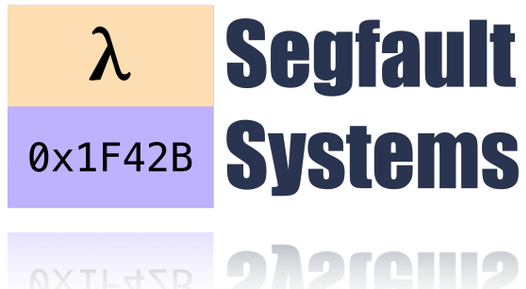
Future of OCaml

“KC” Sivaramakrishnan



Effect Handlers in OCaml 5.00

"KC" Sivaramakrishnan

industrial-strength, pragmatic, functional programming language

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Industry

FACEBOOK
Tarides
Bloomberg
docker
ahrefs
SimCorp
Microsoft
Tezos
Jane Street

Projects

hack
flow
COMPCERT

industrial-strength, pragmatic, functional programming language

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Higher-order functions

Hindley-Milner Type Inference

Powerful module system

industrial-strength, pragmatic, functional programming language

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Higher-order functions

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Powerful module system

Functional core with imperative and object-oriented features

Native (x86, Arm, Power, RISC-V), JavaScript

industrial-strength, pragmatic, functional programming language

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Projects

hack flow COMPCERT

No multicore support!

OCaml 5.00

- Brings native support for *concurrency* and *parallelism* to OCaml

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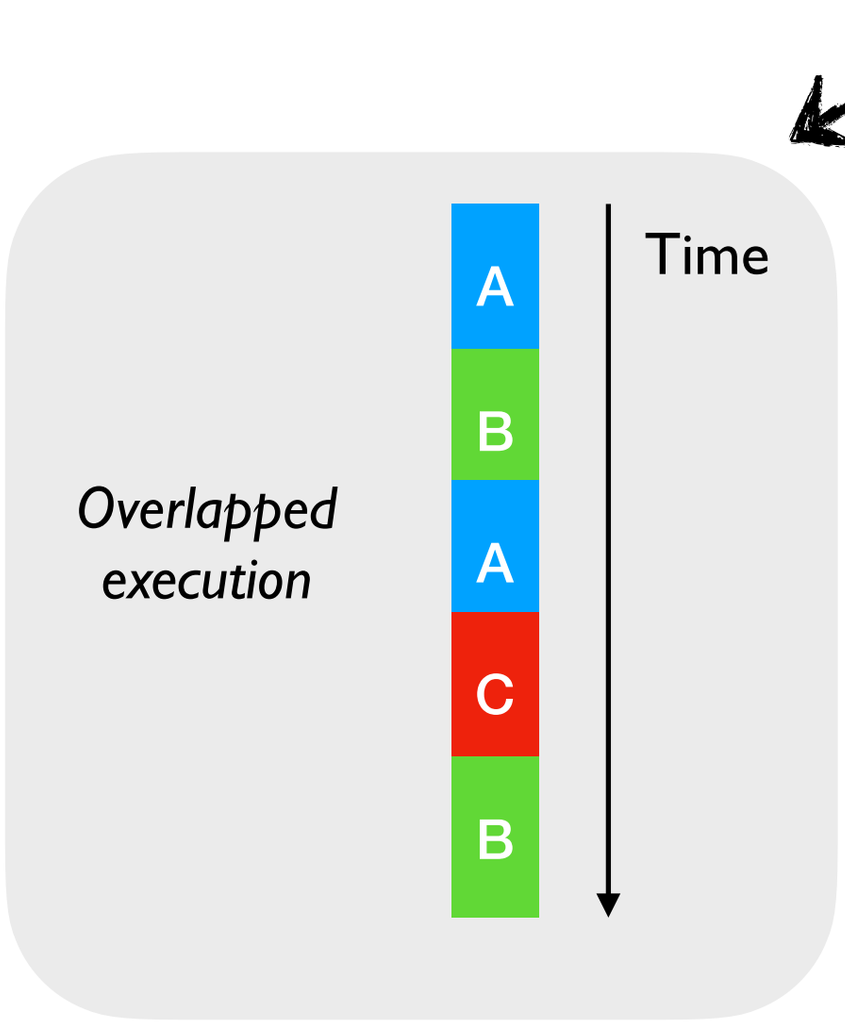

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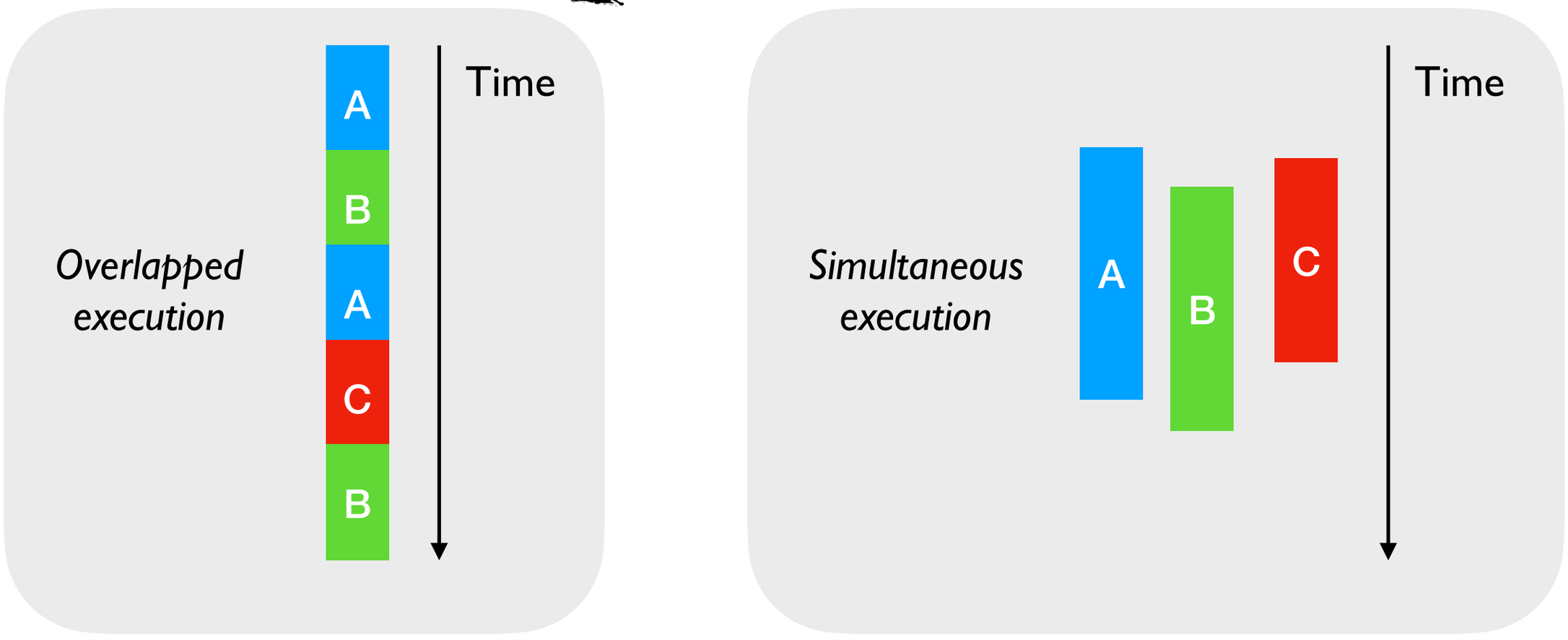

