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Taking Back Control

... or implementing control idioms in user code

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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

This talk is largely based on materials from my CUFP'17 tutorial, c.f. http://cufp.org/2017/c3-daniel-hillerstrom-kc-concurrent-programming-with-effect-handlers.html

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 a 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]
- Expressive user-space for 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[†]

```
exception DivideByZero

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

[†]Benton and Kennedy (2001) style exception handlers

Effect handlers

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transfers control to an enclosing handler

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Effect handlers

Operationally, effect handlers generalise exception handlers[†]

Terminology: abstract operation

```
effect DivideByZero : int

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

[†] Benton and Kennedy (2001) style exception handlers

Effect handlers

Operationally, effect handlers generalise exception handlers†

Terminology: abstract operation

```
effect DivideByZero : int

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

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Effect handlers

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Terminology: abstract operation

```
effect DivideByZero : int

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

[†]Benton and Kennedy (2001) style exception handlers

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Effect handlers

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transfers control back to the invocation site
with the provided value

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transfers control back to the invocation site with the provided value

```
continue : (‘a,‘b) continuation -> ‘a -> ‘b
```

†Benton and Kennedy (2001) style exception handlers

Handlers in action

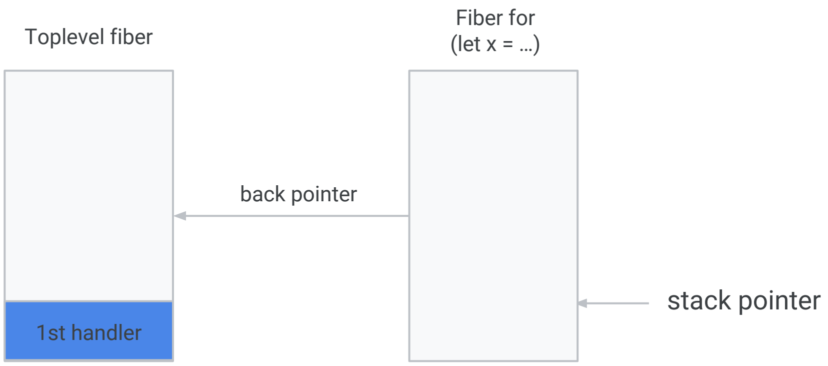
File: https://github.com/dhil/google-tech-talk-2018/blob/master/live/guess_the_number.ml

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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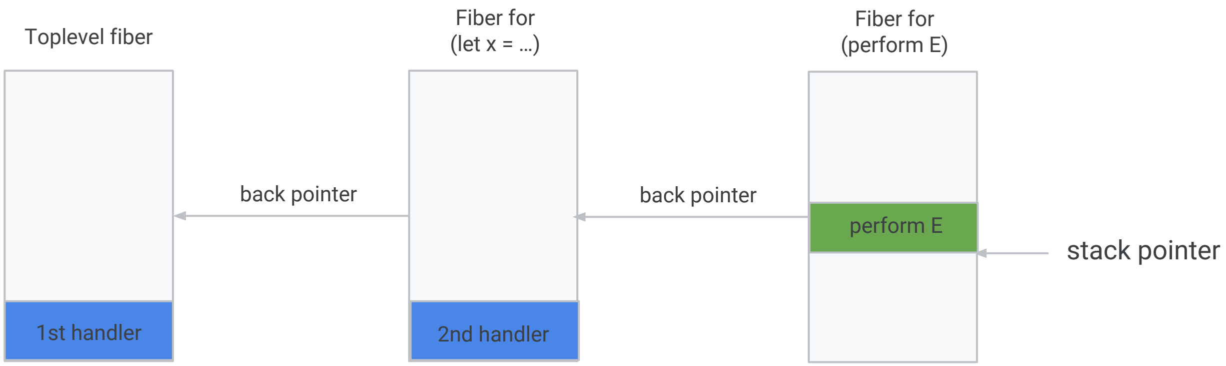

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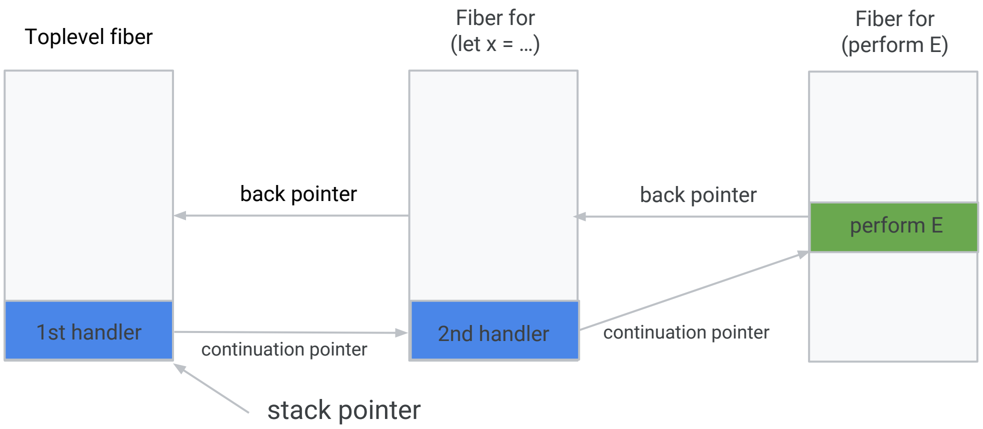

