Handling Fibred Computational Effects

Effect Handlers in a Dependently Typed Setting

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Outline

- Setting the scene
  - Algebraic effects and their handlers
  - A core dependently typed effectful calculus (FoSSaCS'16)
- Why handlers + dependent types?
  - Programming with handlers + expressiveness of dep. types
  - Useful for defining predicates/types depending on computations
- Extending the FoSSaCS'16 calculus with handlers
  - Take 1: The common term-level def. of handlers (unsound)
  - Take 2: A type-level treatment of handlers

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Algebraic effects and their handlers

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

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

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

$$\mathsf{raise} : \mathsf{Exc} \longrightarrow 0 \qquad \mathsf{read} : \mathsf{Loc} \longrightarrow \mathsf{Val} \qquad \mathsf{write} : \mathsf{Loc} \times \mathsf{Val} \longrightarrow 1$$

  - **equations** – describing the computational behaviour

$$\ell{:}\mathsf{Loc} \mid w{:}1 \vdash \mathtt{read}_\ell(x.\mathtt{write}_{\langle \ell, x\rangle}(w(\star))) = w(\star)$$

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

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- Plotkin and Pretnar's **handlers** of algebraic effects
  - generalise exception handlers
  - given by redefining the given operations (they denote **algebras**)
  - example uses – rollbacks, stream redirection, concurrency, ...

- Usually included in languages using the **handling** construct

$$M \;\texttt{handled with}\; \{\mathsf{op}_x(x') \mapsto N_{\mathsf{op}}\}_{\mathsf{op} \in \mathcal{S}_{\mathsf{eff}}} \;\texttt{to}\; y : A \;\texttt{in}_{\underline{C}}\; N_{\mathsf{ret}}$$

  denoting the **homomorphism** $FA \longrightarrow \{\mathsf{op}_x(x') \mapsto N_{\mathsf{op}}\}_{\mathsf{op} \in \mathcal{S}_{\mathsf{eff}}}$

$$(\texttt{op}_V(y.M)) \;\texttt{handled with}\; \{\ldots\}_{\mathsf{op} \in \mathcal{S}_{\mathsf{eff}}} \;\texttt{to}\; y : A \;\texttt{in}_{\underline{C}}\; N_{\mathsf{ret}}$$
$$=$$
$$N_{\mathsf{op}}[V/x][\lambda\, y : O \,.\, \texttt{thunk}\,(M \;\texttt{handled with}\; \ldots)/x']$$

  and

$$(\texttt{return}\; V) \;\texttt{handled with}\; \{\ldots\}_{\mathsf{op} \in \mathcal{S}_{\mathsf{eff}}} \;\texttt{to}\; y : A \;\texttt{in}_{\underline{C}}\; N_{\mathsf{ret}} \;=\; N_{\mathsf{ret}}[V/y]$$

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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** ($\Gamma \vdash \underline{C}$)

$$A, B ::= \ \ldots \ \mid \ U\underline{C} \qquad \underline{C}, \underline{D} ::= FA \mid \Pi\, x{:}A \,.\, \underline{C} \ \mid \ \Sigma\, x{:}A \,.\, \underline{C}$$

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

$$V, W ::= x \ \mid \ \ldots \ \mid \ \mathtt{thunk}\ M$$

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

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Defining predicates on effectful comps.

- For time being, assume that we have **handlers** in the calculus
  - In particular, assume that we can also **handle into values**

$$M \;\mathtt{handled}\;\mathtt{with}\; \{\mathtt{op}_x(x') \mapsto V_{\mathtt{op}}\}_{\mathtt{op} \in \mathcal{S}_{\mathsf{eff}}} \;\mathtt{to}\; y\!:\!A \;\mathtt{in}_B\; V_{\mathsf{ret}}$$

- Also assume that we have a Tarski-style **value universe** $\mathcal{U}$

- Then we can define **predicates** $P : UFA \to \mathcal{U}$ (a value term) by
  - equipping $\mathcal{U}$ with an **algebra** structure
  - **handling** the given computation using that algebra
  - intuitively, $P\ (\mathtt{thunk}\ M)$ computes a **proof obligation** for M

- Examples
  - **lifting predicates** from return values to (I/O)-computations
  - Dijkstra's **weakest precondition semantics** of state
  - specifying **allowed patterns** of (I/O)-computations

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Lifting predicates to effectful comps.