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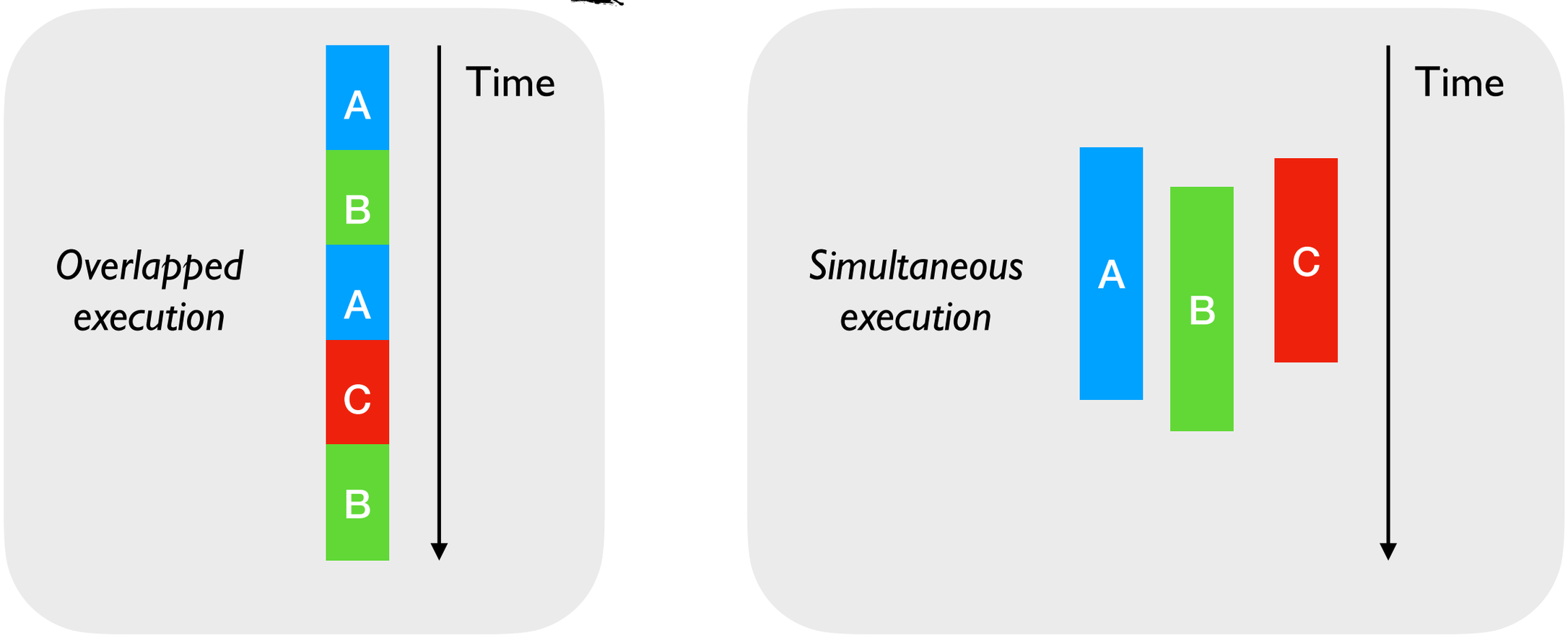

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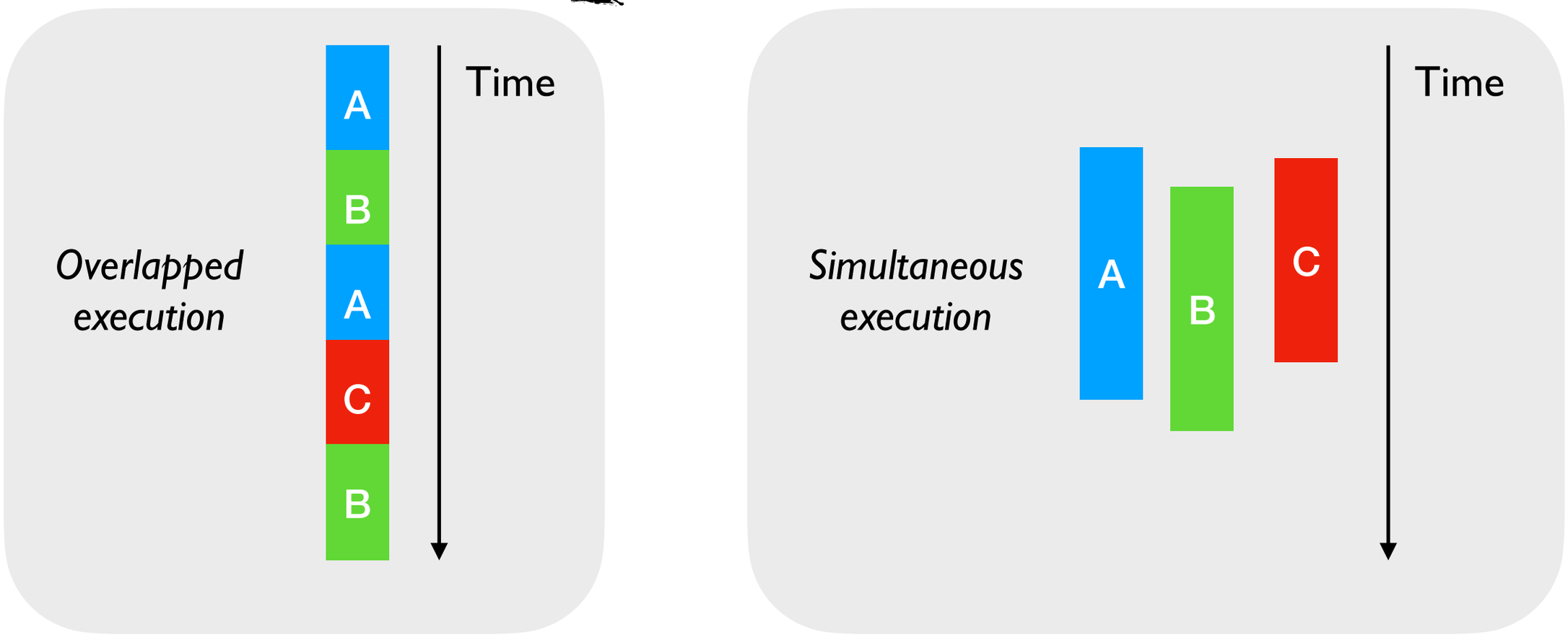

Effect Handlers

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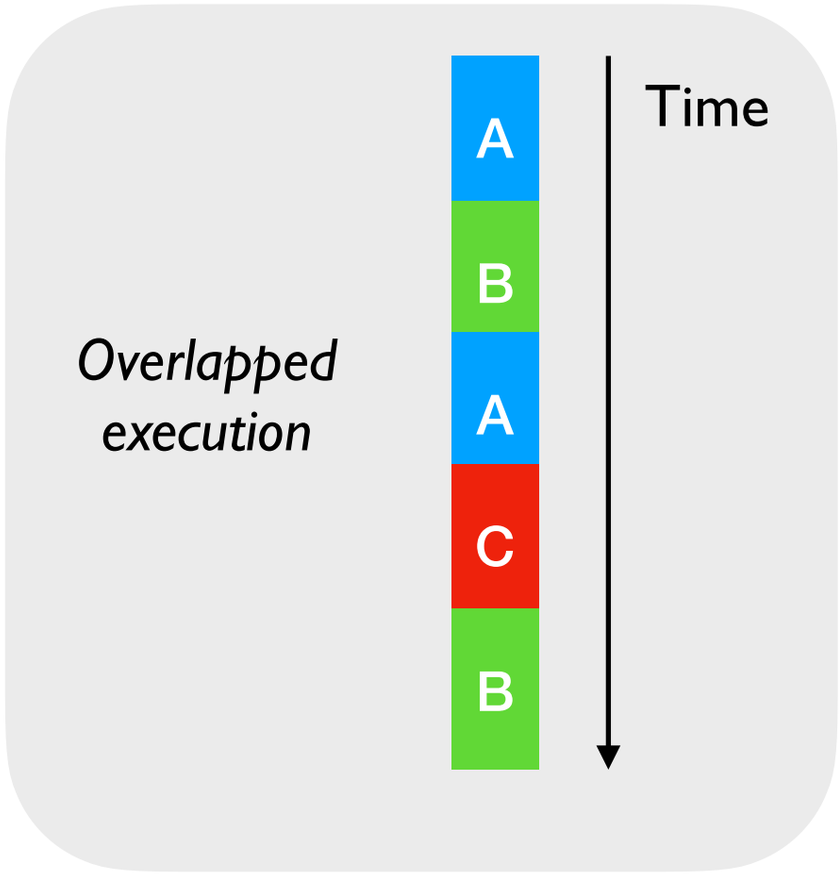

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  - ✦ async/await — JavaScript, Python, Rust, C# 5.0, F#, Swift, …
  - ✦ generators — Python, Javascript, …
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  - ✦ futures & promises — JavaScript, Swift, …
- Often include different primitives for concurrent programming
  - ✦ JavaScript has async/await, generators, promises, and callbacks!!

