Comodels as a gateway for interacting with the external world

Danel Ahman

(joint work with Andrej Bauer)

University of Ljubljana, Slovenia

MSR Redmond, 15 May 2019

A modular programming abstraction for using external resources

Danel Ahman

(joint work with Andrej Bauer)

University of Ljubljana, Slovenia

MSR Redmond, 15 May 2019

Computational effects in FP

Computational effects in FP

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

```
type St a = String → (a, String)

f :: St a → St (a, a)
f c = c >>= (\x → c >>= (\y → return (x, y)))
```

Computational effects in FP

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

```
type St a = String → (a, String)

f :: St a → St (a, a)
f c = c >>= (\x → c >>= (\y → return (x, y)))
```

- 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 ())
```

Computational effects in FP

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

```
type St a = String → (a, String)

f :: St a → St (a, a)
f c = c >>= (\x → c >>= (\y → return (x, y)))
```

- 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 ())
```

- 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

An issue — difficult to cover all use cases

Ohad 🗿 12:17 PM
Can I do file IO (or just O) in Eff?

An issue — difficult to cover all use cases

Ohad 🕯 12:17 PM
Can I do file IO (or just O) in Eff?

Žiga Lukšič 12:18 PM
not currently

An issue — difficult to cover all use cases

Ohad 12:17 PM
Can I do file IO (or just O) in Eff?

Žiga Lukšič 12:18 PM
not currently

Ohad 8:35 PM
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)
      )
```

An issue — difficult to cover all use cases

Ohad 12:17 PM
Can I do file IO (or just O) in Eff?

Žiga Lukšič 12:18 PM
not currently

Ohad 8:35 PM
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)
      )
```

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

A bigger issue — linearity or lack thereof

A bigger issue — linearity or lack thereof

-
```
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

-
```
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    (* fh not open ! *)
```

A bigger issue — linearity or lack thereof

-
```
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      (* fh not open ! *)
```

- 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 ()
```

A bigger issue — linearity or lack thereof

- ```
  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     (* fh not open ! *)
  ```

- 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 ! *)
  ```

So, how could we solve these issues?

So, how could we solve these issues?

- 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**

So, how could we solve these issues?

- 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**

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

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

Algebraic digression: What's a comodel?

- A **signature** Σ is a set of operation symbols op $: A_{\mathrm{op}} \rightsquigarrow B_{\mathrm{op}}$

Algebraic digression: What's a comodel?

- A **signature** Σ is a set of operation symbols $\mathsf{op} : A_{\mathsf{op}} \rightsquigarrow B_{\mathsf{op}}$

- A **model**/**algebra**/**handler** $\mathcal{M}$ of Σ is given by

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

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

- A **signature** Σ is a set of operation symbols $\mathsf{op} : A_{\mathsf{op}} \rightsquigarrow B_{\mathsf{op}}$

- A **model**/**algebra**/**handler** $\mathcal{M}$ of Σ is given by

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

- A **comodel**/**coalgebra**/**cohandler** $\mathcal{W}$ of Σ is given by

$$\mathcal{W} = \langle\ W : \mathsf{Set}\ ,\ \{\overline{\mathsf{op}}_{\mathcal{W}} : A_{\mathsf{op}} \times W \longrightarrow B_{\mathsf{op}} \times W\}_{\mathsf{op} \in \Sigma}\ \rangle$$

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

Algebraic digression: What's a comodel?

- A **signature** Σ is a set of operation symbols $\mathsf{op} : A_{\mathsf{op}} \rightsquigarrow B_{\mathsf{op}}$

- A **model**/**algebra**/**handler** $\mathcal{M}$ of Σ is given by

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

- A **comodel**/**coalgebra**/**cohandler** $\mathcal{W}$ of Σ is given by

$$\mathcal{W} = \langle\ W : \mathsf{Set}\ ,\ \{\overline{\mathsf{op}}_{\mathcal{W}} : A_{\mathsf{op}} \times W \longrightarrow B_{\mathsf{op}} \times W\}_{\mathsf{op} \in \Sigma}\ \rangle$$

- Intuitively, 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)

Back to the essence: What is it then?

Back to the essence: What is it then?

- Let's look at HASKELL's **IO monad** again

Back to the essence: What is it then?

- Let's look at HASKELL's **IO monad** again

- A common explanation is to think of functions

$$a \rightarrow IO\ b$$

as

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

which is the same as

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

Back to the essence: What is it then?

- Let's look at HASKELL's **IO monad** again

- A common explanation is to think of functions

$$a \to IO\ b$$

  as

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

  which is the same as

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

- 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

Back to the essence: What is it then?

- Let's look at HASKELL's **IO monad** again

- A common explanation is to think of functions

$$a \rightarrow IO\ b$$

as

$$a \rightarrow (RealWorld \rightarrow (b, RealWorld))$$

which is the same as

$$(a, RealWorld) \rightarrow (b, RealWorld)$$

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

hGetLine : (Handle, RealWorld) $\rightarrow$ (String, RealWorld)

hClose : (Handle, RealWorld) $\rightarrow$ ((), RealWorld)

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

Towards a general programming abstraction

Towards a general programming abstraction