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

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

  $$\lambda\, y : UFA \,.\, (\mathtt{force}\, y)\ \mathtt{handled\ with}\ \{\ldots\}_{\mathsf{op} \in \mathcal{S}_{\mathsf{IO}}}\ \mathtt{to}\ y' : A\ \mathtt{in}_{\mathcal{U}}\ P\, y'$$

  using the handler given by

  $$V_{\mathsf{read}} \stackrel{\text{def}}{=} \lambda\, y : (\Sigma\, x : 1 \,.\, \mathsf{Chr} \to \mathcal{U}) \,.\, \mathtt{v\text{-}pi\text{-}code}(\mathtt{chr\text{-}code}\,, y' . (\mathtt{snd}\, y)\, y')$$

  $$V_{\mathsf{write}} \stackrel{\text{def}}{=} \lambda\, y : (\Sigma\, x : \mathsf{Chr} \,.\, 1 \to \mathcal{U}) \,.\, (\mathtt{snd}\, y) \star$$

- $\widehat{P}$ is similar to the **necessity modality** from Evaluation Logic

  $$\Gamma \vdash \mathsf{El}(\widehat{P}\ (\mathtt{thunk}\,(\mathtt{read}^{FA}(x \,.\, \mathtt{return}\, W)))) = \Pi\, x : \mathsf{Chr} \,.\, P\, W$$

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Dijkstra's weakest precondition semantics

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

$$Q : A \to \mathsf{St} \to \mathcal{U}$$

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

$$\mathrm{wp}_Q : UFA \to \mathsf{St} \to \mathcal{U}$$

by

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

$$V_{\mathrm{get}}, V_{\mathrm{put}} \quad \text{on} \quad \mathsf{St} \to (\mathcal{U} \times \mathsf{St}) \qquad \text{and} \qquad V_{\mathrm{ret}} \text{ "="} \ V_Q$$

ii) feeding in the initial state, and **iii)** projecting out the proposition

- Then wp_Q satisfies the expected properties, e.g.,

$$\Gamma \vdash \mathrm{wp}_Q\ (\mathtt{thunk}\,(\mathtt{return}\,V)) \ = \ \lambda\, x_S\!:\!\mathsf{St}\,.\,Q\ V\ x_S \qquad : \mathsf{St} \to \mathcal{U}$$

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$$\Gamma \vdash \mathrm{wp}_Q\ (\mathtt{thunk}\,(\mathtt{return}\ V)) \ = \ \lambda x_S\!:\!\mathrm{St}\,.\,Q\ V\ x_S \qquad : \mathrm{St} \to \mathcal{U}$$

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Dijkstra's weakest precondition semantics

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

$$Q : A \to \mathsf{St} \to \mathcal{U}$$

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

$$\mathsf{wp}_Q : UFA \to \mathsf{St} \to \mathcal{U}$$

by

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

$$V_{\mathsf{get}}, V_{\mathsf{put}} \quad \text{on} \quad \mathsf{St} \to (\mathcal{U} \times \mathsf{St}) \qquad \text{and} \qquad V_{\mathsf{ret}} \text{ "="} \; V_Q$$

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Specifying allowed patterns of I/O-effects

- We assume an **inductive type** Protocol, given by

$$\texttt{e} : \mathrm{Protocol} \qquad \texttt{r} : (\mathrm{Chr} \to \mathrm{Protocol}) \to \mathrm{Protocol}$$

