

Chapter 8: Applicative functors and profunctors

Part 2: Their laws and structure

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Deriving the `ap` operation from `map2`

Can we avoid having to define map_n separately for each n ?

- Use curried arguments, $\text{fmap}_2 : (A \Rightarrow B \Rightarrow Z) \Rightarrow F^A \Rightarrow F^B \Rightarrow F^Z$
- Set $A \equiv (B \Rightarrow Z)$ and apply fmap_2 to the identity $\text{id}^{(B \Rightarrow Z) \Rightarrow (B \Rightarrow Z)}$: obtain $\text{ap}^{[B, Z]} : F^{B \Rightarrow Z} \Rightarrow F^B \Rightarrow F^Z \equiv \text{fmap}_2(\text{id})$
- The functions `fmap2` and `ap` are computationally equivalent:

$$\text{fmap}_2 f^{A \Rightarrow B \Rightarrow Z} = \text{fmap } f \circ \text{ap}$$

$$\begin{array}{ccc} & F^{B \Rightarrow Z} & \\ \text{fmap } f \nearrow & & \searrow \text{ap} \\ F^A & \xrightarrow{\text{fmap}_2 (f^{A \Rightarrow B \Rightarrow Z})} & (F^B \Rightarrow F^Z) \end{array}$$

- The functions `fmap3`, `fmap4` etc. can be defined similarly:

$$\text{fmap}_3 f^{A \Rightarrow B \Rightarrow C \Rightarrow Z} = \text{fmap } f \circ \text{ap} \circ \text{fmap}_{F^B \Rightarrow ?} \text{ap}$$

$$\begin{array}{ccccc} & F^{B \Rightarrow C \Rightarrow Z} & \xrightarrow{\text{ap}^{[B, C \Rightarrow Z]}} & (F^B \Rightarrow F^{C \Rightarrow Z}) & \\ \text{fmap } f \nearrow & & & & \searrow \text{fmap}_{F^B \Rightarrow ?} \text{ap}^{[C, Z]} \\ F^A & \xrightarrow{\text{fmap}_3 (f^{A \Rightarrow B \Rightarrow C \Rightarrow Z})} & & & (F^B \Rightarrow F^C \Rightarrow F^Z) \end{array}$$

- Using the infix syntax will get rid of $\text{fmap}_{F^B \Rightarrow ?} \text{ap}$ (see example code)
 - ▶ Note the pattern: a natural transformation is equivalent to a lifting

Deriving the `zip` operation from `map2`

- The types $A \Rightarrow B \Rightarrow C$ and $A \times B \Rightarrow C$ are equivalent (curry/uncurry)
- Uncurry `fmap2` to `fmap2` : $(A \times B \Rightarrow C) \Rightarrow F^A \times F^B \Rightarrow F^C$
- Compute `fmap2(f)` with $f = \text{id}^{A \times B \Rightarrow A \times B}$, expecting to obtain a simpler natural transformation:

$$\text{zip} : F^A \times F^B \Rightarrow F^{A \times B}$$

- This is quite similar to `zip` for lists:

`List(1, 2).zip(List(10, 20)) = List((1, 10), (2, 20))`

- The functions `zip` and `fmap2` are computationally equivalent:

$$\begin{aligned}\text{zip} &= \text{fmap2}(\text{id}) \\ \text{fmap2}(f^{A \times B \Rightarrow C}) &= \text{zip} \circ \text{fmap } f\end{aligned}$$

$$\begin{array}{ccc} & F^{A \times B} & \\ \text{zip} \nearrow & & \searrow \text{fmap } f^{A \times B \Rightarrow C} \\ F^A \times F^B & \xrightarrow{\quad \text{fmap2}(f^{A \times B \Rightarrow C}) \quad} & F^C \end{array}$$

- The functor F is **zipable** if such a `zip` exists (with appropriate laws)
 - ▶ The same pattern: a natural transformation is equivalent to a lifting

