A fibrational view on computational effects

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Background – dependent types

The Curry-Howard correspondence:

```
\begin{array}{lll} \text{Simple Types} & \sim & \text{Propositional Logic} & & (\text{Nat}, \text{String}, \ldots) \\ \\ \text{Dependent Types} & \sim & \text{Predicate Logic} & & (\Sigma, \Pi, =, \ldots) \end{array}
```

A tiny example: we can use dep. types to express sorted lists

$$\ell$$
: (List Nat) \vdash Sorted(ℓ) $\stackrel{\text{def}}{=}$ Πi : Nat. ($0 < i < \text{len } \ell$) \rightarrow ($\ell[i-1] \le \ell[i]$)

which in turn could be used for typing sorting functions

```
\forall sort : \Pi \ell: (List Nat) . \Sigma \ell': (List Nat) . (Sorted(\ell') \times \dots)
```

Large examples: CompCert (Coq), miTLS and HACL* (F*), ...

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Background – computational effects

Examples:

• state, exceptions, divergence, IO, nondeterminism, probability, . . .

Meta-languages and models for comp. effects: based on

• monads (λ_c , λ_{ML} , FGCBV) (Moggi; Levy)

$$\llbracket \Gamma \vdash M : A \rrbracket_{\lambda_{\mathsf{c}}} : \llbracket \Gamma \rrbracket \longrightarrow T \llbracket A \rrbracket$$

• adjunctions (CBPV, EEC) (Levy; Egger et al.)

$$\llbracket \Gamma \vdash V : A \rrbracket_{CBPV} : \llbracket \Gamma \rrbracket \longrightarrow \llbracket A \rrbracket \qquad \llbracket \Gamma \vdash M : \underline{C} \rrbracket_{CBPV} : \llbracket \Gamma \rrbracket \longrightarrow U(\llbracket \underline{C} \rrbracket)$$

• algebraic presentations (Plotkin and Power)

get :
$$1 \rightharpoonup S$$
 put : $S \rightharpoonup 1$ (+ equations)

We investigate the combination of

```
• dependent types  (\Pi, \Sigma, V =_{\mathcal{A}} W, ...)
```

• computational effects (state, nondeterminism, IO, ...)

- tell a mathematically natural story
- use established math. techniques
- cover a wide range of comp. effects
- discover smth. interesting

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Goals

- tell a mathematically natural story (via a clean core calculus)
- use established math. techniques (fibrations and adjunctions)
- cover a wide range of comp. effects (alg. effects, continuations)
- discover smth. interesting (using handlers to reason about effects)

Two guiding problems

- effectful programs in types (e.g., get and put in types)
- typing of effectful programs (e.g., sequential composition)

(type-dependency in the presence of effects)

Q: Should we allow situations such as Sorted[receive(y.M)/ ℓ]?

A1: In this work, we say not directly

- types should only depend on static information about effects
- allow dependency on effectful comps. via analysing thunks

A2: Various people are also looking at the direct case

- type-dependency needs to be "homomorphic"
- intuitively
 - need to lift Sorted(ℓ) to Sorted[†](c), where c: T(List Chr)
 - $\mathsf{Sorted}^\dagger(\mathtt{receive}(y.\mathtt{return}\,y)) = \langle \mathtt{receive} \rangle (y.\mathtt{Sorted}(y))$
 - for this Sorted needs to be a T-algebra
- (cf. recent papers by Pédrot and Tabareau; Bowman et al.)

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Aim: Types should only depend on static info about effects

Solution: CBPV/EEC style distinction between vals. and comps

- value types $\Gamma \vdash A$ (MLTT + thunks + ...)
- computation types $\Gamma \vdash \underline{C}$ (dep. typed CBPV/EEC)
- where Γ contains only value variables $x_1: A_1, \dots, x_n: A_n$

Could have also considered Moggi's λ_{ML} or Levy's FGCBV

- building on CBPV/EEC gives a more general story
- especially for the treatment of sequential composition
- and also for (Idris-style parameterised) dependent effect-typing

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Typing of effectful programs

(e.g., sequential composition)

The problem: The standard typing rule for seq. composition

$$\frac{\Gamma \vdash_{\overline{c}} M : F \land A \qquad \Gamma, x : A \vdash_{\overline{c}} N : \underline{C}(x)}{\Gamma \vdash_{\overline{c}} M \text{ to } x : A \text{ in } N : \underline{C}(x)}$$

is not correct any more because it potentially allows

$$x \in FV(\underline{C})$$

in the conclusion

Aim: To fix the typing rule of sequential composition

Option 1: We could restrict the free variables in \underline{C} : [Levy'04] $\underline{\Gamma \vDash M : FA \qquad \Gamma \vdash \underline{C} \qquad \Gamma, x : A \vDash N : \underline{C}}$

But: Sometimes it is useful if C can depend on x!

sav we consider

fopen (return true, return false) to x: Bool in N

• then it would be natural to let \underline{C} depend on x, e.g.,

 $x: Bool \vdash \underline{C}(x) \stackrel{\text{def}}{=} \text{if } x \text{ then "allow fread, fwrite, and fclose"}$ else "allow fopen"

needs more expressive comp. types than in the core calculus)

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Aim: To fix the typing rule of sequential composition

Option 2: One could lift sequential composition to type level

$$\Gamma \vdash M \text{ to } x : A \text{ in } N : M \text{ to } x : A \text{ in } \underline{C}$$

But: Then comp. types would be singleton-like!?!

