

# Handling Fibred Algebraic Effects

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A Venn diagram consisting of two overlapping rounded rectangles. The left rectangle has a blue border and contains the text 'Dependent Types' and 'Programming + Logic'. The right rectangle has a red border and contains the text 'Effect Handlers' and 'Effectful Programming'. The overlapping area is the intersection of the two rectangles.

**Dependent Types**

Programming + Logic

**Effect Handlers**

Effectful Programming

**Dependent Types**

Programming + Logic



**Effect Handlers**

Effectful Programming

# Outline

- Setting the scene
  - **Algebraic effects** and their **handlers**
  - An effectful dependently typed **core calculus** (FoSSaCS'16)  
[A., Ghani, Plotkin'16]
- What can we gain from handlers + dependent types?
  - Modular programming with handlers + expressiveness of d. types
  - **Extrinsic reasoning** about effectful computations
- Extending the FoSSaCS'16 calculus with alg. effects and handlers
  - Take 1: The common **term-level def.** of handlers (unsoundness)
  - Take 2: A new **type-level treatment** of handlers

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# Algebraic effects

- Moggi taught us to model comp. effects using **monads**  $(T, \eta, (-)^\dagger)$

$$\eta_A : A \rightarrow TA \qquad (f : A \rightarrow TB)^\dagger_{A,B} : TA \rightarrow TB$$

- Plotkin and Power showed that most of these monads arise from
  - **operation symbols** – representing the **sources** of effects

$$\text{raise} : \text{Exc} \longrightarrow 0 \qquad \text{get} : \text{Loc} \longrightarrow \text{Val} \qquad \text{put} : \text{Loc} \times \text{Val} \longrightarrow 1$$

- **equations** – describing the computational **behaviour**

$$\ell : \text{Loc} \mid w : 1 \vdash \text{get}_\ell(x.\text{put}_{\langle \ell, x \rangle}(w(\star))) = w(\star)$$

- The algebraic approach significantly simplifies
  - **choosing** a monad/adjunction to model a given language
  - modelling **combinations** of two or more comp. effects
  - **generic** effectful programming (via **handlers**)

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# Handlers of algebraic effects

- Plotkin and Pretnar's **handlers** of algebraic effects
  - generalisation of exception handlers
  - given by **redefining** the given ops. (handlers denote **algebras**)
  - many uses – rollbacks, stream redirection, concurrency, ...
- Usually included in languages using the **handling** construct

$M$  handled with  $\{\text{op}_{x_v}(x_k) \mapsto N_{\text{op}}\}_{\text{op} \in S_{\text{eff}}}$  to  $y:A \text{ in } \underline{C} \ N_{\text{ret}}$

interpreted using the **homomorphism**  $FA \longrightarrow \langle U\underline{C}, \overrightarrow{N_{\text{op}}} \rangle$ , i.e.,

$(\text{op}_V(y.M))$  handled with  $\{\dots\}_{\text{op} \in S_{\text{eff}}}$  to  $y:A \text{ in } \underline{C} \ N_{\text{ret}}$   
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$N_{\text{op}}[V/x_v][\lambda y:O. \text{thunk}(M \text{ handled with } \dots)/x_k]$

and

$(\text{return } V)$  handled with  $\{\dots\}_{\text{op} \in S_{\text{eff}}}$  to  $y:A \text{ in } \underline{C} \ N_{\text{ret}} = N_{\text{ret}}[V/y]$

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# A core dependently typed effectful calculus

- (Model-theoretically) natural extension of type theory
  - clear distinction between **values** and **computations** (CBPV, EEC)
- Value types  $(\Gamma \vdash A)$  and computation types  $(\Gamma \vdash \underline{C})$

$$A, B ::= \dots \mid U\underline{C} \quad \underline{C}, \underline{D} ::= FA \mid \Pi x:A. \underline{C} \mid \boxed{\Sigma x:A. \underline{C}}$$