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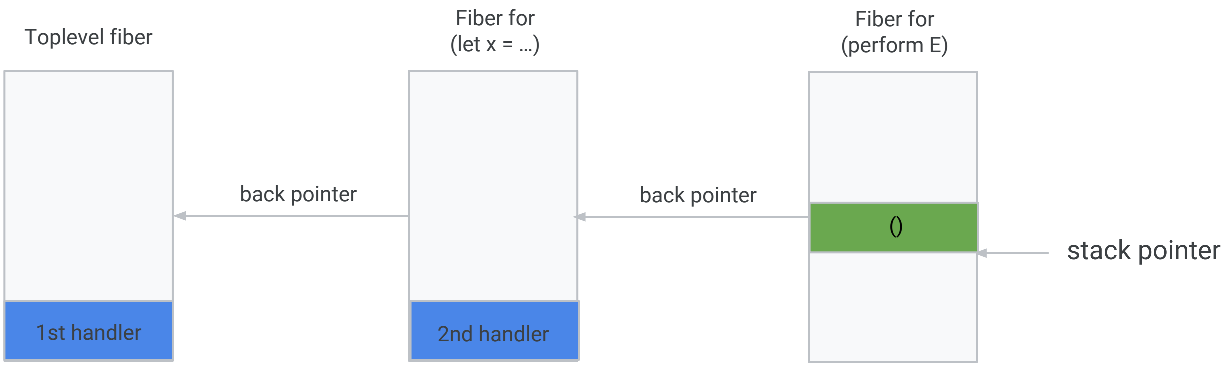
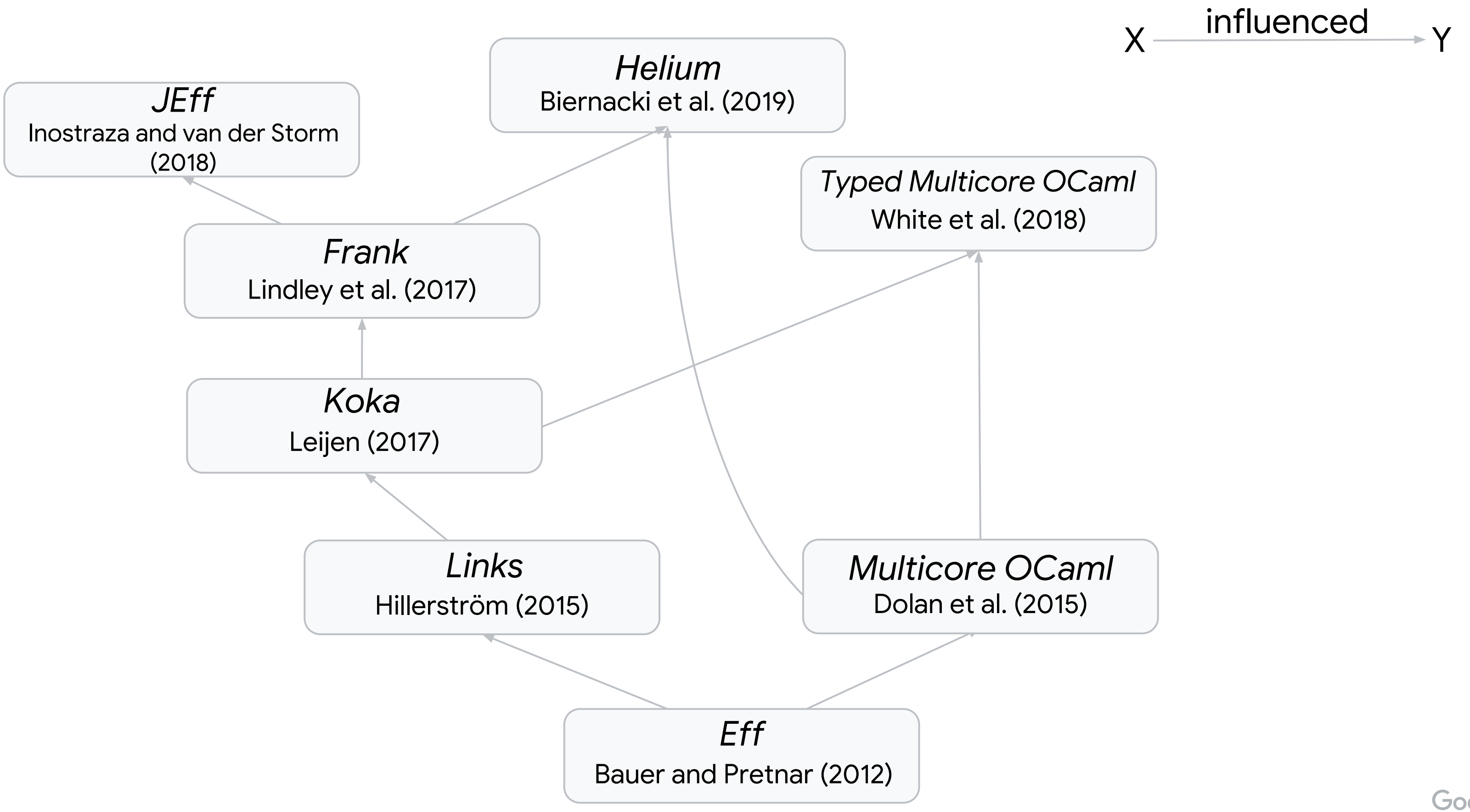


