Practical Algebraic Effect Handlers in Multicore OCaml

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OCaml Labs

Multicore OCaml

- Native support for concurrency and parallelism

  https://github.com/ocamllabs/ocaml-multicore

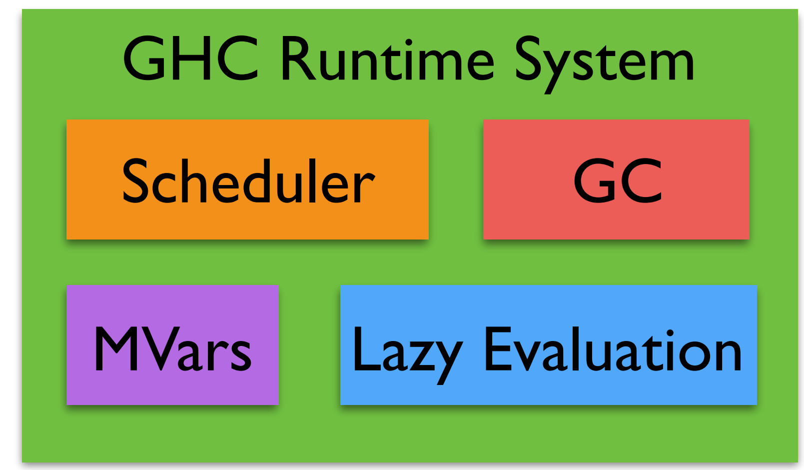
- Led from OCaml Labs
  - KC, Stephen Dolan, Leo White (Jane Street) & others..
- In this talk: *Practical* algebraic effect handlers
  - Why algebraic effects in multicore OCaml?
  - How to make them practical?
    - Don't break existing programs
    - Performance backwards compatibility

Concurrency ≠ Parallelism

- Concurrency
  - Overlapped execution of processes
  - Fibers — language level lightweight threads
  - *12M/s on 1 core. 30M/s on 4 cores.*
- Parallelism
  - Simultaneous execution of computations
  - Domains — System thread + Context
- Concurrency ∩ Parallelism ➔ ***Scalable Concurrency***

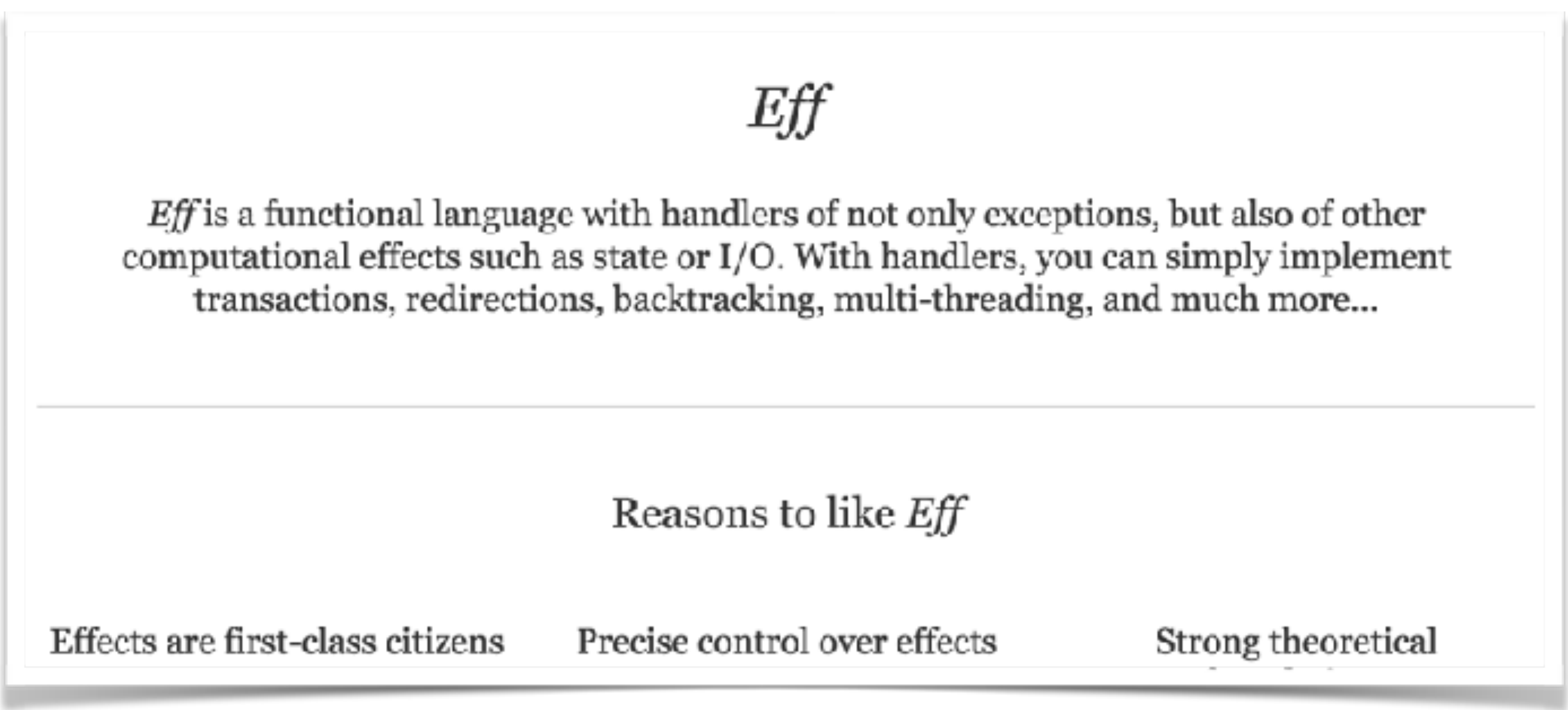
User-level Schedulers

- Multiplexing fibers over domain(s)
- Bake scheduler into the runtime system (GHC)
  - Lack of flexibility
  - Maintenance onus on the compiler developers
- Allow programmers to describe schedulers!
  - Parallel search ➔ LIFO work-stealing
  - Web-server ➔ FIFO runqueue
  - Data parallel ➔ Gang scheduling
- ***Algebraic Effects and Handlers***



Algebraic effects & handlers

- Reasoning about computational effects in a pure setting
  - G. Plotkin and J. Power, Algebraic Operations and Generic Effects, 2002
- Handlers for programming
  - G. Plotkin and M. Pretnar, Handlers of Algebraic Effects, 2009



