



# Taking Back Control

... or implementing control idioms in user code



Daniel Hillerström/2018-12-13

Intern, Google Aarhus, Denmark

PhD student, The University of Edinburgh, UK

# This talk

A programmer's introduction to effect handlers (my research topic).

- Toy examples
- My PhD work at glance
- Implementing asynchrony as a library
- Some (semi-)open problems
- The future

# Why one might care

The programmer's perspective: take control from the runtime.

- Direct-style alternative to continuation passing style (CPS) and monadic programming
- Useful across diverse spectrum
  - Probabilistic programming [Bingham et al., 2018]
  - Multi-stage programming [Yallop, 2017]
  - Concurrent programming [Dolan et al., 2017 and Leijen, 2017]
  - Modular program construction [Kammar et al., 2013]
- Unikernels

The compiler writer's perspective: hand control to the programmer.

- Deep mathematical foundations [Plotkin and Power, 2001 and Plotkin and Pretnar, 2009]
- General enough to capture contemporary control idioms [Dolan et al., 2017, Leijen, 2017]
- Concrete enough to be amenable to optimisation [Wu and Schrijvers, 2015 and Leijen, 2018]
- Reduce complexity of the runtime/compiler [Dolan et al., 2016, Leijen, 2017]

# Effect handlers

Operationally, effect handlers generalise exception handlers<sup>†</sup>

```
exception DivideByZero

let divide n d =
  match
    if d = 0 then raise DivideByZero
    else n / d
  with
    | result -> result
    | exception DivideByZero -> 0
```

<sup>†</sup>Benton and Kennedy (2001) style exception handlers

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```
exception DivideByZero
```

```
let divide n d =
```

```
  match
```

```
    if d = 0 then raise DivideByZero
```

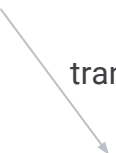
```
    else n / d
```

```
  with
```

```
  | result -> result
```

```
  | exception DivideByZero -> 0
```

transfers control to an enclosing handler



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# Effect handlers

Operationally, effect handlers generalise exception handlers<sup>†</sup>

Terminology: abstract operation



```
effect DivideByZero : int
```


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  match  
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let divide n d =  
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    if d = 0 then perform DivideByZero  
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let divide n d =  
  match  
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    else n / d  
  with  
    | result -> result  
    | effect DivideByZero k -> continue k 0
```

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```
    else n / d
```

```
  with
```

```
    | result -> result
```

```
    | effect DivideByZero k -> continue k 0
```

transfers control back to the invocation site  
with the provided value



<sup>†</sup>Benton and Kennedy (2001) style exception handlers

# Handlers in action



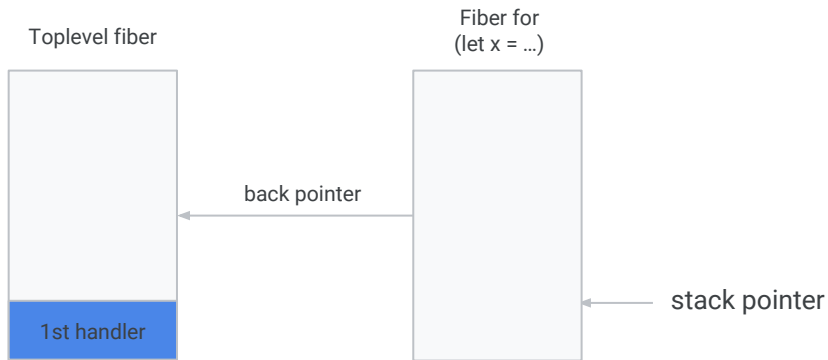
File: [https://github.com/dhil/google-tech-talk-2018/blob/master/live/guess\\_the\\_number.ml](https://github.com/dhil/google-tech-talk-2018/blob/master/live/guess_the_number.ml)

# Execution stack

Fiber: heap allocated stack; grows and shrinks on demand.

Execution stack: a stack of fibers.

