybeError(j) : Try[Int]
} yield f(k)
// What should be the type of result??
```

```scala
// This is not valid Scala!
(1 to n).flatMap { i ⇒
    Future(q(i)).flatMap { j ⇒
      maybeError(j).map { k ⇒
        f(k)
      }}}
```

- The code will work if we "unify" all effects in a new, larger monad
- Need to compute the type of new monad that contains all given effects

Combining monadic effects I. Trial and error

There are several ways of combining two monads into a new monad:

- If M_1^A and M_2^A are monads then $M_1^A \times M_2^A$ is also a monad
  - ▶ But $M_1^A \times M_2^A$ describes two separate values with two separate effects
- If M_1^A and M_2^A are monads then $M_1^A + M_2^A$ is usually not a monad
  - ▶ If it worked, it would be a choice between two different values / effects
- If M_1^A and M_2^A are monads then one of $M_1^{M_2^A}$ or $M_2^{M_1^A}$ is often a monad
- Examples and counterexamples for functor composition:
  - ▶ Combine $Z \Rightarrow A$ and List^A as $Z \Rightarrow \text{List}^A$
  - ▶ Combine `Future[A]` and `Option[A]` as `Future[Option[A]]`
  - ▶ But `Either[Z, Future[A]]` and `Option[Z ⇒ A]` are not monads
  - ▶ Neither `Future[State[A]]` nor `State[Future[A]]` are monads
- The order of effects matters when composition works both ways:
  - ▶ Combine `Either` ($M_1^A = Z + A$) and `Writer` ($M_2^A = W \times A$)
    - ★ as $Z + W \times A$ – either compute result and write a message, or all fails
    - ★ as $(Z + A) \times W$ – message is always written, but computation may fail
- Find a general way of defining a new monad with combined effects
- Derive properties required for the new monad

Combining monadic effects II. Lifting into a larger monad

If a "big monad" `BigM[A]` *somehow* combines all the needed effects:

```scala
// This could be valid Scala...        // If we define the various
val result: BigM[Int] = for {          // required "lifting" functions:
    i ← lift₁(1 to n)                   def lift₁[A]: Seq[A] ⇒ BigM[A] = ???
    j ← lift₂(Future{ q(i) })           def lift₂[A]: Future[A] ⇒ BigM[A] = ???
    k ← lift₃(maybeError(j))            def lift₃[A]: Try[A] ⇒ BigM[A] = ???
} yield f(k)
```

- Example 1: combining as `BigM[A] = Future[Option[A]]` with liftings:
  ```scala
  def lift₁[A]: Option[A] ⇒ Future[Option[A]] = Future.successful(_)
  def lift₂[A]: Future[A] ⇒ Future[Option[A]] = _.map(x ⇒ Some(x))
  ```
- Example 2: combining as `BigM[A] = List[Try[A]]` with liftings:
  ```scala
  def lift₁[A]: Try[A] ⇒ List[Try[A]] = x ⇒ List(x)
  def lift₂[A]: List[A] ⇒ List[Try[A]] = _.map(x ⇒ Success(x))
  ```

Remains to be understood:

- Finding suitable laws for the liftings; checking that the laws hold
- Building a "big monad" out of "smaller" ones, with lawful liftings
  - ▶ Is this always possible? Unique? Are there alternative solutions?
- Ways of reducing the complexity of code; make liftings automatic

Laws for monad liftings I. Identity laws

Whatever identities we expect to hold for monadic programs must continue to hold after lifting `M_1` or `M_2` values into the "big monad" `BigM`

- We assume that `M_1`, `M_2`, and `BigM` already satisfy all the monad laws

Consider the various functor block constructions containing the liftings:

- Left identity law after `lift_1`

```
// Anywhere inside a for/yield:          // Must be equivalent to...
i ← lift_1(M_1.pure(x))                  i = x
j ← bigM(i) // Any BigM value.           j ← bigM(x)
```

`lift_1(M_1.pure(x)).flatMap(b) = b(x)` — in terms of Kleisli composition ($\diamond$):

$$\left(\text{pure}_{M_1} \, \mathring{,} \, \text{lift}_1\right)^{:X \Rightarrow \text{BigM}^X} \diamond b^{:X \Rightarrow \text{BigM}^Y} = b \text{ with } f^{:X \Rightarrow M^Y} \diamond g^{:Y \Rightarrow M^Z} \equiv x \Rightarrow f(x).\text{flatMap}(g)$$

- Right identity law after `lift_1`