Algebraic Effects: Example

- Nice abstraction for programming with control-flow
- Separation effect *declaration* from its *interpretation*

```
exception Foo of int

let f () = 1 + (raise (Foo 3))

let r =
    try
      f ()
    with Foo i -> i + 1
```

```
val r : int = 4
```

```
effect Foo : int -> int

let f () = 1 + (perform (Foo 3))

let r =
  try
    f ()
  with effect (Foo i) k ->
         continue k (i + 1)
```

```
('a,'b) continuation
```

Algebraic Effects: Example

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exception Foo of int

let f () = 1 + (raise (Foo 3))

let r =
    try
      f ()
    with Foo i -> i + 1

      val r : int = 4
```

```
effect Foo : int -> int

let f () = 1 + (perform (Foo 3)) 4

let r =
  try
    f ()
  with effect (Foo i) k ->
          continue k (i + 1)

      val r : int = 5
```

fiber — lightweight stack

Algebraic Effects in Multicore OCaml

- Unchecked

```
effect Foo : unit
let _ = perform Foo

Exception: Unhandled.
```

- WIP: Effect System for OCaml
  - Accurately track user-defined as well as native effects
  - Makes OCaml *a pure language*

```
effect foo = Foo : unit
let _ = perform Foo

Error: This expression
performs effect foo, which has
no default handler.
```

- Deep handler semantics

```
let f () = (perform (Foo 3)) (* 3 + 1 *)
         + (perform (Foo 3)) (* 3 + 1 *)

let r = try f () with effect (Foo i) k ->
          (* continuation resumed outside try/with *)
          continue k (i + 1)
```

Demo

Concurrent round-robin scheduler

Asynchronous I/O in direct-style

```
fs.readdir(source, function (err, files) {
  if (err) {
    console.log('Error finding files: ' + err)
  } else {
    files.forEach(function (filename, fileIndex) {
      console.log(filename)
      gm(source + filename).size(function (err, values) {
        if (err) {
          console.log('Error identifying file size: ' + err)
        } else {
          console.log(filename + ' : ' + values)
          aspect = (values.width / values.height)
          widths.forEach(function (width, widthIndex) {
            height = Math.round(width / aspect)
            console.log('resizing ' + filename + 'to ' + height + 'x' + height)
            this.resize(width, height).write(dest + 'w' + width + '_' + filename, function(err) {
              if (err) console.log('Error writing file: ' + err)
            })
          }.bind(this))
        }
      })
    })
  }
})
```

Callback Hell

Asynchronous I/O in direct-style

- Demo: Echo server
- Killer App

~~Callback Hell~~

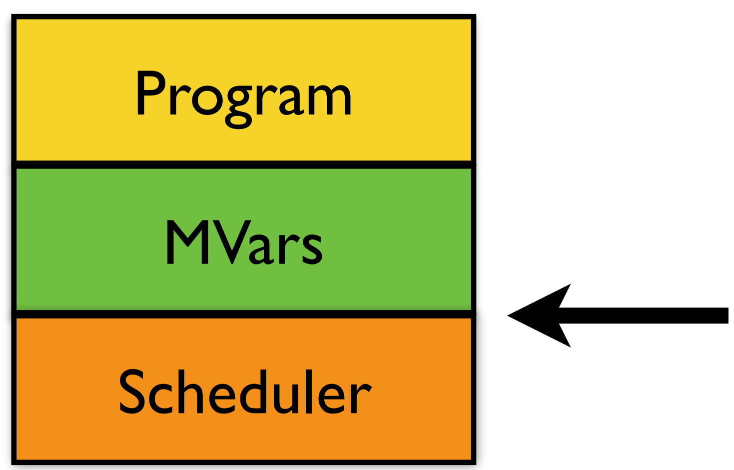
+

Facebook's new skin for OCaml

Optimising compiler for OCaml to JavaScript

Concurrent data/sync structures

- Channels, MVars, Queues, Stacks, Countdown latches, etc,.
    - *Need to interface with the scheduler!*
- `MVar_put` & `MVar_get` as algebraic operations?



What is this interface?

Handler stack

Scheduler Interface

```
effect Suspend : (('a,unit) continuation -> unit) -> 'a
effect Resume  : (('a,unit) continuation * 'a) -> unit
```

```
let rec spawn f =
  match f () with
  | () -> dequeue ()
  | effect Yield k -> enqueue k (); dequeue ()
  | effect (Fork f) k -> enqueue k (); spawn f
  | effect (Suspend f) k -> f k; dequeue ()
  | effect (Resume (k', v)) k ->
      enqueue k' v; ignore (continue k ())
```

MVar

```
type 'a mvar_state =
  | Full  of 'a * ('a * (unit,unit) continuation) Queue.t
  | Empty of ('a,unit) continuation Queue.t

type 'a t = 'a mvar_state ref

let put v mv =
  match !mv with
  | Full (_, q) ->
      perform @@ Suspend (fun k -> Queue.push (v,k) q)
  | Empty q ->
      if Queue.is_empty q then
        mv := Full (v, Queue.create ())
      else
        let t = Queue.pop q in
        perform @@ Resume (t, v)
```

- ***Reagents*** https://github.com/ocamllabs/reagents
  - Composable lock-free programming

Preemptive Multithreading

- Conventional way: Build on top of signal handling

```
open Sys
set_signal sigalrm (Signal_handle (fun _ ->
  let k = (* Get current continuation *) in
  Sched.enqueue k;
  let k' = Sched.dequeue () in
  (* Set current continuation to k' *)));;

Unix.setitimer interval Unix.ITIMER_REAL
```

- Not compositional: Signal handler is a *callback*
  - *Unclear where the handler runs..*
- Can we do better with effect handlers?

Preemptive Multithreading

- Treat asynchronous interrupts as effects!
  - Can be raised asynchronously on demand

