Central Submonads and Notions of Computation

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Overview

- For any monoid M, its centre $Z(M)$ is a commutative submonoid;
- For any semiring R, its centre $Z(R)$ is a commutative subsemiring.
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Context:

- a symmetric monoidal category $(\mathbf{C}, I, \otimes)$,
- a strong monad $(\mathcal{T}, \eta, \mu, \tau)$.

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Context:

- a symmetric monoidal category $(\mathbf{C}, I, \otimes)$,
- a strong monad $(\mathcal{T}, \eta, \mu, \tau)$.

We wonder:

- Is there a commutative submonad of $\mathcal{T}$ which is its centre? When does it exist?
- Is there an appropriate computational interpretation?

Background

The Strength of a Monad

- For a monoid M, its centre is defined as

$$Z(M) \stackrel{\text{def}}{=} \{x \in M \mid \forall y \in M.\ x \cdot y = y \cdot x\}.$$

- Notice there is an implicit *swap* in the arguments.
- *But,* the definition of a monad is independent of any monoidal structure on the base category.
- Unclear how to define a suitable notion of centre for such monads.
- Instead, we introduce the centre for *strong* monads acting on symmetric monoidal categories.
- The monadic strength is a natural transformation $\tau_{X,Y} \colon X \otimes \mathcal{T} Y \to \mathcal{T}(X \otimes Y)$ that satisfies some coherence conditions w.r.t. monoidal structure.
- The monadic costrength is a natural transformation $\tau'_{X,Y} \colon \mathcal{T} X \otimes Y \to \mathcal{T}(X \otimes Y)$ that may be defined via τ and the monoidal symmetry.

Commutative Monads

Definition (Commutative Monad)

A strong monad $\mathcal{T}$ is said to be *commutative* if the following diagram:

$$\begin{array}{ccccc}
\mathcal{T}X \otimes \mathcal{T}Y & \xrightarrow{\tau_{\mathcal{T}X,Y}} & \mathcal{T}(\mathcal{T}X \otimes Y) & \xrightarrow{\mathcal{T}\tau'_{X,Y}} & \mathcal{T}^2(X \otimes Y) \\
\downarrow{\scriptstyle \tau'_{X,\mathcal{T}Y}} & & & & \downarrow{\scriptstyle \mu_{X\otimes Y}} \\
\mathcal{T}(X \otimes \mathcal{T}Y) & \xrightarrow[\mathcal{T}\tau_{X,Y}]{} & \mathcal{T}^2(X \otimes Y) & \xrightarrow[\mu_{X\otimes Y}]{} & \mathcal{T}(X \otimes Y)
\end{array}$$

commutes for every choice of objects X and Y.

Commutative vs Strong Monads

- The Kleisli category of a strong monad $\mathcal{T}$ does *not* have a canonical monoidal structure, in general. It has a canonical *premonoidal* structure [Power and Robinson, 1997].
- This premonoidal structure is monoidal iff $\mathcal{T}$ is commutative.
- This has important consequences for the computational interpretation as well.

Central Submonads on Set

The first example

Given a monoid (M, e, m), the writer monad: $(M \times -) : \mathbf{Set} \to \mathbf{Set}$ has the following monad structure:

- $\eta_X : X \to M \times X :: x \mapsto (e, x)$;
- $\mu_X : M \times (M \times X) \to M \times X :: (z, (z', x)) \mapsto (m(z, z'), x)$,
- $\tau_{X,Y} : X \times (M \times Y) \to M \times (X \times Y) :: (x, (z, y)) \mapsto (z, (x, y))$.

What should be the centre? What about $Z(M) \times -$?
Indeed, it is a commutative submonad of $(M \times -)$.

