

# (Higher-Order) Asynchronous Effects

Danel Ahman   Matija Pretnar   Janez Radešček

University of Ljubljana, Slovenia

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# Today's Plan

- Synchrony of algebraic effects
- Asynchrony through decoupling operation calls
- $\lambda_{\text{ae}}$ -calculus
- Examples

D. Ahman, M. Pretnar. *Asynchronous Effects*. (POPL 2021)

<https://github.com/matijapretnar/aeff>

<https://github.com/danelahman/aeff-agda>

- Some recent extensions (the higher-order part of the talk's title)

# Æff web interface

<https://matija.pretnar.info/aeff/>

Æff

```
run waitForStop 2;  
  let b = let b = let b = (+) (10, 10) in (+) (10, b) in (+) (10, b) in  
  (+) (10, b)  
||  
run waitForStop 1;  
  let b = let b = let b = (+) (1, 1) in (+) (1, b) in (+) (1, b) in  
  (+) (1, b)
```

## Interaction

Re-edit source code

Undo last step

1

random steps

applyFun



applyFun

Inter

payload



## History

# Synchrony of algebraic effects

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- The conventional operational treatment of algebraic effects

...  $\rightsquigarrow$   $\text{op}(V, y.M)$

# Synchrony of algebraic effects

- The conventional operational treatment of algebraic effects

$$\begin{array}{c} M_{\text{op}}[V/x] \\ \uparrow \\ \text{signal op's implementation} \\ \dots \rightsquigarrow \text{op}(V, y.M) \end{array}$$

- $M_{\text{op}}$  - handler, runner, top-level default implementation, ...

# Synchrony of algebraic effects

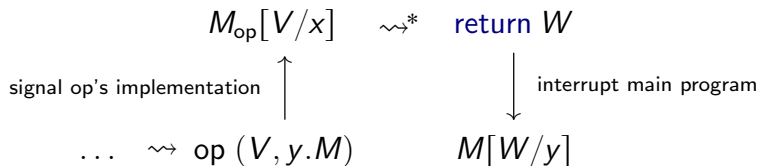
- The conventional operational treatment of algebraic effects

$$\begin{array}{ccc} M_{\text{op}}[V/x] & \rightsquigarrow^* & \text{return } W \\ \text{signal op's implementation} & \uparrow & \\ \dots & \rightsquigarrow & \text{op}(V, y.M) \end{array}$$

- $M_{\text{op}}$  - handler, runner, top-level default implementation, ...

# Synchrony of algebraic effects

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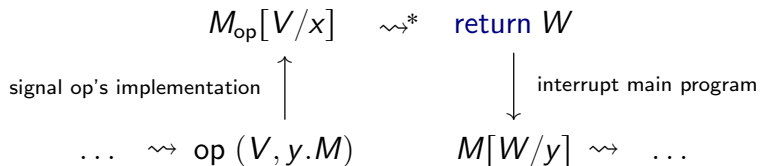


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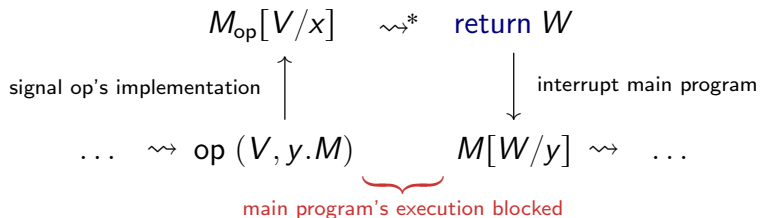
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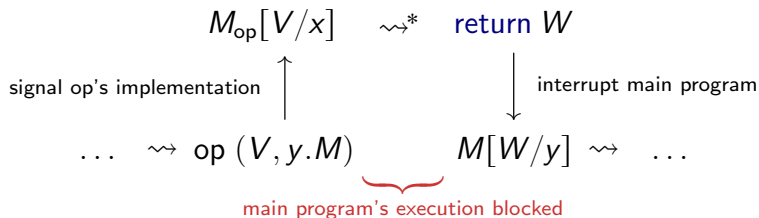
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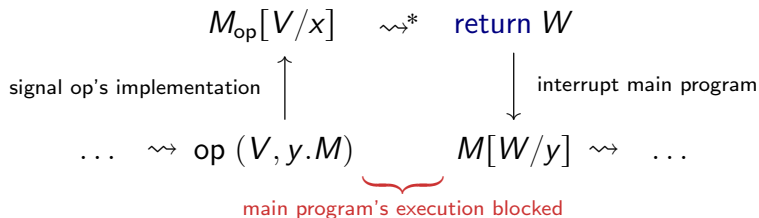
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- Forces **all uses** of algebraic operations to be synchronous