Concurrent Programming in OCaml

- No primitive support for concurrent programming in OCaml
  - ✦ **Lwt** and **Async** - concurrent programming libraries
  - ✦ Callback-oriented programming with monadic syntax **>>=**

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  - ✦ **Lwt** and **Async** - concurrent programming libraries
  - ✦ Callback-oriented programming with monadic syntax **>>=**
- Suffers many pitfalls of *callback-oriented programming*
  - ✦ No backtraces, no exceptions, more closures

Concurrent Programming in OCaml

- Monadic concurrency splits the ecosystem into *Asynchronous* and *Synchronous* in OCaml
  - ✦ Different calling conventions for *synchronous* and *asynchronous* code
  - ✦ Any potentially blocking code should be *asynchronous*
  - ✦ See Bob Nystrom, *"What colour is your function?"*

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  - ✦ Different calling conventions for *synchronous* and *asynchronous* code
  - ✦ Any potentially blocking code should be *asynchronous*
  - ✦ See Bob Nystrom, *"What colour is your function?"*
- Go (goroutines) and GHC Haskell (threads) have better abstractions — lightweight threads
  - ✦ *Should we add lightweight threads to OCaml?*

Solution

Effect Handlers

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- *Modular* and *composable* basis of non-local control-flow mechanisms
  - ✦ Exceptions, generators, lightweight threads, promises, asynchronous IO, coroutines as *libraries*

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- Effect handlers ~= *first-class, restartable exceptions*
  - ✦ Structured programming with *delimited continuations*

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- Effect handlers ~= *first-class, restartab*
  - ✦ Structured programming with *delimited*

- Direct-style asynchronous I/O
- Generators
- Resumable parsers
- Probabilistic Programming
- Reactive UIs
- ....