```
effect E : unit
match
  let x = match perform E with
    | effect F k -> ...
  in ...
with
  | effect E k -> continue k ()
```

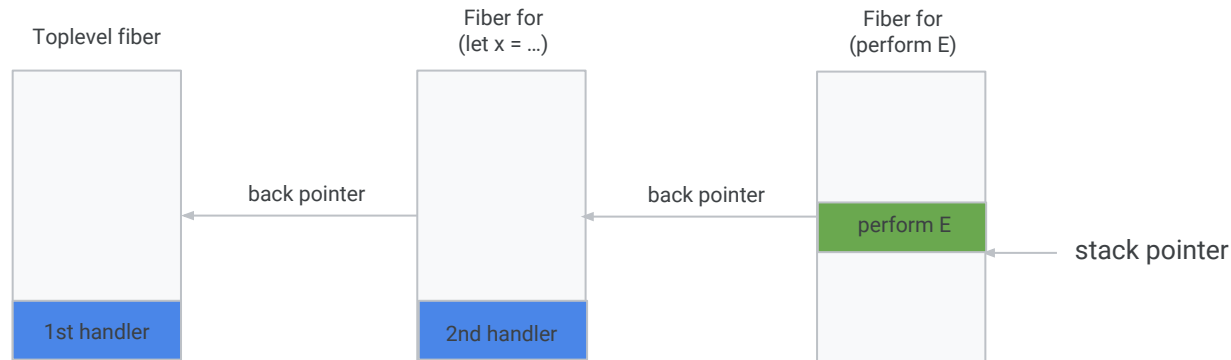


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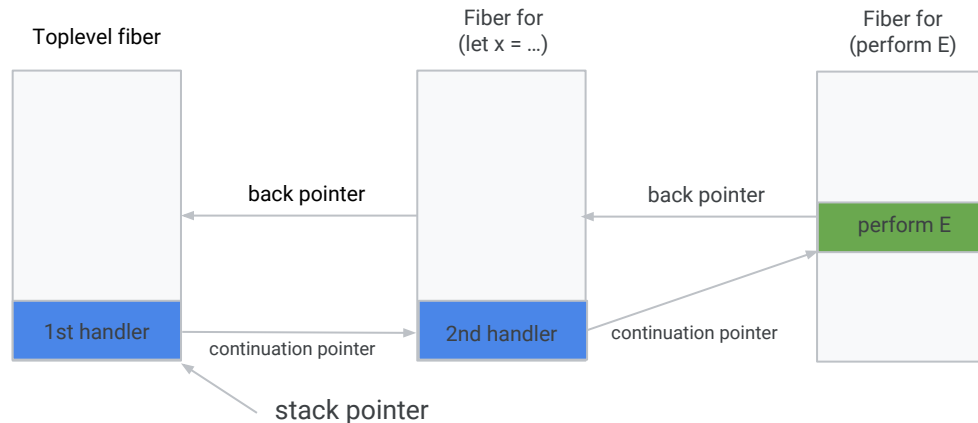


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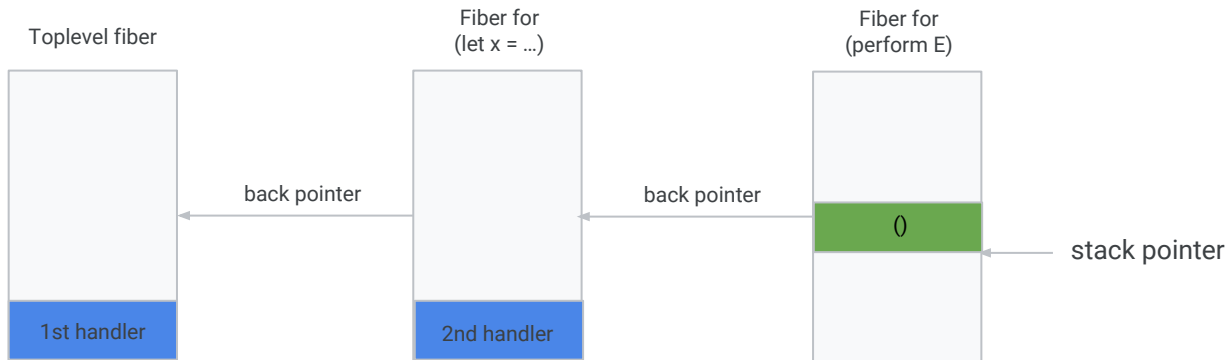


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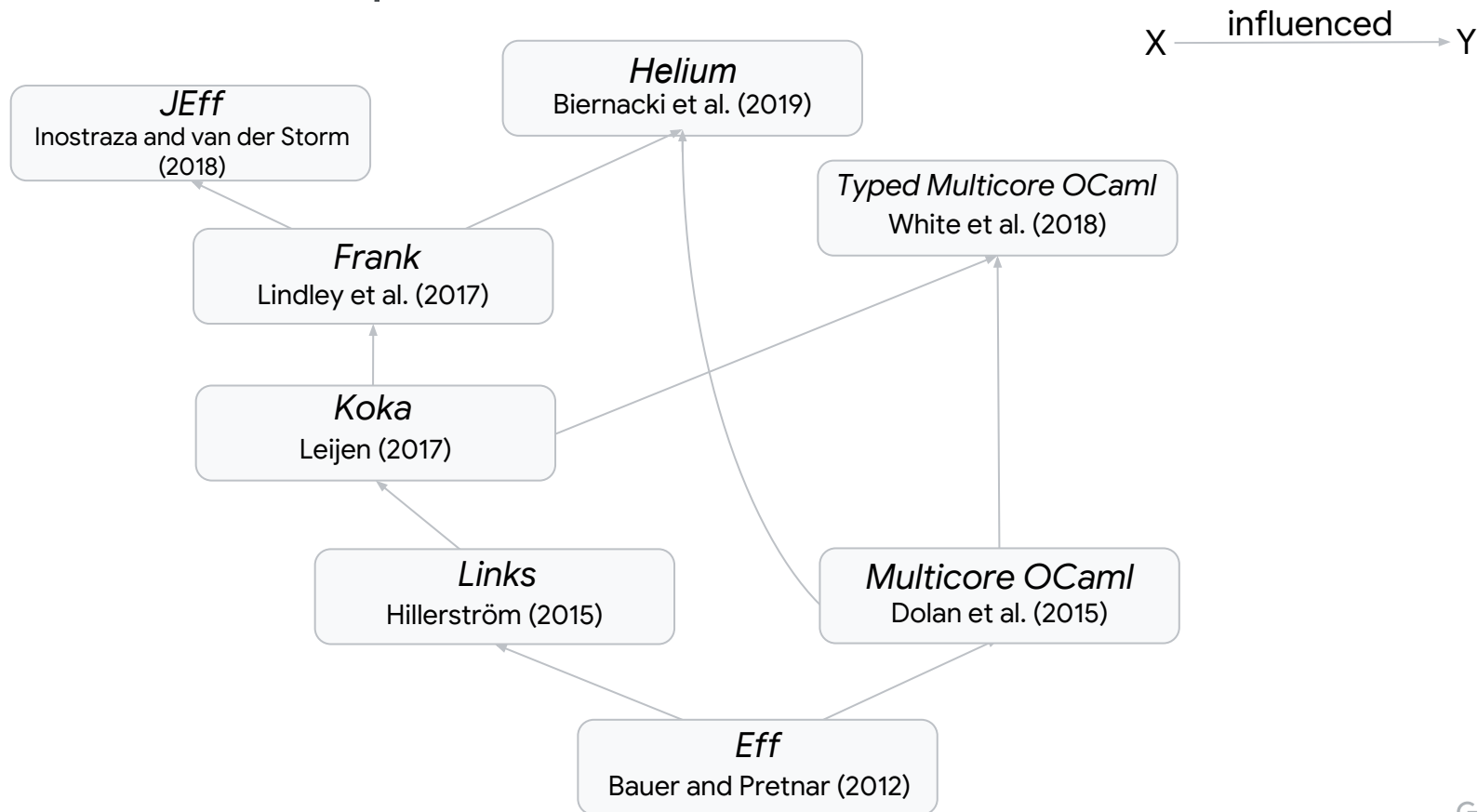


# Generators and iterators



Files: <https://github.com/dhil/google-tech-talk-2018/blob/master/live/generators.ml>  
<https://github.com/dhil/google-tech-talk-2018/blob/master/live/pi.ml>

# An overview of implementations



# My PhD at glance

Year 0

Applications of effect handlers (wrt. parallelism and concurrency)

Year 1

Compilation strategies. Abstract machines, CPS translations.

Year 2

Expressive power.

Year 3

??? Commences once I return.

# My PhD at gl

Ye

Ye

Ye 2

Year 3

## A First-Order One-Pass CPS Transformation \*

Olivier Danvy and Lasse R. Nielsen

BRICS <sup>†</sup>

Department of Computer Science

University of Aarhus <sup>‡</sup>

December 2001

### Abstract

We present a new transformation of call-by-value lambda-terms into continuation-passing style (CPS). This transformation operates in one pass and is both compositional and first-order. Because it operates in one pass, it directly yields compact CPS programs that are comparable to what one would write by hand. Because it is compositional, it allows proofs by structural induction. Because it is first-order, reasoning about it does not require the use of a logical relation.

This new CPS transformation connects two separate lines of research. It has already been used to state a new and simpler correctness proof of a direct-style transformation, and to develop a new and simpler CPS transformation of control-flow information.

Expressive power.

??? Commences once I return.

# My PhD at glance

Year 0

Applications of effect handlers (wrt. parallelism and concurrency)

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Compilation strategies. Abstract machines, CPS translations.

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Expressive power.

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# Implementing asynchrony



File: [https://github.com/dhil/google-tech-talk-2018/blob/master/live/async\\_await.ml](https://github.com/dhil/google-tech-talk-2018/blob/master/live/async_await.ml)

# (Semi-)Open problems I

Abstract operations are not abstracted.