* Equivalence of the operations `ap` and `zip`

- Set $A \equiv B \Rightarrow C$, get $\text{zip}^{[B \Rightarrow C, B]} : F^{B \Rightarrow C} \times F^B \Rightarrow F^{(B \Rightarrow C) \times B}$
- Use `eval` : $(B \Rightarrow C) \times B \Rightarrow C$ and $\text{fmap}(\text{eval}) : F^{(B \Rightarrow C) \times B} \Rightarrow F^C$
- Uncurry: $\text{app}^{[B, C]} : F^{B \Rightarrow C} \times F^B \Rightarrow F^C \equiv \text{zip} \circ \text{fmap}(\text{eval})$
- The functions `zip` and `app` are computationally equivalent:
 - ▶ use $\text{pair} : (A \Rightarrow B \Rightarrow A \times B) = a^A \Rightarrow b^B \Rightarrow a \times b$
 - ▶ use $\text{fmap}(\text{pair}) \equiv \text{pair}^\uparrow$ on an fa^{F^A} , get $(\text{pair}^\uparrow fa) : F^{B \Rightarrow A \times B}$; then

$$\text{zip}(fa \times fb) = \text{app}\left((\text{pair}^\uparrow fa) \times fb\right)$$

$$\text{app}^{[B, C]} = \text{zip}^{[B \Rightarrow C, B]} \circ \text{fmap}(\text{eval})$$

$$F^{B \Rightarrow C} \times F^B \begin{array}{c} \xrightarrow{\text{zip}} F^{(B \Rightarrow C) \times B} \\ \xrightarrow{\text{app}^{[B, C]}} F^C \\ \searrow \text{fmap}(\text{eval}) \end{array}$$

- Rewrite this using curried arguments: $\text{fzip}^{[A, B]} : F^A \Rightarrow F^B \Rightarrow F^{A \times B}$; $\text{ap}^{[B, C]} : F^{B \Rightarrow C} \Rightarrow F^B \Rightarrow F^C$; then $\text{ap } f = \text{fzip } f \circ \text{fmap}(\text{eval})$.
- Now $\text{fzip } p^{F^A} q^{F^B} = \text{ap}(\text{pair}^\uparrow p) q$, hence we may omit the argument q : $\text{fzip} = \text{pair}^\uparrow \circ \text{ap}$. With explicit types: $\text{fzip}^{[A, B]} = \text{pair}^\uparrow \circ \text{ap}^{[B, A \Rightarrow B]}$.

Motivation for applicative laws. Naturality laws for `map2`

Treat `map2` as a replacement for a monadic block with independent effects:

<pre>for { x ← cont1 y ← cont2 } yield g(x, y)</pre>	<pre>map2 (cont1, cont2) { (x, y) ⇒ g(x, y) }</pre>
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- Main idea: Formulate the monad laws in terms of `map2` and `pure`

Naturality laws: Manipulate data in one of the containers

<pre>for { x ← cont1.map(f) y ← cont2 } yield g(x, y)</pre>	<pre>for { x ← cont1 y ← cont2 } yield g(f(x), y)</pre>
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and similarly for `cont2` instead of `cont1`; now rewrite in terms of `map2`:

- **Left naturality** for `map2`:

```
map2(cont1.map(f), cont2)(g)  
= map2(cont1, cont2){ (x, y) ⇒ g(f(x), y) }
```

- **Right naturality** for `map2`:

```
map2(cont1, cont2.map(f))(g)  
= map2(cont1, cont2){ (x, y) ⇒ g(x, f(y)) }
```

Associativity and identity laws for `map2`

Inline two generators out of three, in two different ways:

```
for {
  x ← cont1
  (y, z) ← for {
    yy ← cont2
    zz ← cont3
  } yield (yy, zz)
} yield g(x, y, z)

for {
  (x, y) ← for {
    xx ← cont1
    yy ← cont2
  } yield (xx, yy)
  z ← cont3
} yield g(x, y, z)
```

Write this in terms of `map2` to obtain the **associativity law** for `map2`:

```
map2(cont1, map2(cont2, cont3)((_,_)) { case(x,(y,z)) ⇒ g(x,y,z) })
= map2(map2(cont1, cont2)((_,_)), cont3) { case((x,y),z) ⇒ g(x,y,z) }
```