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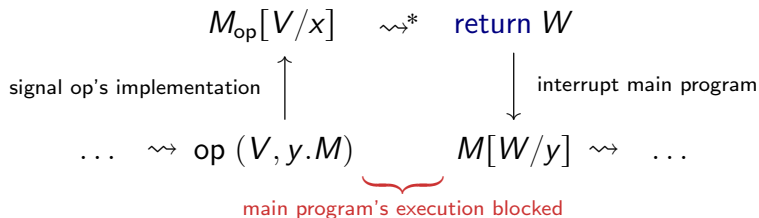
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- Forces **all uses** of algebraic operations to be synchronous
- Existing langs. do async. by **delegating** it to their lang. backends

# Synchrony of algebraic effects

- The conventional operational treatment of algebraic effects



- $M_{\text{op}}$  - handler, runner, top-level default implementation, ...
- Forces **all uses** of algebraic operations to be synchronous
- Existing langs. do async. by **delegating** it to their lang. backends
- In contrast, we capture async. in a **self-contained core calculus**

$\lambda_{\text{æ}}$ -calculus

## $\lambda_{\text{æ}}$ -calculus: basics

- Extension of Levy's fine-grain call-by-value  $\lambda$ -calculus
- **Types:**  $X, Y ::= \mathbf{b} \mid \dots \mid X \rightarrow Y!(o, \iota) \mid \dots$
- **Values:**  $V, W ::= x \mid \dots \mid \mathbf{fun} (x : X) \mapsto M \mid \dots$
- **Computations:**  $M, N ::= \mathbf{return} V \mid \mathbf{let} x = M \mathbf{in} N \mid \dots$
- **Typing judgements:**  $\Gamma \vdash V : X \quad \Gamma \vdash M : X!(o, \iota)$
- **Small-step operational semantics:**  $M \rightsquigarrow N$

## $\lambda_{\text{æ}}$ -calculus: signals

- Signalling that some op's implementation needs to be executed

$$\frac{\text{TYCOMP-SIGNAL} \quad \text{op} : A_{\text{op}} \in \mathcal{O} \quad \Gamma \vdash V : A_{\text{op}} \quad \Gamma \vdash M : X!(\mathcal{O}, \iota)}{\Gamma \vdash \uparrow \text{op}(V, M) : X!(\mathcal{O}, \iota)}$$

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- Operationally behave like algebraic operations
  - $\text{let } x = \uparrow \text{op}(V, M) \text{ in } N \rightsquigarrow \uparrow \text{op}(V, \text{let } x = M \text{ in } N)$

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- But importantly, they do not block their continuations
  - $M \rightsquigarrow M' \implies \uparrow \text{op}(V, M) \rightsquigarrow \uparrow \text{op}(V, M')$

## $\lambda_{\text{æ}}$ -calculus: interrupts

- Environment interrupting a computation (with some op's result)

$$\frac{\text{TYCOMP-INTERRUPT} \quad \Gamma \vdash V : A_{\text{op}} \quad \Gamma \vdash M : X! (o, \iota)}{\Gamma \vdash \downarrow_{\text{op}}(W, M) : X! (\text{op} \downarrow (o, \iota))}$$