- ```
  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**

Towards a general programming abstraction

- ```
  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**

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

  Better, but **have to explicitly open** and **thread through** `fh`

Towards a general programming abstraction

- ```
  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**

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

  Better, but **have to explicitly open** and **thread through** `fh`

- **Our solution:** **Modular treatment** of **external worlds**

Modular treatment of external worlds
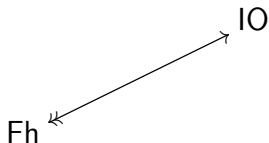
- **For example**

IO   (ext. world)

Fh   (inner world)

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

Modular treatment of external worlds

- **For example**

- Fh   —   "**world** which consists of **exactly one** `fh`"
- IO ⟶ Fh   —   "call `fopen` with `foo.txt`, store returned `fh`"
- Fh ⟶ IO   —   "call `fclose` with stored `fh`"

- Fc   —   "**world** that is **blissfully unaware** of `fh`"

Modular treatment of external worlds
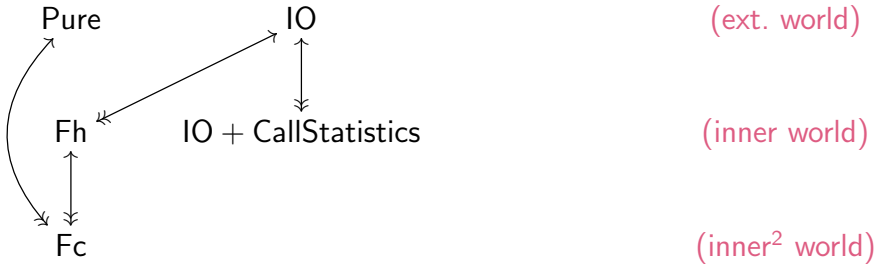
- **For example**

$$
\begin{array}{lll}
& \text{IO} & \text{(ext. world)} \\
& \uparrow\downarrow & \\
\text{Fh} \quad & \text{IO} + \text{CallStatistics} & \text{(inner world)} \\
\uparrow\downarrow & & \\
\text{Fc} & & \text{(inner}^2\text{ world)}
\end{array}
$$

- Fh   —   "**world** which consists of **exactly one** `fh` "
- 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` "
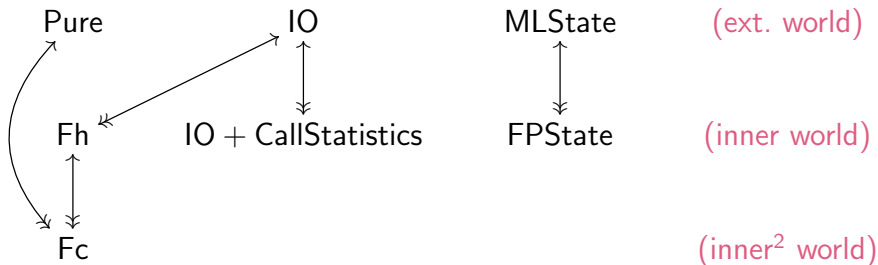
Modular treatment of external worlds

