Comodels as a gateway for interacting with the external world

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MSR Redmond, 15 May 2019

A modular programming abstraction for using external resources

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Computational effects in FP

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- Using **monads** (as in HASKELL)

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type St a = String → (a,String)

f :: St a → St (a,a)
f c = c >>= (\x → c >>= (\y → return (x,y)))
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- Using **alg. effects** and **handlers** (as in EFF, FRANK, KOKA)

```
effect Get : int
effect Put : int → unit
                                        (*: int → a*int!{} *)
let g (c:unit → a!{Get,Put}) =
  with st_h handle (perform (Put 42); c ())
```

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```

- Both are good for **faking comp. effects** in a pure language!

  But what about effects that need access to the **external world**?

External world in FP

- Declare a **signature of monads** or **algebraic effects**, e.g.,

```
(* System.IO *)
type IO a
openFile :: FilePath → IOMode → IO Handle
```

```
(* pervasives.eff *)
effect RandomInt   : int → int
effect RandomFloat : float → float
```

- And then **treat them specially** in the compiler, e.g.,

```
(* eff/src/backends/runtime/eval.ml *)
let rec top_handle op =
  match op with
  | ...
```

but . . .

An issue — difficult to cover all use cases

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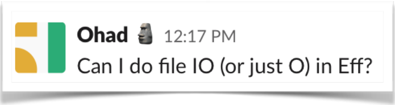

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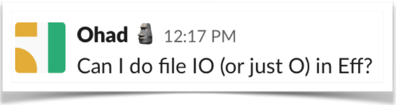

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not currently

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So here's the hack I added. We should do something a bit more principled

In `pervasives.eff`:

```
effect Write : (string*string) -> unit
```

in `eval.ml`, under `let rec top_handle op =` add the case:

```
    | "Write" ->
      (match v with
       | V.Tuple vs ->
          let (file_name :: str :: _)  = List.map V.to_str vs in
          let file_handle = open_out_gen
                             [Open_wronly
                             ;Open_append
                             ;Open_creat
                             ;Open_text
                             ] 0o666 file_name in
          Printf.fprintf file_handle "%s" str;
          close_out file_handle;
          top_handle (k V.unit_value)
      )
```

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This talk — a principled modular (co)algebraic approach!

A bigger issue — linearity or lack thereof

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- ```
  let f (s:string) =
    let fh = fopen "foo.txt" in
    fwrite fh (s^s);
    fclose fh;
    return fh

  let g s =
    let fh = f s in fread fh
  ```
  ```

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- Even worse when we wrap `f` in a **handler**?

```
let h = handler
          | effect (fwrite fh s k) ↦ return ()

let g' s =
  with h handle f ()
```
```

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- Even worse when we wrap `f` in a **handler**?

  ```
  let h = handler
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  let g' s =
    with h handle f ()           (* dangling fh ! *)
  ```
  ```

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- We could try using **existing PL techniques**, e.g.,
  - **Modules** and **abstraction**, e.g., `System.IO`

```
type IO a

hClose :: Handle → IO ()
```

  - **Linear** (and **non-linear**) **types** and **effects**

```
linear type fhandle

effect FClose : (linear fhandle) → unit

linear effect FClose : fhandle → unit
```

  - Handlers with **`initially`** and **`finally`** **clauses**

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- **Problem:** They don't really capture the **essence of the problem**

Algebraic digression: What's a comodel?

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- Intutively, comodels describe **evolution of worlds** $w_1, w_2, w_3, \ldots$

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- Intutively, comodels describe **evolution of worlds** $w_1, w_2, w_3, \ldots$
  - Operational semantics using a tensor of a model and a comodel (Plotkin & Power, Abou-Saleh & Pattinson)
  - Stateful runners of effectful programs (Uustalu)
  - Linear state-passing translation (Møgelberg and Staton)
  - Top-level behaviour of alg. effects in EFF v2 (Bauer & Pretnar)

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- With the `System.IO` **module abstraction** ensuring that
  - We **cannot get our hands on** RealWorld (no `get` and `put`)
  - We have the impression of RealWorld **used linearly**
  - We **don't ask more** from RealWorld than it can provide

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But wait a minute! RealWorld looks a lot like a **comodel**!

$$\mathsf{hGetLine} : (\mathsf{Handle}, \mathsf{RealWorld}) \to (\mathsf{String}, \mathsf{RealWorld})$$

$$\mathsf{hClose} \quad : (\mathsf{Handle}, \mathsf{RealWorld}) \to ((), \mathsf{RealWorld})$$

Important: co-operations (hClose) make a **promise to return**!

