

# 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 (see code)

- “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**)?

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

- 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  $\text{List}^A$  as  $Z \Rightarrow \text{List}^A$
  - ▶ Combine `Future[A]` and `Option[A]` as `Future[Option[A]]`
  - ▶ But `Either[Z, Future[A]]` and `Option[Z  $\Rightarrow$  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:

```
// 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:

```
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:

```
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”  $\text{BigM}$

- We assume that  $M_1$ ,  $M_2$ , and  $\text{BigM}$  already satisfy all the monad laws

Consider the various functor block constructions containing the liftings:

- Left identity law after  $\text{lift}_1$

// Anywhere inside a for/yield:	// Must be equivalent to...
$i \leftarrow \text{lift}_1(M_1.\text{pure}(x))$	$i = x$
$j \leftarrow \text{bigM}(i)$ // Any BigM value.	$j \leftarrow \text{bigM}(x)$

$\text{lift}_1(M_1.\text{pure}(x)).\text{flatMap}(b) = b(x)$  — in terms of Kleisli composition ( $\diamond$ ):  
 $(\text{pure}_{M_1} \circ \text{lift}_1)^{X \Rightarrow \text{BigM}^Y} \diamond b^{X \Rightarrow \text{BigM}^Y} = b$  with  $f^{X \Rightarrow M^Y} \diamond g^{Y \Rightarrow M^Z} \equiv x \Rightarrow f(x).\text{flatMap}(g)$

- Right identity law after  $\text{lift}_1$

// Anywhere inside a for/yield:	// Must be equivalent to...
$x \leftarrow \text{bigM}$ // Any BigM value.	$x \leftarrow \text{bigM}$
$i \leftarrow \text{lift}_1(M_1.\text{pure}(x))$	$i = x$

$b.\text{flatMap}(M_1.\text{pure} \text{ andThen } \text{lift}_1) = b$  — in terms of Kleisli composition:

$$b^{X \Rightarrow \text{BigM}^Y} \diamond (\text{pure}_{M_1} \circ \text{lift}_1)^{Y \Rightarrow \text{BigM}^Y} = b$$

- The same identity laws must hold for  $M_2$  and  $\text{lift}_2$  as well

## Laws for monad liftings II. Simplifying the laws

$(\text{pure}_{M_1} \circ \text{lift}_1)$  is a unit for the Kleisli composition  $\diamond$  in the monad `BigM`

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

$$\text{pure}_{M_1} \circ \text{lift}_1 = \text{pure}_{\text{BigM}}$$

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

<code>// Anywhere inside a for/yield, this...</code>	<code>// must be equivalent to...</code>
<code>i ← lift<sub>1</sub>(p) // Any M<sub>1</sub> value.</code>	<code>pq = p.flatMap(q) // In M<sub>1</sub>.</code>
<code>j ← lift<sub>1</sub>(q(i)) // Any M<sub>1</sub> value.</code>	<code>j ← lift<sub>1</sub>(pq) // Now lift it.</code>

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

- Rewritten equivalently through  $\text{flm}_M : (A \Rightarrow M^B) \Rightarrow M^A \Rightarrow M^B$  as  $\text{lift}_1 \circ \text{flm}_{\text{BigM}} (q \circ \text{lift}_1) = \text{flm}_{M_1} q \circ \text{lift}_1$  – both sides are functions  $M_1^A \Rightarrow \text{BigM}^B$
- Rewritten equivalently through  $\text{ftn}_M : M^{M^A} \Rightarrow M^A$ , the law is  $\text{lift}_1 \circ \text{fmap}_{\text{BigM}} \text{lift}_1 \circ \text{ftn}_{\text{BigM}} = \text{ftn}_{M_1} \circ \text{lift}_1$  – both sides are functions  $M_1^{M^A} \Rightarrow \text{BigM}^A$
- In terms of Kleisli composition  $\diamond_M$  it becomes the **composition law**:  
$$(b^{X \Rightarrow M_1^Y} \circ \text{lift}_1) \diamond_{\text{BigM}} (c^{Y \Rightarrow M_1^Z} \circ \text{lift}_1) = (b \diamond_{M_1} c) \circ \text{lift}_1$$
- Liftings `lift1` and `lift2` 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  $\text{pure}_{M_1}$  to  $\text{pure}_{\text{BigM}}$  and  $\text{flm}_{M_1}$  to  $\text{flm}_{\text{BigM}}$ 
  - ▶  $\text{lift}_1$  is a **monadic morphism** between monads  $M_1^\bullet$  and  $\text{BigM}^\bullet$