```
effect TimerInterrupt : unit

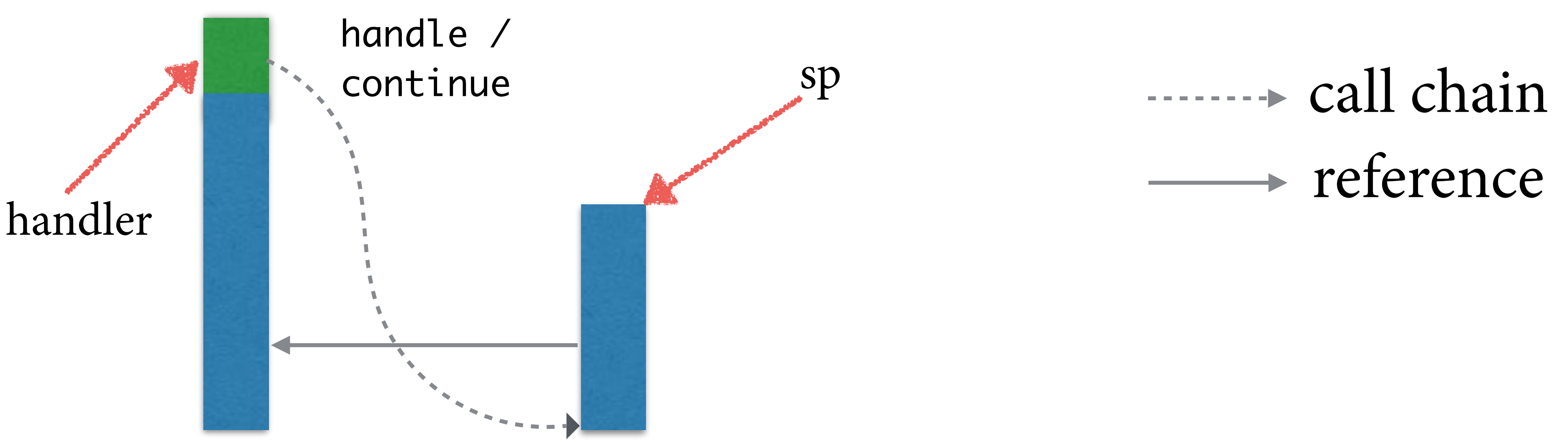
let rec spawn f =
  match f () with
  | () -> dequeue ()
  | effect Yield k -> yield k
  ...
  | effect TimerInterrupt k -> yield k

and yield k = enqueue k; dequeue ()
```

- What is the default behaviour for `TimerInterrupt` effect?
- Should all signals be handled this way? `effect Signal : int -> unit`

Implementation

- Fibers: Heap allocated, dynamically resized stacks
    - ~10s of bytes
    - No unnecessary closure allocation costs unlike CPS
- One-shot delimited continuations
    - Simplifies reasoning about resources - sockets, locks, etc.
- Handlers —> Linked-list of fibers



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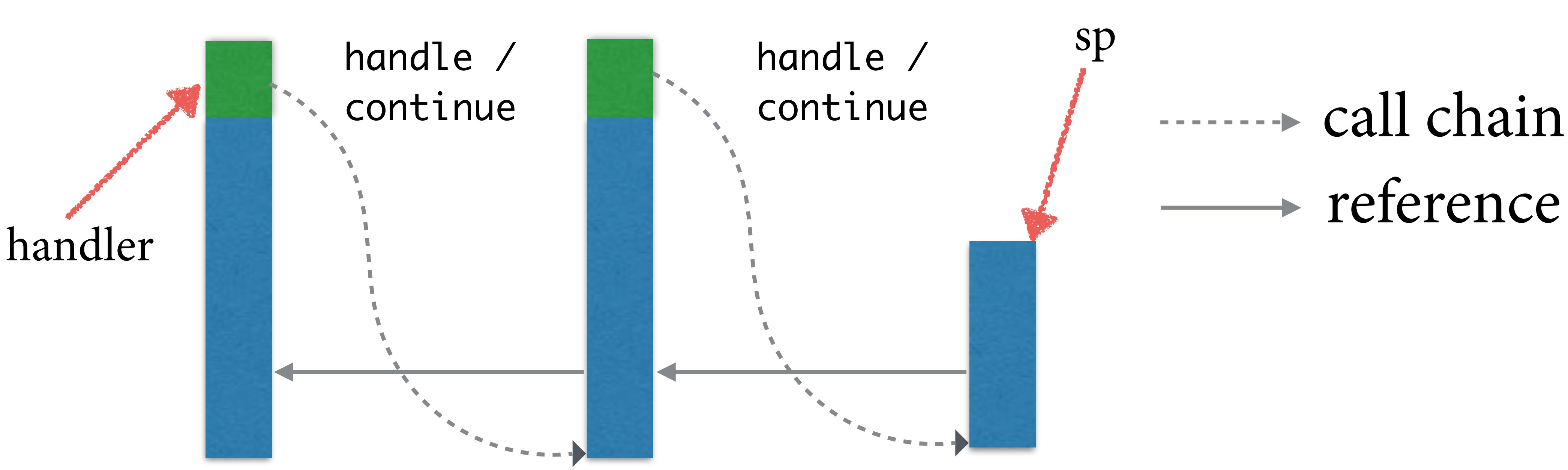

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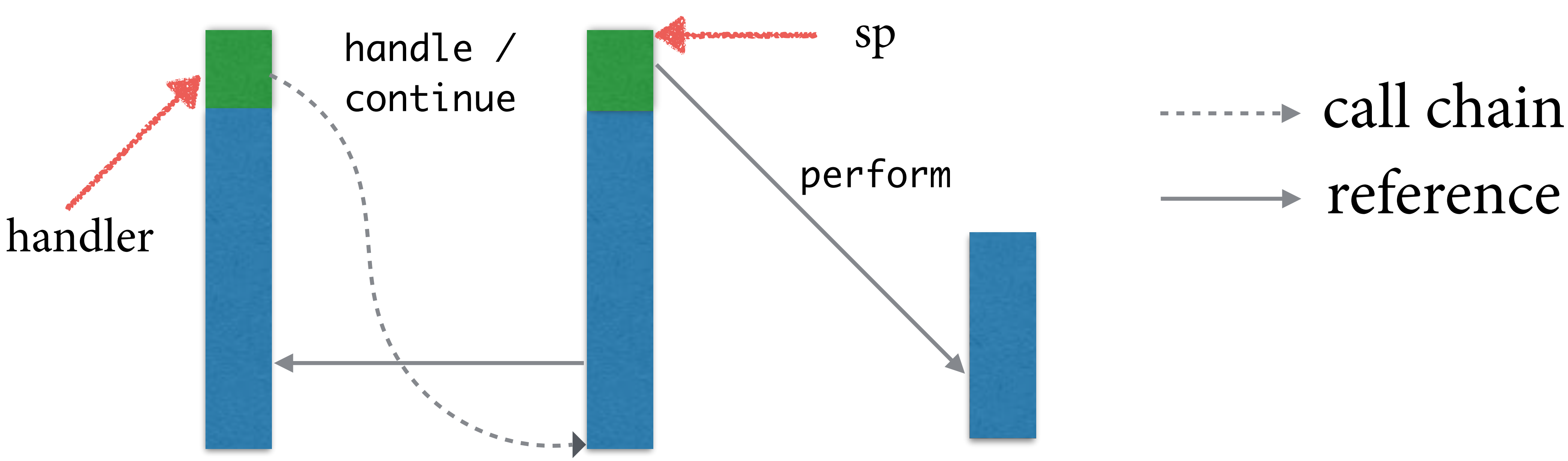


Tricky bug

- One-shot continuations + multicore schedulers