Empty context precedes a generator, or follows a generator:

```
for { x ← pure(a)
      y ← cont
    } yield g(x, y)

for {
  y ← cont
} yield g(a, y)
```

Write this in terms of `map2` to obtain the **identity laws** for `map2` and `pure`:

```
map2(pure(a), cont)(g) = cont.map { y ⇒ g(a, y) }
map2(cont, pure(b))(g) = cont.map { x ⇒ g(x, b) }
```

Deriving the laws for `zip`: naturality law

- The laws for `map2` in a short notation; here $f \otimes g \equiv \{a \times b \Rightarrow f(a) \times g(b)\}$

$$\text{fmap2} \left(g^{A \times B \Rightarrow C} \right) \left(f^\uparrow q_1 \times q_2 \right) = \text{fmap2} \left((f \otimes \text{id}) \circ g \right) (q_1 \times q_2)$$

$$\text{fmap2} \left(g^{A \times B \Rightarrow C} \right) \left(q_1 \times f^\uparrow q_2 \right) = \text{fmap2} \left((\text{id} \otimes f) \circ g \right) (q_1 \times q_2)$$

$$\text{fmap2} (g_{1.23}) (q_1 \times \text{fmap2} (\text{id}) (q_2 \times q_3)) = \text{fmap2} (g_{12.3}) (\text{fmap2} (\text{id}) (q_1 \times q_2) \times q_3)$$

$$\text{fmap2} \left(g^{A \times B \Rightarrow C} \right) \left(\text{pure } a^A \times q_2^{F^B} \right) = (b \Rightarrow g(a \times b))^\uparrow q_2$$

$$\text{fmap2} \left(g^{A \times B \Rightarrow C} \right) \left(q_1^{F^A} \times \text{pure } b^B \right) = (a \Rightarrow g(a \times b))^\uparrow q_1$$

- Express `map2` through `zip`:

$$\text{fmap}_2 g^{A \times B \Rightarrow C} \left(q_1^{F^A} \times q_2^{F^B} \right) \equiv (\text{zip} \circ g^\uparrow) (q_1 \times q_2)$$

$$\text{fmap}_2 g^{A \times B \Rightarrow C} \equiv \text{zip} \circ g^\uparrow$$

- Combine the two naturality laws into one by using two functions f_1, f_2 :

$$(f_1^\uparrow \otimes f_2^\uparrow) \circ \text{fmap2 } g = \text{fmap2} \left((f_1 \otimes f_2)^\uparrow \circ g \right)$$

$$(f_1^\uparrow \otimes f_2^\uparrow) \circ \text{zip} \circ g^\uparrow = \text{zip} \circ (f_1 \otimes f_2)^\uparrow \circ g^\uparrow$$

- The **naturality law** for `zip` then becomes: $(f_1^\uparrow \otimes f_2^\uparrow) \circ \text{zip} = \text{zip} \circ (f_1 \otimes f_2)^\uparrow$

Deriving the laws for `zip`: associativity law

- Express `map2` through `zip` and substitute into the associativity law:

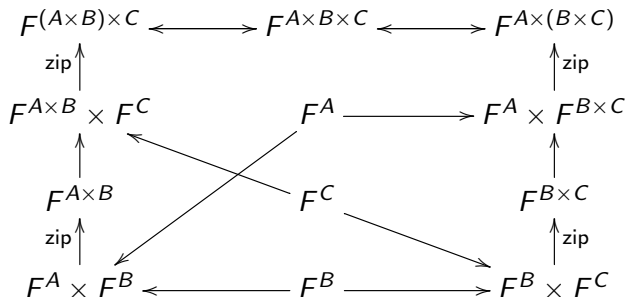
$$g_{1.23}^{\uparrow}(\text{zip}(q_1 \times \text{zip}(q_2 \times q_3))) = g_{12.3}^{\uparrow}(\text{zip}(\text{zip}(q_1 \times q_2) \times q_3))$$