```
(* Module trace.ml *)
effect Trace : unit
let trace f =
  match f (fun () -> perform Trace) with
  | result -> result
  | effect Trace k -> print_endline "Called"; continue k ()

(* Module other.ml *)
open Trace
let f g =
  match g () with
  | _ -> ()
  | effect Trace _ -> ()

let _ = trace f (* prints nothing. *)
```

Biernacki et al. (2018), Biernacki et al. (2019), Convent et al. (2018), Zhang and Myers (2019) provide potential answers.

# (Semi-)Open problems II

In general, effect handlers do not interact well with resources

```
let take_while predicate file =  
  let fh = open_in file in  
  let rec take acc =  
    try  
      let line = input_line fh in  
      if predicate line then  
        take (line :: acc)  
      else acc  
    with  
      | End_of_file -> acc  
  in  
  let lines = take [] in  
  close_in fh; lines
```

```
effect Abort : 'a  
let leaks () =  
  let predicate _ = perform Abort in  
  match take_while predicate "fruits.dat" with  
  | result -> result  
  | effect Abort _ -> [] (* leaks. *)
```



# (Semi-)Open problems II

In general, effect handlers do not interact well with resources

```
let take_while predicate file =  
  let fh = open_in file in  
  let rec take acc =  
    try  
      let line = input_line fh in  
      if predicate line then  
        take (line :: acc)  
      else acc  
    with  
      | End_of_file -> acc  
  in  
  let lines = take [] in  
  close_in fh; lines
```