```
val call1cc : ('a cont -> 'a) -> 'a
val throw   : 'a cont -> 'a -> 'b

let put v mv =
  match !mv with
  | Full (v', q) -> call1cc (fun k ->
      Queue.push (v,k) q;
      let k' = Sched.dequeue () in
      throw k' ())
  ....
```

- `call1cc f`, f run on the same stack!
- *Possible that k is concurrently resumed on a different core!*

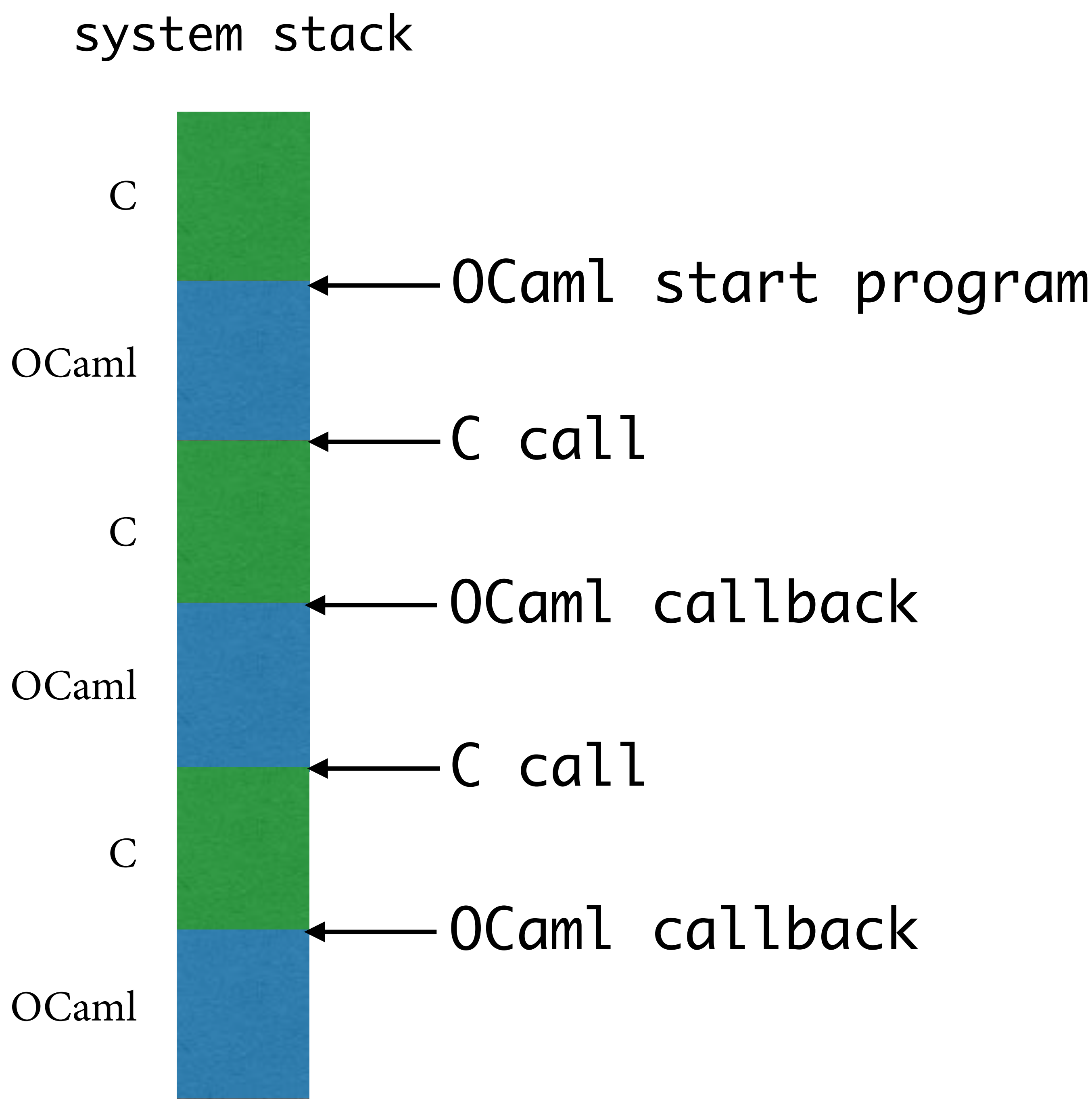
Tricky bug

- No such bug here

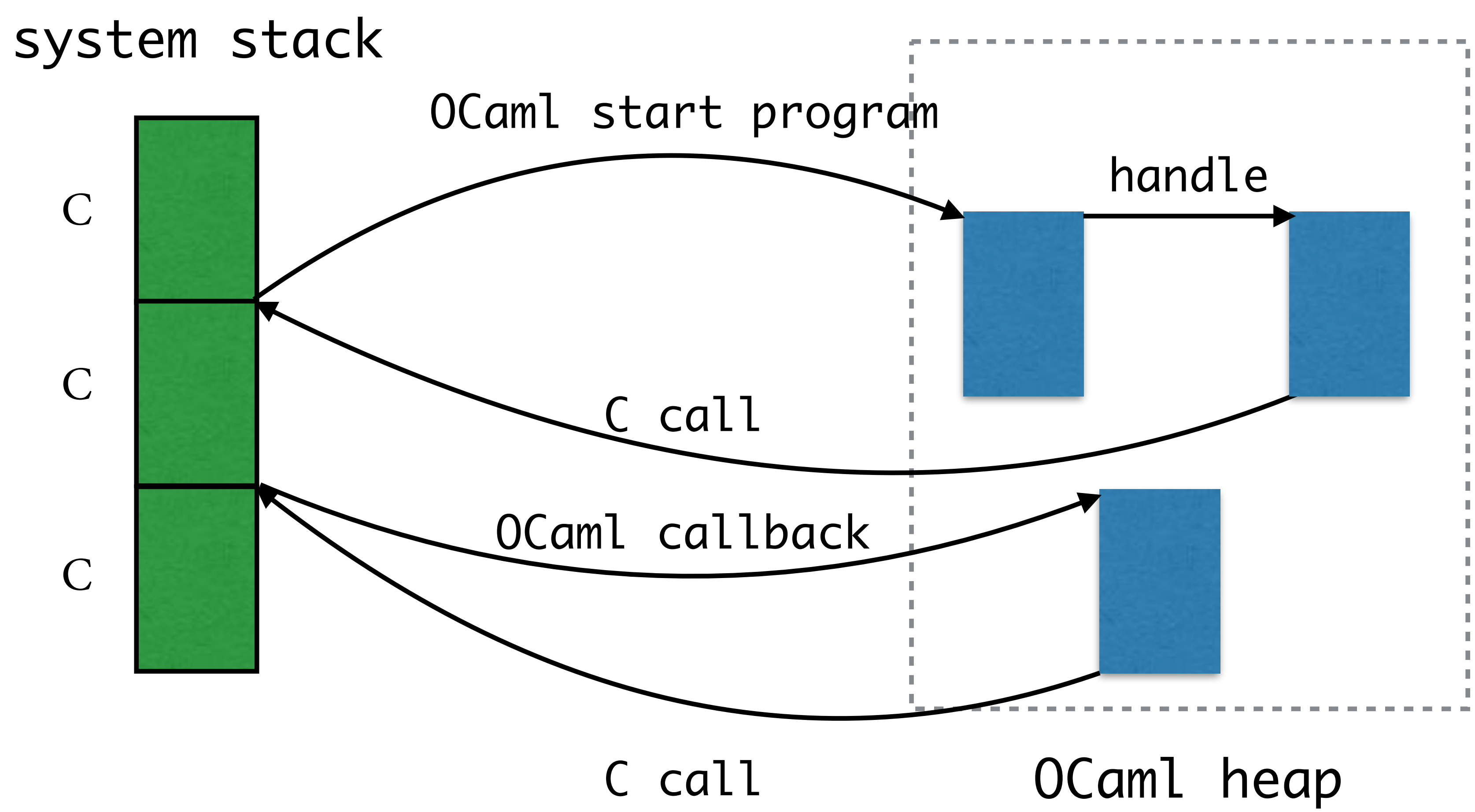
```
let rec spawn f =
  match f () with
  | () -> dequeue ()
  | effect Yield k -> enqueue k (); dequeue ()