  - ▶ example: monad “interpreters”  $M^A \Rightarrow N^A$  are monadic morphisms

The (functor) naturality law: for any  $f : X \Rightarrow Y$ ,

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

Derivation of the functor naturality law for  $\text{lift}_1$ :

- Express  $\text{fmap}$  as  $\text{fmap}_M f \equiv f^\uparrow M = \text{flm}_M (f \circ \text{pure}_M)$  for both monads
- Given  $f : X \Rightarrow Y$ , use the law  $\text{flm}_{M_1} q \circ \text{lift}_1 = \text{lift}_1 \circ \text{flm}_{\text{BigM}} (q \circ \text{lift}_1)$  to compute
$$\begin{aligned} \text{flm}_{M_1} (f \circ \text{pure}_{M_1}) \circ \text{lift}_1 &= \text{lift}_1 \circ \text{flm}_{\text{BigM}} (f \circ \text{pure}_{M_1} \circ \text{lift}_1) = \\ &= \text{lift}_1 \circ \text{flm}_{\text{BigM}} (f \circ \text{pure}_{\text{BigM}}) = \text{lift}_1 \circ \text{fmap}_{\text{BigM}} f \end{aligned}$$

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

# Monad transformers I: Motivation

- 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  $M_2^{M_1^\bullet}$ 
    - ★ Example: state monad  $\text{St}_S^A \equiv S \Rightarrow A \times S$  does not compose
- The trick: for a fixed **base** monad  $L^\bullet$ , let  $M^\bullet$  (**foreign** monad) vary
- Call the desired result  $T_L^{M, \bullet}$  the **monad transformer for  $L$** 
  - ▶ In Scala: `LT[M[_]: Monad, A]` – e.g. `ReaderT`, `StateT`, etc.
- $T_L^{M, \bullet}$  is generic in  $M$  but not in  $L$ 
  - ▶ No general formula for monad transformers seems to exist
  - ▶ For each base monad  $L$ , a different construction is needed
    - ★ Some transformers are compositions  $L^{M^\bullet}$  or  $M^{L^\bullet}$ , others are not
  - ▶ Some monads  $L$  do not seem to have a transformer (?)
- To combine 3 or more monads, compose the transformers:  $T_{L_1}^{T_{L_2}^{M, \bullet}}$ 
  - ▶ Example in Scala: `StateT[S, ListT[Reader[R, ?], ?], A]`
- This is called a **monad stack** – but may not be *functor composition*
  - ▶ because e.g. `State[S, List[Reader[R, A]]]` is not a monad



# Monad transformers II: The requirements

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  $\text{lift}_L^M : M^A \rightsquigarrow T_L^{M,A}$
- “Base lifting” – a monadic morphism  $\text{blift} : L^A \rightsquigarrow T_L^{M,A}$ 
  - ▶ The “base lifting” could not possibly be natural in  $L^\bullet$
- Transformed identity monad ( $\text{Id}$ ) must become  $L$ , i.e.  $T_L^{\text{Id},\bullet} \cong L^\bullet$
- $T_L^{M,\bullet}$  is **monadically natural** in  $M^\bullet$  (but not in  $L^\bullet$ )
  - ▶  $T_L^{M,\bullet}$  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:  $\text{mrunc}_L^M : (M^\bullet \rightsquigarrow N^\bullet) \Rightarrow T_L^{M,\bullet} \rightsquigarrow T_L^{N,\bullet}$  commuting with **lift** / **blift**
    - ★ 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  $F^\bullet$
  - ▶ This can be used for lifting a “runner”  $M^A \rightsquigarrow A$  to  $T_L^{M,\bullet} \rightsquigarrow T_L^{\text{Id},\bullet} = L^\bullet$
- “Base runner”: lifts  $L^A \rightsquigarrow A$  into a monadic morphism  $T_L^{M,\bullet} \rightsquigarrow M^\bullet$ ; so  $\text{brunc}_L^M : (L^\bullet \rightsquigarrow \bullet) \Rightarrow T_L^{M,\bullet} \rightsquigarrow M^\bullet$ , must commute with **lift** and **blift**

# Monad transformers III: 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 base monads `Reader`, `Writer`, `Either`:

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

- `ReaderT` composes with the foreign monad from the *outside*
- `EitherT` and `WriterT` must be composed *inside* the foreign monad

Remaining questions:

- What are transformers for other standard monads (`List`, `State`, `Cont`)?
