

Mechanising Recursion Schemes with Magic-Free Coq Extraction

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02-05-2024



Background

Hylomorphisms

Fold over Lists

One way to guarantee **recursive functions** are **well-defined** is via **Recursion Schemes**.

```
foldr :: (a -> b -> b) -> b -> [a] -> b
foldr g b [] = b
foldr g b (x : xs) = g x (foldr g b xs)
```

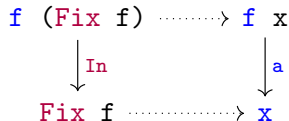
There are many different kinds of Recursion Schemes (e.g. Folds, Paramorphisms, Unfolds, Apomorphisms, ...)

Folds as Initial Algebras

```
data Fix f = In { inOp :: f (Fix f) }
```

```
fold :: Functor f =>  
      (f x -> x) ->  
      Fix f ->  
      x
```

```
fold a = a . fmap (fold a) . inOp
```



Folds as Initial Algebras

Least Fixed-Point

$\text{Fix } f \cong f (\text{Fix } f)$

```
data Fix f = In { in0p :: f (Fix f) }
```

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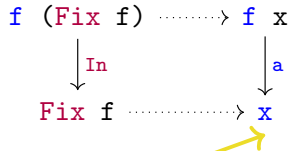
$$\begin{array}{ccc} f (\text{Fix } f) & \cdots \rightarrow & f x \\ \downarrow \text{In} & & \downarrow a \\ \text{Fix } f & \cdots \rightarrow & x \end{array}$$

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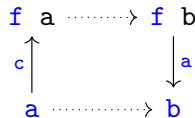
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f-algebra

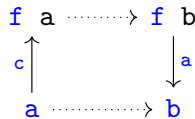
Hylomorphisms: Divide-and-conquer Computations

```
hylo :: Functor f =>
    (f b -> b) ->
    (a -> f a) ->
    a -> b
hylo a c = a . fmap (hylo a c) . c
```



Hylomorphisms: Divide-and-conquer Computations

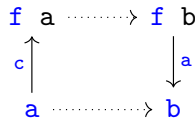
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f-algebra
("divide")

Hylomorphisms: Divide-and-conquer Computations

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hylo :: Functor f =>
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f -coalgebra
("conquer")

Folds as Hylomorphisms

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data Fix f = In { inOp :: f (Fix f) }
```

```
fold :: Functor f =>  
      (f x -> x) ->  
      Fix f ->  
      x
```

```
fold a = a ← fmap (fold a) . inOp
```

f-coalgebra

$f \text{ (Fix f)} \cdots \rightarrow f \text{ x}$
 $\text{inOp} \uparrow$
 $\text{Fix f} \cdots \rightarrow \text{x}$
 $\downarrow \text{a}$

f-algebra

Adjoint Folds

Given an adjunction:

$$\mathcal{D} \begin{array}{c} \xrightarrow{R} \\ \perp \\ \xleftarrow{L} \end{array} \mathcal{C}$$

- There is a correspondence of arrows $[\cdot] : \text{Hom}_{\mathcal{D}}(L A, B) \cong \text{Hom}_{\mathcal{C}}(A, R B) : [\cdot]$.
- An initial algebra on the right corresponds to an universal property on the left $(\mu F \cong F \mu F)$:

$$\text{Hom}_{\mathcal{D}}(L \mu F, B) \cong \text{Hom}_{\mathcal{C}}(\mu F, R B)$$

Conjugate Hylomorphisms

Every recursion scheme is a conjugate hylomorphism

<i>recursion scheme</i>	<i>adjunction</i>	<i>conjugates</i>	<i>para-hylo equation</i>	<i>algebra</i>
(hylo-shift law)	$\text{Id} \dashv \text{Id}$	$\alpha \dashv \alpha$	$x = a \cdot (\text{id} \triangle D x \cdot \alpha C \cdot c) : A \leftarrow C$	$a : C \times D A \rightarrow A$
mutual recursion	$\Delta \dashv (\times)$	ccf	$x_1 = a_1 \cdot (\text{id} \triangle D (x_1 \triangle x_2) \cdot c) : A_1 \leftarrow C$ $x_2 = a_2 \cdot (\text{id} \triangle D (x_1 \triangle x_2) \cdot c) : A_2 \leftarrow C$	$a_1 : C \times D (A_1 \times A_2) \rightarrow A_1$ $a_2 : C \times D (A_1 \times A_2) \rightarrow A_2$
accumulator	$- \times P \dashv (-)^P$	ccf	$x = a \cdot (\text{outl} \triangle ((D (\wedge x) \cdot c) \times P)) : A \leftarrow C \times P$	$a : C \times D (A^P) \times P \rightarrow A$
course-of-values (§5.6)	$U_D \dashv \text{Cofree}_D$	ccf	$x = a \cdot (\text{id} \triangle D (D_\infty x \cdot [c]) \cdot c) : A \leftarrow C$	$a : C \times D (D_\infty A) \rightarrow A$
finite memo-table (§5.6)	$U_* \dashv \text{Cofree}_*$	ccf	$x = a \cdot (\text{id} \triangle D (D_* x \cdot [c]_*) \cdot c) : A \leftarrow C$	$a : C \times D (D_* A) \rightarrow A$

Table 1. Different types of para-hylos building on the canonical control functor (ccf); the coalgebra is $c : C \rightarrow D C$ in each case.

Why Mechanising Hylomorphisms in Coq?

- Structured Recursion Schemes have been used in Haskell to structure functional programs, but they do not ensure termination/productivity
- On the other hand, Coq does not capture all recursive definitions
- The benefits of formalising hyls in Coq is two fold:
 - Giving the Coq programmer a library where for most recursion schemes they do not have to prove termination properties
 - Extracting code into ML/Haskell to provide termination guarantees even in languages with non-termination

Goals

1. Avoiding axioms: functional extensionality, heterogeneous equality,
2. Extracting “clean” code: close to what a programmer would have written directly in OCaml.
3. Fixed-points of functors, non-termination, etc.

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3. **Containers & recursive coalgebras**

Roadmap

Part I: Extractable Containers in Coq

Part II: Recursive Coalgebras & Coq Hylomorphisms

Part III: Code Extraction & Examples

Part I

Extractable Containers in Coq

Part II

Recursive Coalgebras & Coq Hylomorphisms

Part III

Code Extraction & Examples

Wrap-up