https://github.com/ocaml-multicore/effects-examples

An example

```
effect E : string

let comp () =
  print_string "0 ";
  print_string (perform E);
  print_string "3 "

let main () =
  try
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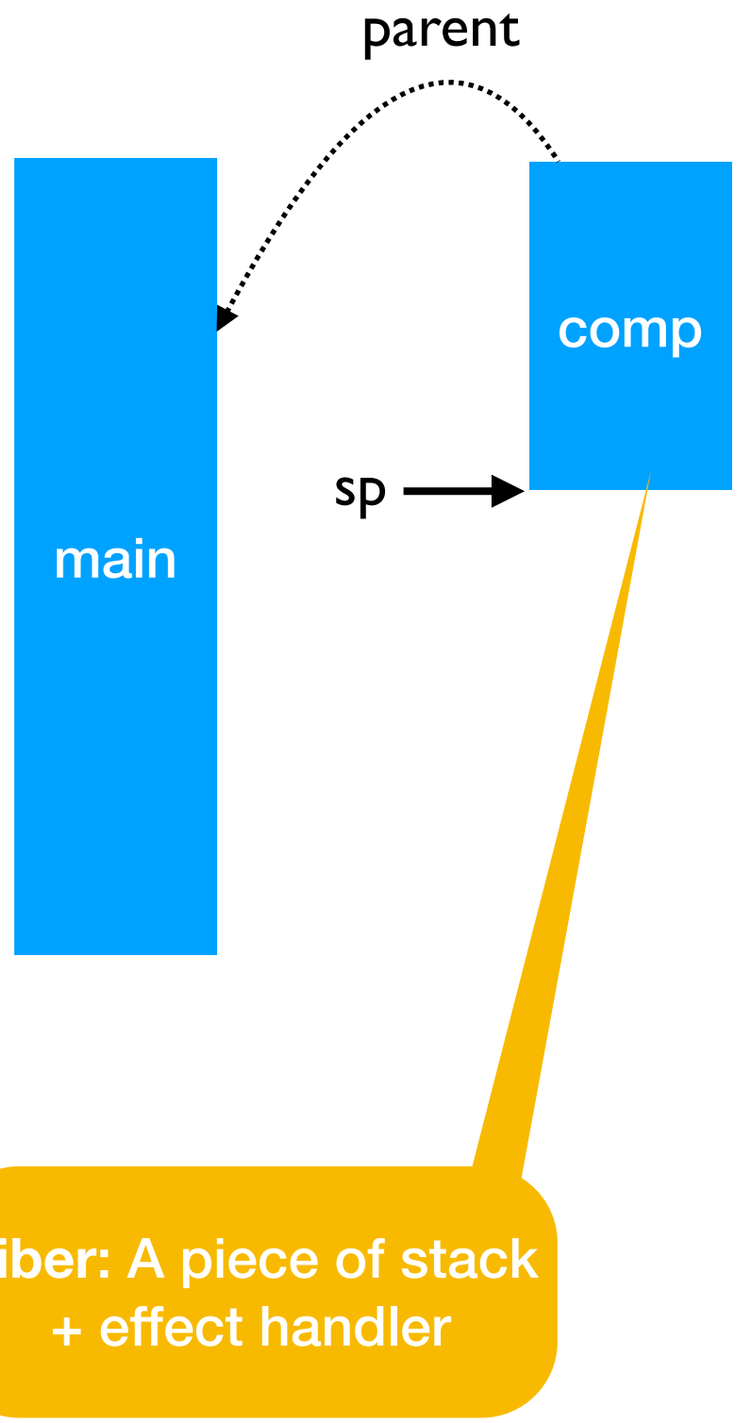

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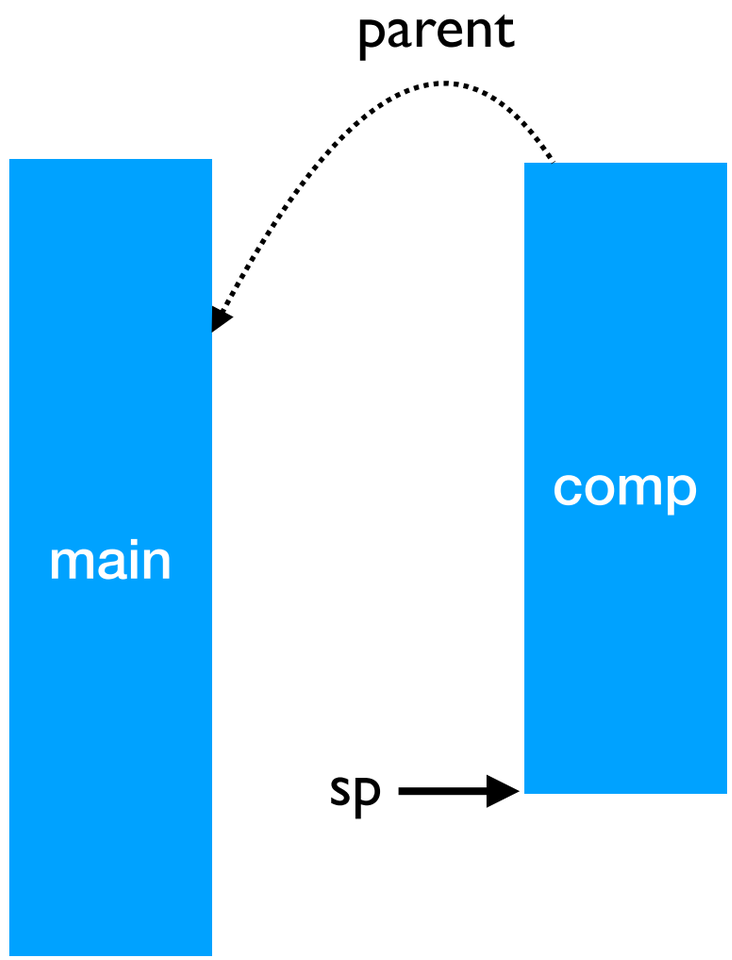

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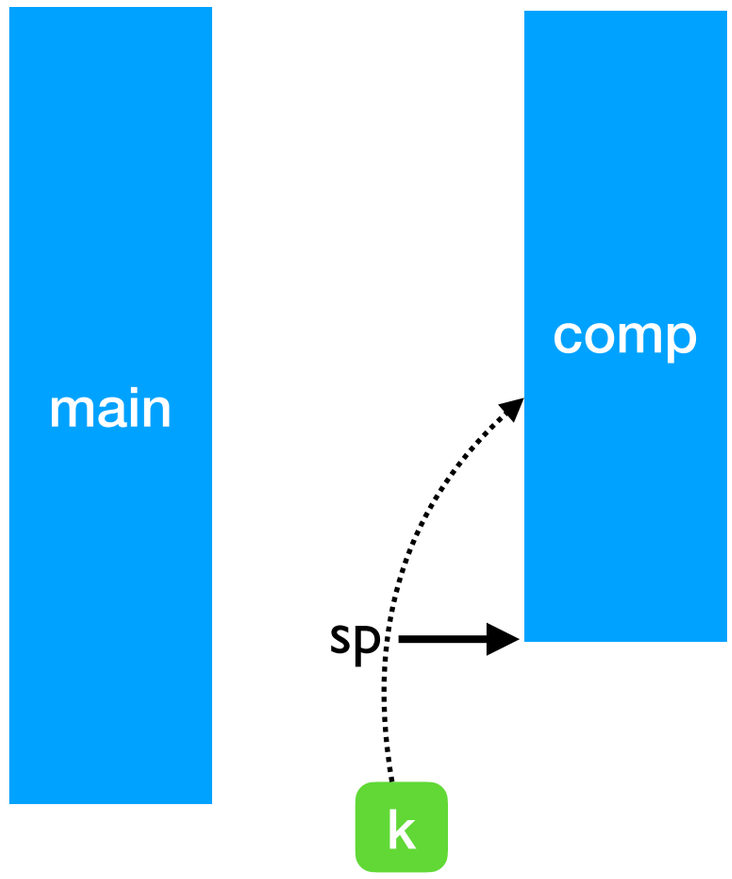

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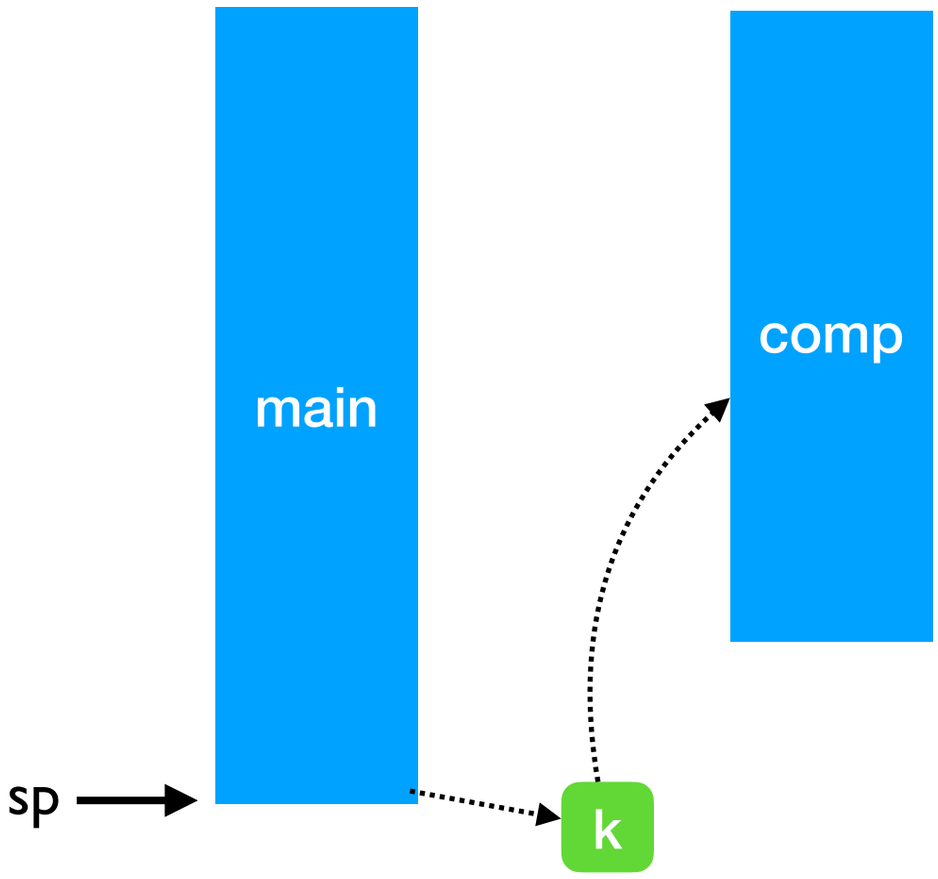

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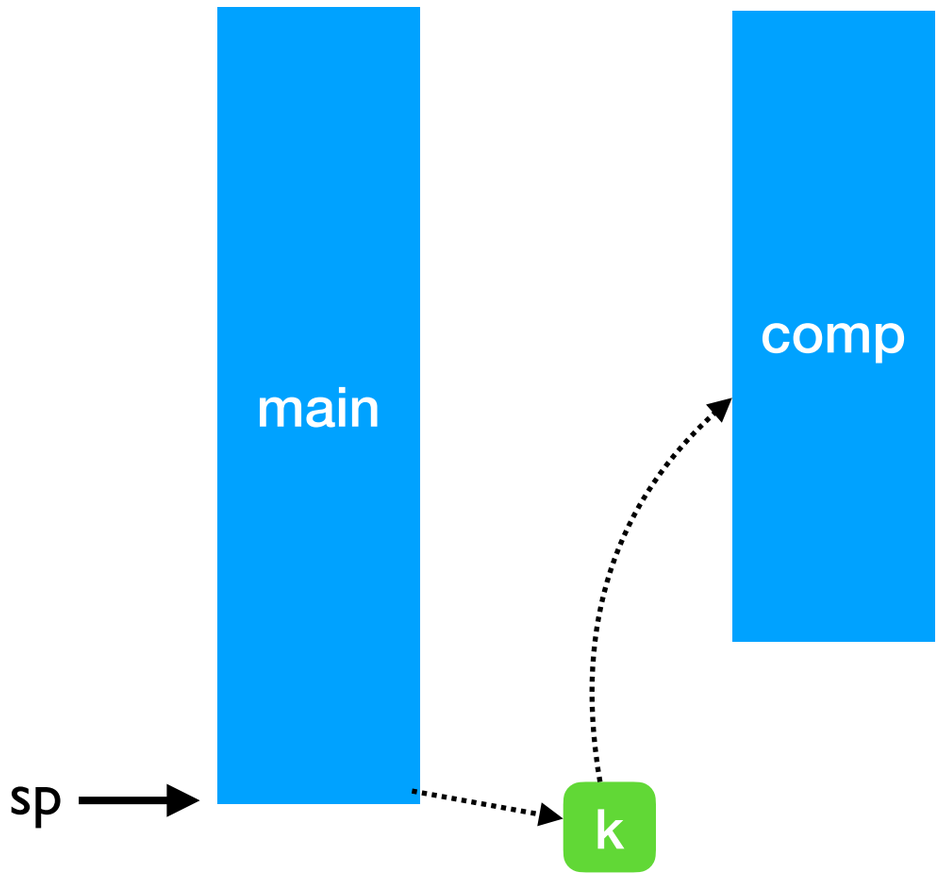