Generators and iterators

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



Library implementations omitted, c.f. https://github.com/yallop/effects-bibliography

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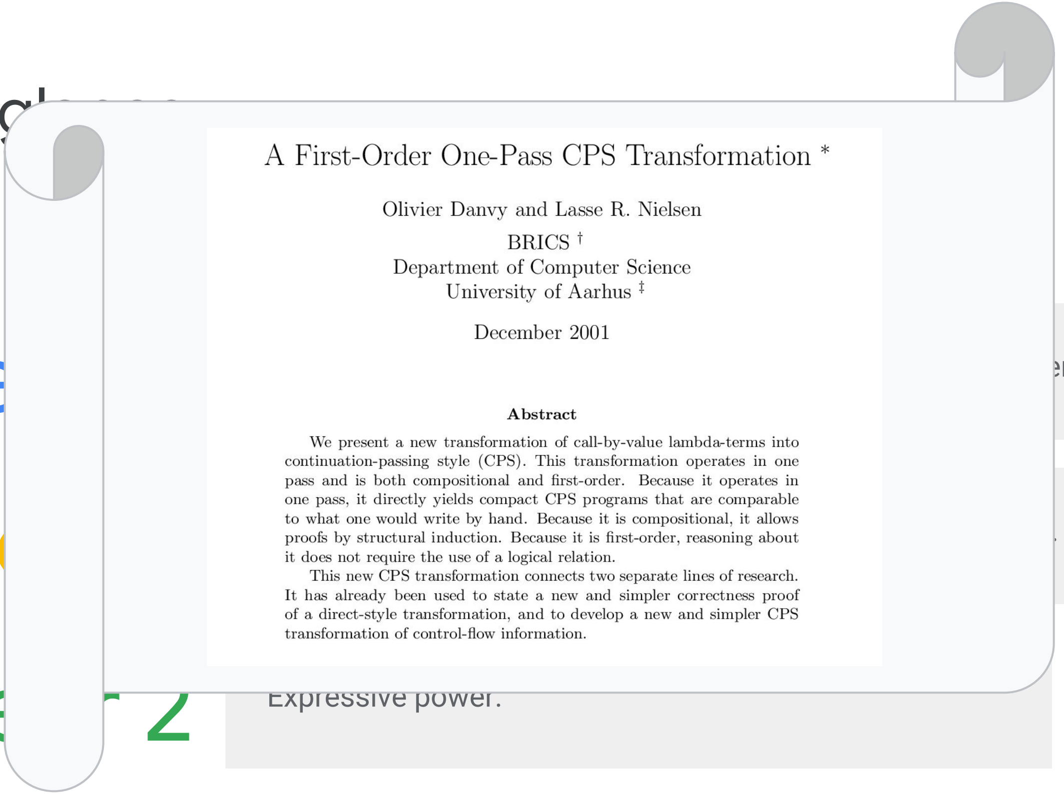
My PhD at glance

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 g



A First-Order One-Pass CPS Transformation *

Olivier Danvy and Lasse R. Nielsen

BRICS †
Department of Computer Science
University of Aarhus ‡

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.

Ye | ency)

Y

Ye 2 | Expressive power.

Year 3 | ??? Commences once I return.

c.f. Hillerström and Lindley (2016), Hillerström et al. (2017), and Hillerström and Lindley (2018)

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My PhD at glance

Year 0	Applications of effect handlers (wrt. parallelism and concurrency)
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Implementing asynchrony

File: 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. *)
```

Dolan et. al (2017) and Leijen (2018) 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 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 *)
```

Dolan et. al (2017) and Leijen (2018) provide potential answers

(Semi-)Open problems III

Handler-oriented programming can occur 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)

Concluding remarks and the future

Summary

- Effect handlers provide an abstraction for modular effectful programming
- Contemporary control idioms are really special instances of effect handlers
- OCaml provides an industrial-strength implementation of effect handlers

Future work

- Loads of design questions (type systems, modular abstraction, etc)
- Loads of compiler questions (optimisation schemes, runtime representations, etc)
- Effect handlers as a primitive in WebAssembly?

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