  - ▶ These monads do not compose (neither “inside” nor “outside” works)!
- How to derive a monad transformer for an arbitrary given monad?
  - ▶ For monads obtained via known monad constructions?
  - ▶ For monads constructed via other monad transformers?
  - ▶ Is it always possible? (unknown; may be impossible for some monads)
- Is a given monad’s transformer unique? (No.)
- How to avoid the boilerplate around `lift`? (`mtl`-style transformers)

# Monad transformers IV: The zoology of *ad hoc* methods

Need to choose the correct monad transformer construction, per monad:

- “Composed-inside”, base monad is inside foreign monad:  $T_L^{M,A} = M^{L^A}$ 
  - ▶ Examples: the “linear-value” monads `OptionT`, `WriterT`, `EitherT`
- “Composed-outside” – the base monad is outside:  $T_L^{M,A} = L^{M^A}$ 
  - ▶ Examples: `ReaderT`; `SearchT` for search monad  $S[A] = (A \Rightarrow Z) \Rightarrow A$
  - ▶ More generally: all “rigid” monads have “outside” transformers
- “Recursive”: interleaves the base monad and the foreign monad
  - ▶ Examples: `ListT`, `NonEmptyListT`, `FreeMonadT`
- Monad constructions: defining a transformer for new monads
  - ▶ Product monads  $L_1^A \times L_2^A$  – product transformer  $T_{L_1}^{M,A} \times T_{L_2}^{M,A}$
  - ▶ “Contrafunctor-choice”  $H^A \Rightarrow A$  – composed-outside transformer
  - ▶ Free pointed monads  $A + L^A$  – transformer  $M^{A+T_L^{M,A}}$
- “Irregular”: none of the above constructions work, need something else
  - ▶  $T_{\text{State}}^{M,A} = S \Rightarrow M^{S \times A}$ ;  $T_{\text{Cont}}^{M,A} = (A \Rightarrow M^R) \Rightarrow M^R$ ; “selector”  $F^{A \Rightarrow P^Q} \Rightarrow P^A$   
– transformer  $F^{A \Rightarrow T_P^{M,Q}} \Rightarrow T_P^{M,A}$ ; codensity  $\forall R. (A \Rightarrow M^R) \Rightarrow M^R$
- Examples of monads  $K^A$  for which no transformers exist? (not known)
  - ▶  $T_{\text{Cod}}$ ,  $T_{\text{Sel}}$ , and  $T_{\text{Cont}}$  transformers have no `blift`, `brun`, or `mrn`

# Composed-inside transformers I

Base monad  $L^\bullet$ , foreign monad  $M^\bullet$ , transformer  $T_L^{M,\bullet} \equiv T^\bullet \equiv M^{L^\bullet}$

- Monad instance: use the natural transformation  $\text{seq}^A : L^{M^A} \Rightarrow M^{L^A}$ 
  - ▶  $\text{pure}_T : A \Rightarrow M^{L^A}$  is defined as  $\text{pure}_T = \text{pure}_M \circ \text{pure}_L^{\uparrow M}$
  - ▶  $\text{ftn}_T : T^{T^A} \Rightarrow T^A$  is defined as  $\text{ftn}_T = \text{seq}^{\uparrow M} \circ \text{ftn}_L^{\uparrow M \uparrow M} \circ \text{ftn}_M$

$$T^{T^A} \equiv M^{L^{M^{L^A}}} \xrightarrow{\text{fmap}_M(\text{seq}^{L^A})} M^{M^{L^{L^A}}} \xrightarrow{\text{fmap}_M(\text{fmap}_M \text{ftn}_L)} M^{M^{L^A}} \xrightarrow{\text{ftn}_M} M^{L^A} \equiv T^A$$

- Monad laws must hold for  $T^A$  (must check this separately)
  - ▶ This depends on special properties of  $\text{seq}$ , e.g.  $\text{pure}_L \circ \text{seq} = \text{pure}_L^{\uparrow M}$  ( $L$ -identity);  $\text{pure}_M^{\uparrow L} \circ \text{seq} = \text{pure}_M$  ( $M$ -identity)
    - ★ See example code that verifies these properties for  $L^A \equiv E + W \times A$
    - ★ It is not enough to have *any* traversable functor  $L^\bullet$  here!