- Value terms  $(\Gamma \vdash V : A)$

$$V, W ::= \dots \mid \text{thunk } M$$

- Computation terms  $(\Gamma \vdash M : \underline{C})$

$$M, N ::= \text{return } V \mid M \text{ to } x:A \text{ in}_{\underline{C}} N \mid \lambda x:A. M \mid M V \\ \mid \langle V, M \rangle \mid \boxed{M \text{ to } (x:A, z:\underline{C}) \text{ in}_{\underline{D}} K} \mid \text{force}_{\underline{C}} V$$

- Homomorphism terms  $(\Gamma \mid z:\underline{C} \vdash K : \underline{D})$

$$K, L ::= z \mid K \text{ to } x:A \text{ in}_{\underline{C}} M \mid \dots \quad (\text{stack terms, eval, cbs.})$$

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# The calculus we work in

- We work in an extension to the FoSSaCS'16 calculus, with
  - a Tarski-style **value universe**  $\mathcal{U}$ 
    - with **codes** written as  $\hat{\Pi}, \hat{\Sigma}, \hat{0}, \hat{1}, \dots$
    - but thinking of them as  $\forall, \exists, \perp, \top, \dots$
  - fibred **algebraic effects**
    - dep. typed **operation symbols**  $\text{op} : (x_v : I) \longrightarrow O$
    - ops. determine **comp. terms**  $\text{op}_V^C(y : O[V/x_v]. M)$
    - effect eqs. determine **definitional eqs.**
  - a **derivable** “into-comps.” variant of **handlers** and **handling**  
 $M$  handled with  $\{\text{op}_{x_v}(x_k) \mapsto N_{\text{op}}; \overrightarrow{W_{\text{eq}}}\}_{\text{op} \in S_{\text{eff}}}$  to  $y : A$  in  $\underline{C} \ N_{\text{ret}}$
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# Reasoning about effectful computations

- Handlers are useful for **extrinsic reasoning**!
- They help us to reason about effectful computations  $M : FA$ 
  - Can be used to define **predicates**  $P : UFA \rightarrow \mathcal{U}$  by
    - 1) equipping  $\mathcal{U}$  (or a resp. type) with an **algebra** structure
    - 2) **handling** the given computation using that algebra
  - Intuitively,  $P$  (**think**  $M$ ) computes a **proof obligation** for  $M$
  - We discuss **three examples** of such predicates
- Also, can be an alternative to mon. reification for **rel. reasoning**
  - E.g., relating **stateful comps.**  $M, N : FA$  as **functions**  $S \rightarrow A \times S$
  - Not investigated in this paper
  - See [Grimm et al.'18] for **reification-based** relational reasoning

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# Ex1: Lifting predicates to effectful comps.

- Given a predicate  $P : A \rightarrow \mathcal{U}$  on **return values**,

we define a predicate  $\Box P : UFA \rightarrow \mathcal{U}$  on **(I/O)-comps.** as

$$\Box P \stackrel{\text{def}}{=} \lambda y : UFA. (\text{force } y) \text{ handled with } \{\dots\}_{\text{op} \in \mathcal{S}_{\text{I/O}}} \text{ to } y' : A \text{ in } P y'$$

using the **handler** given by

$$\text{read}(x_k) \mapsto \widehat{\Pi} y : \text{El}(\widehat{\text{Chr}}). x_k y \quad (\text{where } x_k : \text{Chr} \rightarrow \mathcal{U})$$

$$\text{write}_{x_v}(x_k) \mapsto x_k \star \quad (\text{where } x_v : \text{Chr}, x_k : 1 \rightarrow \mathcal{U})$$

- $\Box P$  is similar to the **necessity modality** from Evaluation Logic

$$\Gamma \vdash \Box P (\text{think}(\text{read}(x.\text{write}_{e'}(\text{return } V)))) = \widehat{\Pi} x : \text{El}(\widehat{\text{Chr}}). P V$$

- To get  $\Diamond P$ , we only have to replace  $\widehat{\Pi}$  with  $\widehat{\Sigma}$  in the handler