  | effect (Fork f) k -> enqueue k (); spawn f
  | effect (Suspend f) k -> f k; dequeue ()
  | effect (Resume (k', v)) k ->
      enqueue k' v; ignore (continue k ())
```

- `f` is run by the handler
  - *Fiber performing suspend effect already suspended!*

Native-code fibers — Vanilla



Native-code fibers — Effects

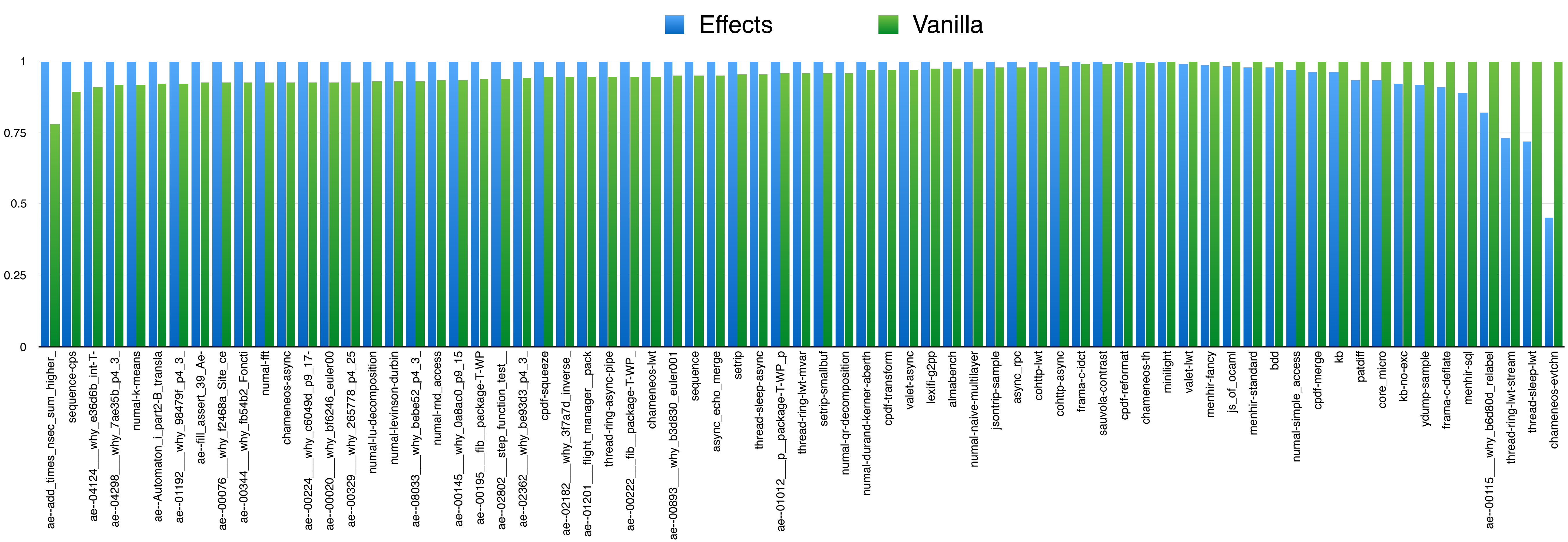


Native-code fibers — Effects

- Stack overflow checks for OCaml functions
  - Eliminate SO checks for small tail recursive leaf functions
    - Slop space (16 words) at the bottom of stack
    - Frame sizes statically known