- Monad transformer methods for  $T_L^{M,\bullet} \equiv M^{L^\bullet}$ :
  - ▶ Lifting,  $\text{lift} : M^A \Rightarrow M^{L^A}$  is defined as  $\text{lift} = \text{pure}_L^{\uparrow M}$
  - ▶ Base lifting,  $\text{blift} : L^A \Rightarrow M^{L^A}$  is equal to  $\text{pure}_M$
  - ▶ Runner,  $\text{mrun} : (\forall B. M^B \Rightarrow N^B) \Rightarrow M^{L^A} \Rightarrow N^{L^A}$  is equal to  $\text{id}$
  - ▶ Base runner,  $\text{brun} : (\forall B. L^B \Rightarrow B) \Rightarrow M^{L^A} \Rightarrow M^A$  is equal to  $\text{fmap}_M$

## \* Composed-inside transformers II. Proofs

Base monad  $L^\bullet$ , foreign monad  $M^\bullet$ , transformer  $T_L^{M,\bullet} \equiv T^\bullet \equiv M^{L^\bullet}$

- Identity laws for the monad  $T^\bullet$  hold if they hold for  $L^\bullet$  and  $M^\bullet$  and if the properties  $\text{pure}_L \circ \text{seq} = \text{pure}_L^{\uparrow M}$  and  $\text{pure}_M^{\uparrow L} \circ \text{seq} = \text{pure}_M$  hold
- $\text{pure}_T \circ \text{fth}_T = \text{id}$ . Proof:  $(\text{pure}_M \circ \text{pure}_L^{\uparrow M}) \circ (\text{seq}^{\uparrow M} \circ \text{fth}_L^{\uparrow M \uparrow M} \circ \text{fth}_M) = \text{pure}_M \circ (\text{pure}_L \circ \text{seq})^{\uparrow M} \circ \text{fth}_L^{\uparrow M \uparrow M} \circ \text{fth}_M = \text{pure}_M \circ \text{pure}_L^{\uparrow M \uparrow M} \circ \text{fth}_L^{\uparrow M \uparrow M} \circ \text{fth}_M = \text{id}$
- $\text{pure}_T^{\uparrow T} \circ \text{fth}_T = \text{id}$ . Proof:  $\text{pure}_T = \text{pure}_M \circ \text{pure}_L^{\uparrow M} = \text{pure}_L \circ \text{pure}_M$  (naturality); for all  $f$ :  $f^{\uparrow T} = f^{\uparrow L \uparrow M}$  and  $f \circ \text{pure}_M = \text{pure}_M \circ f^{\uparrow M}$  (naturality); so  $\text{pure}_T^{\uparrow T} \circ \text{fth}_T$  is  $(\text{pure}_L \circ \text{pure}_M)^{\uparrow L \uparrow M} \circ (\text{seq}^{\uparrow M} \circ \text{fth}_L^{\uparrow M \uparrow M} \circ \text{fth}_M) = \text{pure}_L^{\uparrow L \uparrow M} \circ \text{pure}_M^{\uparrow M} \circ \text{fth}_L^{\uparrow M \uparrow M} \circ \text{fth}_M = \text{pure}_M^{\uparrow M} \circ (\text{pure}_L^{\uparrow L} \circ \text{fth}_L)^{\uparrow M \uparrow M} \circ \text{fth}_M = \text{id}$  where we used naturality with  $f = \text{pure}_L^{\uparrow L}$
- Identity law for lift:  $\text{pure}_M \circ \text{lift} = \text{pure}_T$  (this is the definition of  $\text{pure}_T$ )
- Composition law:  $\text{lift} \circ \text{lift}^{\uparrow T} \circ \text{fth}_T = \text{fth}_M \circ \text{lift}$ . Proof:  $\text{fth}_M \circ \text{pure}_L^{\uparrow M} = \text{pure}_L^{\uparrow M \uparrow M} \circ \text{fth}_M$  and  $\text{pure}_L^{\uparrow M} \circ (\text{pure}_L^{\uparrow M \uparrow L \uparrow M} \circ \text{seq}^{\uparrow M}) \circ \text{fth}_L^{\uparrow M \uparrow M} \circ \text{fth}_M = (\text{pure}_L^{\uparrow M} \circ \text{seq}^{\uparrow M}) \circ (\text{pure}_L^{\uparrow L \uparrow M \uparrow M} \circ \text{fth}_L^{\uparrow M \uparrow M}) \circ \text{fth}_M = \text{pure}_L^{\uparrow M \uparrow M} \circ \text{fth}_M$
- Identity law for blift:  $\text{pure}_L \circ \text{blift} = \text{pure}_T$ . ( $\text{pure}_L \circ \text{pure}_M = \text{pure}_M \circ \text{pure}_L^{\uparrow M}$ )