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$$\Box P \stackrel{\text{def}}{=} \lambda y : UFA. (\text{force } y) \text{ handled with } \{\dots\}_{\text{op} \in \mathcal{S}_{\text{I/O}}} \text{ to } y' : A \text{ in } P y'$$

using the **handler** given by

$$\text{read}(x_k) \mapsto \hat{\Pi} y : \text{El}(\widehat{\text{Chr}}). x_k y \quad (\text{where } x_k : \text{Chr} \rightarrow \mathcal{U})$$

$$\text{write}_{x_v}(x_k) \mapsto x_k \star \quad (\text{where } x_v : \text{Chr}, x_k : 1 \rightarrow \mathcal{U})$$

- $\Box P$  is similar to the **necessity modality** from Evaluation Logic

$$\Gamma \vdash \Box P (\text{thunk} (\text{read}(x.\text{write}_{e'}(\text{return } V)))) = \hat{\Pi} x : \text{El}(\widehat{\text{Chr}}). P V$$

- To get  $\Diamond P$ , we only have to replace  $\hat{\Pi}$  with  $\hat{\Sigma}$  in the handler

## Ex2: Dijkstra's weakest precondition sem.

- Given a postcondition on **return values** and **final states**

$$Q : A \rightarrow S \rightarrow \mathcal{U} \qquad (S \stackrel{\text{def}}{=} \prod \ell : \text{Loc}. \text{Val}(\ell))$$

we define a precondition for **stateful comps.** on **initial states**

$$\text{wp}_Q : \text{UFA} \rightarrow S \rightarrow \mathcal{U}$$

by

- 1) handling the given comp. into a **state-passing function** using

$$V_{\text{get}}, V_{\text{put}} \quad \text{on} \quad S \rightarrow \mathcal{U} \times S \qquad \text{and} \qquad V_{\text{ret}} \text{ ``="} Q$$

- 2) feeding in the **initial state**; and 3) projecting out the **value of  $\mathcal{U}$**

- Then,  $\text{wp}_Q$  satisfies the **expected properties**, such as

$$\Gamma \vdash \text{wp}_Q (\text{think} (\text{return } V)) \quad = \quad \lambda x_S : S. Q \ V \ x_S$$

$$\Gamma \vdash \text{wp}_Q (\text{think} (\text{put}_{(\ell, V)}(M))) \quad = \quad \lambda x_S : S. \text{wp}_Q (\text{think } M) \ x_S[\ell \mapsto V]$$

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## Ex3: Allowed patterns of (I/O)-effects

- Assuming an inductive type of **I/O-protocols**, given by

$$e : \text{Protocol} \quad r : (\text{Chr} \rightarrow \text{Protocol}) \rightarrow \text{Protocol}$$

$$w : (\text{Chr} \rightarrow \mathcal{U}) \times \text{Protocol} \rightarrow \text{Protocol}$$

- We can define a **relation** between **comps.** and **protocols**

$$\text{Allowed} : \text{UFA} \rightarrow \text{Protocol} \rightarrow \mathcal{U}$$

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given by (using pattern-matching lambda notation)

$$\begin{aligned} \text{read}(x_k) &\mapsto \lambda \{ (r \ x_{pr}) \rightarrow \widehat{\Pi} y : \text{El}(\widehat{\text{Chr}}) . x_k \ y \ (x_{pr} \ y) ; \\ &\quad - \rightarrow \widehat{0} \} \end{aligned}$$

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# Outline

- Setting the scene
  - **Algebraic effects** and their **handlers**
  - An effectful dependently typed **core calculus** (FoSSaCS'16)  
[A., Ghani, Plotkin'16]
- What can we gain from handlers + dependent types?
  - Modular programming with handlers + expressiveness of d. types
  - **Extrinsic reasoning** about effectful computations
- Extending the FoSSaCS'16 calculus with alg. effects and handlers
  - Take 1: The common **term-level def.** of handlers (unsoundness)
  - Take 2: A new **type-level treatment** of handlers