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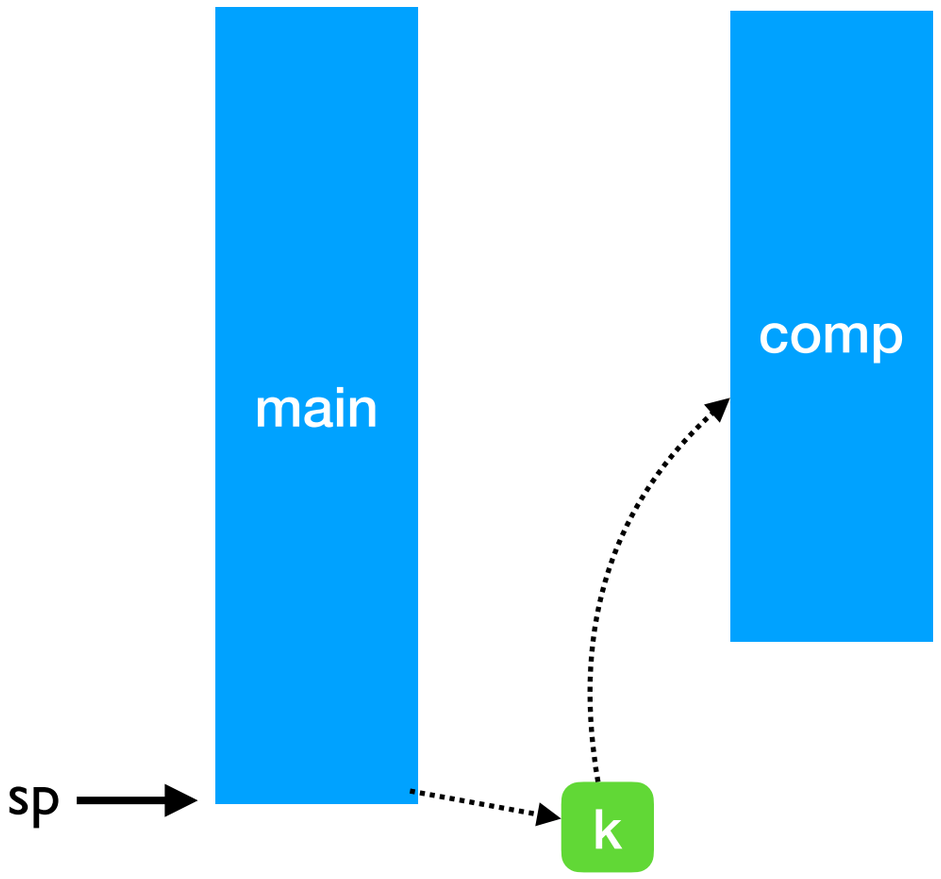

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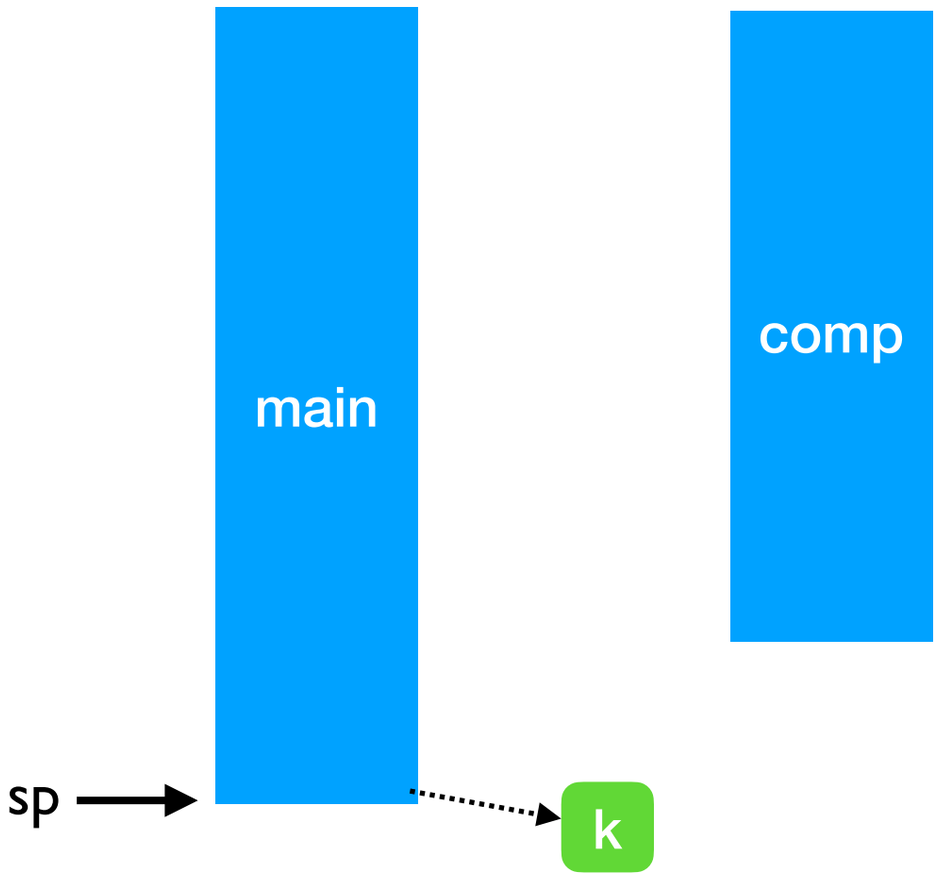

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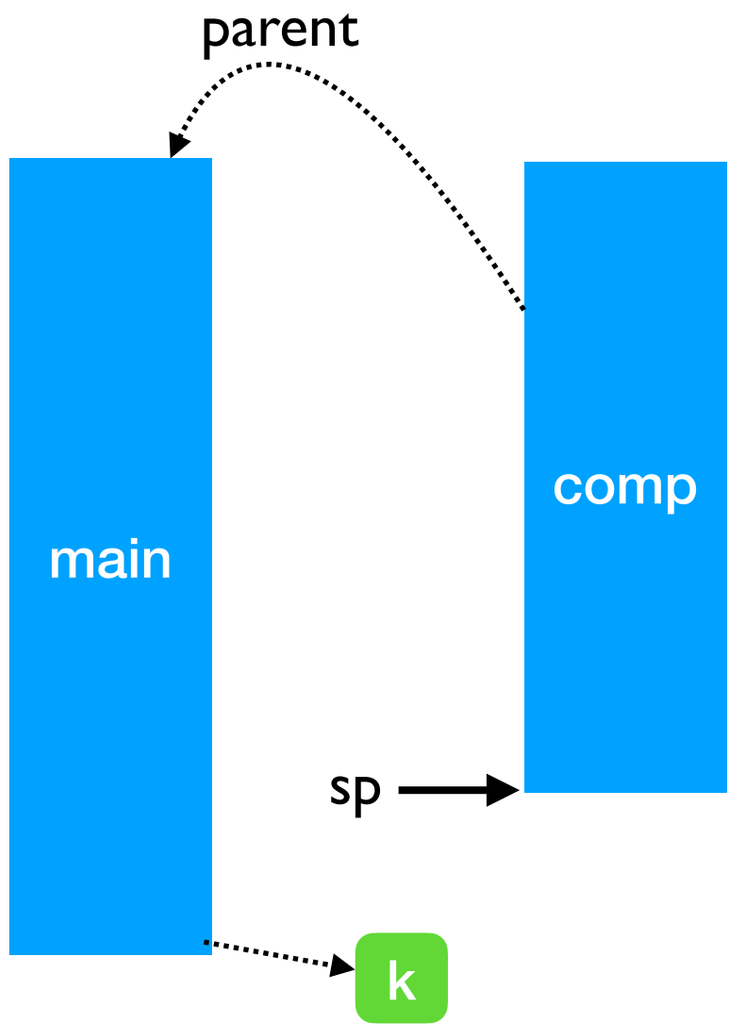

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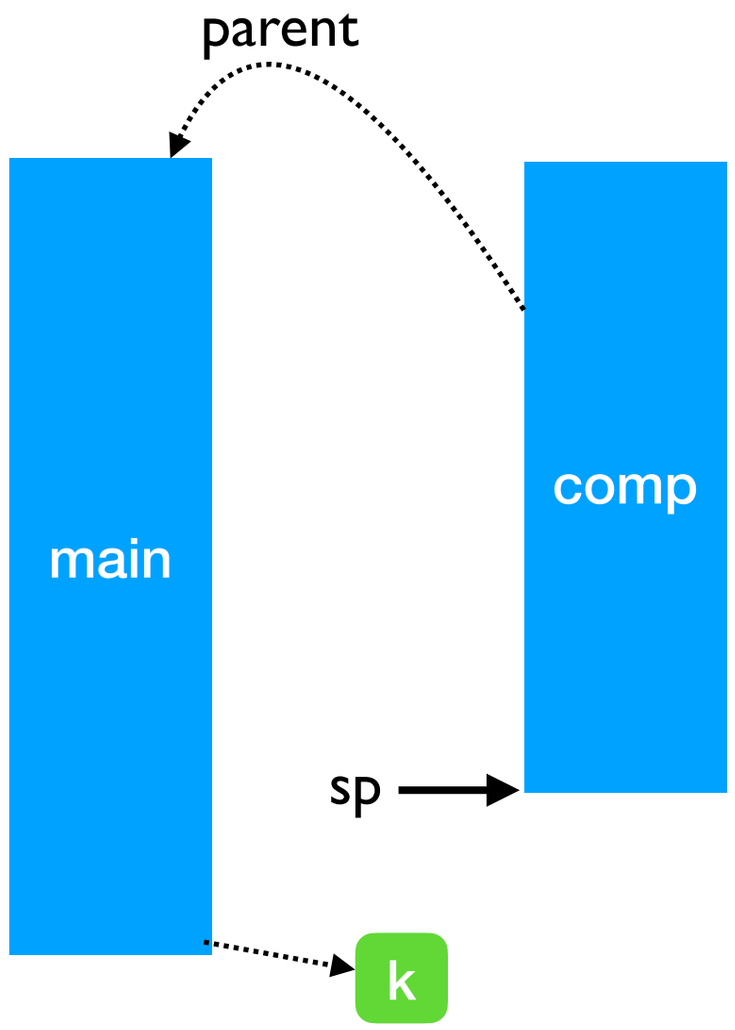

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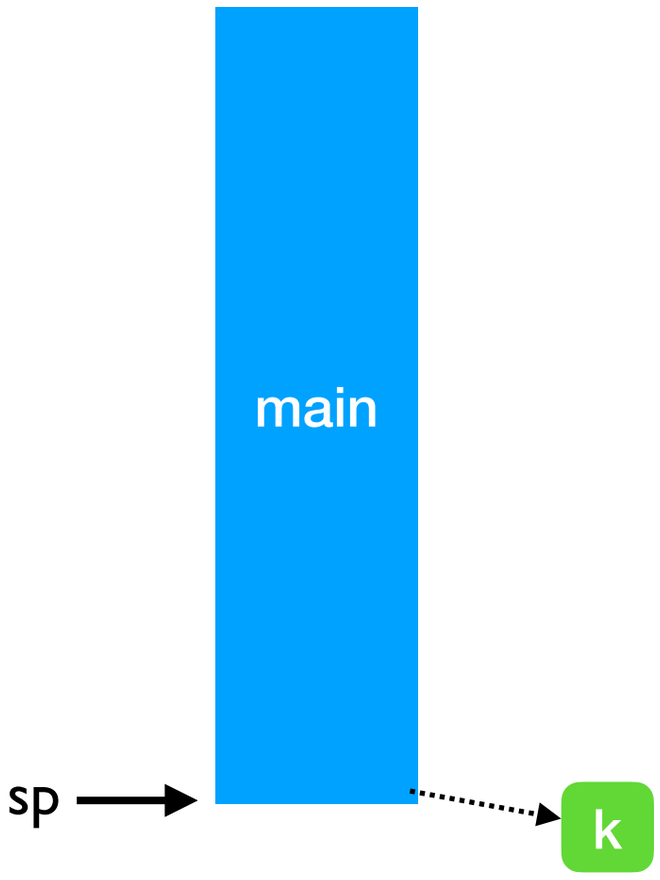

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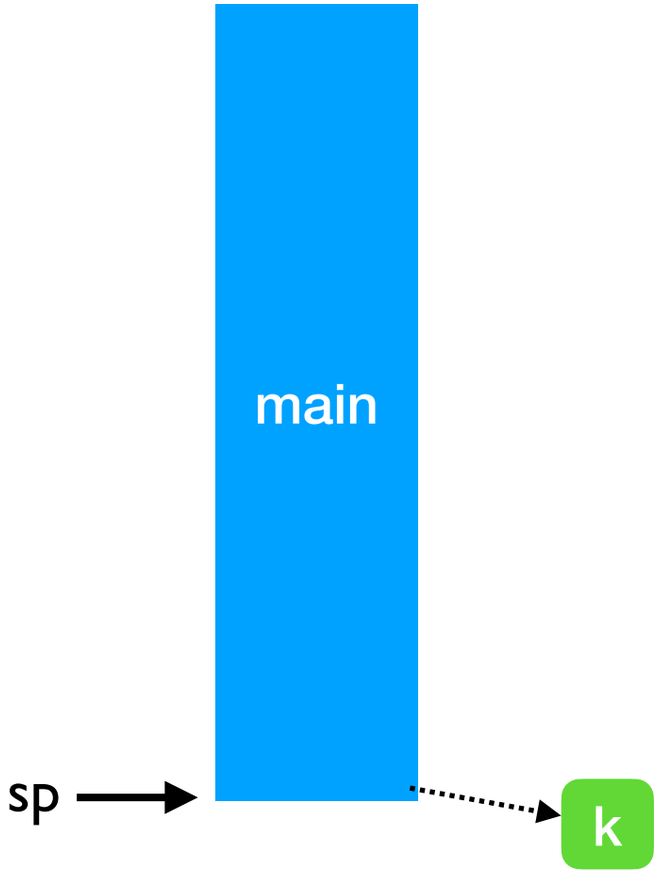

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Handlers can be nested