Option 3: In the monadic metalanguage λ_{ML} , one could try

$$\Gamma \vdash M : TA$$
 $\Gamma, x : A \vdash N : TB(x)$
 $\Gamma \vdash M \text{ to } x : A \text{ in } N : T(\Sigma x : A.B)$

But: What makes this a principled solution? Why is it correct?

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Aim: To fix the typing rule of sequential composition

Our solution: We draw inspiration from algebraic effects
and combine this with restricting <u>C</u> in seq. comp. (Option 1)

E.g., consider the non-deterministic prog. (for $x : \text{Nat } \vdash N : \underline{C}(x)$) $M \stackrel{\text{def}}{=} \text{choose (return 4. return 2) to } x : \text{Nat in } N$

After making the non-det. choice, this program evaluates as either $N[4/x] : \underline{C}[4/x]$ or $N[2/x] : \underline{C}[2/x]$

Idea: M denotes an element of the coproduct of algebras

$$\underline{C}[4/x] + \underline{C}[2/x] \stackrel{\text{def}}{=} F\left(U\left(\underline{C}[4/x]\right) + U\left(\underline{C}[2/x]\right)\right)_{=}$$

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W = choose (return 4, return 2) to x:Nat in W

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Idea: *M* denotes an element of the coproduct of algebras

$$\underline{C}[4/x] + \underline{C}[2/x] \stackrel{\text{def}}{=} F\left(U\left(\underline{C}[4/x]\right) + U\left(\underline{C}[2/x]\right)\right)_{/\equiv}$$

Putting these ideas together

(eMLTT: a core dep.-typed calculus with comp. effects)

eMLTT – value and comp. types

Value types: MLTT + thunks + ...

$$A, B ::=$$
Nat $\mid 1 \mid 0 \mid \Pi x : A . B \mid \Sigma x : A . B \mid V =_A W \mid U \subseteq \mid \dots$

• $U\underline{C}$ is the type of thunked (i.e., suspended) computations

Computation types: dep.-typed version of EEC's comp. types

$$\underline{C}, \underline{D} ::= FA \mid \Pi x : A \cdot \underline{C} \mid \Sigma x : A \cdot \underline{C}$$

- FA is the type of computations returning values of type A
- Π x : A . C is the type of dependent effectful functions
 - generalises CBPV/EEC's comp. types $A \to \underline{C}$ and $\underline{C} \times \underline{D}$
- $\Sigma x: A \cdot C$ is the type of dep. pairs of values and effectful comps.
 - captures the intuition about seq. comp. and coprods. of algebras
 - generalises EEC's comp. types $!A \otimes C$ and $C \oplus D$

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eMLTT – value and comp. terms

```
Value terms: MLTT + thunks + ... V, W ::= x \mid zero \mid succ V \mid ... \mid thunk M \mid ...
```

equational theory based on intensional MLTT

Comp. terms: dep.-typed version of CBPV/EEC's comp. terms

```
\begin{array}{lll} M,N ::= & \operatorname{force} V \\ & | & \operatorname{return} V \\ & | & M \operatorname{to} x : A \operatorname{in} N \\ & | & \lambda x : A . M \\ & | & MV \\ & | & \langle V,M \rangle & (\operatorname{comp.} \Sigma \operatorname{intro.}) \\ & | & M \operatorname{to} \langle x : A,z : \underline{C} \rangle \operatorname{in} K & (\operatorname{comp.} \Sigma \operatorname{elim.}) \end{array}
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But: Value and comp. terms alone do not suffice, as in EEC!

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equational theory based on intensional MLTT

Comp. terms: dep.-typed version of CBPV/EEC's comp. terms

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eMLTT - homomorphism terms

Note: We need to define K in such a way that the intended left-to-right evaluation order is preserved, e.g., consider

$$\Gamma \vdash_{\!\!\!\!c} \langle V, M \rangle \text{ to } \langle x \colon\! A, \mathbf{z} \colon\! \underline{C} \rangle \text{ in } \mathbf{K} = \mathbf{K}[V/x, M/\mathbf{z}] \colon\! \underline{D}$$

Homomorphism terms: dep.-typed version of EEC's linear terms

$$K, L := z$$
 (linear comp. vars.)
 $\mid K \text{ to } x : A \text{ in } M$
 $\mid \lambda x : A . K$
 $\mid KV$
 $\mid \langle V, K \rangle$ (comp. $\Sigma \text{ intro.}$)
 $\mid K \text{ to } \langle x : A, z : C \rangle \text{ in } L$ (comp. $\Sigma \text{ elim.}$)

Typing judgments:

- Γ ⋈ V : A
- [to M : C
- $\Gamma \mid z : \underline{C} \mid_{\overline{h}} K : \underline{D}$ (linear in z; comp. bound to z happens first

eMLTT - homomorphism terms

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$$\Gamma \vdash \langle V, M \rangle$$
 to $\langle x : A, z : \underline{C} \rangle$ in $K = K[V/x, M/z] : \underline{D}$

Homomorphism terms: dep.-typed version of EEC's linear terms