```
// Anywhere inside a for/yield:          // Must be equivalent to...
x ← bigM // Any BigM value.              x ← bigM
i ← lift_1(M_1.pure(x))                  i = x
```

`b.flatMap(M_1.pure andThen lift_1) = b` — in terms of Kleisli composition:

$$b^{:X \Rightarrow \text{BigM}^Y} \diamond \left(\text{pure}_{M_1} \, \mathring{,} \, \text{lift}_1\right)^{:Y \Rightarrow \text{BigM}^Y} = b$$

- The same identity laws must hold for `M_2` and `lift_2` as well

Laws for monad liftings II. Simplifying the laws

$\left(\mathsf{pure}_{M_1}\,\mathring{,}\,\mathsf{lift}_1\right)$ is a unit for the Kleisli composition $\diamond$ in the monad `BigM`

- But the monad `BigM` already has a unit element: $\mathsf{pure}_{\mathsf{BigM}}$
- The two-sided unit element is always unique: $\mathsf{id} = \mathsf{id} \diamond \mathsf{id}' = \mathsf{id}'$
- So the two identity laws for $\left(\mathsf{pure}_{M_1}\,\mathring{,}\,\mathsf{lift}_1\right)$ can be reduced to one law:

$$\mathsf{pure}_{M_1}\,\mathring{,}\,\mathsf{lift}_1 = \mathsf{pure}_{\mathsf{BigM}}$$

Refactoring a portion of a monadic program under `lift₁` gives another law:

```
// Anywhere inside a for/yield:        // Must be equivalent to...
i ← lift₁(p) // Any M₁ value.          pq = p.flatMap(q)  // In M₁.
j ← lift₁(q(i)) // Any M₁ value.       j ← lift₁(pq)  // Now lift it.
```