Towards a general programming abstraction

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- ```
  let f (s:string) =        (* in top level world *)
    using IO run
      let fh = fopen "foo.txt" in
      fwrite fh (s^s);
      fclose fh                          (* in IO world *)
  ```

  Now **external world** explicit, but **dangling** `fh` etc **still possible**
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- **Our solution: Modular treatment of external worlds**

Modular treatment of external worlds

- **For example**

- Fh — "**world** which consists of **exactly one** `fh`"
- IO $\longrightarrow$ Fh — "call `fopen` with `foo.txt`, store returned `fh`"
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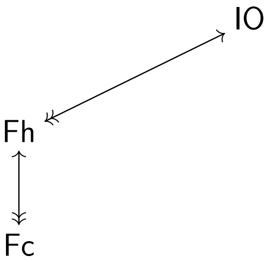

(ext. world)

(inner world)

(inner^2 world)

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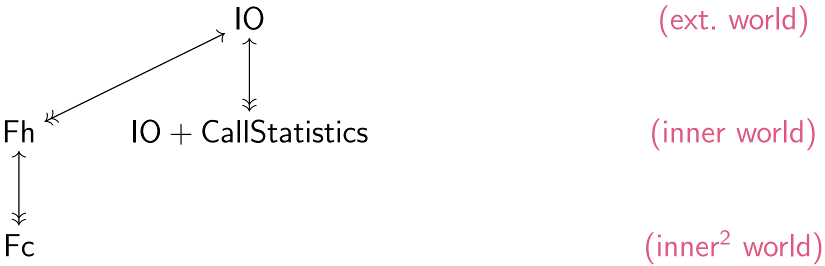

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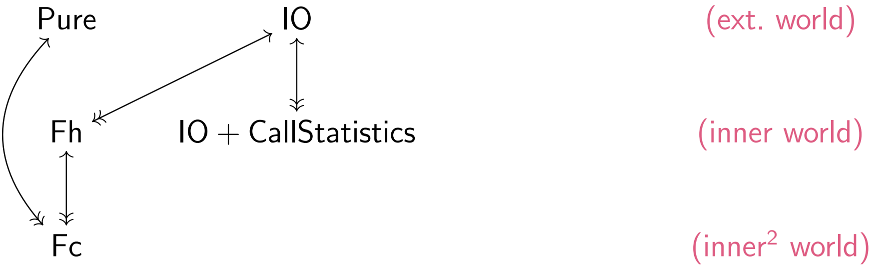

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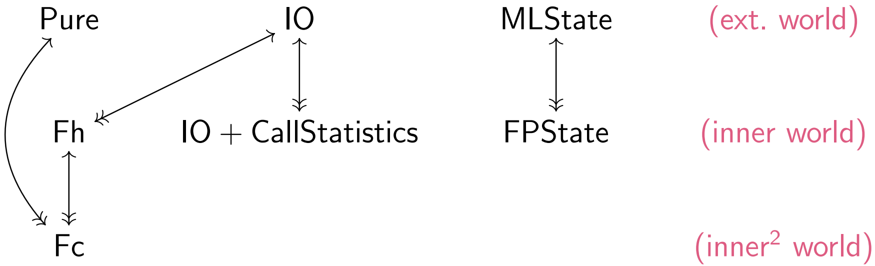

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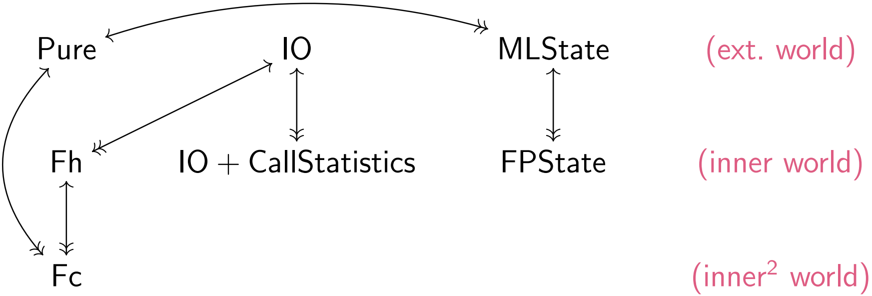

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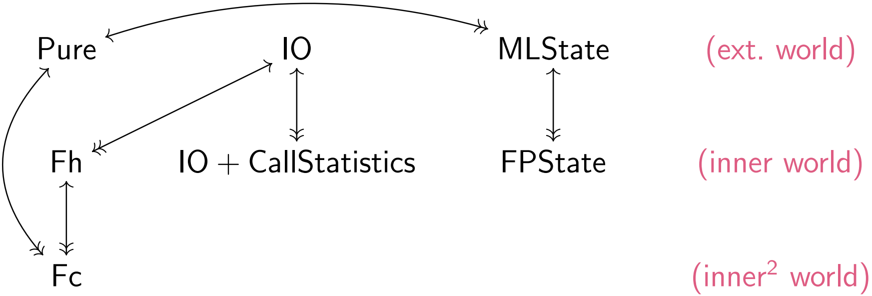

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- Fh ⟶ IO — "call `fclose` with stored `fh`"
- Fc — "**world** that is **blissfully unaware** of `fh`"
- **Observation:** IO ⟷↠ Fh and other ⟷↠ look a lot like **lenses**

Comodels as a gateway to the external world

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- **Running a program** on a **comodel** (**using external resources**)