Commutative Monads in Set

$\mathcal{T}$: **Set** $\rightarrow$ **Set** is said to be *commutative* if the following diagram:

$$
\begin{array}{ccccc}
\mathcal{T}X \times \mathcal{T}Y & \xrightarrow{\tau_{\mathcal{T}X,Y}} & \mathcal{T}(\mathcal{T}X \times Y) & \xrightarrow{\mathcal{T}\tau'_{X,Y}} & \mathcal{T}^2(X \times Y) \\
{\scriptstyle \tau'_{X,\mathcal{T}Y}} \downarrow & & & & \downarrow {\scriptstyle \mu_{X \times Y}} \\
\mathcal{T}(X \times \mathcal{T}Y) & \xrightarrow[\mathcal{T}\tau_{X,Y}]{} & \mathcal{T}^2(X \times Y) & \xrightarrow[\mu_{X \times Y}]{} & \mathcal{T}(X \times Y)
\end{array}
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commutes for every choice of sets X and Y.

Commutative Monads in Set

$\mathcal{T} : \mathbf{Set} \to \mathbf{Set}$ is said to be *commutative* if the following diagram:

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\begin{array}{ccccc}
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\end{array}
$$

commutes for every choice of sets X and Y.
How would you define a <u>central submonad</u> $\mathcal{Z}$ of $\mathcal{T}$?

Central Subset

The trick is to consider all the monadic elements of $\mathcal{T}X$ that make the previous diagram commute.

Definition (Centre)

Given a set X, the *centre* of $\mathcal{T}$ at X, written $\mathcal{Z}X$, is defined to be the set

$$\mathcal{Z}X \stackrel{\text{def}}{=} \{t \in \mathcal{T}X \mid \forall Y \in \mathrm{Ob}(\mathbf{Set}).\forall s \in \mathcal{T}Y.$$
$$\mu(\mathcal{T}\tau'(\tau(t,s))) = \mu(\mathcal{T}\tau(\tau'(t,s)))\}.$$

We write $\iota_X : \mathcal{Z}X \subseteq \mathcal{T}X$ for the indicated subset inclusion.

The Central Submonad

- **Lemma:** The assignment $\mathcal{Z}(-)$ extends to a functor $\mathcal{Z} : \mathbf{Set} \to \mathbf{Set}$ when we define
$$\mathcal{Z}f \stackrel{\text{def}}{=} \mathcal{T}f|_{\mathcal{Z}X} : \mathcal{Z}X \to \mathcal{Z}Y,$$
for any function $f : X \to Y$.
- **Lemma:** For any two sets X and Y, the monadic unit $\eta_X : X \to \mathcal{T}X$, the monadic multiplication $\mu_X : \mathcal{T}^2X \to \mathcal{T}X$, and the monadic strength $\tau_{X,Y} : X \times \mathcal{T}Y \to \mathcal{T}(X \times Y)$ (co)restrict respectively to functions $\eta^{\mathcal{Z}}_X : X \to \mathcal{Z}X$, $\mu^{\mathcal{Z}}_X : \mathcal{Z}^2X \to \mathcal{Z}X$ and $\tau^{\mathcal{Z}}_{X,Y} : X \times \mathcal{Z}Y \to \mathcal{Z}(X \times Y)$.
- **Theorem:** The assignment $\mathcal{Z}(-)$ extends to a *commutative submonad* $(\mathcal{Z}, \eta^{\mathcal{Z}}, \mu^{\mathcal{Z}}, \tau^{\mathcal{Z}})$ of $\mathcal{T}$ with $\iota_X : \mathcal{Z}X \subseteq \mathcal{T}X$ the submonad morphism. Furthermore, there exists a canonical[1] isomorphism $\mathbf{Set}_{\mathcal{Z}} \cong Z(\mathbf{Set}_{\mathcal{T}})$.

[1] Details later.

Examples

- Continuation monad: $\mathcal{T} = [[-, S], S] : \mathbf{Set} \to \mathbf{Set}$.

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    - The centre is naturally isomorphic to the *identity monad*; therefore the centre is trivial.
- If $\mathcal{T}$ is commutative, its centre is itself.
- The centre of $(M \times -)$ is indeed $(Z(M) \times -)$.

Centralisable Monads in Symmetric Monoidal Categories

What about other categories?

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- What about strong monads in other categories?
- For this, we introduce the notion of central cone first.