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$$V_{\mathrm{read}}, V_{\mathrm{write}} \qquad \text{on} \qquad \mathrm{Protocol} \to \mathcal{U}$$

where

$$\begin{aligned}
V_{\mathrm{read}}\ \langle V, V_{\mathrm{rk}} \rangle\ (\texttt{r}\ \mathrm{Pr}') &\overset{\mathrm{def}}{=} \texttt{v-pi-code}(\texttt{chr-code}\,, y\,.\,(V_{\mathrm{rk}}\, y)\,(\mathrm{Pr}'\, y)) \\
V_{\mathrm{write}}\ \langle V, V_{\mathrm{wk}} \rangle\ (\texttt{w}\ \langle P, \mathrm{Pr}' \rangle) &\overset{\mathrm{def}}{=} \texttt{v-sigma-code}(P\, V, y\,.\, V_{\mathrm{wk}} \star \mathrm{Pr}') \\
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Outline

- Setting the scene
  - Algebraic effects and their handlers
  - A core dependently typed effectful calculus (FoSSaCS'16)
- Why handlers + dependent types?
  - Programming with handlers + expressiveness of dep. types
  - Useful for defining predicates/types depending on computations
- Extending the FoSSaCS'16 calculus with handlers
  - Take 1: The common term-level def. of handlers (unsound)
  - Take 2: A type-level treatment of handlers

Fibred algebraic effects

- To include fib. alg. effects $(\mathcal{S}_{\text{eff}}, \mathcal{E}_{\text{eff}})$ in our calculus, we
  - extend its computation terms with **algebraic operations**

$$\frac{\Gamma \vdash V : I \quad \Gamma \vdash \underline{C} \quad \Gamma, y : O[V/x] \vdash M : \underline{C}}{\Gamma \vdash \mathrm{op}^{\underline{C}}_{V}(y.M) : \underline{C}}$$

    for every operation symbol $\mathrm{op} : (x : I) \longrightarrow O$ in $\mathcal{S}_{\text{eff}}$

  - include **equations** $\Gamma \mid \Delta \vdash T_1 = T_2$ in $\mathcal{E}_{\text{eff}}$

  - include a general **algebraicity equation**

$$\frac{\Gamma \mid z : \underline{C} \vdash K : \underline{D} \quad \Gamma \vdash V : I \quad \Gamma, y : O[V/x] \vdash M : \underline{C}}{\Gamma \vdash K[\mathrm{op}^{\underline{C}}_{V}(y.M)/z] = \mathrm{op}^{\underline{D}}_{V}(y.K[M/z]) : \underline{D}}$$

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Handlers for fibred algebraic effects

- **Take 1:** Let's use their conventional term-level definition
  - include the handling construct for **computation terms**

    $$M \ \texttt{handled with} \ \{\texttt{op}_{\mathsf{x}}(x') \mapsto N_{\mathsf{op}}\}_{\mathsf{op} \in \mathcal{S}_{\mathsf{eff}}} \ \texttt{to} \ y\!:\!A \ \texttt{in}_{\underline{C}} \ N_{\mathsf{ret}}$$

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  - but then we can prove the **unsound equation**

    $$\Gamma \vdash \texttt{write}^{F1}_{\mathsf{a}}(\texttt{return}\,\star) = \texttt{write}^{F1}_{\mathsf{z}}(\texttt{return}\,\star) : F1$$

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Handlers for fibred algebraic effects ctd.

- Possible ways to solve this unsoundness problem
  - **Option 1:** Change the FoSSaCS'16 calculus
    - change the equational theory of homomorphism terms
    - hom. terms wouldn't denote homomorphisms any more
    - investigated for exceptions in CBPV with stacks in [Levy'06]
  - **Option 2:** Keep the FoSSaCS'16 calculus unchanged
    - extend it so that handling for comp. terms is derivable
    - while making sure that the calculus remains sound
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- **Take 2:** A type-based treatment of handlers
  - we introduce the **user-defined algebra type** (comp. type)

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  - we introduce corresponding **elimination forms**

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  - extend the equational theory of **value types** with

$$\Gamma \vdash U\,\langle A, \{V_{\mathsf{op}}\}_{\mathsf{op} \in \mathcal{S}_{\mathsf{eff}}}\rangle = A$$

(what about the corresponding η-equation for comp. types?)