  - OCaml Compiler: 18K functions; *Eliminate checks for 11k functions*
- FFI calls are more expensive due to stack switching
  - Small context
    - No callee saved registers in OCaml
    - Allocation, exception, stack pointers in registers
  - Specialise for calls which {allocate / pass arguments on stack / do neither}

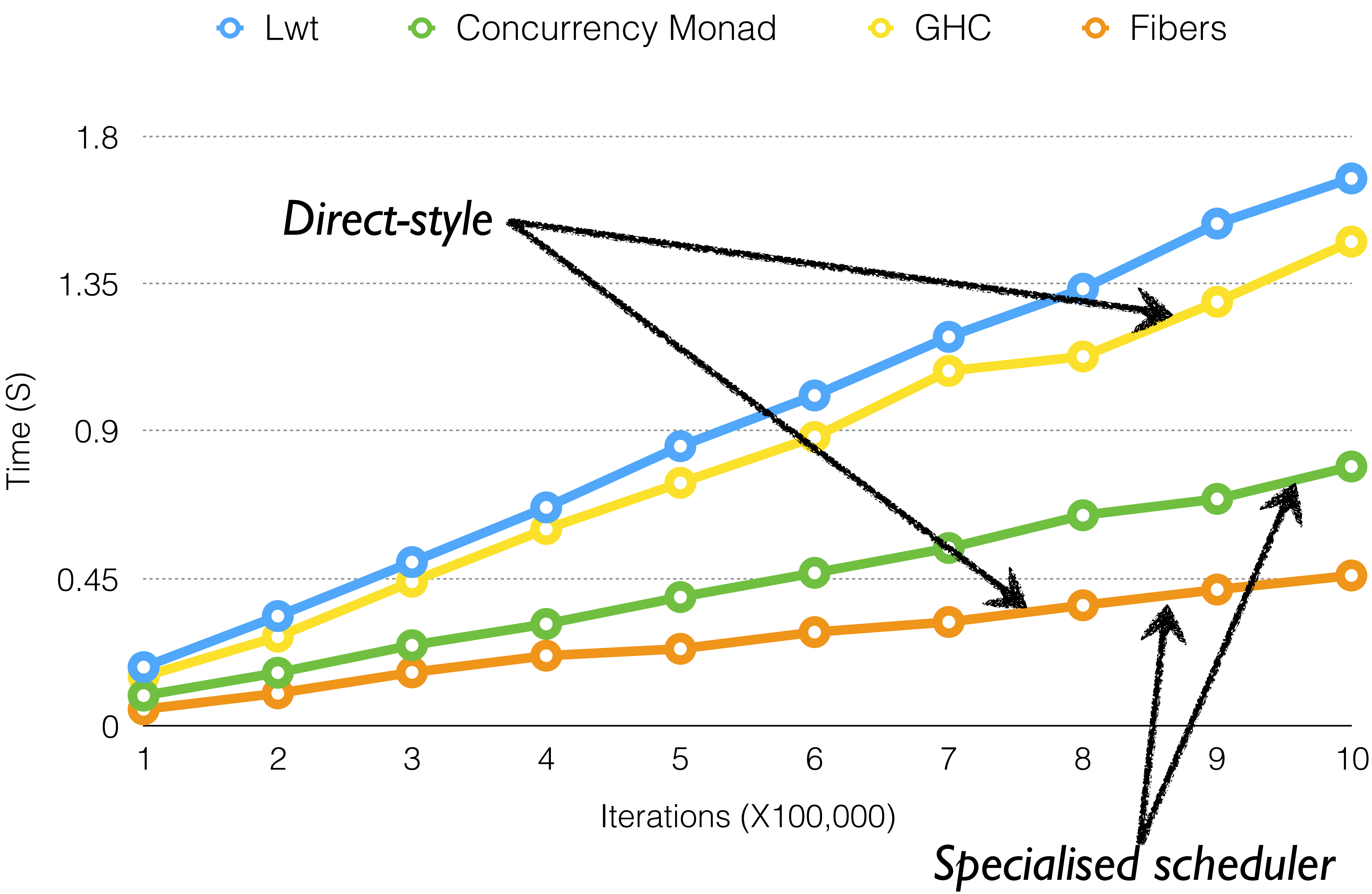
Performance: Vanilla OCaml

Normalised time (lower is better)



Effects **~0.9%** slower

Performance : Chameneos-Redux



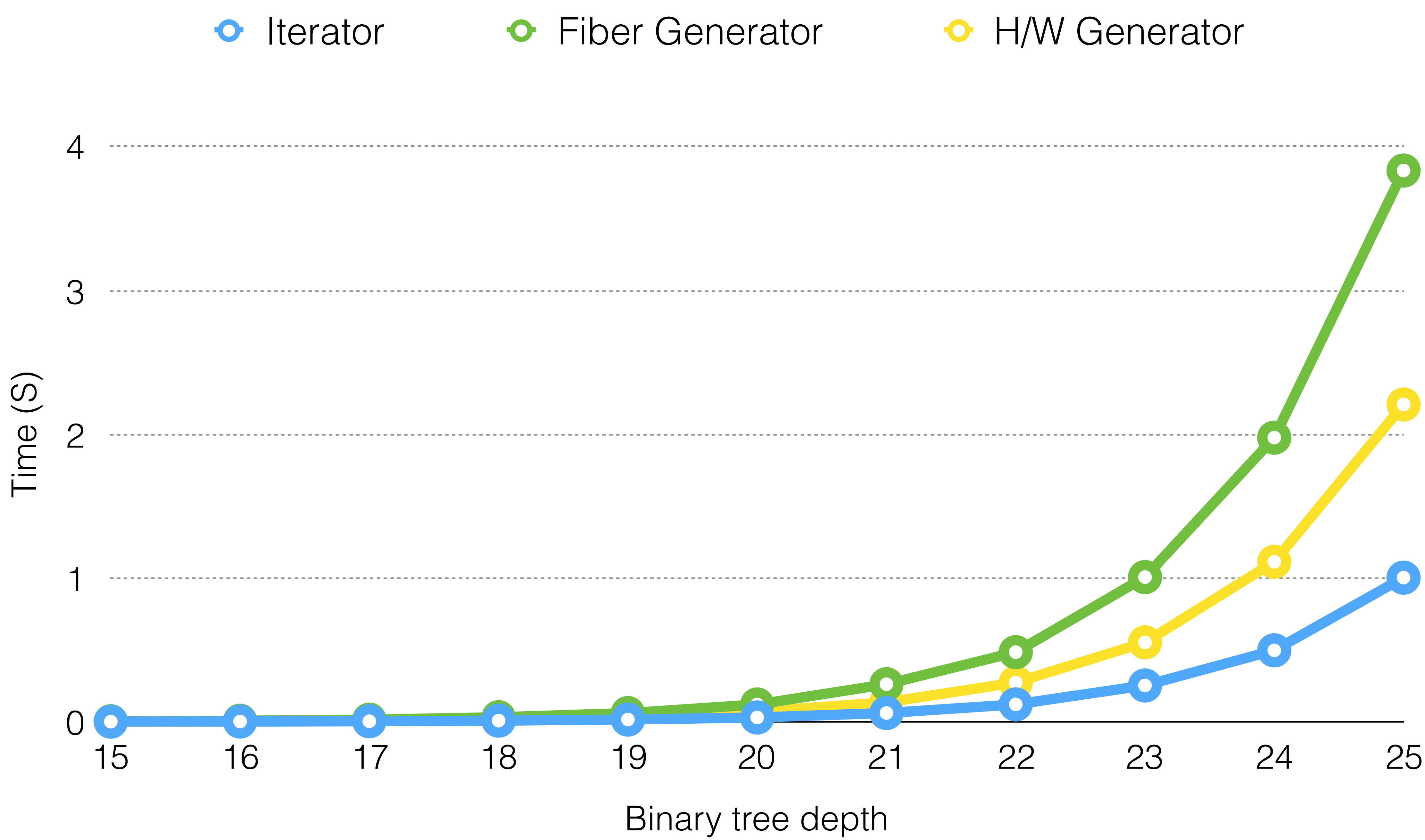
Generator from Iterator