```
lift₁(p).flatMap(q andThen lift₁) = lift₁(p flatMap q)
```

- Rewritten equivalently through $\mathsf{flm}_M : \left(A \Rightarrow M^B\right) \Rightarrow M^A \Rightarrow M^B$ as

$$\mathsf{lift}_1\,\mathring{,}\,\mathsf{flm}_{\mathsf{BigM}}\left(q\,\mathring{,}\,\mathsf{lift}_1\right) = \mathsf{flm}_{M_1}\,q\,\mathring{,}\,\mathsf{lift}_1$$

- Rewritten in terms of Kleisli composition:

$$\left(b^{:X \Rightarrow M_1^Y}\,\mathring{,}\,\mathsf{lift}_1\right) \diamond \left(c^{:Y \Rightarrow M_1^Z}\,\mathring{,}\,\mathsf{lift}_1\right) = (b \diamond c)\,\mathring{,}\,\mathsf{lift}_1$$

- Liftings lift_1 and lift_2 must obey an identity law and a composition law
- The laws say that the liftings **commute with** the monads' operations

Laws for monad liftings III. The naturality law

Show that $\text{lift}_1 : M_1^A \Rightarrow \text{BigM}^A$ is a natural transformation

- It maps pure_{M_1} to $\text{pure}_{\text{BigM}}$ and flm_{M_1} to flm_{BigM}
  - lift_1 is a **monadic morphism** between monads $M_1^{\bullet}$ and $\text{BigM}^{\bullet}$

The (functor) naturality law:

$$\text{lift}_1 \, \mathring{\,}\, \text{fmap}_B \, f^{:X \Rightarrow Y} = \text{fmap}_{M_1} \, f^{:X \Rightarrow Y} \, \mathring{\,}\, \text{lift}_1$$

$$
\begin{array}{ccc}
M_1^X & \xrightarrow{\ \text{lift}_1\ } & \text{BigM}^X \\
{\scriptstyle \text{fmap}_{M_1}\, f^{:X \Rightarrow Y}} \downarrow & & \downarrow {\scriptstyle \text{fmap}_{\text{BigM}}\, f^{:X \Rightarrow Y}} \\
M_1^Y & \xrightarrow{\ \text{lift}_1\ } & \text{BigM}^Y
\end{array}
$$

Derivation of the naturality law:

- Express fmap as $\text{fmap}_M \, f = \text{flm}_M \left(f \, \mathring{\,}\, \text{pure}_M \right)$ for both monads
- Given $f^{:X \Rightarrow Y}$, use the law $\text{flm}_{M_1} \, q \, \mathring{\,}\, \text{lift}_1 = \text{lift}_1 \, \mathring{\,}\, \text{flm}_{\text{BigM}} \left(q \, \mathring{\,}\, \text{lift}_1 \right)$ to compute
  $\text{flm}_{M_1} \left(f \, \mathring{\,}\, \text{pure}_{M_1} \right) \, \mathring{\,}\, \text{lift}_1 = \text{lift}_1 \, \mathring{\,}\, \text{flm} \left(f \, \mathring{\,}\, \text{pure}_{M_1} \, \mathring{\,}\, \text{lift}_1 \right) = \text{lift}_1 \, \mathring{\,}\, \text{flm} \left(f \, \mathring{\,}\, \text{pure}_{\text{BigM}} \right) = $
  $\text{lift}_1 \, \mathring{\,}\, \text{fmap}_{\text{BigM}} \, f$

A monadic morphism is always also a natural transformation of the functors

Monad transformers I: The requirements

- Combine $Z \Rightarrow A$ and $1 + A$: only $Z \Rightarrow 1 + A$ works, not $1 + (Z \Rightarrow A)$
  - It is not possible to combine monads via a natural bifunctor B^{M_1, M_2}
  - It is not possible to combine arbitrary monads as $M_1^{M_2^\bullet}$ or $M_2^{M_1^\bullet}$
- The trick: for a fixed **base** monad $L^\bullet$, let $M^\bullet$ (**foreign** monad) vary
- Call the desired result the "L's monad transformer", $T_L^{M,A}$
  - (We don't yet have a general formula for monad transformers)

A **monad transformer** for a **base** monad $L^\bullet$ is a type constructor $T_L^{M,\bullet}$ parameterized by a monad $M^\bullet$, such that for all monads $M^\bullet$

- $T_L^{M,\bullet}$ is a monad (the monad M **transformed with** T_L)
- "Lifting" – a monadic morphism $\mathrm{lift}_L^M : M^A \rightsquigarrow T_L^{M,A}$, natural in $M^\bullet$
- "Injection" – a monadic morphism $\mathrm{inj} : L^A \rightsquigarrow T_L^{M,A}$
- $T_L^{M,\bullet}$ is **monadically natural** in $M^\bullet$
  - $T_L^{M,\bullet}$ is natural w.r.t. a monadic functor $M^\bullet$ as a type parameter
  - For any monad $N^\bullet$ and a monadic morphism $f : M^\bullet \rightsquigarrow N^\bullet$ we need to have a monadic morphism $T_L^{M,\bullet} \rightsquigarrow T_L^{N,\bullet}$ for the transformed monads
  - If we implement $T_L^{M,\bullet}$ only via M's monad methods, naturality will hold
  - Cf. `traverse`: $L^A \Rightarrow (A \Rightarrow F^B) \Rightarrow F^{L^B}$ – natural w.r.t. applicative $F^\bullet$

Monad transformers II: First examples

Recall these monad constructions:

- If M^A is a monad then $R \Rightarrow M^A$ is also a monad (for a fixed type R)
- If M^A is a monad then $M^{Z+A \times W}$ is also a monad (for fixed W, Z)

This gives the monad transformers for `Reader`, `Writer`, `Either` base monads:

```
type ReaderT[R, M[_], A] = R ⇒ M[A]
type EitherT[Z, M[_], A] = M[Either[Z, A]]
type WriterT[W, M[_], A] = M[(W, A)]
```

- `ReaderT` wraps the foreign monad from the outside
- `EitherT` and `WriterT` require the foreign monad to wrap *them*

Remaining questions:

- What are transformers for other standard monads (`List`, `State`, `Cont`)?
  - ...turns out, these monads do not compose either "inside" or "outside"!
- How to construct a monad transformer for an arbitrary given monad?
  - Can we combine monad transformers for known monad constructions?
- For a given monad, is the corresponding monad transformer unique?

Monad transformers III: The zoology

Recall some known monad constructions:

- If M^A is a monad then $R \Rightarrow M^A$ is also a monad (for a fixed type R)

Exercises

1. Show that the method `pure`: $A \Rightarrow M^A$ is a monadic morphism between monads $\text{Id}^A \equiv A$ and M^A.

2. Show that $M_1^A + M_2^A$ is *not* a monad when $M_1^A \equiv 1 + A$ and $M_2^A \equiv Z \Rightarrow A$.