  - extend the equational theory of **comp.** and **hom. terms** with

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$$\Gamma \vdash (\mathtt{force}_{\langle A, \{V_{\mathsf{op}}\}_{\mathsf{op} \in \mathcal{S}_{\mathsf{eff}}} \rangle}\, V) \mathbin{\mathtt{as}} x\!:\!A \mathbin{\mathtt{in}} N = N[V/x] : \underline{C}$$

$$\Gamma \vdash M \mathbin{\mathtt{as}} x\!:\!A \mathbin{\mathtt{in}} K[\mathtt{force}_{\langle A, \{V_{\mathsf{op}}\}_{\mathsf{op} \in \mathcal{S}_{\mathsf{eff}}} \rangle}\, x/z] = K[M/z] : \underline{C}$$

$$\begin{aligned}\Gamma \vdash\ & \mathsf{op}_V^{\langle A, \{V_{\mathsf{op}}\}_{\mathsf{op} \in \mathcal{S}_{\mathsf{eff}}} \rangle}(y.M) \\ &= \mathtt{force}_{\langle A, \{V_{\mathsf{op}}\}_{\mathsf{op} \in \mathcal{S}_{\mathsf{eff}}} \rangle}\,(V_{\mathsf{op}}\langle V, \lambda\, y.\mathtt{thunk}\, M\rangle) : \langle A, \{V_{\mathsf{op}}\}_{\mathsf{op} \in \mathcal{S}_{\mathsf{eff}}} \rangle\end{aligned}$$

Handlers for fibred algebraic effects ctd.

- **Take 2:** A type-based treatment of handlers
  - we can then routinely derive the **handling construct**

$$M \; \texttt{handled with} \; \{\mathtt{op}_x(x') \mapsto N_{\mathsf{op}}\}_{\mathsf{op} \,\in\, \mathcal{S}_{\mathsf{eff}}} \; \texttt{to} \; y\!:\!A \; \texttt{in}_{\underline{C}} \; N_{\mathsf{ret}}$$

using **sequential composition**, thunking, and forcing:

$$\texttt{force}_{\underline{C}}\left(\texttt{thunk}\left(\underbrace{M \; \texttt{to} \; y\!:\!A \; \texttt{in} \; \left(\texttt{force}_{\langle U\underline{C}, \{V_{\mathsf{op}}\}_{\mathsf{op}\in\mathcal{S}_{\mathsf{eff}}}\rangle} \left(\texttt{thunk} \, N_{\mathsf{ret}}\right)\right)}_{\text{has type } \langle U\underline{C}, \{V_{\mathsf{op}}\}_{\mathsf{op}\in\mathcal{S}_{\mathsf{eff}}}\rangle}\right)\right)$$

where the value terms V_{op} are derived from the comp. terms N_{op}

  - satisfies the standard β-equations for handling
  - **handling into values** can be derived analogously

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Conclusion

- In this talk, we saw that
  - handlers are useful for defining preds./types on computations
    - more generally, homomorphic type dep. on comps. is natural
    - this naturality was also observed in [Pédrot,Tabareau'17]
  - unsoundness problems can arise when accommodating handlers
    - handlers defined at term-level, while denoting algebras
  - handlers admit a principled type-based treatment
    - conventional term-level def. is derivable using seq. comp.

- Future work includes
  - general account of defining predicates on alg. effects
  - operational semantics (complex values + eq. for ops.)
  - presentations of the calculus without hom. terms (eq. proof obl.)

Thank you!

Questions?