- The arbitrary function g is preceded by transformations of the tuples,

$$a \times (b \times c) \equiv (a \times b) \times c \quad (\text{type isomorphism})$$

- Assume that the isomorphism transformations are applied as needed, then we may formulate the **associativity law** for `zip` more concisely:

$$\text{zip}(\text{zip}(q_1 \times q_2) \times q_3) \cong \text{zip}(q_1 \times \text{zip}(q_2 \times q_3))$$



Deriving the laws for `zip`: identity laws

- Identity laws seem to be complicated, e.g. the left identity:

$$g^\uparrow (\text{zip} (\text{pure } a \times q)) = (b \Rightarrow g (a \times b))^\uparrow q$$

- Replace `pure` by an *equivalent* “wrapped unit” method `wu: F[Unit]`

$$\text{wu}^{F^1} \equiv \text{pure}(1); \quad \text{pure}(a^A) = (1 \Rightarrow a)^\uparrow \text{wu}$$

Then the left identity law can be simplified using left naturality:

$$g^\uparrow (\text{zip} (((1 \Rightarrow a)^\uparrow \text{wu}) \times q)) = g^\uparrow (((1 \Rightarrow a) \otimes \text{id})^\uparrow \text{zip} (\text{wu} \times q))$$

- Denote $\phi^{B \Rightarrow 1 \times B} \equiv b \Rightarrow 1 \times b$ and $\beta_a^{1 \times B \Rightarrow A \times B} \equiv (1 \Rightarrow a) \otimes \text{id}$; then the function $b \Rightarrow g (a \times b)$ can be expressed more simply as $\phi \circ \beta_a \circ g$, and the identity law becomes

$$g^\uparrow (\beta_a^\uparrow \text{zip} (\text{wu} \times q)) = (\beta_a \circ g)^\uparrow (\text{zip} (\text{wu} \times q)) = (\phi \circ \beta_a \circ g)^\uparrow q = (\beta_a \circ g)^\uparrow (\phi^\uparrow q)$$

Omitting the common prefix $(\beta_a \circ g)^\uparrow$, we obtain the **left identity law**:

$$\text{zip} (\text{wu} \times q) = \phi^\uparrow q$$

- Note that ϕ^\uparrow is an isomorphism between F^B and $F^{1 \times B}$
 - ★ Assume that this isomorphism is applied as needed, then we may write

$$\text{zip} (\text{wu} \times q) \cong q$$

- Similarly, the **right identity law** can be written as $\text{zip} (q \times \text{wu}) \cong q$

Similarity between applicative laws and monoid laws

- Define infix syntax for `zip` and write $\text{zip}(p \times q) \equiv p \bowtie q$
- Then the associativity and identity laws may be written as

$$q_1 \bowtie (q_2 \bowtie q_3) \cong (q_1 \bowtie q_2) \bowtie q_3$$

$$(w u \bowtie q) \cong q$$

$$(q \bowtie w u) \cong q$$

These are the laws of a monoid (with some assumed transformations)

- Naturality law for `zip` written in the infix syntax:

$$f_1^\uparrow q_1 \bowtie f_2^\uparrow q_2 = (f_1 \otimes f_2)^\uparrow (q_1 \bowtie q_2)$$

- `wu` has no laws; the naturality for `pure` follows automatically
- The laws are simplest when formulated in terms of `zip` and `wu`
 - ▶ Naturality for `zip` will usually follow from parametricity
 - ★ A third naturality law for `map2` follows from defining `map2` through `zip`!
- “Zippable” functors have only the associativity and naturality laws
- Applicative functors are a strict superset of monadic functors
 - ▶ There are applicative functors that *cannot* be monads
 - ▶ Applicative functor implementation may disagree with the monad

A third naturality law for `map2`

- There must be one more naturality law for `map2`
- Transform the result of a `map2`:

```
( for {
  x ← cont1
  y ← cont2
} yield g(x, y) ).map(f)           for {
                                   x ← cont1
                                   y ← cont2
} yield f( g(x, y) )
```