```
effect A : unit
effect B : unit

let baz () =
  perform A

let bar () =
  try
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let foo () =
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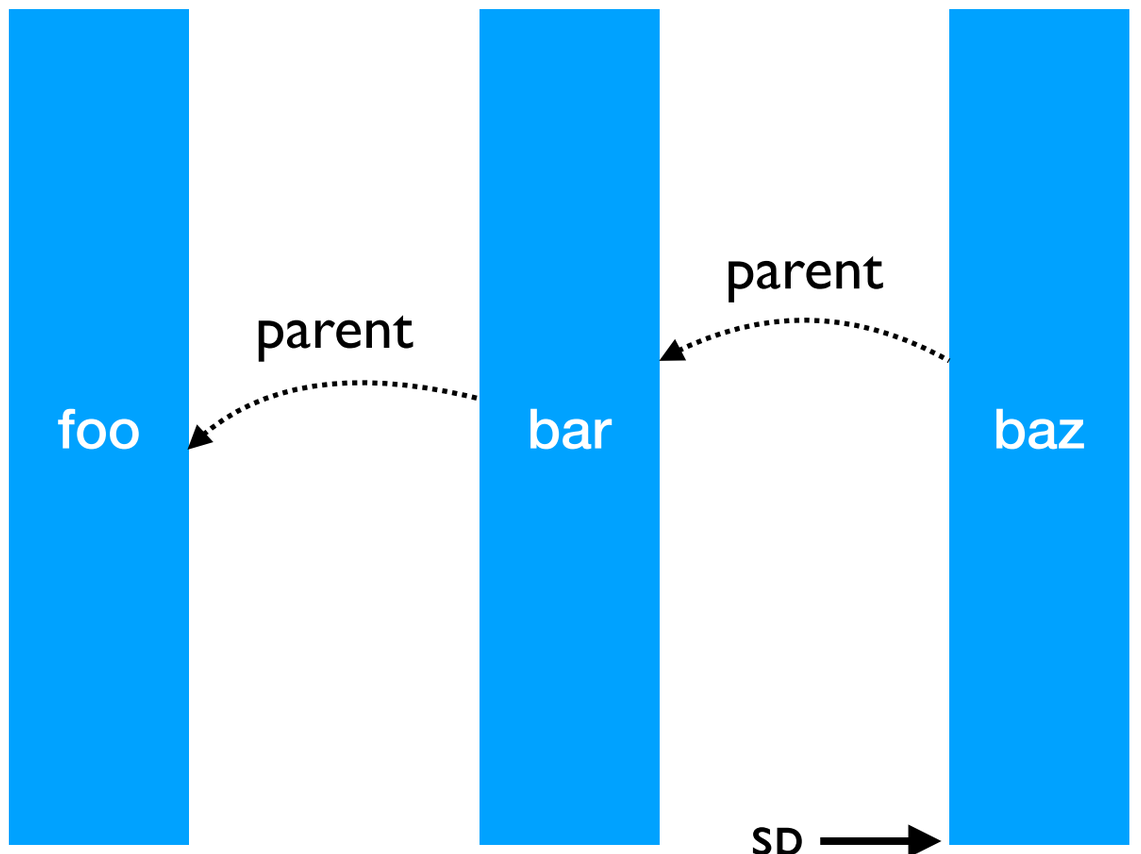

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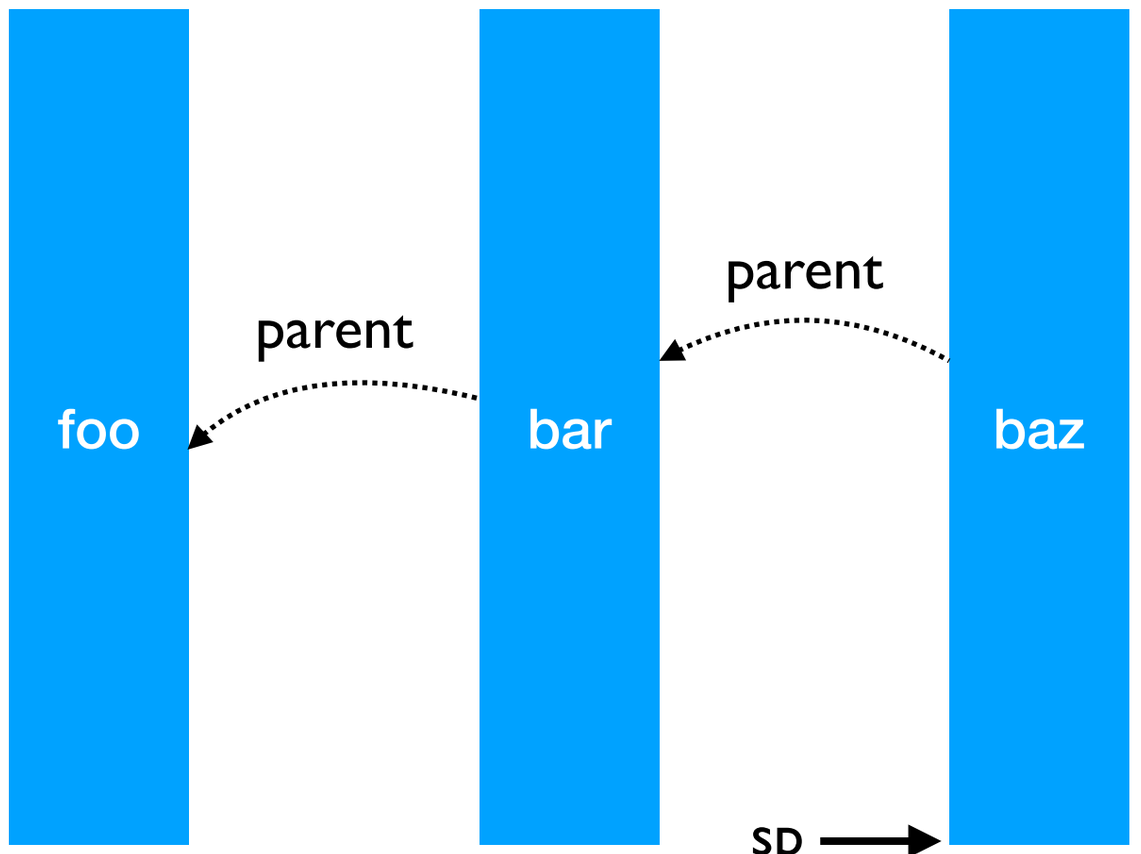