- Composition law:  $\text{blift} \circ \text{blift}^{\uparrow T} \circ \text{fth}_T = \text{fth}_L \circ \text{blift}$ . Proof:  $\text{pure}_M \circ \text{pure}_L^{\uparrow L \uparrow M} \circ (\text{seq}^{\uparrow M} \circ \text{fth}_L^{\uparrow M \uparrow M} \circ \text{fth}_M) = \text{pure}_M \circ (\text{pure}_M^{\uparrow M} \circ \text{fth}_L^{\uparrow M \uparrow M}) \circ \text{fth}_M = \text{pure}_M \circ (\text{fth}_L^{\uparrow M} \circ \text{pure}_M^{\uparrow M}) \circ \text{fth}_M = \text{fth}_L \circ \text{pure}_M \circ (\text{pure}_M^{\uparrow M} \circ \text{fth}_M) = \text{fth}_L \circ \text{blift}$
- Runner laws follow from naturality of id and fmap

# Rigid monads I: Definitions

- A **rigid monad**  $R^\bullet$  has a composed-outside transformer,  $T_R^{M,A} \equiv R^{M^A}$ 
  - ▶ Examples:  $R^A \equiv A \times A$  and  $R^A \equiv Z \Rightarrow A$  are rigid;  $R^A \equiv 1 + A$  is not
  - ▶ For any monad  $M$ , we then have  $\text{seq} : M^{R^A} \Rightarrow R^{M^A}$  defined by

$$\text{seq} = \text{pure}_M^{\uparrow R \uparrow M} \circ \text{pure}_{R^\circ} \circ \text{ftn}_T$$

$$M^{R^A} \xrightarrow{\text{fmap}_M(\text{fmap}_R(\text{pure}_M))} M^{R^{M^A}} \xrightarrow{\text{pure}_R} R^{M^{R^{M^A}}} = T^{T^A} \xrightarrow{\text{ftn}_T} T^A \equiv R^{M^A}$$

- Open question: is  $\text{ftn}_T$  definable via  $\text{seq}$  with some additional laws?

Examples and constructions of rigid monads:

- Rigid: **Id**, **Reader**, and  $R^A \equiv H^A \Rightarrow A$  (where  $H$  is a contrafunctor)
  - ▶ The construction  $R^A \equiv H^A \Rightarrow A$  covers  $R^A \equiv 1$ ,  $R^A \equiv A$ ,  $R^A \equiv Z \Rightarrow A$
- The **selector monad**  $S^A \equiv F^{A \Rightarrow R^Q} \Rightarrow R^A$  is rigid if  $R^\bullet$  is rigid
  - ▶ Simple example: search with failure,  $S^A \equiv (A \Rightarrow \text{Bool}) \Rightarrow 1 + A$
- The composition of rigid monads,  $R_1^{R_2^A}$ , is a rigid monad
- The product of rigid monads,  $R_1^A \times R_2^A$ , is a rigid monad

# Rigid functors, their laws and structure I

- A **rigid functor**  $R^\bullet$  has the method `fuseIn`:  $(A \Rightarrow R^B) \Rightarrow R^{A \Rightarrow B}$ 
  - ▶ Rigid monads are rigid functors since `fi` = seq with  $M^A \equiv Z \Rightarrow A$
  - ▶ Compare with `fuseOut`:  $R^{A \Rightarrow B} \Rightarrow A \Rightarrow R^B$ , which exists for *any* functor
    - ★ Implementation: `fo`  $h^{R^{A \Rightarrow B}} = x^A \Rightarrow (f^{A \Rightarrow B} \Rightarrow f\ x)^{\uparrow R} h$
- Nondegeneracy law: `fuseOut(fuseIn(x)) == x` or `fi; fo` = id
- `fi` must be natural in both type parameters
  - ▶ Naturality: `fi (f; g↑R) = (qA⇒B ⇒ q; g)↑R (fi f)` for  $\forall f:A \Rightarrow R^B, g:B \Rightarrow C$   
and `fi (f; g) = (qB⇒C ⇒ f; q)↑R (fi g)` for  $\forall f:A \Rightarrow B, g:B \Rightarrow R^C$
- Connection between monadic `flatMap` and applicative `ap` for monadic  $R$ :
  - ▶ `flm` :  $(A \Rightarrow R^B) \Rightarrow R^A \Rightarrow R^B$
  - ▶ `ap` :  $R^{A \Rightarrow B} \Rightarrow R^A \Rightarrow R^B$
  - ▶ The connection is `flm = fi; ap` and `ap = fo; flm`