```
\begin{array}{lll} \textit{K}, \textit{L} ::= & \textit{z} & \text{(linear comp. vars.)} \\ & \mid & \textit{K} \text{ to } x : \textit{A} \text{ in } \textit{M} \\ & \mid & \lambda x : \textit{A} . \textit{K} \\ & \mid & \textit{KV} \\ & \mid & \langle \textit{V}, \textit{K} \rangle & \text{(comp. } \Sigma \text{ intro.)} \\ & \mid & \textit{K} \text{ to } \langle x : \textit{A}, \textit{z} : \underline{\textit{C}} \rangle \text{ in } \textit{L} & \text{(comp. } \Sigma \text{ elim.)} \end{array}
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- Γ ⋈ V : A
- Γ |_c M : C
- $\Gamma \mid z : \underline{C} \mid_{\overline{h}} K : \underline{D}$ (linear in z; comp. bound to z happens first)

eMLTT – typing sequential composition

We can then account for type-dependency in seq. comp. as

$$\frac{\Gamma, x : A \vdash_{\overline{c}} N : \underline{C}(x)}{\Gamma \vdash_{\overline{c}} M : FA \qquad \Gamma \vdash_{\overline{c}} \Sigma x : A \cdot \underline{C}(x) \qquad \overline{\Gamma, x : A \vdash_{\overline{c}} \langle x, N \rangle : \Sigma x : A \cdot \underline{C}(x)}}{\Gamma \vdash_{\overline{c}} M \text{ to } x : A \text{ in } \langle x, N \rangle : \Sigma x : A \cdot \underline{C}(x)}$$

ullet As a bonus, the comp. Σ -type can also be used to explain Idris's

$$\begin{array}{c|c} \Gamma \vdash \varepsilon_1 : \mathsf{Effect} & \Gamma \vdash A & \Gamma \vdash \varepsilon_2 : A \to \mathsf{Effect} \\ \hline \qquad \qquad \Gamma \vdash T \varepsilon_1 A \varepsilon_2 \end{array}$$

in terms of standard parameterised effect-typing as

$$T \varepsilon_1 A \varepsilon_2 \stackrel{\text{def}}{=} U_{\varepsilon_1}(\Sigma \times : A \cdot F_{\varepsilon_2 \times} 1)$$

and thus naturally accommodate examples like

fopen (return true, return false) to x: Bool in Λ

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$$\frac{\Gamma, x : A \vdash N : \underline{C}(x)}{\Gamma \vdash E M : F A \qquad \Gamma \vdash \Sigma x : A \cdot \underline{C}(x) \qquad \overline{\Gamma, x : A \vdash C}(x, N) : \Sigma x : A \cdot \underline{C}(x)}{\Gamma \vdash E M \text{ to } x : A \text{ in } \langle x, N \rangle : \Sigma x : A \cdot \underline{C}(x)}$$

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$$\frac{\Gamma \vdash \varepsilon_1 : \mathsf{Effect} \quad \Gamma \vdash A \quad \Gamma \vdash \varepsilon_2 : A \to \mathsf{Effect}}{\Gamma \vdash T \varepsilon_1 A \varepsilon_2}$$

in terms of standard parameterised effect-typing as

$$T \varepsilon_1 A \varepsilon_2 \stackrel{\text{def}}{=} U_{\varepsilon_1}(\Sigma \times : A \cdot F_{\varepsilon_2 \times} 1)$$

and thus naturally accommodate examples like

fopen (return true, return false) to x: Bool in N

eMLTT – typing sequential composition

We can then account for type-dependency in seq. comp. as

$$\frac{\Gamma, x : A \vdash R \quad : \underline{C}(x)}{\Gamma \vdash R \quad \Gamma \vdash \Sigma x : A \cdot \underline{C}(x)} \frac{\Gamma, x : A \vdash R \quad : \underline{C}(x)}{\Gamma, x : A \vdash R \quad \langle x, N \rangle : \Sigma x : A \cdot \underline{C}(x)}$$

$$\Gamma \vdash R \quad \text{to } x : A \text{ in } \langle x, N \rangle : \Sigma x : A \cdot \underline{C}(x)$$

ullet As a bonus, the comp. Σ -type can also be used to explain Idris's

$$\frac{\Gamma \vdash \varepsilon_1 : \mathsf{Effect} \quad \Gamma \vdash A \quad \Gamma \vdash \varepsilon_2 : A \to \mathsf{Effect}}{\Gamma \vdash T \varepsilon_1 A \varepsilon_2}$$

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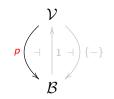
and thus naturally accommodate examples like

Fibred adjunction models

(categorical semantics of eMLTT)

Fibred adjunction models – value part

Given by a split closed comprehension category p, as in



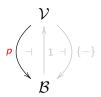
allowing us to define a partial interpretation fun. [-], that maps:

- a context Γ to and object $\llbracket \Gamma \rrbracket$ in \mathcal{B} , with

 - $\llbracket \Gamma, x : A \rrbracket \stackrel{\mathsf{def}}{=} \{ \llbracket \Gamma; A \rrbracket \}$ (if $x \notin \mathit{Vars}(\Gamma)$ and $\llbracket \Gamma; A \rrbracket$ is defined)
- a context Γ and a value type A to an object $\llbracket \Gamma; A \rrbracket$ in $\mathcal{V}_{\llbracket \Gamma \rrbracket}$
- a context Γ and a value term V to $\llbracket \Gamma; V \rrbracket : 1_{\llbracket \Gamma \rrbracket} \longrightarrow A$ in $\mathcal{V}_{\llbracket \Gamma \rrbracket}$