Central cones

Definition (Central Cone)

A *central cone* of $\mathcal{T}$ at X is given by a pair (Z, ι), an object Z and a morphism $\iota : Z \to \mathcal{T}X$, such that the diagram:

$$
\begin{array}{ccccc}
Z \otimes \mathcal{T}Y & \xrightarrow{\iota \otimes \mathcal{T}Y} & \mathcal{T}X \otimes \mathcal{T}Y & \xrightarrow{\tau'_{X,\mathcal{T}Y}} & \mathcal{T}(X \otimes \mathcal{T}Y) \\
{\scriptstyle \iota \otimes \mathcal{T}Y}\downarrow & & & & \downarrow{\scriptstyle \mathcal{T}\tau_{X,Y}} \\
\mathcal{T}X \otimes \mathcal{T}Y & & & & \mathcal{T}^2(X \otimes Y) \\
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commutes.

Centralisable Monad

If (Z, ι) and (Z', ι') are two central cones of $\mathcal{T}$ at X, then a *morphism of central cones* $\varphi : (Z', \iota') \to (Z, \iota)$ is a morphism $\varphi : Z' \to Z$, such that $\iota \circ \varphi = \iota'$.

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Definition

We say that the monad $\mathcal{T}$ is *centralisable* if for any object X, a terminal central cone of $\mathcal{T}$ at X exists. We write $(\mathcal{Z}X, \iota_X)$ for the terminal central cone of $\mathcal{T}$ at X.

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Theorem

The assignment $\mathcal{Z}(-)$ extends to a commutative submonad $(\mathcal{Z}, \eta^{\mathcal{Z}}, \mu^{\mathcal{Z}}, \tau^{\mathcal{Z}})$ of $\mathcal{T}$ with $\iota : \mathcal{Z} \Rightarrow \mathcal{T}$ the submonad monomorphism.

Note that a submonad morphism induces a canonical embedding $\mathcal{I} : \mathbf{C}_{\mathcal{Z}} \to \mathbf{C}_{\mathcal{T}}$.

Kleisli Categories and Premonoidal Categories

Premonoidal category

- If $\mathbf{C}$ is symmetric monoidal and $\mathcal{T} : \mathbf{C} \to \mathbf{C}$ a strong monad;
- then $\mathbf{C}_{\mathcal{T}}$ does not necessarily have a monoidal structure,

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Definition (Central morphism [Power and Robinson, 1997])

A morphism $f : X \to Y$ in $\mathbf{C}_{\mathcal{T}}$ is *central* if for any morphism $f' : X' \to Y'$

in $\mathbf{C}_{\mathcal{T}}$, the following diagram:

$$\begin{array}{ccc} X \otimes X' & \xrightarrow{f \otimes_l X'} & Y \otimes X' \\ {\scriptstyle X \otimes_r f'} \downarrow & & \downarrow {\scriptstyle Y \otimes_r f'} \\ X \otimes Y' & \xrightarrow[f \otimes_l Y']{} & Y \otimes Y' \end{array}$$

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Central <u>cones</u> and central <u>morphisms</u> are actually equivalent notions!

Premonoidal Centre

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Proposition

If the strong monad $\mathcal{T}$ is centralisable, then the canonical embedding $\mathcal{I} : \mathbf{C}_{\mathcal{Z}} \to \mathbf{C}_{\mathcal{T}}$ corestricts to an isomorphism of categories $\hat{\mathcal{I}} : \mathbf{C}_{\mathcal{Z}} \to Z(\mathbf{C}_{\mathcal{T}})$.

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This is why we call $\mathcal{Z}$ <u>the</u> central submonad of $\mathcal{T}$.

Premonoidal adjunction

Kleisli adjunction

- In the Kleisli adjunction between $\mathbf{C}$ and $\mathbf{C}_{\mathcal{T}}$, the left adjoint, $\mathcal{J} : \mathbf{C} \to \mathbf{C}_{\mathcal{T}}$ always corestricts to $\hat{\mathcal{J}} : \mathbf{C} \to Z(\mathbf{C}_{\mathcal{T}})$.

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Proposition

If the strong monad $\mathcal{T}$ is centralisable, then $\hat{\mathcal{J}}$ is also a left adjoint and the adjunction induces the central submonad $\mathcal{Z}$.