# Extending the FoSSaCS'16 calculus

- We assume given a **fibred effect theory**  $\mathcal{T} = (\mathcal{S}, \mathcal{E})$
- First, we extend the calculus with **algebraic effects** as follows:

- we extend the **computation terms** with

$$M, N ::= \dots \mid \text{op}_V^{\underline{C}}(y : O[V/x_v]. M) \quad (\text{op} : (x_v : I) \longrightarrow O \in \mathcal{S})$$

- we extend the **equational theory** with equations given in  $\mathcal{E}$
- we capture the **interaction** of comp. terms and ops. with the eq.

$$\frac{\Gamma \vdash V : I \quad \Gamma, x : O[V/x_v] \vdash M : \underline{C} \quad \Gamma \mid z : \underline{C} \vdash K : \underline{D}}{\Gamma \vdash K[\text{op}_V^{\underline{C}}(x.M)/z] = \text{op}_V^{\underline{D}}(x.K[M/z]) : \underline{D}} \quad (\text{op} : (x_v : I) \longrightarrow O \in \mathcal{S})$$

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# Take 1: Term-level definition of handlers

- Begin by extending the FoSSaCS'16 **computation terms** with
$$M, N ::= \dots \mid M \text{ handled with } \{\text{op}_{x_v}(x_k) \mapsto N_{\text{op}}\}_{\text{op} \in S_{\text{eff}}} \text{ to } y:A \text{ in}_{\underline{C}} N_{\text{ret}}$$
- But as handling denotes a **homomorphism**, then perhaps also
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$$\Gamma \vdash \text{write}_a(\text{return } \star) = \text{write}_z(\text{return } \star) : F1$$

- At a very high-level, the problem is (see the paper for details)
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# How to proceed?

- Possible ways to solve this unsoundness problem
  - **Option 1:** Change the FoSSaCS'16 calculus
    - change the equational theory of homomorphism terms
    - hom. terms would not denote homomorphisms any more
    - investigated for exceptions in CBPV with stacks by [Levy'06]
  - **Option 2:** Keep the FoSSaCS'16 calculus **unchanged**
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## Take 2: A type-level treatment of handlers

- Instead, we extend the FoSSaCS'16 **computation types** with
  - a **user-defined algebra type**

$$\underline{C}, \underline{D} ::= \dots \mid \langle A; \overrightarrow{V_{\text{op}}}; \overrightarrow{W_{\text{eq}}} \rangle$$

where

- $A$  is the **carrier** value type
  - $\overrightarrow{V_{\text{op}}}$  is a set of user-defined **operations**
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- As a result, we can derive the **handing construct** as

$$\begin{array}{c} M \text{ handled with } \{\text{op}_{x_v}(x_k) \mapsto \overrightarrow{N_{\text{op}}}; \overrightarrow{W_{\text{eq}}}\}_{\text{op} \in S_{\text{eff}}} \text{ to } y:A \text{ in } \underline{C} \ N_{\text{ret}} \\ \underline{\text{def}} \\ \text{force}_{\underline{C}}(\text{thunk}(\underbrace{M \text{ to } y:A \text{ in force}_{\langle \underline{C}; \overrightarrow{V_{N_{\text{op}}}}; \overrightarrow{W_{\text{eq}}} \rangle}(\text{thunk } N_{\text{ret}}))}_{\text{temporarily working at type } \langle \underline{C}; \overrightarrow{V_{N_{\text{op}}}}; \overrightarrow{W_{\text{eq}}} \rangle})) \end{array}$$

and similarly for the “**into-values**” variant of it

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# Conclusion

- In conclusion
  - handlers are natural for defining **predicates on computations**
    - lifting predicates from return values to computations
    - Dijkstra's weakest precondition semantics of state
    - specifying patterns of allowed (I/O)-effects
  - they admit a principled **type-based treatment**
- See the paper for
  - **formal details** of what I have shown you today
  - families fibrations based **denotational semantics**
  - discussion about the calculus's inherent **extensional nature**
  - **Agda code** for the example predicates  $P : UFA \rightarrow \mathcal{U}$

Thank you!

Questions?