    - ★ However, here we need to flip the order of  $R$ -effects in `ap`
  - ▶ Connection between `ap` and `fo` is `fo x a = ap x (pure a)`
- If `flm = fi; ap` then `fi; fo` = id. Proof: set  $x^{R^{A \Rightarrow B}} = \text{fi } h^{A \Rightarrow R^B}$  and get `fo x a = ap (fi h) (pure a) = flm h (pure a) = h a`, so `fo (fi h) = h`
- Conversely: If `fi; fo` = id and `ap = fo; flm` then `flm = fi; ap`. Proof:  
`fi; ap = fi; fo; flm = flm`

# Rigid functors, their laws and structure II

Examples and constructions of rigid functors (see code):

- $R^A \equiv H^A \Rightarrow Q^A$  is a rigid functor (not monad) if  $Q^A$  is a rigid functor
- Not rigid:  $R^A \equiv W \times A$ ,  $R^A \equiv E + A$ ,  $\text{List}^A$ ,  $\text{Cont}^A$ ,  $\text{State}^A$

Use cases for rigid functors:

- A rigid functor is pointed: a natural transformation  $A \Rightarrow R^A$  exists
- A rigid functor has a single constructor because  $R^1 \cong 1$
- Handle multiple  $M^\bullet$  effects at once: For a rigid functor  $R^\bullet$  and any monad  $M^\bullet$ , have “ $R$ -valued  $M$ -flatMap”:  $M^A \times (A \Rightarrow R^{M^B}) \Rightarrow R^{M^B}$
- Uptake monadic API: For a rigid functor  $R^\bullet$ , can implement a general refactoring function, `refactor`:  $((A \Rightarrow B) \Rightarrow C) \Rightarrow (A \Rightarrow R^B) \Rightarrow R^C$ , to transform a program  $p(f^{A \Rightarrow B}) : C$  into  $\tilde{p}(\tilde{f}^{A \Rightarrow R^B}) : R^C$



# Rigid monads II: Composed-outside transformers

Base rigid monad  $R^\bullet$ , foreign monad  $M^\bullet$ , transformer  $T_R^{M,\bullet} \equiv T^\bullet \equiv R^{M^\bullet}$

- Monad instance: define the Kleisli category with morphisms  $A \Rightarrow R^{M^A}$
- $\text{pure}_T : A \Rightarrow R^{M^A}$  is defined by  $\text{pure}_T \equiv \text{pure}_M \circ \text{pure}_R = \text{pure}_R \circ \text{pure}_M^{\uparrow R}$
- $\text{ftn}_T : T^{T^A} \Rightarrow T^A$  must be defined case by case for each construction
  - ▶ If  $R^{M^\bullet}$  is a monad then we can define  $\text{seq} : M^{R^\bullet} \leadsto R^{M^\bullet}$
  - ▶ Choosing  $M^A \equiv Z \Rightarrow A$ , we get  $\text{seq} = \text{fi} : (Z \Rightarrow R^A) \Rightarrow R^{Z \Rightarrow A}$ 
    - ★ Open question: Is a rigid monad always a rigid functor?

Define **rigid monads** via the existence of composed-outside transformers

- Monad transformer methods for  $T_R^{M,\bullet} \equiv R^{M^\bullet}$ :
  - ▶ Lifting,  $\text{lift} : M^A \Rightarrow R^{M^A}$  is equal to  $\text{pure}_M$
  - ▶ Base lifting,  $\text{blift} : R^A \Rightarrow R^{M^A}$  is equal to  $\text{pure}_M^{\uparrow R}$
  - ▶ Runner,  $\text{mrun} : (\forall B. M^B \Rightarrow N^B) \Rightarrow R^{M^A} \Rightarrow R^{N^A}$  is equal to  $\text{fmap}_R$
  - ▶ Base runner,  $\text{brun} : (\forall B. R^B \Rightarrow B) \Rightarrow R^{M^A} \Rightarrow M^A$  is equal to  $\text{id}$
- Checking the monad transformer laws, case by case
  - ▶ The laws hold for  $R^A \equiv H^A \Rightarrow A$  and  $R^A \equiv F^{A \Rightarrow P^Q} \Rightarrow P^A$
  - ▶ The laws hold for composition and product of rigid monads
    - ★ Any other constructions or examples?