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- Operationally behave like homomorphisms/effect handling
  - $\downarrow \text{op} (W, \text{return } V) \rightsquigarrow \text{return } V$
  - $\downarrow \text{op} (W, \uparrow \text{op}' (V, M)) \rightsquigarrow \uparrow \text{op}' (V, \downarrow \text{op} (W, M))$
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- And they also do not block their continuations
  - $M \rightsquigarrow M' \implies \downarrow \text{op} (V, M) \rightsquigarrow \downarrow \text{op} (V, M')$

# $\lambda_{\text{æ}}$ -calculus: interrupt handlers

- Allow computation to react to interrupts

TY-COMP-PROMISE

$$\frac{\begin{array}{c} \iota(\text{op}) = (o', \iota') \\ \Gamma, x : A_{\text{op}} \vdash M : \langle X \rangle ! (o', \iota') \quad \Gamma, p : \langle X \rangle \vdash N : Y ! (o, \iota) \end{array}}{\Gamma \vdash \text{promise } (\text{op } x \mapsto M) \text{ as } p \text{ in } N : Y ! (o, \iota)}$$

where  $p : \langle X \rangle$  is a **promise-typed variable**

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- Operationally **behave like (scoped) algebraic operations (!)**
  - $\text{let } x = (\text{promise } (\text{op } x \mapsto M_1) \text{ as } p \text{ in } M_2) \text{ in } N$   
 $\rightsquigarrow \text{promise } (\text{op } x \mapsto M_1) \text{ as } p \text{ in } (\text{let } x = M_2 \text{ in } N)$
  - $\text{promise } (\text{op } x \mapsto M) \text{ as } p \text{ in } \uparrow \text{op } (V, N)$   
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  - $\text{promise } (\text{op } x \mapsto M) \text{ as } p \text{ in } \uparrow \text{op } (\boxed{V}, N)$  (type safety!)  
 $\rightsquigarrow \uparrow \text{op } (\boxed{V}, \text{promise } (\text{op } x \mapsto M) \text{ as } p \text{ in } N)$  ( $p \notin FV(V)$ )



## $\lambda_{\text{æ}}$ -calculus: interrupt handlers ctd.

- Allow computation to react to interrupts

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where  $p : \langle X \rangle$  is a **promise-typed variable**

- They are **triggered by matching interrupts**
  - $\downarrow \text{op} (W, \text{promise } (\text{op } x \mapsto M) \text{ as } p \text{ in } N)$   
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 $\rightsquigarrow \text{let } p = M[W/x] \text{ in } \downarrow_{\text{op}} (W, N)$
- And **non-matching interrupts** ( $\text{op} \neq \text{op}'$ ) are passed through
  - $\downarrow_{\text{op}} (W, \text{promise } (\text{op}' x \mapsto M) \text{ as } p \text{ in } N)$   
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- They also **do not block their continuations**

- $N \rightsquigarrow N'$

$\implies$

**promise** (op  $x \mapsto M$ ) **as**  $p$  **in**  $N$

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- For type safety, important that  $p$  **does not get an arbitrary type**

## $\lambda_{\text{æ}}$ -calculus: awaiting

- Enables programmers to selectively block execution

$$\frac{\text{TYCOMP-AWAIT} \quad \Gamma \vdash V : \langle X \rangle \quad \Gamma, x : X \vdash N : Y ! (o, \iota)}{\Gamma \vdash \text{await } V \text{ until } \langle x \rangle \text{ in } N : Y ! (o, \iota)}$$

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- Operationally behave like pattern-matching (and alg. ops.)
  - $\text{await } \langle V \rangle \text{ until } \langle x \rangle \text{ in } N \rightsquigarrow N[V/x]$
  - $\text{let } y = (\text{await } V \text{ until } \langle x \rangle \text{ in } M) \text{ in } N$   
 $\rightsquigarrow \text{await } V \text{ until } \langle x \rangle \text{ in } (\text{let } y = M \text{ in } N)$
- In contrast to earlier gadgets, **await blocks its cont.'s execution (!)**

## $\lambda_{\text{æ}}$ -calculus: environment

- We model the environment by running computations in parallel

$$P, Q ::= \text{run } M \mid P \parallel Q \mid \uparrow \text{op}(V, P) \mid \downarrow \text{op}(W, P)$$