```
using
  C (* : Comodel(Sig,W) *) @ c_init (* : W *)
run
  c (* : A *)
finally @ (w:W) {
  return(x:A) ↦ c_fin(w,x) (* : B *) } (* : B *)
```

- **Comodels** are defined as follows

```
C =
  {
    op (x:A) @ (w:W) ↦ c_op(x,w),  (* : B * W *)
    ...
  }
```

for all **operations** op : $A \rightsquigarrow B$ in a given signature Σ

Focussing on a fragment of the external world

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```
let f (s:string) =
  using
    Fh @ (fopen_of_io "foo.txt")
  run
    fwrite_of_fh (s^s)
  finally @ fh {
    return(x) ↦ fclose_of_io fh }
```

Focussing on a fragment of the external world

```
let f (s:string) =                          (* in IO *)
  using
    Fh @ (fopen_of_io "foo.txt")            (* in IO *)
  run
    fwrite_of_fh (s^s)                      (* in Fh *)
  finally @ fh {
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Focussing on a fragment of the external world

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    Fh @ (fopen_of_io "foo.txt")          (* in IO *)
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    fwrite_of_fh (s^s)                    (* in Fh *)
  finally @ fh {
    return(x) ↦ fclose_of_io fh }         (* in IO *)
```

where

```
Fh =                                  (* W = fhandle *)
  { fread  _ @ fh ↦ ...,
    fwrite s @ fh ↦ fwrite_of_io s fh;
                    return ((),fh)       }

        (* fread : (unit * W) → (string * W) *)
       (* fwrite : (string * W) → (unit * W) *)
```

Modular treatment of worlds (IO $\longleftrightarrow$ Fh $\longleftrightarrow$ Fc)

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```
let f (s:string) =                              (* in IO *)
  using Fh @ (fopen_of_io "foo.txt")
  run

    using Fc @ (fread_of_fh ())                 (* in Fh *)
    run
      fwrite_of_fc (s^s)                        (* in Fc *)
    finally @ s {
      return(_) ↦ fwrite_of_fh s }

  finally @ fh {
    return(_) ↦ fclose_of_io fh }
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where

```
Fc = { fwrite s @ s' ↦ return ((),s'^s) }
```

Modular treatment of worlds (IO ⟷ Fh ⟷ Fc)

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    run
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    finally @ s {
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where

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- **More generally:** comodels allow **transactions** and **sandboxing**

Tracking the world usage (IO $\longleftrightarrow$ IO+Stats)

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```
let f (fh:fhandle) (s:string) =        (* in IO *)
  using
    IO+Stats @ (return 0)
  run
    fwrite_of_stats fh (s^s)    (* in IO+Stats *)
  finally @ c {
    return(_) ↦
          let fh' = fopen_of_io "stats.txt" in
          fwrite_of_io fh' c; fclose_of_io fh' }
```

where

```
IO+Stats =                                (* W = nat*)
  { fwrite fh s @ c ↦ fwrite_of_io fh s;
                       return ((),c+1),
    ... }
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IO+Stats =                                 (* W = nat*)
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- **More generally:** allows to slot in **instrumentation/monitors**

The external world can also be pure ($\mathsf{Pure} \longleftrightarrow \mathsf{Str}$)