## \* Rigid monads III: Some tricks for proving the laws

- Several classes of monads involve a higher-order function, e.g.:
  - $R^A \equiv H^A \Rightarrow A$ ,  $R^A \equiv (A \Rightarrow P^Q) \Rightarrow P^A$ ,  $R^A \equiv \forall B. (A \Rightarrow F^B) \Rightarrow F^B$
- Proving laws for these monads is easier with these tricks:

- 1 Instead of defining  $\text{flm}_R$  or  $\text{ftn}_R$  directly, use the Kleisli functions and  $\diamond_R$

$$f:A \Rightarrow R^B \diamond_R g:B \Rightarrow R^C : A \Rightarrow R^C$$

- 2 Flip the arguments of the Kleisli functions: for example, instead of  $A \Rightarrow R^B \equiv A \Rightarrow (B \Rightarrow P^Q) \Rightarrow P^B$ , work with  $(B \Rightarrow P^Q) \Rightarrow A \Rightarrow P^B$
- 3 Use the Kleisli product for the nested monad: for example, to define

$$f:(B \Rightarrow P^Q) \Rightarrow A \Rightarrow P^B \diamond_R g:(C \Rightarrow P^Q) \Rightarrow B \Rightarrow P^C : (C \Rightarrow P^Q) \Rightarrow A \Rightarrow P^C$$

use the Kleisli product  $\diamond_P$  as  $m:A \Rightarrow P^B \diamond_P n:B \Rightarrow P^C : A \Rightarrow P^C$  to obtain  $B \Rightarrow P^Q$  from  $B \Rightarrow P^C$  and  $C \Rightarrow P^Q$ , and then to get  $A \Rightarrow P^C$

- Use “compatibility laws”: for any monad  $M$ , and denoting  $T^\bullet \equiv R^{M^\bullet}$ ,

$$\begin{array}{ccc} \text{ftn}_R = \text{pure}_M^{\uparrow R} \circ \text{ftn}_T & & (\text{ftn}_M)^{\uparrow R} = \text{pure}_R^{\uparrow T} \circ \text{ftn}_T \\ \begin{array}{ccc} R^{R^M A} & \xrightarrow{\text{ftn}_R} & R^{M A} \\ & \searrow \text{pure}_M^{\uparrow R} & \nearrow \text{ftn}_T \\ & R^{M R^M A} & \end{array} & & \begin{array}{ccc} R^{M^M A} & \xrightarrow{\text{ftn}_M^{\uparrow R}} & R^{M A} \\ & \searrow \text{pure}_R^{\uparrow T} & \nearrow \text{ftn}_T \\ & R^{M R^M A} & \end{array} \end{array}$$

# Rigid monads IV: Open questions

- What properties of  $\text{fi} : (A \Rightarrow R^B) \Rightarrow R^{A \Rightarrow B}$  define rigid monads?
  - ▶ The law  $\text{fi} \circ \text{fo} = \text{id}$  does not appear to be sufficient
  - ▶ Not clear if  $\text{fi} \circ \text{fo} = \text{id}$  follows from monadicity of  $R^{M^*}$
- A (generalized) functor from Kleisli category to “applicative” category?
  - ▶ Identity law:  $\text{fi}(\text{pure}_R) = \text{pure}_R(\text{id})$  – this holds
  - ▶ Composition law:  $\text{fi}(f \diamond_R g) = (p \times q \Rightarrow p \circ q)^{\uparrow R} (\text{fi } f \bowtie \text{fi } g)$

$$\begin{array}{ccccc}
 A \Rightarrow R^B & \times & B \Rightarrow R^C & \xrightarrow{\text{use } \diamond_R} & A \Rightarrow R^C \\
 \downarrow \text{fi} & & \downarrow \text{fi} & & \downarrow \text{fi} \\
 R^{A \Rightarrow B} & \times & R^{B \Rightarrow C} & \xrightarrow{\text{use } \bowtie} R^{(A \Rightarrow B) \times (B \Rightarrow C)} & \xrightarrow{\text{fmap}(\circ)} R^{A \Rightarrow C}
 \end{array}$$

★ not clear whether this holds

Define the rigid monad transformer using  $\text{fi}$ ?