(omitting typing judgement, typing rules, and type reduction)

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- Small-step operational semantics  $P \rightsquigarrow Q$ : congruence rules +
  - $\text{run}(\uparrow \text{op}(V, M)) \rightsquigarrow \uparrow \text{op}(V, \text{run } M)$



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  - $(\uparrow \text{op}(V, P)) \parallel Q \rightsquigarrow \uparrow \text{op}(V, (P \parallel \downarrow \text{op}(V, Q)))$
  - $P \parallel (\uparrow \text{op}(V, Q)) \rightsquigarrow \uparrow \text{op}(V, (\downarrow \text{op}(V, P) \parallel Q))$

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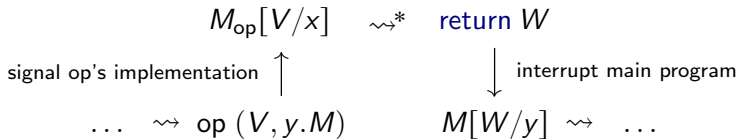
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  - $(\uparrow \text{op}(V, P)) \parallel Q \rightsquigarrow \uparrow \text{op}(V, (P \parallel \downarrow \text{op}(V, Q)))$
  - $P \parallel (\uparrow \text{op}(V, Q)) \rightsquigarrow \uparrow \text{op}(V, (\downarrow \text{op}(V, P) \parallel Q))$
  - $\downarrow \text{op}(W, \text{run } M) \rightsquigarrow \text{run}(\downarrow \text{op}(W, M))$
  - ...

# Examples

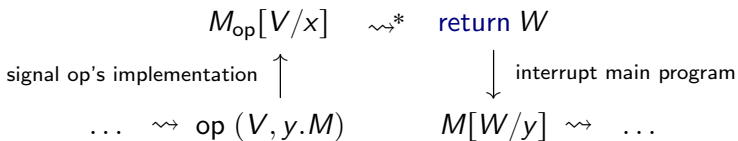
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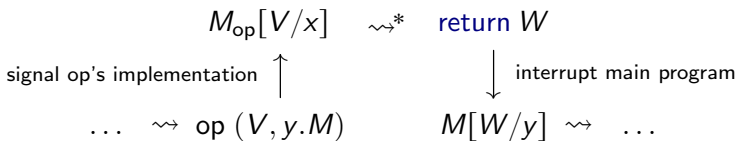


- At **call site**

$$\begin{array}{c} \text{op}(V, y.M) \\ \stackrel{\text{def}}{=} \\ \uparrow \text{call}_{\text{op}}(V, \text{promise}(\text{result}_{\text{op}} y \mapsto \text{return } \langle y \rangle)) \text{ as } p \text{ in} \\ \text{await } p \text{ until } \langle y \rangle \text{ in } M \end{array}$$

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- At **implementation site**

$$\begin{array}{c} \text{promise}(\text{call}_{\text{op}} x \mapsto \text{let } y = M_{\text{op}} \text{ in return } \langle y \rangle) \text{ as } p \text{ in} \\ \text{await } p \text{ until } \langle y \rangle \text{ in } \uparrow \text{result}_{\text{op}}(y, \text{return } ()) \end{array}$$

# Example: remote function calls

- Server

```
let server f =  
  let rec loop () =  
    promise (call (x, callNo)  $\mapsto$  let y = f x in  $\uparrow$  result (y, callNo); loop ())  
    as p in return p  
  in loop ()
```

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```

- Client

```
let callWith x =  
  let callNo = !callCounter in callCounter := !callCounter + 1;  
   $\uparrow$  call (x, callNo);  
  promise (result (y, callNo') when callNo = callNo'  $\mapsto$  return  $\langle y \rangle$ ) as resultProm in  
  return (fun ()  $\rightarrow$  await resultProm until  $\langle$ resultValue $\rangle$  in return resultValue)
```