```
effect Choose : bool  
let bad_descriptor () =  
  let predicate _ = perform Choose in  
  match take_while predicate "fruits.dat" with  
  | result -> [result]  
  | effect Choose k ->  
    continue k true @ continue k false  
    (* bad file descriptor exception *)
```

# (Semi-)Open problems III

Handler-oriented programming can incur a significant overhead

Some ideas on how to eliminate the overhead:

- Alternative, more efficient runtime representations of the handler stack
- Apply fusion laws (catamorphisms/folds) [Wu and Tom Schrijvers, 2015]
- Generalise tail-call elimination to “tail-resumptive elimination” [Leijen, 2018]
- Use a substructural typing discipline to guide optimisations
- Power of JIT compilation: profile-guided optimisations at runtime? (Speculation)

# References

# References I

- ❖ Andrej Bauer and Matija Pretnar, “Programming with Algebraic Effects and Handlers”, 2012
- ❖ Nick Benton and Andrew Kennedy, “Exceptional Syntax”, 2001
- ❖ Eli Bingham, Jonathan P. Chen, Martin Jankowiak, Fritz Obermeyer, Neeraj Pradhan, Theofanis Karaletsos, Rohit Singh, Paul Szerlip, Paul Horsfall, and Noah D. Goodman, “Pyro: Deep Universal Probabilistic Programming”, 2018
- ❖ Dariusz Biernacki, Maciej Piróg, Piotr Polesiuk, and Filip Sieczkowski, “Handle with Care: Relational Interpretation of Algebraic Effects and Handlers”, 2018
- ❖ Dariusz Biernacki, Maciej Piróg, Piotr Polesiuk, and Filip Sieczkowski, “Abstracting Algebraic Effects”, 2019
- ❖ Lukas Convent, Sam Lindley, Conor McBride, and Craig McLaughlin, “Encapsulating Effects in Frank”, draft 2018
- ❖ Stephen Dolan, Leo White, KC Sivaramakrishnan, Jeremy Yallop, and Anil Madhavapeddy, “Effective Concurrency through Algebraic Effects”, 2015
- ❖ Stephen Dolan, Spiros Eliopoulos, Daniel Hillerström, Anil Madhavapeddy, KC Sivaramakrishnan, and Leo White, “Concurrent System Programming with Effect Handlers”, 2017

# References II

- ❖ Daniel Hillerström, “Handlers for Algebraic Effects in Links”, 2015
- ❖ Daniel Hillerström and Sam Lindley, “Liberating Effects with Rows and Handlers”, 2016
- ❖ Daniel Hillerström, Sam Lindley, Robert Atkey, KC Sivaramakrishnan, “Continuation Passing Style for Effect Handlers”, 2017
- ❖ Daniel Hillerström and Sam Lindley, “Shallow Effect Handlers”, 2018
- ❖ Pablo Inostroza and Tijs van der Storm, “JEff: Objects for Effect”, 2018
- ❖ Ohad Kammar, Sam Lindley, and Nicolas Oury, “Handlers in Action”, 2013
- ❖ Daan Leijen, “Type Directed Compilation of Row-Typed Algebraic Effects”, 2017
- ❖ Daan Leijen, “Structured Asynchrony with Algebraic Effects”, 2017
- ❖ Daan Leijen, “Algebraic Effect Handlers with Resources and Deep Finalization”, 2018
- ❖ Sam Lindley, Conor McBride, and Craig McLaughlin, “Do be do be do”, 2017
- ❖ Gordon D. Plotkin and John Power, “Adequacy for Algebraic Effects”, 2001
- ❖ Gordon D. Plotkin and Matija Pretnar, “Handlers of Algebraic Effects”, 2009

# References III

- ❖ Leo White, “Effective Programming: Adding an Effect System to OCaml”, 2018 (talk)
- ❖ Jeremy Yallop, “Staged Generic Programming”, 2017
- ❖ Yizhou Zhang and Andrew Myers, “Abstraction-Safe Effect Handlers via Tunnelling”, 2019
- ❖ Nicolas Wu and Tom Schrijvers, “Fusion for Free: Efficient Algebraic Effect Handlers”, 2015