- Define  $\diamond_T$  by  $f \diamond_T g \equiv \text{fo}((p \times q \Rightarrow p \diamond_M q)^{\uparrow R} (\text{fi } f \bowtie_R \text{fi } g))$

$$\begin{array}{ccccc}
 (A \Rightarrow R^{M^B}) & \diamond_T & (B \Rightarrow R^{M^C}) & \xrightarrow{\text{define } \diamond_T \text{ as}} & (A \Rightarrow R^{M^C}) \\
 \downarrow \text{fi} & & \downarrow \text{fi} & & \text{fo} \uparrow \\
 R^{A \Rightarrow M^B} & \bowtie_R & R^{B \Rightarrow M^C} & \xrightarrow{\text{fmap}_R(\diamond_M)} & R^{A \Rightarrow M^C}
 \end{array}$$

- ▶ not clear whether this holds

★ not clear whether associativity can be shown to hold in general

# Attempts to create a general monad transformer

General recipes for combining two functors  $L^\bullet$  and  $M^\bullet$  all fail:

- “Fake” transformers:  $T_L^{M,A} \equiv L^A$ ; or  $T_L^{M,A} \equiv M^A$ ; or just  $T_L^{M,A} \equiv 1$ 
  - ▶ no **lift** and/or no base runner and/or  $T_L^{\text{Id},A} \not\equiv L^A$
- Functor composition, disjunction, or product:  $L^{M^\bullet}$ ,  $M^{L^\bullet}$ ,  $L^\bullet + M^\bullet$  – not a monad in general;  $L^\bullet \times M^\bullet$  – no **lift** :  $M^\bullet \rightsquigarrow L^\bullet \times M^\bullet$
- Making a monad out of functor composition or disjunction:
  - ▶ free monad over  $L^{M^\bullet}$ ,  $\text{Free}^{L^{M^\bullet}}$  – **lift** violates lifting laws
  - ▶ free monad over  $L^\bullet + M^\bullet$ ,  $\text{Free}^{L^\bullet + M^\bullet}$  – **lift** violates lifting laws
    - ★ Laws will hold after interpreting the free monad into a concrete monad
  - ▶ codensity monad over  $L^{M^\bullet}$ :  $F^A \equiv \forall B. (A \Rightarrow L^{M^B}) \Rightarrow L^{M^B}$  – no **lift**
- Codensity-L transformer:  $\text{Cod}_L^{M,A} \equiv \forall B. (A \Rightarrow L^B) \Rightarrow L^{M^B}$  – no **lift**
  - ▶ applies the continuation transformer to  $M^A \cong \forall B. (A \Rightarrow B) \Rightarrow M^B$
- Codensity composition:  $F^A \equiv \forall B. (M^A \Rightarrow L^B) \Rightarrow L^B$  – not a monad
  - ▶ Counterexample:  $M^A \equiv R \Rightarrow A$  and  $L^A \equiv S \Rightarrow A$
- “Monoidal” convolution:  $(L \star M)^A \equiv \exists P \exists Q. (P \times Q \Rightarrow A) \times L^P \times M^Q$ 
  - ▶ combines  $L^A \cong \exists P. L^P \times (P \Rightarrow A)$  with  $M^A \cong \exists Q. M^Q \times (Q \Rightarrow A)$
  - ▶  $L \star M$  is not a monad for e.g.  $L^A \equiv 1 + A$  and  $M^A \equiv R \Rightarrow A$

# Exercises

- 1 Show that the method `pure`:  $A \Rightarrow M^A$  is a monadic morphism between monads  $\text{Id}^A \equiv A$  and  $M^A$ . Show that  $1 \Rightarrow 1 + A$  is not a monadic morphism.
- 2 Show that  $M_1^A + M_2^A$  is *not* a monad when  $M_1^A \equiv 1 + A$  and  $M_2^A \equiv Z \Rightarrow A$ .
- 3 Derive the composition law for `lift` written using `ftn` as  $\text{lift}_1 \circ \text{fmap}_{\text{BigM}} \text{lift}_1 \circ \text{ftn}_{\text{BigM}} = \text{ftn}_{M_1} \circ \text{lift}_1$  from the `flm`-based law  $\text{lift}_1 \circ \text{flm}_{\text{BigM}} (q \circ \text{lift}_1) = \text{flm}_{M_1} q \circ \text{lift}_1$ . Draw type diagrams for both laws.
- 4 Show that the continuation monad is not rigid and does not compose with arbitrary other monads. Show that the list and state monads are not rigid.
- 5 Show that  $\text{fo}(\text{pure}_P(f^{A \Rightarrow B})) = f \circ \text{pure}_P$  for any pointed functor  $P$ .
- 6 A rigid monad has a `pure` method because it is a monad, and also another `pure` method because it is a rigid functor. Show that these two `pure` methods must be the same.
- 7 Show that  $T_{L_1}^{M,A} \times T_{L_2}^{M,A}$  is the transformer for the monad  $L_1 \times L_2$ .