Characterisation

The Main Theorem

Theorem (Centralisability)

Let $\mathbf{C}$ *be a symmetric monoidal category and* $\mathcal{T}$ *a strong monad on it. The following are equivalent:*

1. *For any object* X *of* $\mathbf{C}$, $\mathcal{T}$ *admits a terminal central cone at* X*;*
2. *There exists a commutative submonad* $\mathcal{Z}$ *of* $\mathcal{T}$ *such that the canonical embedding functor* $\mathcal{I} : \mathbf{C}_{\mathcal{Z}} \to \mathbf{C}_{\mathcal{T}}$ *corestricts to an isomorphism of categories* $\mathbf{C}_{\mathcal{Z}} \cong Z(\mathbf{C}_{\mathcal{T}})$*;*
3. *The corestriction of the Kleisli left adjoint* $\mathcal{J} : \mathbf{C} \to \mathbf{C}_{\mathcal{T}}$ *to the premonoidal centre* $\hat{\mathcal{J}} : \mathbf{C} \to Z(\mathbf{C}_{\mathcal{T}})$ *also is a left adjoint.*

Some Centralisable Monads and a non Centralisable one

- Using the main theorem, it follows every strong monad on many categories of interest (e.g., **Set**, **DCPO**, **Meas**, **Top**, **Hilb**, **Vect**) is centralisable.
- If **C** is a symmetric monoidal closed category that is total, then every strong monad on it is centralisable.
- If $\mathcal{T}$ is a commutative monad, then $\mathcal{T}$ is centralisable and its centre coincides with itself.

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Is every strong monad centralisable? No!
Example built with a full subcategory **C** of **Set** where not all subsets of $\mathcal{T}X$ are objects of **C**.

More monads with non-trivial centres

Example

The valuation monad $\mathcal{V}$: $\mathbf{DCPO} \to \mathbf{DCPO}$ is strong, but its commutativity is an open problem [Jones, 1990]. The central submonad of $\mathcal{V}$ is precisely the "central valuations monad" described in [Jia et al., 2021].

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Example

The *unbounded* Giry monad $\mathcal{G}$: **Meas** $\to$ **Meas**, which assigns the space of all (possibly unbounded) measures to a measurable space, is a strong monad which is *not* commutative. This monad is centralisable and its central submonad $\mathcal{Z}$ is such that $\mathcal{Z}X$ contains all discrete measures on the measurable space X (and possibly others).

Computational interpretation

A meta language

Refinement of Moggi's metalanguage;

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$A, B ::= \quad 1 \mid A \times B \mid A \to B \mid \mathcal{Z}A \mid \mathcal{T}A$

$$\frac{\Gamma, x : A \vdash M : B}{\Gamma \vdash \lambda x^A.M : A \to B} \qquad \frac{\Gamma \vdash M : A \to B \quad \Gamma \vdash N : A}{\Gamma \vdash MN : B}$$

$$\frac{\Gamma \vdash M : A}{\Gamma \vdash \texttt{ret}_{\mathcal{Z}}\ M : \mathcal{Z}A} \qquad \frac{\Gamma \vdash M : \mathcal{Z}A \quad \Gamma, x : A \vdash N : \mathcal{Z}B}{\Gamma \vdash \texttt{do}\ x \leftarrow_{\mathcal{Z}} M\ ;\ N : \mathcal{Z}B}$$

$$\frac{\Gamma \vdash M : \mathcal{Z}A}{\Gamma \vdash \iota M : \mathcal{T}A} \qquad \frac{\Gamma \vdash M : \mathcal{T}A \quad \Gamma, x : A \vdash N : \mathcal{T}B}{\Gamma \vdash \texttt{do}\ x \leftarrow_{\mathcal{T}} M\ ;\ N : \mathcal{T}B}$$

Computational use case for the centre of a monad

```
do                      do
  x <- op1                y <- op2
  y <- op2                x <- op1
  f x y                   f x y
```

If *at least one* of op1 or op2 is central, then the two programs are contextually equivalent!

Thank you!

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