Fibred adjunction models – value part

Given by a split closed comprehension category p, as in

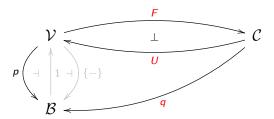


such that

- p has split fibred strong colimits of shape **0** and **2** [Jacobs'99]
 - (in thesis, also Jacobs-style characterisation for arbitrary shapes)
- p has weak split fibred strong natural numbers
 - (axiomatisation is given in the style of fibrational induction)
- p has split intensional propositional equality
 - (currently very synthetic ax., would like a weak form of adjoints)

Fibred adjunction models - effects part

Given by a split fibration q and a split fib. adjunction $F \dashv U$, as in

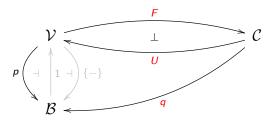


we extend the partial interpretation fun. [-] so that it maps:

- a ctx. Γ and a comp. type \underline{C} to an object $[\![\Gamma;\underline{C}]\!]$ in $\mathcal{C}_{[\![\Gamma]\!]}$
- a ctx. Γ and a comp. term M to $[\![\Gamma;M]\!]:1_{[\![\Gamma]\!]}\longrightarrow U(\underline{C})$ in $\mathcal{V}_{[\![\Gamma]\!]}$
- a ctx. Γ , a comp. var. z, a comp. type \underline{C} , and a hom. term K to $\llbracket \Gamma; z : \underline{C}; K \rrbracket : \llbracket \Gamma; \underline{C} \rrbracket \longrightarrow \underline{D}$ in $\mathcal{C}_{\llbracket \Gamma \rrbracket}$

Fibred adjunction models – effects part

Given by a split fibration q and a split fib. adjunction $F \dashv U$, as in



such that

- q has split dependent p-products (comp. Π-type; r. adj. to wk.)
- q has split dependent p-coproducts (comp. Σ-type; l. adj. to wk.)

and to account for the full calculus presented in the thesis,

• q admits a weak form of fib. enrich. in p (hom. function type $-\circ$)

Fibred adjunction models – correctness

Theorem (Soundness):

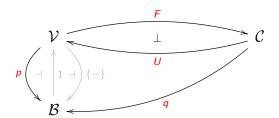
- If $\Gamma \vdash \underline{\mathcal{C}}$, then $[\![\Gamma;\underline{\mathcal{C}}]\!] \in \mathcal{C}_{[\![\Gamma]\!]}$
- If $\Gamma \vDash M : \underline{C}$, then $\llbracket \Gamma ; M \rrbracket : 1_{\llbracket \Gamma \rrbracket} \longrightarrow U(\llbracket \Gamma ; \underline{C} \rrbracket)$
- If $\Gamma \mid z : \underline{C} \models K : \underline{D}$, then $\llbracket \Gamma; z : \underline{C}; K \rrbracket : \llbracket \Gamma; \underline{C} \rrbracket \longrightarrow \llbracket \Gamma; \underline{D} \rrbracket$
- $\bullet \ \ \mathsf{If} \ \Gamma \vdash \underline{C} = \underline{D}, \ \mathsf{then} \ [\![\Gamma;\underline{C}]\!] = [\![\Gamma;\underline{D}]\!] \in \mathcal{C}_{[\![\Gamma]\!]}$
- ...

Theorem (Classifying model):

• The well-formed syntax of eMLTT forms a fib. adjunction model.

Theorem (Completeness):

• If two types or terms are equal in all fibred adjunction models, then they are also equal in the equational theory of eMLTT.



Example 1 (identity adjunctions):

• sound as long as no actual comp. effects in the calculus

Example 2 (simple fibrations from enriched adj. models of EEC):

• given an adj. model of EEC $F\dashv U:\mathcal{C}\longrightarrow\mathcal{V}$ $(\mathcal{V}\text{ a CCC},\dots)$ we can lift it to simple fibrations $\widehat{F}\dashv\widehat{U}:\mathsf{s}(\mathcal{V},\mathcal{C})\longrightarrow\mathsf{s}(\mathcal{V})$ where

$$\mathsf{s}_{\mathcal{V}\!,\mathcal{C}}:\mathsf{s}(\mathcal{V},\mathcal{C})\longrightarrow\mathcal{V}$$

is defined as

$$\mathsf{s}_{\mathcal{V},\mathcal{C}} \Big(X \in \mathcal{V} \,,\, \underline{C} \in \mathcal{C} \Big) \stackrel{\mathsf{def}}{=} X$$

$$\mathsf{s}_{\mathcal{V}\!,\mathcal{C}}\!\left(f:X\longrightarrow Y\,,\,h:X\otimes\underline{C}\longrightarrow\underline{D}\right)\stackrel{\mathsf{def}}{=}f\qquad:\mathsf{s}_{\mathcal{V}\!,\mathcal{C}}(X,\underline{C})\longrightarrow\mathsf{s}_{\mathcal{V}\!,\mathcal{C}}(Y,\underline{D})$$

• doesn't support any real type dependency (constant families)

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• doesn't support any real type dependency (constant families)

Example 3 (families fibrations and lifting of adjunctions):

• given a suitable adjunction $F_{\mathcal{D}}\dashv U_{\mathcal{D}}:\mathcal{D}\longrightarrow \mathsf{Set},$ we can lift it to $\widehat{F_{\mathcal{D}}}\dashv \widehat{U_{\mathcal{D}}}:\mathsf{Fam}(\mathcal{D})\longrightarrow \mathsf{Fam}(\mathsf{Set})$ between

$$\mathsf{fam}_\mathsf{Set} : \mathsf{Fam}(\mathsf{Set}) \longrightarrow \mathsf{Set}$$
 $\mathsf{fam}_\mathcal{D} : \mathsf{Fam}(\mathcal{D}) \longrightarrow \mathsf{Set}$