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  return (fun ()  $\rightarrow$  await resultProm until  $\langle$ resultValue $\rangle$  in return resultValue)
```

- Shortcomings (fixes for those later)

- Necessitates general recursion in the core calculus
- No way to send the function  $f$  from client to server
- Subsequent calls are executed sequentially on the server

# Example: guarded interrupt handlers

- In previous example (and many others) we often write

```
promise (op x when guard  $\mapsto$  comp) as p in cont
```

as a syntactic sugar for the **recursively defined interrupt handler**

```
let rec waitForGuard () =  
  promise (op x  $\mapsto$  if guard then comp else waitForGuard ()) as p' in return p'  
in  
let p = waitForGuard () in cont
```

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in  
let p = waitForGuard () in cont
```

- For well-typedness, important we have  $\text{comp} : \langle X \rangle$  instead of  $\text{comp} : X$
- Again **necessitates gen. rec.** in the core calculus

# Example: preemptive multi-threading

- At the core of our approach is the following recursive definition

```
let rec waitForStop () =  
  promise (stop _ ↦  
    promise (go _ ↦ return <()>) as p in (await p until <-> in waitForStop ())  
  ) as p' in return p'
```

- first **wait for stop interrupt**, but **do not block execution**
- next **wait for go interrupt**, and **block execution**
- repeat the cycle

## Example: preemptive multi-threading

- At the core of our approach is the following recursive definition

```
let rec waitForStop () =  
  promise (stop _ ↦  
    promise (go _ ↦ return <()>) as p in (await p until <-> in waitForStop ())  
  ) as p' in return p'
```

- first **wait for stop interrupt**, but **do not block execution**
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- To initiate preemptive behaviour for some comp, run the composite

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- To initiate preemptive behaviour for some comp, run the composite

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waitForStop (); comp
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- op. sem. propagates **promises** out, and wrap them around comp
- Note:** No need to access the cont. (of comp) in `waitForStop (!)`

## Other examples (see <https://matija.pretnar.info/aeff/>)

- Multi-party web application
- (Simulating) cancellations of remote function calls
- Parallel variant of runners of algebraic effects
- Non-blocking post-processing of promised values

## Other examples (see <https://matija.pretnar.info/aeff/>)

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```
promise (op x  $\mapsto$  original_interrupt_handler) as p in
...
processop p with (<<is>  $\mapsto$  filter (fun i  $\mapsto$  i > 0) is) as q in
processop q with (<<js>  $\mapsto$  fold (fun j j'  $\mapsto$  j * j') 1 js) as r in
processop r with (<<k>  $\mapsto$   $\uparrow$  productOfPositiveElements k) as _ in
...
```

where

```
processop p with (<<x>  $\mapsto$  comp) as q in cont
=
promise (op _  $\mapsto$  await p until <<x> in let y = comp in return <<y>>) as q in cont
```



**Resolving  $\lambda_{\text{æ}}$ 's shortcomings**

# S1: general recursion in the core calculus

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- **Solution:** **reinstallable** interrupt handlers

TY-COMP-REPROMISE

$$\Gamma, x : A_{op}, r : 1 \rightarrow \langle X \rangle ! (o', \iota') \vdash M : \langle X \rangle ! (o', \iota')$$
$$(o', \iota') \sqsubseteq \iota(op) \quad \Gamma, p : \langle X \rangle \vdash N : Y ! (o, \iota)$$

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$$\Gamma \vdash \text{promise } (op \ x \ r \mapsto M) \text{ as } p \text{ in } N : Y ! (o, \iota)$$

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- Operationally only difference in **triggering int. handlers**
  - $\downarrow op (W, \text{promise } (op \ x \ r \mapsto M) \text{ as } p \text{ in } N)$   
 $\rightsquigarrow \text{let } p = M[W/x,$   
 $\quad (\text{fun } \_ \mapsto \text{promise } (op \ x \ r \mapsto M) \text{ as } p \text{ in return } p) / r ]$   
 $\text{in } \downarrow op (W, N)$

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$$\Gamma \vdash \text{promise } (op \ x \ r \mapsto M) \text{ as } p \text{ in } N : Y ! (o, \iota)$$

- For example, the preemptive multithreading now becomes