- Write this in terms of `map2`, obtain a third naturality law:

```
map2(cont1, cont2)(g).map(f)
= map2(cont1, cont2)(g andThen f)
```

$$\text{fmap2}(g) \circ f^\uparrow = \text{fmap2}(g \circ f)$$

$$f^\uparrow(\text{fmap2}(g)(p \times q)) = \text{fmap2}(g \circ f)(p \times q)$$

- This law automatically follows if we define `map2` through `zip`:

$$\text{fmap2}(g) \circ f^\uparrow = \text{zip} \circ g^\uparrow \circ f^\uparrow = \text{zip} \circ (g \circ f)^\uparrow$$

- Note: We always have one naturality law per type parameter

Applicative operation `ap` as a “lifting”

- Consider `ap` as a “lifting” since it has type $F^{A \Rightarrow B} \Rightarrow (F^A \Rightarrow F^B)$
- A “lifting” should obey the identity and the composition laws
 - An “identity” value of type $F^{A \Rightarrow A}$, mapped to $\text{id}^{F^A \Rightarrow F^A}$ by `ap`
 - ★ A good candidate for that value is $\text{id}_\odot \equiv \text{pure}(\text{id}^{A \Rightarrow A})$
 - A “composition” of an $F^{A \Rightarrow B}$ and an $F^{B \Rightarrow C}$, yielding an $F^{A \Rightarrow C}$
 - ★ We can use `map2` to implement this composition, denoted $g \odot h$:

$$g^{F^{A \Rightarrow B}} \odot h^{F^{B \Rightarrow C}} \equiv \text{fmap2}(p^{A \Rightarrow B} \times q^{B \Rightarrow C} \Rightarrow p \circ q)(g, h)$$

- What are the laws that follow for $g \odot h$ from the `map2` laws?

$$\text{id}_\odot \odot h = h; \quad g \odot \text{id}_\odot = g$$

$$g^{F^{A \Rightarrow B}} \odot (h^{F^{B \Rightarrow C}} \odot k^{F^{C \Rightarrow D}}) = (g \odot h) \odot k$$

$$\left((x^{B \Rightarrow C} \Rightarrow f^{A \Rightarrow B} \circ x)^\uparrow g^{F^{B \Rightarrow C}} \right) \odot h^{F^{C \Rightarrow D}} = (x^{B \Rightarrow D} \Rightarrow f^{A \Rightarrow B} \circ x)^\uparrow (g \odot h)$$

$$g^{F^{A \Rightarrow B}} \odot \left((x^{B \Rightarrow C} \Rightarrow x \circ f^{C \Rightarrow D})^\uparrow h^{F^{B \Rightarrow C}} \right) = (x^{A \Rightarrow C} \Rightarrow x \circ f^{C \Rightarrow D})^\uparrow (g \odot h)$$

- The first 3 laws are the identity & associativity laws of a *category*
 - ★ The morphism type is $A \rightsquigarrow B \equiv F^{A \Rightarrow B}$, the composition is \odot
- The last 2 laws are naturality laws, connecting `fmap` and \odot
- Therefore `ap` is a functor’s “lifting” of morphisms from two categories

Deriving the category laws for (id_\odot, \odot)

The five laws for id_\odot and \odot follow from the five `map2` laws

- Consider $\text{id}_\odot \odot h$ and substitute the definition of \odot via `map2`, cf. slide 7:
 $\text{id}_\odot \odot h = \text{fmap2} (p \times q \Rightarrow p \circ q) (\text{pure}(\text{id}) \times h) = (b \Rightarrow \text{id} \circ b)^\uparrow h = h$
- The law $g \odot \text{id}_\odot = g$ is derived similarly
- Associativity law: $g \odot (h \odot k) = \text{fmap2}(\circ) (g \times \text{fmap2}(\circ) (h \times k))$ The 3rd naturality law gives: $\text{fmap2}(\circ) (h \times k) = (\circ)^\uparrow (\text{fmap2}(\text{id}) (h \times k))$, and then:

$$\begin{aligned} g \odot (h \odot k) &= \text{fmap2} (x \times (y \times z) \Rightarrow x \circ y \circ z) (g \times \text{fmap2}(\text{id}) (h \times k)) \\ (g \odot h) \odot k &= \text{fmap2} ((x \times y) \times z \Rightarrow x \circ y \circ z) (\text{fmap2}(\text{id}) (g \times h) \times k) \end{aligned}$$