- resulting in
 - $\bullet \ \ \llbracket \Gamma ; A \rrbracket = (\llbracket \Gamma \rrbracket, \llbracket A \rrbracket) \in \mathsf{Fam}(\mathsf{Set}) \qquad (\llbracket \Gamma \rrbracket \in \mathsf{Set}, \llbracket A \rrbracket \in \llbracket \Gamma \rrbracket \longrightarrow \mathsf{Set})$
 - $\llbracket \Gamma; \underline{C} \rrbracket = (\llbracket \Gamma \rrbracket, \llbracket \underline{C} \rrbracket) \in \mathsf{Fam}(\mathcal{D})$ $(\llbracket \underline{C} \rrbracket \in \llbracket \Gamma \rrbracket \longrightarrow \mathcal{D})$
- examples
 - $F^{\mathsf{T}} \dashv U^{\mathsf{T}} : \mathsf{Set}^{\mathsf{T}} \longrightarrow \mathsf{Set}$
 - $(-) \times S \dashv (-)^S : \mathsf{Set} \longrightarrow \mathsf{Set}$
 - $R^{(-)} \dashv R^{(-)} : \mathsf{Set}^{op} \longrightarrow \mathsf{Set}$

Example 4 (continuous families and CPO-enriched monads):

• given the EM-adjunction $F^{\mathsf{T}}\dashv U^{\mathsf{T}}:\mathsf{CPO^{\mathsf{T}}}\longrightarrow \mathsf{CPO},$ we can lift it to $\widehat{F_{\mathcal{D}}}\dashv \widehat{U_{\mathcal{D}}}:\mathsf{CFam}(\mathsf{CPO^{\mathsf{T}}})\longrightarrow \mathsf{CFam}(\mathsf{CPO})$ between $\mathsf{cfam}_{\mathsf{CPO}}:\mathsf{CFam}(\mathsf{CPO})\longrightarrow \mathsf{CPO}$ $\mathsf{cfam}_{\mathsf{CPO^{\mathsf{T}}}}:\mathsf{CFam}(\mathsf{CPO^{\mathsf{T}}})\longrightarrow \mathsf{CPO}$

• resulting in

• (
$$\llbracket \Gamma \rrbracket$$
, $\llbracket A \rrbracket$) \in CFam(CPO) ($\llbracket \Gamma \rrbracket$ \in CPO, $\llbracket A \rrbracket$ \in $\llbracket \Gamma \rrbracket$ \longrightarrow CPO EP)
• ($\llbracket \Gamma \rrbracket$, $\llbracket \underline{C} \rrbracket$) \in CFam(CPO $^{\mathbf{T}}$) ($\llbracket \underline{C} \rrbracket$ \in $\llbracket \Gamma \rrbracket$ \longrightarrow (CPO $^{\mathbf{T}}$)

if T supports a least zero-ary op., then it also models recursion

$$M ::= \ldots \mid \mu x : U\underline{C} \cdot M$$

Example 4 (continuous families and CPO-enriched monads):

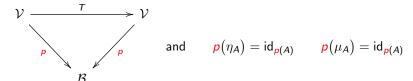
• given the EM-adjunction $F^{\mathsf{T}}\dashv U^{\mathsf{T}}:\mathsf{CPO}^{\mathsf{T}}\longrightarrow \mathsf{CPO},$ we can lift it to $\widehat{F_{\mathcal{D}}}\dashv \widehat{U_{\mathcal{D}}}:\mathsf{CFam}(\mathsf{CPO}^{\mathsf{T}})\longrightarrow \mathsf{CFam}(\mathsf{CPO})$ between $\mathsf{cfam}_{\mathsf{CPO}^{\mathsf{T}}}:\mathsf{CFam}(\mathsf{CPO})\longrightarrow \mathsf{CPO}$ $\mathsf{cfam}_{\mathsf{CPO}^{\mathsf{T}}}:\mathsf{CFam}(\mathsf{CPO}^{\mathsf{T}})\longrightarrow \mathsf{CPO}$

- resulting in
 - ($[\![\Gamma]\!]$, $[\![A]\!]$) \in CFam(CPO) ($[\![\Gamma]\!]$ \in CPO, $[\![A]\!]$ \in $[\![\Gamma]\!]$ \longrightarrow CPO $^{\creat{\it EP}}$)
 - $\bullet \ \ (\llbracket \Gamma \rrbracket, \llbracket \underline{C} \rrbracket) \in \mathsf{CFam}(\mathsf{CPO}^\mathsf{T}) \qquad \qquad (\llbracket \underline{C} \rrbracket \in \llbracket \Gamma \rrbracket \longrightarrow (\mathsf{CPO}^\mathsf{T})^{\underline{\mathit{EP}}})$
- if **T** supports a least zero-ary op., then it also models recursion

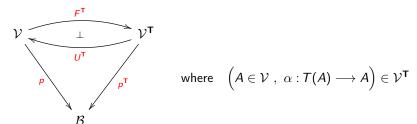
$$M ::= \ldots \mid \mu x : UC \cdot M$$

Example 5 (EM-resolutions of split fibred monads):