- **For example**

Pure   IO   (ext. world)

Fh   IO + CallStatistics   (inner world)

Fc   (inner^2 world)

- Fh   —   "**world** which consists of **exactly one** `fh` "
- IO ⟶ Fh   —   "call `fopen` with `foo.txt` , store returned `fh` "
- Fh ⟶ IO   —   "call `fclose` with stored `fh` "

- Fc   —   "**world** that is **blissfully unaware** of `fh` "
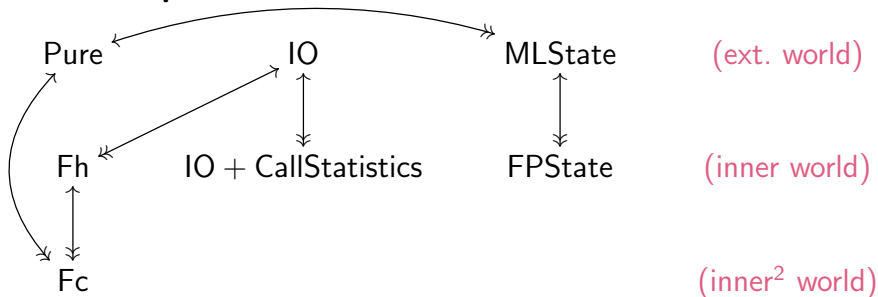
Modular treatment of external worlds

- **For example**

Pure   IO   MLState   (ext. world)

Fh   IO + CallStatistics   FPState   (inner world)

Fc   (inner^2 world)
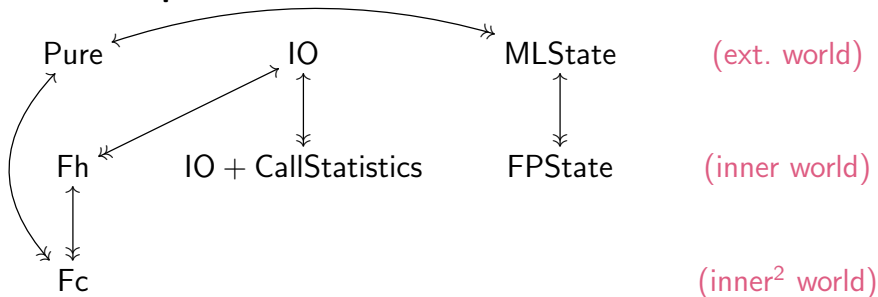
- Fh   —   "**world** which consists of **exactly one** `fh`"
- IO $\longrightarrow$ Fh   —   "call `fopen` with `foo.txt`, store returned `fh`"
- Fh $\longrightarrow$ IO   —   "call `fclose` with stored `fh`"
- Fc   —   "**world** that is **blissfully unaware** of `fh`"

Modular treatment of external worlds

- **For example**

Pure   IO   MLState   (ext. world)

Fh   IO + CallStatistics   FPState   (inner world)

Fc   (inner^2 world)

- Fh   —   "**world** which consists of **exactly one** `fh`"
- 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`"

Modular treatment of external worlds

- **For example**

Pure ← IO → MLState   (ext. world)

Fh ← IO + CallStatistics   FPState   (inner world)

Fc   (inner² world)

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

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) ↦ 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

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 {
    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 {
    return(x) ↦ fclose_of_io fh }            (* in IO *)
```

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 {
    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 ⟷ Fh ⟷ Fc)

Modular treatment of worlds (IO ⟷ Fh ⟷ Fc)

```
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 }
```

where

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

Modular treatment of worlds (IO ⟷ Fh ⟷ Fc)

```
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 }
```

where

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

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

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

Tracking the world usage (IO ⟷ IO+Stats)

```
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),
    ... }
```

Tracking the world usage (IO ⟷ IO+Stats)

```
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),
     ... }
```

- **More generally:** allows to slot in **instrumentation**/**monitors**

The external world can also be pure (Pure $\longleftrightarrow$ Str**)**

The **external world** can also be **pure** (Pure ⟷ Str)

