

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

- 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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Ohad 🤖 12:17 PM

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Žiga Lukšič 12:18 PM

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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!

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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
```

# A bigger issue — **linearity** or lack thereof

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  let fh = f s in fread fh  (* fh not open ! *)
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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  
  | effect (fwrite fh s k) ↦ return ()  
  
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
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```
effect FClose : (linear fhandle) → unit
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- Handlers with **initially** and **finally** clauses

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- Handlers with **initially** and **finally** clauses
- **Problem:** They don't really capture the **essence of the problem**

Algebraic digression: What's a **comodel?**

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$$\mathcal{M} = \langle M : \text{Set} , \{ \text{op}_{\mathcal{M}} : A_{\text{op}} \times M^{B_{\text{op}}} \longrightarrow M \}_{\text{op} \in \Sigma} \rangle$$

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- Intuitively, comodels describe **evolution of worlds** w_1, w_2, w_3, \dots
 - 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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- A common explanation is to think of functions

$$a \rightarrow \text{IO } b$$

as

$$a \rightarrow (\text{RealWorld} \rightarrow (b, \text{RealWorld}))$$

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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**!

`hGetLine` : $(\text{Handle}, \text{RealWorld}) \rightarrow (\text{String}, \text{RealWorld})$

`hClose` : $(\text{Handle}, \text{RealWorld}) \rightarrow ((), \text{RealWorld})$

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

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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 *)
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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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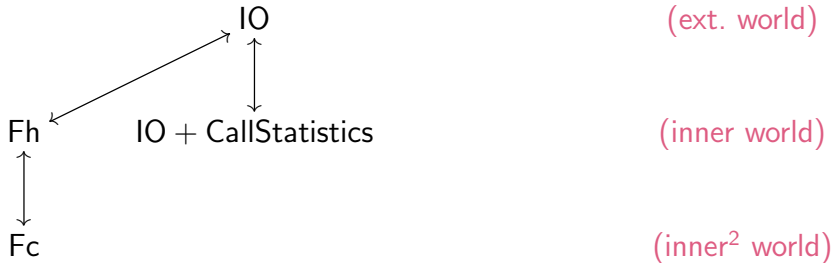
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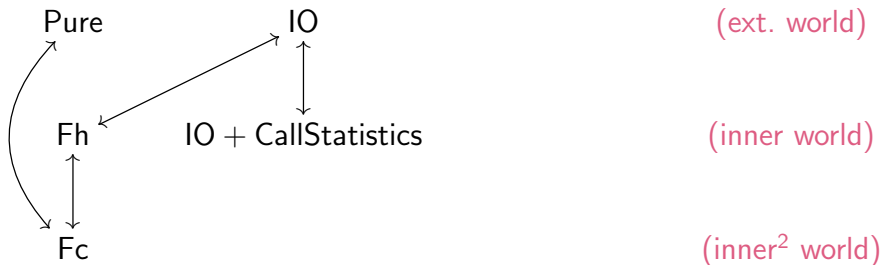
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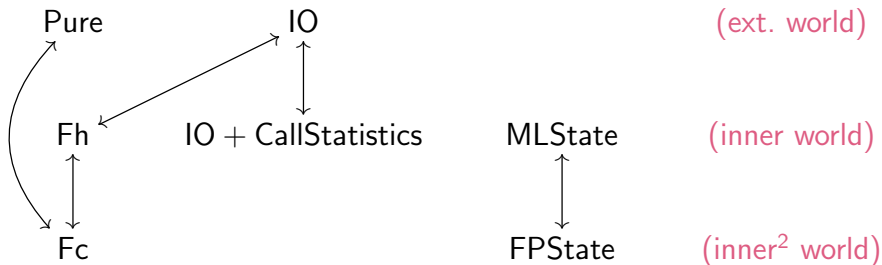
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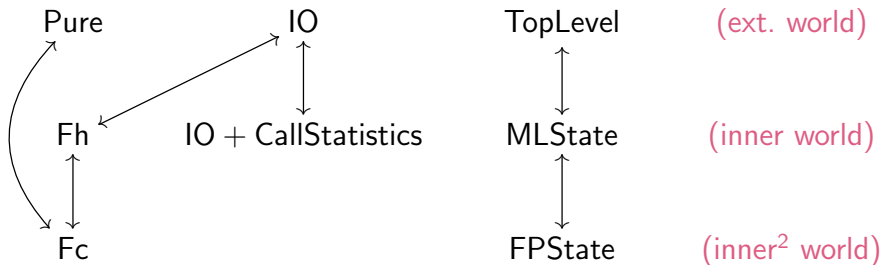
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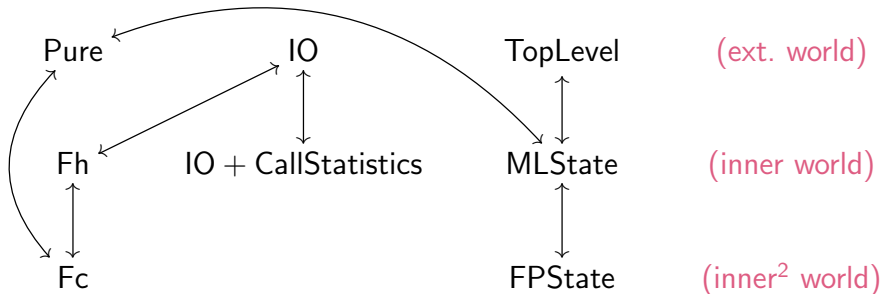


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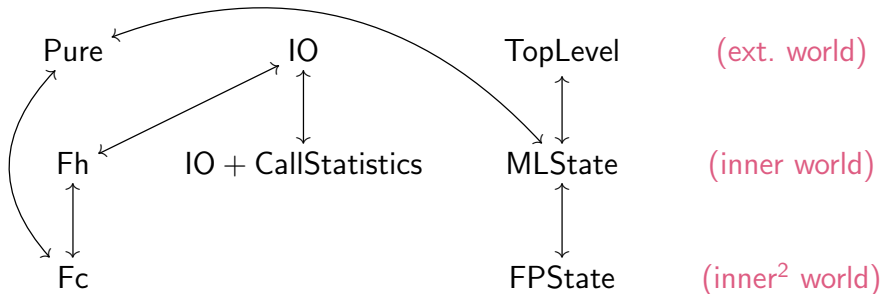
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- IO**  $\longrightarrow$  **Fh** — “call **fopen** with **foo.txt**, store returned **fh**”
- Fh**  $\longrightarrow$  **IO** — “call **fclose** with stored **fh**”
- Fc** — “**world** that is **blissfully unaware** of **fh**”
- Observation:** **IO**  $\longleftrightarrow$  **Fh** and other  $\longleftrightarrow$  look a lot like **lenses**

**Comodels** as a gateway to the **external world**

## Comodels as a gateway to the external world

- 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) \mapsto c_fin(w,x) (* : B *) } (* : B *)
```