• given a split fibred monad $\mathbf{T} = (T, \eta, \mu)$ on \mathbf{p} , i.e.,



we consider models based on the EM-resolution of T



and show that three familiar results hold for this situation

Example 5 (EM-resolutions of split fibred monads):

• **Theorem 1:** If p supports Π -types, then p^{T} also supports Π -types

$$\Pi_A^{\mathsf{T}}(B,\beta) \stackrel{\text{def}}{=} \left(\Pi_A(B), \beta_{\Pi_A^{\mathsf{T}}} \right)$$

• **Prop.:** If p supports Σ -types, then T has a dependent strength

$$\sigma_A: \Sigma_A \circ T \longrightarrow T \circ \Sigma_A \qquad (A \in \mathcal{V})$$

• Theorem 2: If σ_A are natural isos., then p^T supports Σ -types

$$\Sigma_A^{\mathsf{T}}(B,\beta) \stackrel{\text{def}}{=} (\Sigma_A(B), \beta_{\Sigma_A^{\mathsf{T}}})$$

 Theorem 3: If p supports Σ-types and p^T has split fibred reflexive coequalizers, then p^T also supports Σ-types

$$\Sigma_A^{\mathsf{T}}(B,\beta) \stackrel{\text{def}}{=} F^{\mathsf{T}}(\Sigma_A(B))_{/\equiv}$$

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Algebraic effects

(operations and equations)

Fibred effect theories \mathcal{T}_{eff} :

signatures of dependently typed operation symbols

$$\frac{\cdot \vdash I \qquad x_i : I \vdash O \qquad I \text{ and } O \text{ are pure value types}}{\text{op} : (x_i : I) \rightharpoonup O}$$

equipped with equations on derivable effect terms

In eMLTT:

$$M ::= \ldots \mid \operatorname{op}_{V}^{\mathcal{C}}(x.M)$$

General algebraicity equations (in addition to eff. th. eqs.):

$$\frac{\Gamma \trianglerighteq V : I \quad \Gamma, x : O[V/x_i] \trianglerighteq M : \underline{C} \quad \Gamma \mid z : \underline{C} \trianglerighteq_{\overline{h}} K : \underline{D}}{\Gamma \trianglerighteq K[\operatorname{op}_{\overline{V}}^{\underline{C}}(x.M)/z] = \operatorname{op}_{\overline{V}}^{\underline{D}}(x.K[M/z]) : \underline{D}} \text{ (op : } (x_i : I) \to O)$$

•
$$p : \mathsf{Fam}(\mathsf{Set}) \longrightarrow \mathsf{Set}$$
 and $q : \mathsf{Fam}(\mathsf{Mod}(\mathcal{L}_{\mathcal{T}_{\mathsf{eff}}}, \mathsf{Set})) \longrightarrow \mathsf{Set}$

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•
$$p : \mathsf{Fam}(\mathsf{Set}) \longrightarrow \mathsf{Set}$$
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Fibred effect theories \mathcal{T}_{eff} :

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•
$$p: \mathsf{Fam}(\mathsf{Set}) \longrightarrow \mathsf{Set}$$
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Fibred effect theories \mathcal{T}_{eff} :

• signatures of dependently typed operation symbols

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Algebraic effects – examples

Example 1 (interactive IO):

- read : $1
 ightharpoonup \mathsf{Chr} = 1 + \ldots + 1)$ write : $\mathsf{Chr} \rightharpoonup 1$
- no equations

Example 2 (global state with location-dependent store type):

- \diamond \vdash Loc ℓ : Loc \vdash Val \diamond \forall isDec_{Loc} : $\Pi \ell$: Loc Π
 - get: $(\ell:\mathsf{Loc}) \rightharpoonup \mathsf{Val}$ put: $(\Sigma \ell:\mathsf{Loc.Val}) \rightharpoonup 1$
- five equations (two of them branching on isDec_{Loc})

Example 3 (dep. typed update monads $TX \stackrel{\text{def}}{=} \Pi_{s:S}$. $Ps \times X$)

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- get : $(\ell : \mathsf{Loc}) \rightharpoonup \mathsf{Val}$ put : $(\Sigma \ell : \mathsf{Loc} . \mathsf{Val}) \rightharpoonup 1$
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Handlers of algebraic effects (for programming and extrinsic reasoning)

Usual term-level presentation:

 $\Gamma \vDash M \text{ handled with } \{ \operatorname{op}_{X_v}(x_k) \mapsto N_{\operatorname{op}} \}_{\operatorname{op} \in \mathcal{T}_{\operatorname{eff}}} \text{ to } y \colon A \text{ in}_{\underline{C}} N_{\operatorname{ret}} \colon \underline{C}$ satisfying

(return V) handled with $\{...\}_{\mathsf{op}\in\mathcal{T}_{\mathsf{eff}}}$ to y:A in $N_{\mathsf{ret}} = N_{\mathsf{ret}}[V/x]$ (op $^{\underline{C}}_{V}(x.M)$) handled with $\{...\}_{\mathsf{op}\in\mathcal{T}_{\mathsf{eff}}}$ to y:A in $N_{\mathsf{ret}} = N_{\mathsf{op}}[V/x_{V}][.../x_{k}]$

- write your programs using alg. ops. (e.g., get and put)
- use handlers to provide fit-for-purpose impl. (e.g., $S \to X \times S$)

Usual term-level presentation:

 $\Gamma \vdash_{\mathsf{c}} M \text{ handled with } \{ \mathsf{op}_{\mathsf{x}_\mathsf{v}}(\mathsf{x}_k) \mapsto \mathsf{N}_\mathsf{op} \}_{\mathsf{op} \in \mathcal{T}_\mathsf{eff}} \text{ to } y : A \text{ in}_{\underline{C}} \mathsf{N}_\mathsf{ret} : \underline{C}$

(return V) handled with $\{...\}_{\mathsf{op}\in\mathcal{T}_{\mathsf{eff}}}$ to y:A in $N_{\mathsf{ret}}=N_{\mathsf{ret}}[V/x]$ ($\mathsf{op}_V^{\underline{C}}(x.M)$) handled with $\{...\}_{\mathsf{op}\in\mathcal{T}_{\mathsf{eff}}}$ to y:A in $N_{\mathsf{ret}}=N_{\mathsf{op}}[V/x_v][.../x_k]$

- write your programs using alg. ops. (e.g., get and put)
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Usual term-level presentation:

```
\Gamma \vDash M \text{ handled with } \{ \operatorname{op}_{\mathsf{X}_\mathsf{V}}(\mathsf{X}_k) \mapsto \mathsf{N}_{\operatorname{op}} \}_{\operatorname{op} \in \mathcal{T}_{\operatorname{eff}}} \text{ to } y \colon A \text{ in}_{\underline{C}} \text{ } \mathsf{N}_{\operatorname{ret}} \colon \underline{C} satisfying
```

- write your programs using alg. ops. (e.g., get and put)
- use handlers to provide fit-for-purpose impl. (e.g., $S \to X \times S$)

 $\begin{tabular}{ll} \textbf{Idea:} & Generalisation of exception handlers} & & [Plotkin,Pretnar'09] \\ & & Handler \sim Algebra & and & Handling \sim Homomorphism \\ \end{tabular}$

Usual term-level presentation:

```
satisfying  (\text{return } V) \text{ handled with } \{...\}_{\texttt{op} \in \mathcal{T}_{\texttt{eff}}} \text{ to } y \colon A \text{ in } N_{\texttt{ret}} = N_{\texttt{ret}}[V/x]
```

 $\Gamma \vdash M$ handled with $\{ op_{X_k}(x_k) \mapsto N_{op} \}_{op \in \mathcal{T}_{eff}}$ to $y : A \text{ in }_C N_{ret} : \underline{C}$

 $(op_V^C(x.M))$ handled with $\{...\}_{op \in \mathcal{T}_{eff}}$ to y:A in $N_{ret} = N_{op}[V/x_v][.../x_k]$

- write your programs using alg. ops. (e.g., get and put)
- use handlers to provide fit-for-purpose impl. (e.g., $S \to X \times S$)

Handlers of alg. effects – for reasoning

Idea: Using a derived handle-into-values handling construct

M handled with $\{\operatorname{op}_{x_v}(x_k)\mapsto V_{\operatorname{op}}\}_{\operatorname{op}\in\mathcal{T}_{\operatorname{eff}}}$ to y:A in y vecan define natural predicates (essentially, dependent types)

$$\sqcap \vdash P : \mathit{UFA} \to \mathcal{U}$$

by

- ullet equipping a universe ${\cal U}$ with an algebra for ${\cal T}_{\sf eff}$ (sort of), and
- using the above handle-into-values construct to define P

Note 1: P(thunk M) computes a proof obligation for M

Note 2: Formally, this is done in an extension of eMLTT with

- a universe $\mathcal U$ closed under Nat, 1, 0, +, Σ , and Π
- a type-based treatment of handlers $\underline{C} ::= \ldots \mid \langle A; \overrightarrow{V_{op}}; \overrightarrow{W_{eq}} \rangle$
- function extensionality (actually, it's a bit more extensional)

Idea: Using a derived handle-into-values handling construct

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 handled with $\{\operatorname{op}_{\mathsf{x}_{\mathsf{v}}}(\mathsf{x}_k)\mapsto V_{\operatorname{op}}\}_{\operatorname{op}\in\mathcal{T}_{\operatorname{eff}}}$ to $y:A$ in V_{ret} we can define natural predicates (essentially, dependent types)

$$\Gamma \vdash P : UFA \rightarrow U$$

by

- ullet equipping a universe ${\cal U}$ with an algebra for ${\cal T}_{\sf eff}$ (sort of), and
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Example 1 (Evaluation Logic style modalities):

- Given a predicate $P:A \to \mathcal{U}$ on return values, we define a predicate $\Diamond P:UFA \to \mathcal{U}$ on IO-computations as
- $\Diamond P \stackrel{\text{def}}{=} \lambda x : UFA . (\text{force} x) \text{ handled with } \{...\}_{\text{op} \in \mathcal{T}_{10}} \text{ to } y : A \text{ in}_{\mathcal{U}} P y$ using the handler given by

$$\begin{split} V_{\text{read}} & \stackrel{\text{def}}{=} \lambda \, x \colon \! \left(\Sigma \, x_{v} \colon \! 1 \cdot \mathsf{Chr} \to \mathcal{U} \right) \cdot \widehat{\Sigma} \, y \colon \! \mathsf{El}(\widehat{\mathsf{Chr}}) \cdot \left(\mathsf{snd} \, x \right) \, y \\ V_{\text{write}} & \stackrel{\text{def}}{=} \lambda \, x \colon \! \left(\Sigma \, x_{v} \colon \mathsf{Chr} \cdot 1 \to \mathcal{U} \right) \cdot \left(\mathsf{snd} \, x \right) \, \star \end{split}$$

ullet $\Diamond P$ corresponds to Evaluation Logic's possibility modality

$$\Diamond P\left(\texttt{thunk}\left(\texttt{read}(x\,.\,\texttt{write}_{\texttt{e}'}(\texttt{return}\,V))\right)\right) = \widehat{\Sigma}\,x\,: \mathsf{El}(\widehat{\mathsf{Chr}})\,.\,P\,\,V$$