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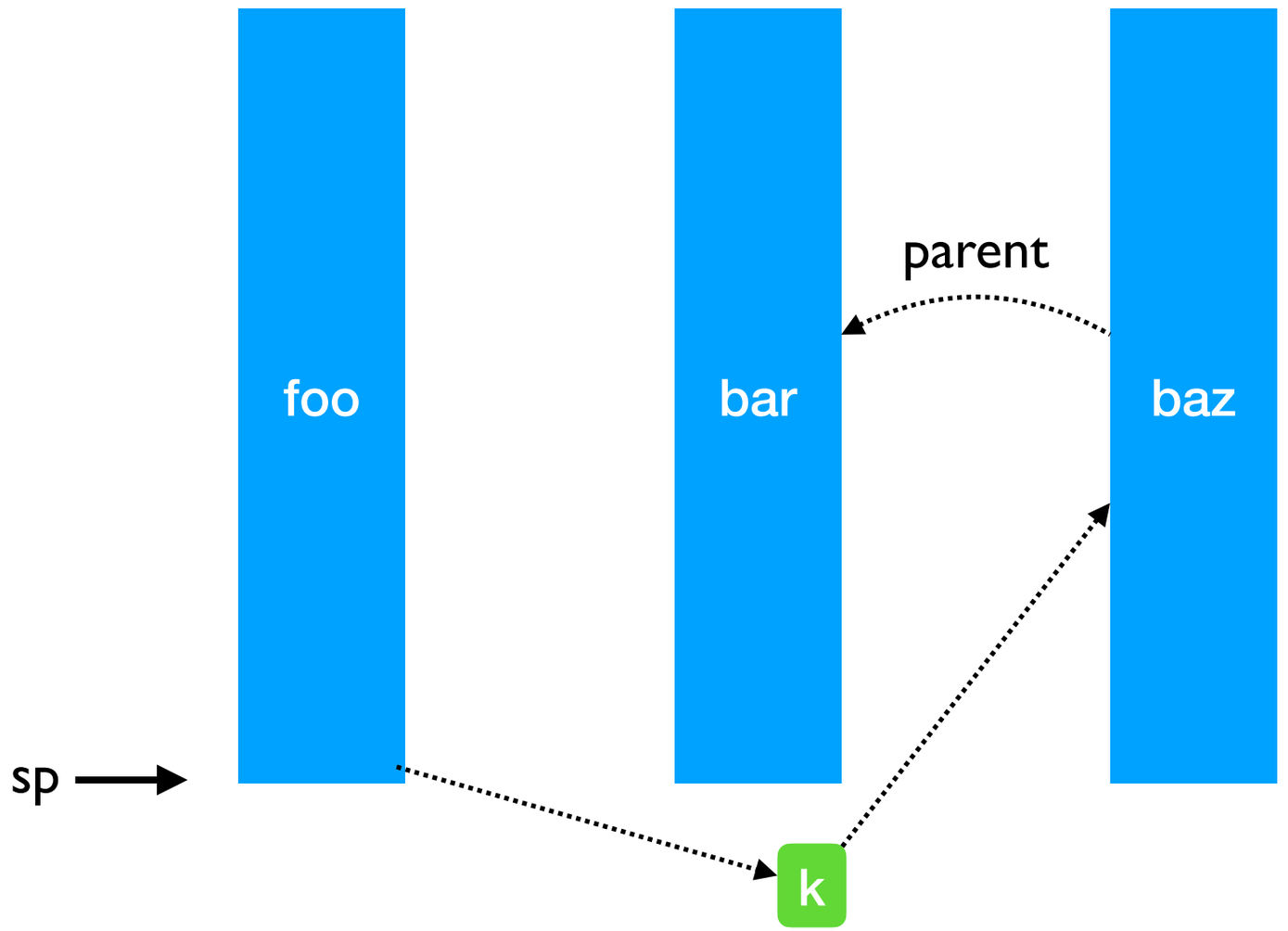

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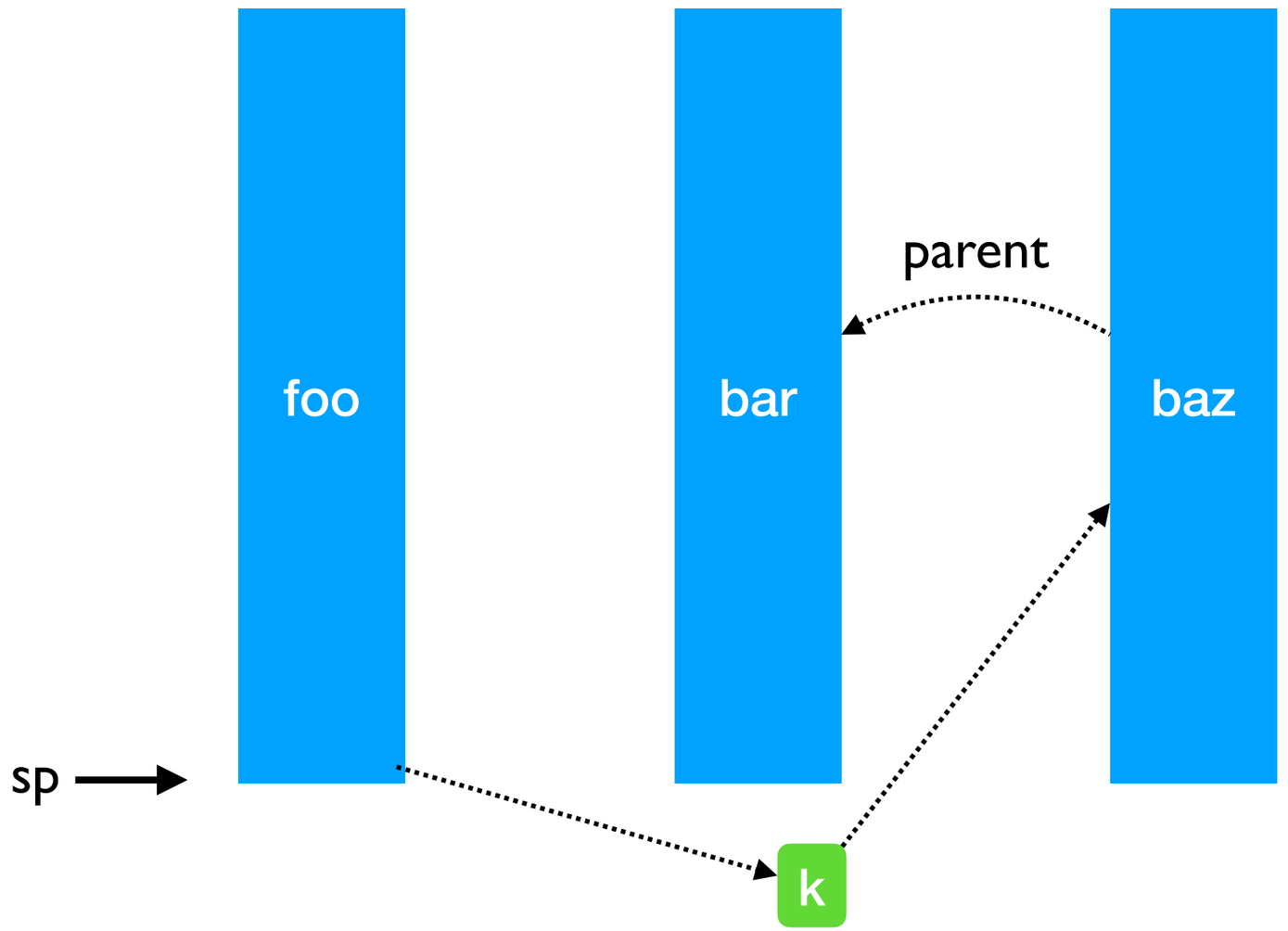

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Lightweight Threading

```
effect Fork  : (unit -> unit) -> unit
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effect Yield : unit

let run main =
  ... (* assume queue of continuations *)
  let run_next () =
    match dequeue () with
    | Some k -> continue k ()
    | None -> ()
in
let rec spawn f =
  match f () with
  | () -> run_next () (* value case *)
  | effect Yield k -> enqueue k; run_next ()
  | effect (Fork f) k -> enqueue k; spawn f
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  spawn main

let fork f = perform (Fork f)
let yield () = perform Yield
```

Lightweight threading

```
let main () =
  fork (fun _ ->
    print_endline "1.a";
    yield ();
    print_endline "1.b");
  fork (fun _ ->
    print_endline "2.a";
    yield ();
    print_endline “2.b")
;;
run main
```

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- Direct-style (no monads)
- User-code need not be aware of effects
- No Async vs Sync distinction

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function* generator(i) {
  yield i;
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}
const gen = generator(10);

console.log(gen.next().value);
// expected output: 10

console.log(gen.next().value);
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- Can be *derived automatically* from any iterator using effect handlers

Generators: effect handlers

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module MkGen (S :sig
  type 'a t
  val iter : ('a -> unit) -> 'a t -> unit
end) : sig
  val gen : 'a S.t -> (unit -> 'a option)
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  let gen : type a. a S.t -> (unit -> a option) = fun l ->
    let module M = struct effect Yield : a -> unit end in
    let open M in
    let rec step = ref (fun () ->
      match S.iter (fun v -> perform (Yield v)) l with
      | () -> None
      | effect (Yield v) k ->
          step := (fun () -> continue k ());
          Some v)
    in
    fun () -> !step ()
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Generators: List