```
type 'a t =
| Leaf
| Node of 'a t * 'a * 'a t

let rec iter f = function
  | Leaf -> ()
  | Node (l, x, r) -> iter f l; f x; iter f r

(* val to_gen : 'a t -> (unit -> 'a option) *)
let to_gen (type a) (t : a t) =
  let module M = struct effect Next : a -> unit end in
  let open M in
  let step = ref (fun () -> assert false) in
  let first_step () =
    try
      iter (fun x -> perform (Next x)) t; None
    with effect (Next v) k ->
      step := continue k; Some v
  in
    step := first_step;
    fun () -> !step ()
```

Performance : Generator



Continuation cloning

- Our continuation are 1-shot.
  - Multi-shot continuations are useful for backtracking computations
- *Explicit cloning on demand!*
  - `Obj.clone_continuation : ('a,'b) continuation -> ('a,'b) continuation`

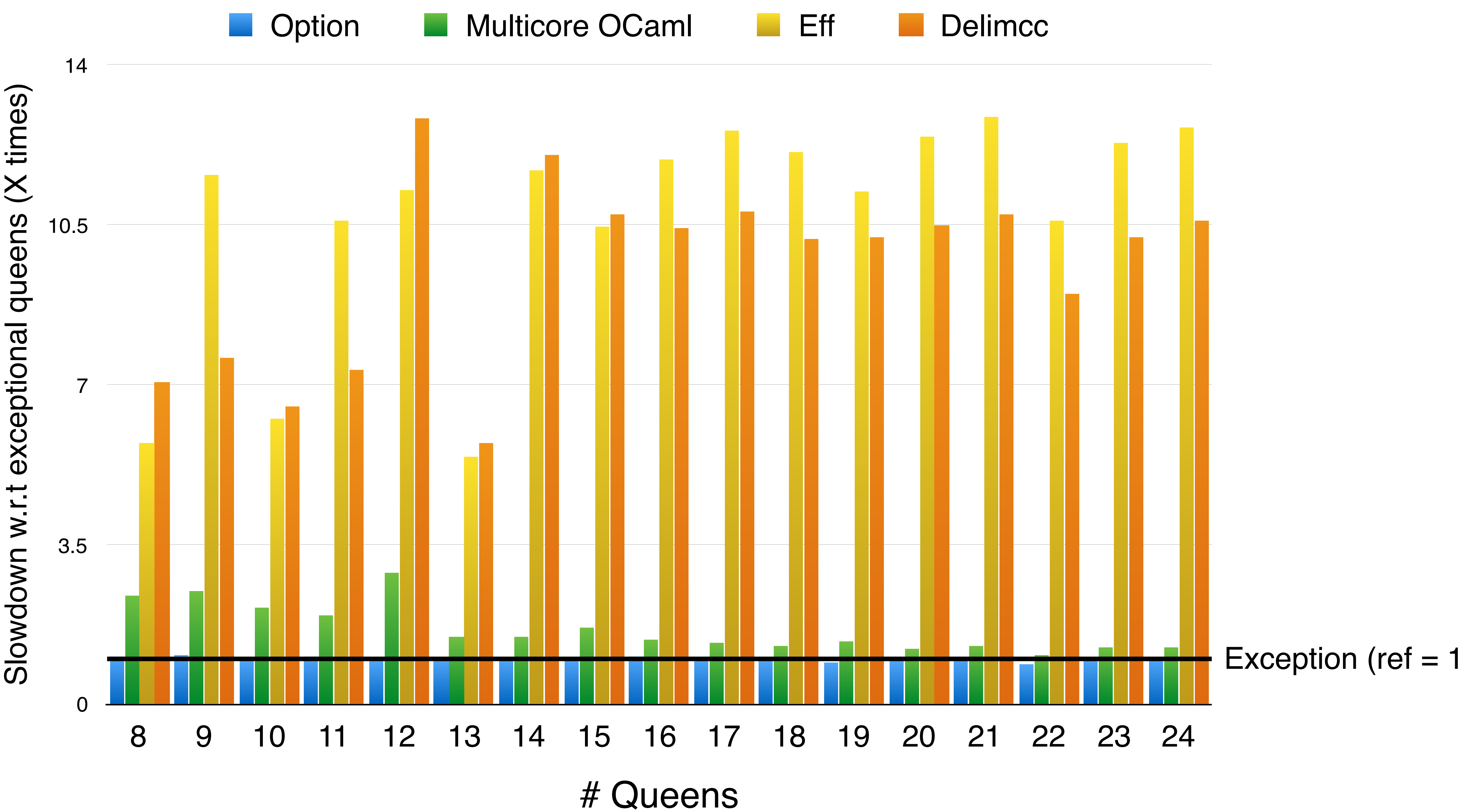
Continuation is resumed twice!