Now the associativity law for `fmap2` yields $g \odot (h \odot k) = (g \odot h) \odot k$

- Derive naturality laws for \odot from the three `map2` naturality laws:
 $((x \Rightarrow f \circ x)^\uparrow g) \odot h = \text{fmap2}(\circ) ((x \Rightarrow f \circ x)^\uparrow g \times h) =$
 $\text{fmap2} (x \times y \Rightarrow f \circ x \circ y) (g \times h) = (x \Rightarrow f \circ x)^\uparrow (\text{fmap2}(\circ) (g \times h)) =$
 $(x \Rightarrow f \circ x)^\uparrow (g \odot h)$
- The law is $g \odot (x \Rightarrow x \circ f)^\uparrow h = (x \Rightarrow x \circ f)^\uparrow (g \odot h)$ is derived similarly

Deriving the functor laws for ap

Now that we established the laws for \odot , we have ap laws:

$$\text{ap}^{[B,Z]} : F^{B \Rightarrow Z} \Rightarrow F^B \Rightarrow F^Z = \text{fmap}_2 \left(\text{id}^{(B \Rightarrow Z) \Rightarrow (B \Rightarrow Z)} \right)$$

Identity law: $\text{ap}(\text{id}_{\odot}) = \text{id}^{F^A \Rightarrow F^A}$

- Derivation: $\text{ap}(\text{id}_{\odot}^{F^A \Rightarrow A})(q^{F^A}) = \text{fmap}_2(\text{id}^{(A \Rightarrow A) \Rightarrow A \Rightarrow A})(\text{pure}(\text{id}^{A \Rightarrow A}))(q^{F^A}) = \text{fmap}_2(f \times x \Rightarrow f(x))(\text{pure}(\text{id}) \times q) = (x \Rightarrow \text{id}(x))^{\uparrow} q = \text{id}^{\uparrow} q = q$
- Easier derivation: first, express ap via \odot using the isomorphisms

$$A \cong 1 \Rightarrow A; \quad F^A \cong F^{1 \Rightarrow A}$$

Then $\text{ap}(p^{F^B \Rightarrow Z})(q^{F^B}) \cong q^{F^{1 \Rightarrow B}} \odot p^{F^B \Rightarrow Z}$ and so $\text{ap}(\text{id}_{\odot})(q) \cong q \odot \text{id}_{\odot} = q$

Composition law: $\text{ap}(g \odot h) = \text{ap}(g) \circ \text{ap}(h)$

- Derivation: use $\text{ap } p \, q \cong q \odot p$ to get $\text{ap}(g \odot h)(q) \cong q \odot (g \odot h)$ while $(\text{ap}(g) \circ \text{ap}(h)) \, q = \text{ap}(h)(\text{ap}(g)(q)) \cong \text{ap}(h)(q \odot g) \cong (q \odot g) \odot h$

Constructions of applicative functors

- All monadic constructions still hold for applicative functors
 - Additionally, there are some non-monadic constructions
- 1 $F^A \equiv 1$ (constant functor) and $F^A \equiv A$ (identity functor)
 - 2 $F^A \equiv G^A \times H^A$ for any applicative G^A and H^A
 - ▶ but $G^A + H^A$ is in general *not* applicative
 - 3 $F^A \equiv A + G^A$ for any applicative G^A (**free pointed** over G)
 - 4 $F^A \equiv A + G^{F^A}$ (recursive) for any functor G^A (**free monad** over G)
 - 5 $F^A \equiv H^A \Rightarrow A$ for any contrafunctor H^A

Constructions that do not correspond to monadic ones:

- 6 $F^A \equiv Z$ (constant functor, Z a monoid)
 - 7 $F^A \equiv Z + G^A$ for any applicative G^A and monoid Z
 - 8 $F^A \equiv G^{H^A}$ when both G and H are applicative
 - 9 $F^A \equiv G^A + H^{G^A}$ where H is any functor and G is applicative
- Applicative that disagrees with its monad: $F^A \equiv 1 + (1 \Rightarrow A \times F^A)$
 - Examples of non-applicative functors: $F^A \equiv (P \Rightarrow A) + (Q \Rightarrow A)$,
 $F^A \equiv (A \Rightarrow P) \Rightarrow Q$, $F^A \equiv (A \Rightarrow P) \Rightarrow 1 + A$

All non-parameterized exp-poly types are monoids

- Using known monoid constructions (Chapter 7), we can implement $X + Y$, $X \times Y$, $X \Rightarrow Y$ as monoids when X and Y are monoids
- All primitive types have at least one monoid instance:
 - ▶ `Int`, `Float`, `Double`, `Char`, `Boolean` are “numeric” monoids
 - ▶ `Seq[A]`, `Set[A]`, `Map[K,V]` are set-like monoids
 - ▶ `String` is equivalent to a sequence of integers; `Unit` is a trivial monoid
- Therefore, all exponential-polynomial types without type parameters are monoids in at least one way
- Example of an exponential-polynomial type without type parameters:
 $\text{Int} + \text{String} \times \text{String} \times (\text{Int} \Rightarrow \text{Bool}) + (\text{Bool} \times \text{String} \Rightarrow 1 + \text{String})$
- Example of a non-monoid type with type parameters: $A \Rightarrow B$

By constructions 1, 3, and 7, *all* polynomial F^A with monoidal coefficients are applicative: write $F^A = Z_1 + A \times (Z_2 + A \times \dots)$ with some monoids Z_i

- Examples: $F^A = 1 + A \times A$ (this F^A cannot be a monad!)
- $F^A = A + A \times A \times Z$ where Z is a monoid (this F^A is a monad)

Previous examples of non-applicative functors are all *non-polynomial*

Definition and constructions of applicative contrafunctors

- The applicative functor laws, if formulated via `zip` and `wu`, do not use `map` and therefore can be formulated for contrafunctors
- Define an **applicative contrafunctor** C^A as having `zip` and `wu`:

$$\text{zip} : C^A \times C^B \Rightarrow C^{A \times B}; \quad \text{wu} : C^1$$

- Identity and associativity laws must hold for `zip` and `wu`
 - ▶ Note: applying `contramap` to the function $a \times b \Rightarrow a$ will yield some $C^A \Rightarrow C^{A \times B}$, but this will *not* give a valid implementation of `zip`!
- Naturality must hold for `zip`, but with `contramap` instead of `map`
 - ▶ There are no corresponding `pure` or `contraap`! But have $\forall A : P^A$

Applicative contrafunctor constructions:

- ① $C^A \equiv Z$ (constant functor, Z a monoid)
 - ② $C^A \equiv G^A \times H^A$ for any applicative contrafunctors G^A and H^A
 - ③ $C^A \equiv G^A + H^A$ for any applicative contrafunctors G^A and H^A
 - ④ $C^A \equiv H^A \Rightarrow G^A$ for any functor H^A and applicative contrafunctor G^A
 - ⑤ $C^A \equiv H^{G^A}$ for any functor H^A and applicative contrafunctor G^A
- All exponential-polynomial contrafunctors with monoidal coefficients are applicative! (These constructions cover all exp-poly cases.)