- Comodels are defined as follows

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

for all **operations**  $\text{op} : A \rightsquigarrow B$  in a given signature  $\Sigma$

**Focussing on a fragment of the external world**

## Focussing on a fragment of the external world

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

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let f (s:string) = (* in IO *)
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 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 {
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Fc = { fwrite s @ s' ↦ return ((), s'^s) }
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where

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Fc = { fwrite s @ s' ↦ return ((), s'^s) }
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- **More generally:** comodels allow **transactions** and **sandboxing**

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

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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' }
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where

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

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

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

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$$\Sigma ::= \{ \text{op}_1 : A_1 \rightsquigarrow B_1, \dots, \text{op}_n : A_n \rightsquigarrow B_n \}$$

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

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

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

- Interfaces (signatures) of external worlds**

$$\Sigma ::= \{ \text{op}_1 : A_1 \rightsquigarrow B_1, \dots, \text{op}_n : A_n \rightsquigarrow B_n \}$$

- Computation terms** (value terms are unsurprising)

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

- Comodels (cohandlers)**

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

So what's happening **formally**?



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- **Typing judgements**

$$\Gamma \vdash v : A$$
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- The two central **typing rules** are

$\Gamma \vdash^{\Sigma} C$  comodel of  $\Sigma'$  with carrier  $W_C$

$$\Gamma \vdash^{\Sigma} c_i : W_C \quad \Gamma \vdash^{\Sigma'} c : A \quad \Gamma, w : W_C, x : A \vdash^{\Sigma} c_f : B$$

$$\Gamma \vdash^{\Sigma} \text{using } C @ c_i \text{ run } c \text{ finally } @ w \{ \text{return}(x) \mapsto c_f \} : B$$

and

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

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# (Denotational) semantics (in $\omega$ -cpos)

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

$$\llbracket \Gamma \vdash v : A \rrbracket : \llbracket \Gamma \rrbracket \longrightarrow \llbracket A \rrbracket \qquad \llbracket \Gamma \stackrel{\Sigma}{\vdash} c : A \rrbracket : \llbracket \Gamma \rrbracket \longrightarrow T_{\Sigma} \llbracket A \rrbracket$$

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# (Denotational) **semantics** (in $\omega$ -cpos)

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- **un-cohandled operations** **wait for a suitable external world!**
- The interesting part is the **interpretation of using ... run**

|                                                                                                                                                                                                                                                                                                                                                                                                 |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $\Gamma \stackrel{\Sigma}{\vdash} C \text{ comodel of } \Sigma' \text{ with carrier } W_C$ $\frac{\Gamma \stackrel{\Sigma}{\vdash} c_i : W_C \quad \Gamma \stackrel{\Sigma'}{\vdash} c : A \quad \Gamma, w : W_C, x : A \stackrel{\Sigma}{\vdash} c_f : B}{\Gamma \stackrel{\Sigma}{\vdash} \text{ using } C @ c_i \text{ run } c \text{ finally } @ w \{ \text{return}(x) \mapsto c_f \} : B}$ |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

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

|                                                                                                                                                                                                                                                                                                                   |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| $\frac{\llbracket C \rrbracket \in \text{Comod}_{\Sigma'}(\text{Kleisli}(T_{\Sigma}))}{\text{run\_on}_{\llbracket C \rrbracket} : T_{\Sigma'} \llbracket A \rrbracket \longrightarrow \left( \llbracket W_C \rrbracket \rightarrow T_{\Sigma}(\llbracket W_C \rrbracket \times \llbracket A \rrbracket) \right)}$ |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

**Computational behaviour of `using ... run`**

# Computational behaviour of **using ... run**

- Two semantically valid program equations

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

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# What if the **world** doesn't keep promises?

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

$$\overline{\text{op}} : \llbracket A_{\text{op}} \rrbracket \times \llbracket W \rrbracket \longrightarrow T_{\Sigma}(\llbracket B_{\text{op}} \rrbracket \times \llbracket W \rrbracket)$$

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- What if **IO** **lost connection** to the HDD where "foo.txt" was?
- Our solution:** Allow the **world** to **raise signals** to talk back

```
C = (* : A * W → T((B * W) + 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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try x = (raise s) in c unless {signal(s) \mapsto c_sig}
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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) \mapsto c_fin(w,x),
 signal(s) \mapsto c_sig(w,s) }
```

vs

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

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- When a signal `s` occurs in `run c`, control jumps to `finally`

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let rec ctr_printer i =
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 while(T) {let j = get_c in print j; incr_c}
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- World-based:** could **store a trace** so as to **replay "old" co-ops**

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using C @ c_init
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it is natural to want that

- **algebraic operations** (in the sense of  $\text{EFF}$ ) are allowed in `c`,  
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- so that we ensure that `finally` block is **definitely reached**
- Where do **multi-handlers** fit? Co-operating handlers-cohandlers?

# Conclusions



# Conclusions

- **Comodels** as a **gateway** for interacting with the **external world**
- `System.IO`, KOKA's **initially** & **finally**, PYTHON's **with**, ...
- Can also be a **basis for FFI**, e.g., in future EFF want to have

$$\frac{f : A \longrightarrow B \in \text{OCAML}}{\bar{f} : A \times W_{\text{top-level}} \longrightarrow B \times W_{\text{top-level}} \in \text{top-level-comodel}}$$

- **Combinatorics** of comodels and their lens-like relationships
- **Promising examples**: sandboxing, instrumentation, monitors, ...
- A proof-of-concept HASKELL **prototype**, long-term plans for EFF
- Future work: **Interface polymorphism**, **linear typing**, ...