```
let waitForStop () =  
  promise (stop _ r  $\mapsto$   
    promise (go _ _  $\mapsto$  return  $\langle () \rangle$ ) as p in (await p until  $\langle - \rangle$  in r ()))  
  ) as p' in return p'
```

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$X$  is mobile  $\vee$   $\mathfrak{A} \notin \Gamma'$

$\Gamma, x : X, \Gamma' \vdash x : X$

TYVAL-BOX

$\Gamma, \mathfrak{A} \vdash V : X$

$\Gamma \vdash [V] : [X]$

TYCOMP-UNBOX

$\Gamma \vdash V : [X] \quad \Gamma, x : X \vdash M : Y!(o, \iota)$

$\Gamma \vdash \text{unbox } V \text{ as } [x] \text{ in } M : Y!(o, \iota)$

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$A_{\text{op}} ::= \text{ground types} \mid [X]$  (mobile types)

- Gives us **type-safe higher-order** payloads for signals/interrupts
  - $\Gamma, \rho : \langle X \rangle \vdash V : A_{\text{op}} \implies \Gamma \vdash V : A_{\text{op}}$



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- Operationally **propagates outwards** (like scoped alg. op.)
  - `let x = spawn (M1, M2) in N`  $\rightsquigarrow$  `spawn (M1, let x = M2 in N)`
  - also propagates through **promises**, where  $\mathbb{A}$  provides **type-safety**
- Eventually gives rise to a **new parallel process**
  - `run (spawn (M, N))`  $\rightsquigarrow$  `run M || run N`
- **Does not block** its continuation

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- Remote function calls can now execute in parallel

```
let server f =  
  promise (call (x, callNo) r  $\mapsto$   
    spawn (let y = f x in  $\uparrow$  result (y, callNo),  
           r ())  
  ) as p in return p
```

# Conclusion

- A core calculus for asynchronous algebraic effects
- Could it serve as a spec. for an efficient/practical implementation?
  - Janez has worked on a more efficient implementation of  $\lambda_{\text{ae}}$
  - Implementing this spec. using handlers? (Lindley & Poulson)
- Various yet to be resolved details concerning  $\lambda_{\text{ae}}$ 's denot. sem.

# Conclusion

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  - Implementing this spec. using handlers? (Lindley & Poulson)
- Various yet to be resolved details concerning  $\lambda_{\text{ae}}$ 's denot. sem.
- Same **algebraic & modal ideas** also applicable without **||**

$\text{async } M \text{ as } p \text{ in } N$

with

$\text{async } (\uparrow \text{op } (V, M)) \text{ as } p \text{ in } N \rightsquigarrow \uparrow \text{op } (V, \text{async } M \text{ as } p \text{ in } N)$

$\text{async } M \text{ as } p \text{ in } (\uparrow \text{op } (V, N)) \rightsquigarrow \uparrow \text{op } (V, \text{async } M \text{ as } p \text{ in } N)$

# Appendix

## $\lambda_{\text{æ}}$ -calculus: effect annotations

- The effect annotations  $(o, \iota)$  are drawn from sets  $O$  and  $I$ , given by

$$O = \mathcal{P}(\Sigma) \quad I = \nu Z . \Sigma \Rightarrow (O \times Z)_{\perp}$$

where  $\Sigma$  is the set of all signal/interrupt names

- Note: for meta-theory only, could also have  $I$  as a least fixpoint



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- Note: for meta-theory only, could also have  $I$  as a least fixpoint
- $O$  and  $I$  come with natural partial orders for subtyping
- The action  $\text{op} \downarrow (o, \iota)$  reveals effects of int. handlers for  $\text{op}$

$$\text{op} \downarrow (o, \iota) \stackrel{\text{def}}{=} \begin{cases} (o \cup o', \iota[\text{op} \mapsto \perp] \cup \iota') & \text{if } \iota(\text{op}) = (o', \iota') \\ (o, \iota) & \text{otherwise} \end{cases}$$