```
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) ↦ return x }

Str =                                       (* W = string *)
  { get _ @ s ↦ return (s,s) ,
    set s @ _ ↦ return ((),s) }
```

The **external world** can also be **pure** (Pure ⟷ Str)

```
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) ↦ return x }
```

```
Str =                                           (* W = string *)
  { get _ @ s ↦ return (s,s) ,
    set s @ _ ↦ return ((),s) }
```

- Similar to **ambient values** (and **ambient functions**) in KOKA

So what's happening formally?

So what's happening formally?

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

So what's happening formally?

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

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

So what's happening formally?

- Core calculus for comodels (wo/ handlers $\Rightarrow$ 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**

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

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**

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

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

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

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**

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

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

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

- **Comodels** (**cohandlers**)

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

So what's happening formally?

So what's happening formally?

- **Typing judgements**

$$\Gamma \vdash v : A \qquad \qquad \Gamma \vdash^{\Sigma} c : A$$

So what's happening **formally**?

- **Typing judgements**

$$\Gamma \vdash v : A \qquad \Gamma \overset{\Sigma}{\vDash} c : A$$

- The two central **typing rules** are

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

and

$$
\frac{
\text{op} : A_{\text{op}} \leadsto B_{\text{op}} \in \Sigma \qquad \Gamma \vdash v : A_{\text{op}} \qquad \Gamma, x : B_{\text{op}} \overset{\Sigma}{\vDash} c : A
}{
\Gamma \overset{\Sigma}{\vDash} \text{op } v \ (x.c) : A
}
$$

(Denotational) semantics (in ω-cpos)

(Denotational) semantics (in ω-cpos)

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

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

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

(Denotational) semantics (in ω-cpos)

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

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

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

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

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

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

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

Computational behaviour of using ...run

Computational behaviour of using . . . run

- Two semantically valid program equations

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

using C @ c_i **run** (op v $(y.c)$) **finally** @ w { **return**$(x) \mapsto c_f$ }
=
let $w' = c_i$ **in** $\Big($
  let $z = C_{\overline{\text{op}}}[w'/w, v/x]$ **in** $\Big($
    match z **with** { $\langle y', w'' \rangle \mapsto$
      using C @ (**return** w'')
      run $(c[y'/y])$
      finally @ w { **return**$(x) \mapsto c_f$ } }$\Big)\Big)$

What if the world doesn't keep promises?

What if the world doesn't keep promises?

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

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

  ensures that the **world always comes back with an answer**

What if the world doesn't keep promises?

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

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

  ensures that the **world always comes back with an answer**

- What if **IO lost connection** to the HDD where `"foo.txt"` was?

What if the world doesn't keep promises?

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

$$\overline{\mathsf{op}} : \llbracket A_{\mathsf{op}} \rrbracket \times \llbracket W \rrbracket \longrightarrow T_{\Sigma_\perp}(\llbracket B_{\mathsf{op}} \rrbracket \times \llbracket W \rrbracket)$$

  ensures that the **world always comes back with an answer**

- 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 x W → T((B x W) + S) ∗)
   { op x @ w ↦ if b then (...) else (raise s) }
```

What if the world doesn't keep promises?

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

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

  ensures that the **world always comes back with an answer**

- 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 x W → T((B x W) + S)  *)
  { op x @ w ↦ if b then (...) else (raise s) }
```

```
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'  *)
```

What if the world doesn't keep promises?

- **User-raised signals can be** handled locally (exceptional syntax)

```
try x = (raise s) in c unless {signal(s) ↦ c_sig}
```

What if the world doesn't keep promises?

- **User-raised signals can be** handled locally (exceptional syntax)

```
try x = (raise s) in c unless {signal(s) ↦ c_sig}
```

- 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
run (try x = (op v) in c unless {...})
finally @ w {
    return(x) ↦ c_fin(w,x),
    signal(s) ↦ (∗∗)c_sig(w,s) }
```

What if the world doesn't keep promises?

What if the world doesn't keep promises?