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```
let f () =                                          (* in Pure *)
  using
    Str @ (return "some default initial value")
  run
    ...
    let s = get () in
    if (s == "foo")
    then (...; set "bar"; ...)
    else (...)
    ...
  finally @ _ {
    return(x) ↦ return x }
```

```
Str =                                               (* W = string *)
  { get _ @ s ↦ return (s,s) ,
    set s @ _ ↦ return ((),s) }
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The external world can also be pure (Pure $\longleftrightarrow$ Str)

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```
Str =                                          (* W = string *)
  { get _ @ s ↦ return (s,s) ,
    set s @ _ ↦ return ((),s) }
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- Similar to **ambient values** (and **ambient functions**) in KOKA

More on ambient values/functions (Pure $\longleftrightarrow$ Amb)

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```
let f (s:string) =
  using                              (* with val amb = ... *)
    Amb @ (return "some default initial value")
  run
    ...
    let amb = get () in
    if (amb == "foo")
    then (...;                       (* with val amb = ... *)
          using Amb @ ... run ... finally ...);
          ...)
    else (...)
    ...
  finally @ _ { return(x) ↦ return x }
```

```
Amb = { get _ @ s ↦ return (s,s) }
```

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    if (amb == "foo")
    then (...;                       (* with val amb = ... *)
          using Amb @ ... run ... finally ...);
          ...)
    else (...)
    ...
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- **Amb. functions** by amb. function application as a co-operation

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- Core calculus for comodels (wo/ handlers $\Rightarrow$ wait a few slides)

So what's happening **formally**?

- Core calculus for comodels (wo/ handlers ⇒ wait a few slides)
- **Types**

$$A, B, W \ ::= \ \mathsf{b} \ | \ 1 \ | \ A \times B \ | \ 0 \ | \ A + B \ | \ A \xrightarrow{\Sigma} B$$

So what's happening **formally**?

- Core calculus for comodels (wo/ handlers ⇒ wait a few slides)
- **Types**

$$A, B, W \ ::= \ \mathsf{b} \mid 1 \mid A \times B \mid 0 \mid A + B \mid A \xrightarrow{\Sigma} B$$

- **Interfaces (signatures)** of **external worlds**

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- **Computation terms** (value terms are unsurprising)

$$\begin{array}{rcl} c & ::= & \textbf{return } v \mid \textbf{let } x = c_1 \textbf{ in } c_2 \mid \textbf{let rec } f \ x = c_1 \textbf{ in } c_2 \\ & \mid & v_1 \, v_2 \\ & \mid & \mathsf{op} \ v \ (x.c) \\ & \mid & \textbf{using } C \ @ \ c_i \textbf{ run } c \textbf{ finally } @ \ w \ \{ \ \textbf{return}(x) \mapsto c_f \ \} \end{array}$$

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- **Comodels (cohandlers)**

$$C \ ::= \ \{ \ \overline{\mathsf{op}}_1\ x\ @\ w \mapsto c_1 \ , \ \ldots \ , \ \overline{\mathsf{op}}_n\ x\ @\ w \mapsto c_n \ \}$$

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- The two central **typing rules** are

$$\frac{\Gamma \models^{\Sigma} \mathsf{C} \text{ comodel of } \Sigma' \text{ with carrier } W_{\mathsf{C}} \qquad \Gamma \models^{\Sigma} c_i : W_{\mathsf{C}} \qquad \Gamma \models^{\Sigma'} c : A \qquad \Gamma, w : W_{\mathsf{C}}, x : A \models^{\Sigma} c_f : B}{\Gamma \models^{\Sigma} \textbf{using } C \ @ \ c_i \textbf{ run } c \textbf{ finally } @ \ w \ \{ \ \textbf{return}(x) \mapsto c_f \ \} : B}$$

and

$$\frac{\mathsf{op} : A_{\mathsf{op}} \rightsquigarrow B_{\mathsf{op}} \in \Sigma \qquad \Gamma \vdash v : A_{\mathsf{op}} \qquad \Gamma, x : B_{\mathsf{op}} \models^{\Sigma} c : A}{\Gamma \models^{\Sigma} \mathsf{op} \ v \ (x.c) : A}$$