• To get the necessity modality $\Box P$, just use $\widehat{\Pi} x : El(\widehat{Chr})$ in V_{read}

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Example 2 (Dijkstra's weakest precondition semantics for state):

Given a postcondition on return values and final states

$$Q: A \to S \to \mathcal{U}$$
 ($S \stackrel{\text{def}}{=} \Pi \ell$: Loc .Val

we define a precondition for stateful comps. on initial states

$$\operatorname{wp}_Q: \mathit{UFA} \to \mathit{S} \to \mathit{U}$$

by

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

$$V_{
m get}, V_{
m put}$$
 on $S
ightarrow (\mathcal{U} imes S)$ and $V_{
m ret}$ "=" Q

- 2) feeding in the initial state; and 3) projecting out $\mathcal U$
- Theorem: wp_Q satisfies expected properties of WPs, e.g., $\operatorname{wp}_Q\left(\operatorname{thunk}\left(\operatorname{return}V\right)\right) = \lambda x_S : S \cdot Q \cdot V \cdot x_S$

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- ullet Theorem: wp $_Q$ satisfies expected properties of WPs, e.g.,

$$wp_Q (thunk (return V)) = \lambda x_S : S . Q V x_S$$

$$wp_Q (thunk (put_{(\ell,V)}(M))) = \lambda x_S : S . wp_Q (thunk M) (x_S[\ell \mapsto V])$$

Example 3 (Patterns of allowed (IO-)effects):

- Assuming an inductive type of IO-protocols, given by
 e : Protocol
 w : (Chr → Protocol) → Protocol
 and potentially also by A. V.
- We can define a rel. between comps. and protocols as follows:

Allowed :
$$\mathit{UFA} o \mathsf{Protocol} o \mathcal{U}$$

by handling the given computation using

$$V_{
m read}, V_{
m write}$$
 on ${
m Protocol}
ightarrow {\cal U}$ ere $V_{
m read} \ \langle -\ , V_{
m rk}
angle \ ({
m r}\ {
m Pr}') \ \stackrel{
m def}{=} \ \widehat{\Pi} \, x \colon {
m El}(\widehat{
m Chr}) \cdot (V_{
m rk} \, x) \ ({
m Pr}' \, x) \ V_{
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$$\begin{array}{c} \textbf{e}: \mathsf{Protocol} & \textbf{r}: (\mathsf{Chr} \to \mathsf{Protocol}) \to \mathsf{Protocol} \\ \\ \textbf{w}: (\mathsf{Chr} \to \mathcal{U}) \to \mathsf{Protocol} \to \mathsf{Protocol} \\ \\ \mathsf{and} \ \mathsf{potentially} \ \mathsf{also} \ \mathsf{by} \ \land, \ \lor, \dots \end{array}$$

We can define a rel. between comps. and protocols as follows

Allowed :
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$$V_{\mathsf{read}}, V_{\mathsf{write}}$$
 on $\mathsf{Protocol} o \mathcal{U}$ V_{rk} $(\mathbf{r} \; \mathsf{Pr'}) \stackrel{\mathsf{def}}{=} \widehat{\Pi} \, x \colon \mathsf{El}(\widehat{\mathsf{Chr}}) \, . \, (V_{\mathsf{rk}} \, x)$

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where

$$\begin{array}{cccc} V_{\mathsf{read}} & \langle -, V_{\mathsf{rk}} \rangle & (\mathbf{r} \; \mathsf{Pr'}) & \stackrel{\mathsf{def}}{=} & \widehat{\Pi} \, x \colon \mathsf{El}(\widehat{\mathsf{Chr}}) \cdot (V_{\mathsf{rk}} \; x) \; (\mathsf{Pr'} \; x) \\ V_{\mathsf{write}} & \langle V, V_{\mathsf{wk}} \rangle \; (\mathbf{w} \; P \; \mathsf{Pr'}) & \stackrel{\mathsf{def}}{=} & \widehat{\Sigma} \, x \colon \mathsf{El}(P \; V) \cdot V_{\mathsf{wk}} \; \star \; \mathsf{Pr'} \\ & \stackrel{\mathsf{def}}{=} & \widehat{\Omega} \end{array}$$

Conclusion

At a high-level, the presented work was about combining dependent types and computational effects

In particular, you saw

- a clean core calculus of dependent types and comp. effects
- a natural category-theoretic semantics
- · alg. effects and handlers, in particular, for reasoning using
 - Evaluation Logic style modalities
 - Dijkstra's weakest precondition semantics for state
 - patterns of allowed (IO-)effects

Some items of future work:

- uniform account of the various handler-defined predicates
- more expressive comp. types (par. adjunctions, Dijkstra monads)

Thank you!

D. Ahman.

Fibred Computational Effects. (PhD Thesis, 2017)

D. Ahman, N. Ghani, G. Plotkin.

 $\textbf{Dependent Types and Fibred Computational Effects.} \ (FoSSaCS'16)$

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Handling Fibred Computational Effects. (POPL'18)