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

```
using C @ c_init
run c
finally @ w {
  return(x) ↦ c_fin(w,x), signal(s) ↦ c_sig(w,s)}
```

from which there is **no automatic resume** back to `run c`

What if the world doesn't keep promises?

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

```
using C @ c_init
run c
finally @ w {
    return(x) ↦ c_fin(w,x), signal(s) ↦ c_sig(w,s)}
```

from which there is **no automatic resume** back to `run c`

- To resume `run c`, the **program and/or world** have to support it

What if the world doesn't keep promises?

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

```
using C @ c_init
run c
finally @ w {
  return(x) ↦ c_fin(w,x), signal(s) ↦ c_sig(w,s)}
```

  from which there is **no automatic resume** back to `run c`

- To resume `run c`, the **program and/or world** have to support it

```
let rec ctr_printer i =
  using Out+Ctr @ (return i)
  run
    while(T) {let j = get_c in print j; incr_c}
  finally @ k {
    return(x) ↦ ...,
    signal(s) ↦ print "foo"; ctr_printer k }
```

What if the world doesn't keep promises?

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

```
using C @ c_init
run c
finally @ w {
  return(x) ↦ c_fin(w,x),  signal(s) ↦ c_sig(w,s)}
```

from which there is **no automatic resume** back to `run c`

- To resume `run c`, the **program** **and/or** **world** have to support it

```
let rec ctr_printer i =
  using Out+Ctr @ (return i)
  run
    while(T) {let j = get_c in print j; incr_c}
  finally @ k {
    return(x) ↦ ... ,
    signal(s) ↦ print "foo"; ctr_printer k }
```

- **World-based:** could **store a trace** so as to **replay "old" co-ops**

What about alg. effects and handlers?

What about **alg. effects** and **handlers**?

- In the following

```
using C @ c_init
run c
finally @ w { return(x) ↦ c_fin(w,x) , ... }
```

  it is natural to want that

  - **algebraic operations** (in the sense of EFF) are allowed in `c`, but they must not be allowed to escape **run**

  - to escape, have to use the **co-operations** of the **external world**

What about **alg. effects** and **handlers**?

- In the following

```
using C @ c_init
run c
finally @ w { return (x) ↦ c_fin (w, x) , ... }
```

  it is natural to want that

  - **algebraic operations** (in the sense of EFF) are allowed in `c`, but they must not be allowed to escape **run**

  - to escape, have to use the **co-operations** of the **external world**

  - the **continuations of handlers** in `c` are delimited by **run**

  - so that we ensure that **finally** block is **definitely reached**

What about alg. effects and handlers?

- In the following

```
using C @ c_init
run c
finally @ w { return(x) ↦ c_fin(w,x) , ... }
```

  it is natural to want that

  - **algebraic operations** (in the sense of EFF) are allowed in `c`, but they must not be allowed to escape `run`

  - to escape, have to use the **co-operations** of the **external world**

  - the **continuations of handlers** in `c` are delimited by `run`

  - 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**, ...

- **Promising examples**: sandboxing, instrumentation, monitors, ...

- Comodels and init.-fin. lenses admit **natural combinators**

Conclusions

- **Comodels** as a **gateway** for interacting with the **external world**

- `System.IO`, KOKA's **initially** & **finally**, PYTHON's **with**, . . .

- **Promising examples**: sandboxing, instrumentation, monitors, . . .

- Comodels and init.-fin. lenses admit **natural combinators**

- Two prototypes: **library** in HASKELL, and **toy language** COOP

- Can also be a **basis for FFI**, e.g., in COOP (and future EFF)

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

Conclusions

- **Comodels** as a **gateway** for interacting with the **external world**

- System.IO , KOKA's **initially** & **finally** , PYTHON's **with** , . . .

- **Promising examples**: sandboxing, instrumentation, monitors, . . .

- Comodels and init.-fin. lenses admit **natural combinators**

- Two prototypes: **library** in HASKELL, and **toy language** COOP

- Can also be a **basis for FFI**, e.g., in COOP (and future EFF)

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

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