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- **Term interpretation** looks very similar to **alg. effects**:

$$[\![\Gamma \vdash v : A]\!] : [\![\Gamma]\!] \longrightarrow [\![A]\!] \qquad [\![\Gamma \overset{\Sigma}{\models} c : A]\!] : [\![\Gamma]\!] \longrightarrow T_{\Sigma_\perp} [\![A]\!]$$

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  - **un-cohandled operations wait for a suitable external world**!

- The interesting part is the **interpretation of using ... run**

$$\frac{\Gamma \mathrel{\models^{\Sigma}} \mathsf{C} \text{ comodel of } \Sigma' \text{ with carrier } W_{\mathsf{C}} \qquad \Gamma \mathrel{\models^{\Sigma}} c_i : W_{\mathsf{C}} \qquad \Gamma \mathrel{\models^{\Sigma'}} c : A \qquad \Gamma, w : W_{\mathsf{C}}, x : A \mathrel{\models^{\Sigma}} c_f : B}{\Gamma \mathrel{\models^{\Sigma}} \textbf{using } C \text{ @ } c_i \textbf{ run } c \textbf{ finally } \text{@ } w \ \{ \textbf{return}(x) \mapsto c_f \} : B}$$

which is based on M&S's **linear state-passing translation**, i.e.,

$$\frac{[\![\mathsf{C}]\!] \in \mathrm{Comod}_{\Sigma'_\perp}(\mathrm{Kleisli}(T_{\Sigma_\perp}))}{\mathrm{run\_on}_{[\![\mathsf{C}]\!]} : T_{\Sigma'_\perp} [\![A]\!] \longrightarrow \Big([\![W_{\mathsf{C}}]\!] \to T_{\Sigma_\perp}([\![W_{\mathsf{C}}]\!] \times [\![A]\!]) \Big)}$$

Computational behaviour of using . . . run

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- Two semantically valid program equations

$$\mathbf{using}\ C \mathbin{@} c_i\ \mathbf{run}\ (\mathbf{return}\, v)\ \mathbf{finally} \mathbin{@} w\ \{\ \mathbf{return}(x) \mapsto c_f\ \}$$
$$=$$
$$\mathbf{let}\ w' = c_i\ \mathbf{in}\ c_f[w'/w, v/x]$$

$$\mathbf{using}\ C \mathbin{@} c_i\ \mathbf{run}\ (\mathrm{op}\, v\, (y.c))\ \mathbf{finally} \mathbin{@} w\ \{\ \mathbf{return}(x) \mapsto c_f\ \}$$
$$=$$
$$\begin{aligned}&\mathbf{let}\ w' = c_i\ \mathbf{in}\ \Big(\\ &\quad \mathbf{let}\ z = C_{\overline{\mathrm{op}}}[w'/w, v/x]\ \mathbf{in}\ (\\ &\qquad \mathbf{match}\ z\ \mathbf{with}\ \{\ \langle y', w''\rangle \mapsto\\ &\qquad\quad \mathbf{using}\ C \mathbin{@} (\mathbf{return}\, w'')\\ &\qquad\quad \mathbf{run}\ (c[y'/y])\\ &\qquad\quad \mathbf{finally} \mathbin{@} w\ \{\ \mathbf{return}(x) \mapsto c_f\ \}\ \})\Big)\end{aligned}$$

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- Recall that the **semantics of co-operations**

$$\overline{\mathsf{op}} : [\![A_{\mathsf{op}}]\!] \times [\![W]\!] \longrightarrow T_{\Sigma_\bot}([\![B_{\mathsf{op}}]\!] \times [\![W]\!])$$

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- **Our solution:** Allow the **world** to **raise signals** to talk back

```
C =                          (* : A x W → T((B x W) + S) *)
  { op x @ w ↦ if b then (...) else (raise s) }
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```
using C @ c_init
run c                                          (* : A ! S  *)
finally @ w {
  return(x) ↦ c_fin(w,x),                      (* : B ! S' *)
  signal(s) ↦ c_sig(w,s) }                     (* : B ! S' *)
```

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- But **worldly signals cannot be** handled locally, e.g., consider

```
using C @ c_init
run (try x = (raise s) in c unless {(**)...})
finally @ w {
  return(x) ↦ c_fin(w,x),
  signal(s) ↦ c_sig(w,s) }
```

vs

```
using C @ c_init
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let rec ctr_printer i =
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- **World-based:** could **store a trace** so as to **replay "old" co-ops**

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- Where do **multi-handlers** fit? Co-operating handlers-cohandlers?

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- **For the future: interface polymorphism**, **linear typing**, ...