Definition and constructions of applicative profunctors

- **Profunctors** have the type parameter in both contravariant and covariant positions; they can have neither `map` nor `contramap`
 - ▶ They have `dimap` of type $(A \Rightarrow B) \times (B \Rightarrow A) \Rightarrow (F^A \Rightarrow F^B)$
- Examples of profunctors: $P^A \equiv \text{Int} \times A \Rightarrow A$; $P^A \equiv A + (A \Rightarrow R)$
- Example of non-profunctor: a GADT, $F^A \equiv \text{String}^{F^{\text{Int}}} + \text{Int}^{F^1}$
- All exp-poly type constructors are profunctors since the type parameter is always in either a covariant or a contravariant position
- Definition of **applicative profunctor**: has `zip` and `wu` with the laws
 - ▶ There is no corresponding `diap`! But have `pure` : $A \Rightarrow P^A$

Applicative profunctors admit all previous constructions, and in addition:

- ① $P^A \equiv G^A \times H^A$ for any applicative profunctors G^A and H^A
- ② $P^A \equiv Z + G^A$ for any applicative profunctor G^A and monoid Z
- ③ $P^A \equiv A + G^A$ for any applicative profunctor G^A
- ④ $P^A \equiv G^A + H^{G^A}$ for any functor H^A and applicative profunctor G^A
- ⑤ $P^A \equiv H^A \Rightarrow A$ for any profunctor H^A
- ⑥ $P^A \equiv H^{G^A}$ and G^{H^A} for any functor H^A and applicative profunctor G^A

Examples of non-applicative profunctors:

- $P^A \equiv (A \Rightarrow R) + (S \Rightarrow A)$; $P^A \equiv (A \Rightarrow A) \Rightarrow 1 + A$

Categorical overview of standard functor classes

The “liftings” show the types of category’s morphisms

class name	lifting’s name and type signature	category’s morphism
functor	$\text{fmap} : (A \Rightarrow B) \Rightarrow F^A \Rightarrow F^B$	$A \Rightarrow B$
filterable	$\text{fmapOpt} : (A \Rightarrow 1 + B) \Rightarrow F^A \Rightarrow F^B$	$A \Rightarrow 1 + B$
monad	$\text{flm} : (A \Rightarrow F^B) \Rightarrow F^A \Rightarrow F^B$	$A \Rightarrow F^B$
applicative	$\text{ap} : F^{A \Rightarrow B} \Rightarrow F^A \Rightarrow F^B$	$F^{A \Rightarrow B}$
contrafunctor	$\text{contrafmap} : (B \Rightarrow A) \Rightarrow F^A \Rightarrow F^B$	$B \Rightarrow A$
profunctor	$\text{dimap} : (A \Rightarrow B) \times (B \Rightarrow A) \Rightarrow F^A \Rightarrow F^B$	$(A \Rightarrow B) \times (B \Rightarrow A)$
contra-filterable	$\text{contrafmapOpt} : (B \Rightarrow 1 + A) \Rightarrow F^A \Rightarrow F^B$	$B \Rightarrow 1 + A$
Not yet considered:		
comonad	$\text{coflm} : (F^A \Rightarrow B) \Rightarrow F^A \Rightarrow F^B$	$F^A \Rightarrow B$

The laws are always just the category laws and the naturality laws

Need to define each category’s composition and identity morphism

- Obtained a systematic picture of the “standard” type classes
- Some classes (e.g. contra-applicative) aren’t covered by this scheme
- Some of the possibilities (e.g. “contramonad”) don’t actually work out

Exercises

- 1 Show that `pure` will be automatically a natural transformation when it is defined using `wu` as shown.
- 2 Use naturality of `pure` to show that $\text{pure } f \odot \text{pure } g = \text{pure } (f \circ g)$
- 3 Show that $F^A \equiv (A \Rightarrow Z) \Rightarrow (1 + A)$ is a functor but not applicative.
- 4 Show that P^S is a monoid if S is a monoid and P is any applicative functor, contrafunctor, or profunctor.
- 5 For any contrafunctor H^A , construction 5 shows that $F^A \equiv H^A \Rightarrow A$ is applicative. Implement the code of `zip(fa, fb)` for this construction.
- 6 Show that the recursive functor $F^A \equiv 1 + G^{A \times F^A}$ is applicative if G^A is applicative and wu_F is defined recursively as $0 + \text{pure}_G (1 \times \text{wu}_F)$.