```
effect Foo : unit

let _ =
  try begin
    try perform Foo
    with effect Foo k -> continue k (perform Foo)
  end with effect Foo k ->
    continue (Obj.clone k) (); continue k ()
```

```
Exception: Invalid_argument "continuation already taken".
```

Continuation cloning



Affine ➔ Linear

- Affine continuations: resumed *at-most* once
  - Difficult to reason about resource cleanup

```
let fd = Unix.openfile "hello.ml" [Unix.O_RDWR] 0o640
try
  foo fd; Unix.close fd
with e -> Unix.close fd; raise e

let foo fd = perform DoesNotReturn
```

Affine → Linear

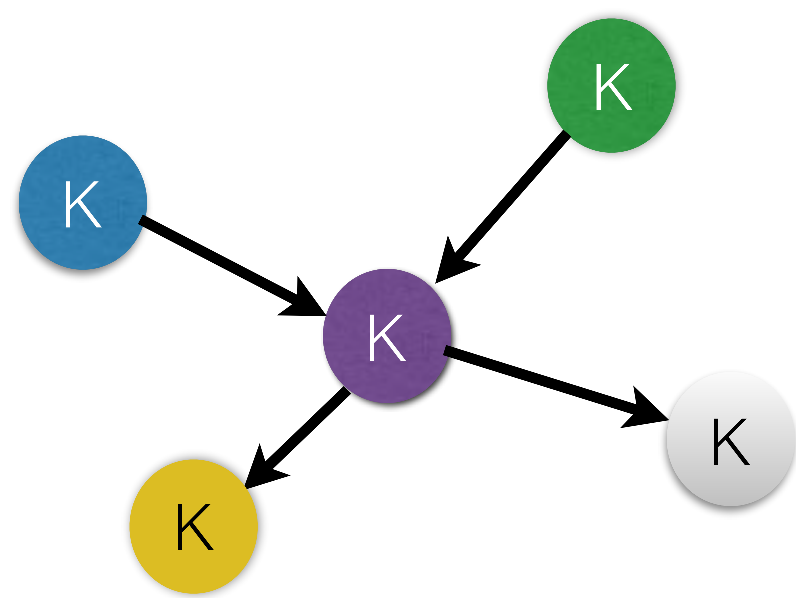
- Affine continuations: resumed *at-most* once
  - Difficult to reason about resource cleanup

```
let fd = ref @@ Unix.openfile "hello.ml" [Unix.O_RDWR] 0o640
try
  foo !fd; Unix.close !fd
with e -> Unix.close !fd; raise e
   | effect e k ->
       (* Dynamic wind *)
       Unix.close !fd;
       let res = perform e in
       fd := Unix.openfile "hello.ml" [Unix.O_RDWR] 0o640;
       continue k res

let foo fd = perform DoesNotReturn
```

Affine ➔ Linear

- Affine continuations: resumed *at-most* once
  - Difficult to reason about resource cleanup
- Linear continuations: resumed *exactly* once
  - Implicit finalisers for fibers
  - Always unwind the stack with `exception ThreadDeath`



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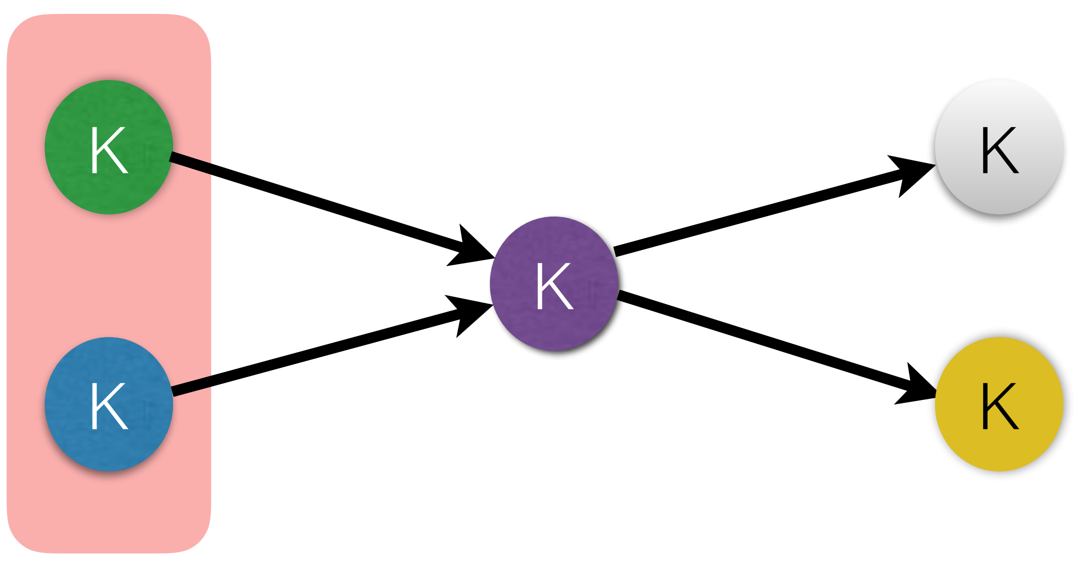

`raise ThreadDeath`

Affine → Linear

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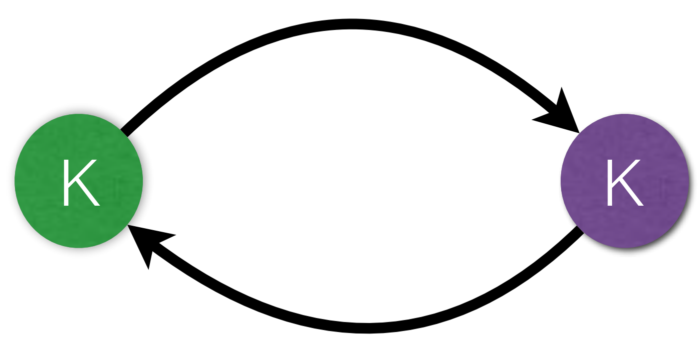

`raise ThreadDeath (??)`

Summary

- Generalises control-flow programming
  - Async I/O, generators, promises, delimited control, etc,.
- Practicality
  - Native one-shot fibers for performance backwards compatibility
  - Backwards compatible effect system (Leo White, Hope 2016 Keynote)
- Real world Impact ➔ JavaScript :-)
  - React Fiber is based on OCaml effect handlers
  - Proposal to add effect handlers to EcmaScript
- *Effect-based programming still in its infancy*