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let next = L.gen [1;2;3]
next() (* Some 1 *)
next() (* Some 2 *)
next() (* Some 3 *)
next() (* None *)
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Generators: Tree

```
type 'a tree =
| Leaf
| Node of 'a tree * 'a * 'a tree

let rec iter f = function
  | Leaf -> ()
  | Node (l, x, r) ->
      iter f l; f x; iter f r
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(* Make a complete binary tree of
   depth [n] using [O(n)] space *)
let rec make = function
  | 0 -> Leaf
  | n -> let t = make (n-1)
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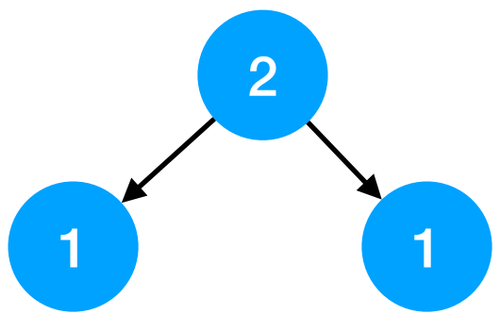

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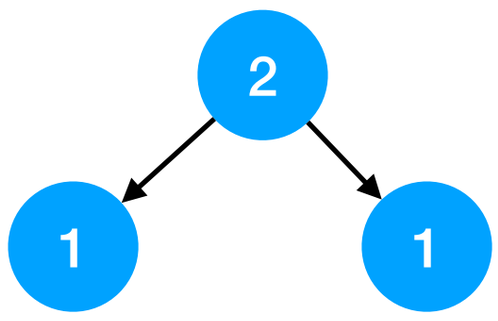

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- *Iterator* — idiomatic recursive traversal
- Generator
  - ✦ Hand-written generator (*hw-generator*)
    - ✤ Specialised for in-order traversal of binary trees
    - ✤ CPS translation + defunctionalization to remove intermediate closure allocation
  - ✦ Generator using effect handlers (*eh-generator*)

Performance: Generators

OCaml 5.00

Variant	Time (milliseconds)
Iterator (baseline)	202
hw-generator	837 (**3.76x**)
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nodejs 14.07

Variant	Time (milliseconds)
Iterator (baseline)	492
generator	43842 (**89.1x**)

Performance: WebServer

- **eio**: effects-based direct-style I/O
  - ✦ Multiple backends — Linux *io_uring, epoll*, MacOS *GCD*, Windows *IOCP*, FreeBSD *kqueue*

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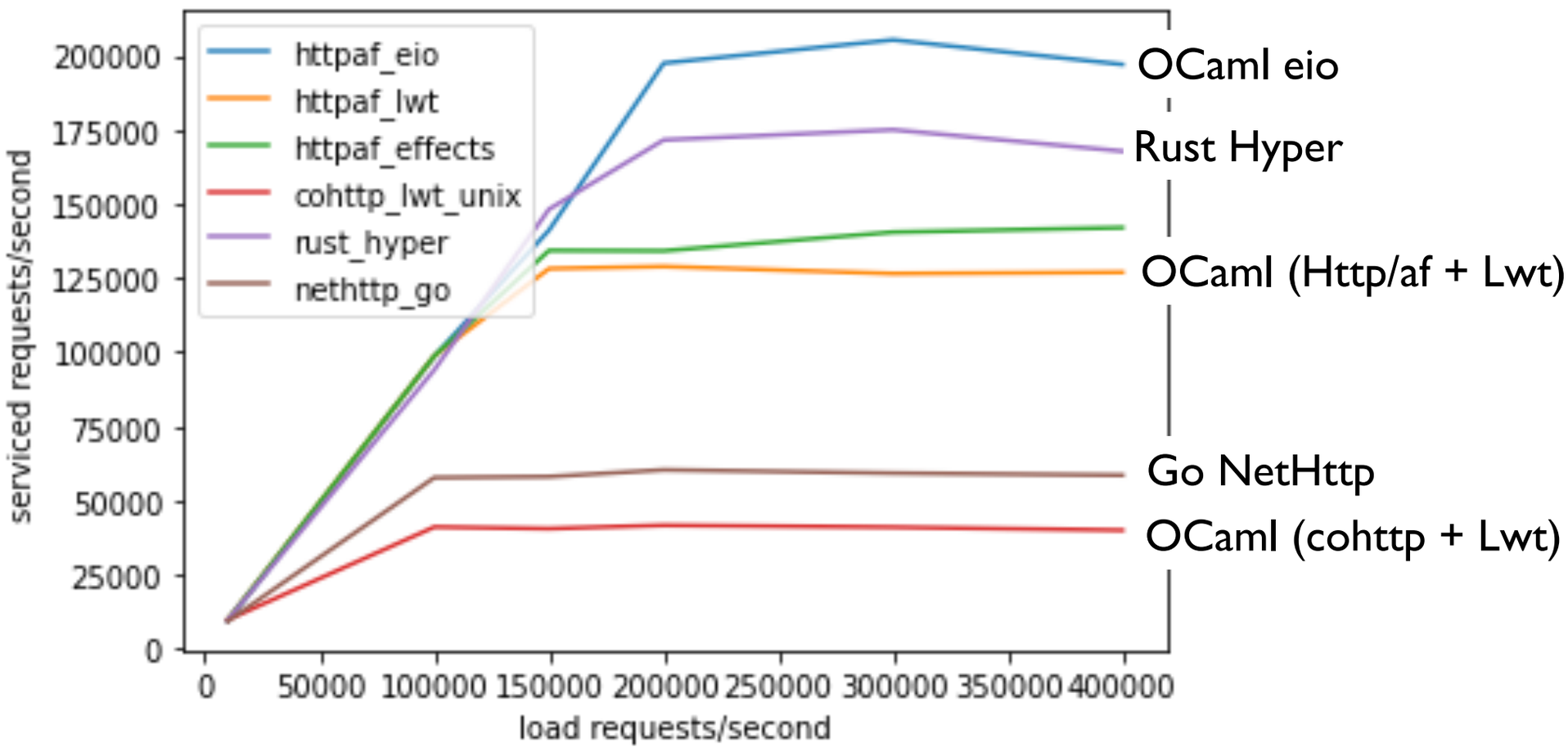

100 open connections, 60 seconds w/ io_uring

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

Retrofitting Challenges

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Must preserve
feature, tooling, performance
compatibility

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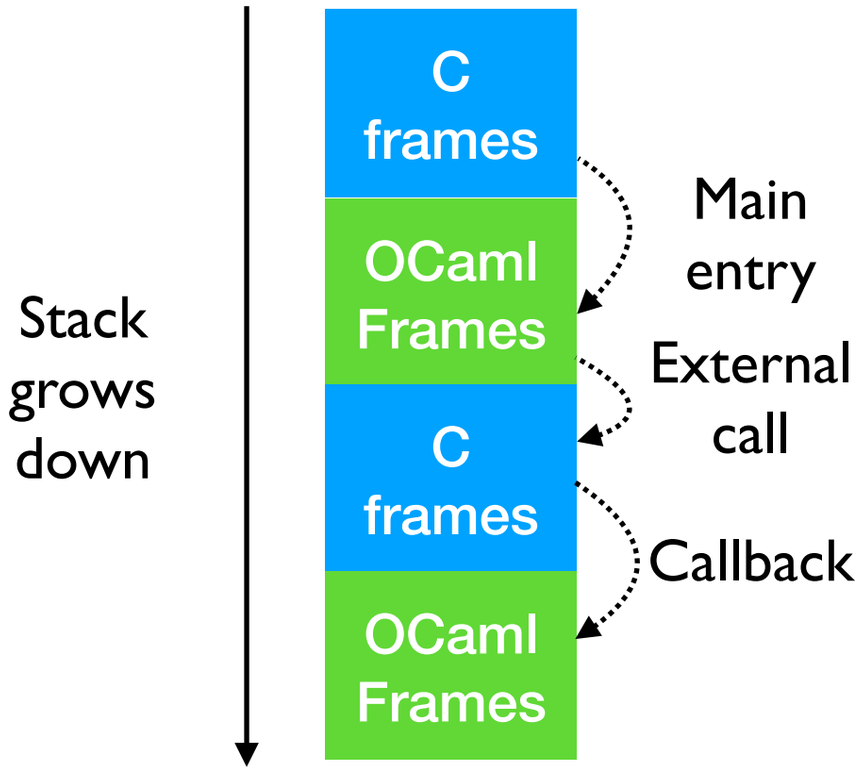

OCaml 4.xx

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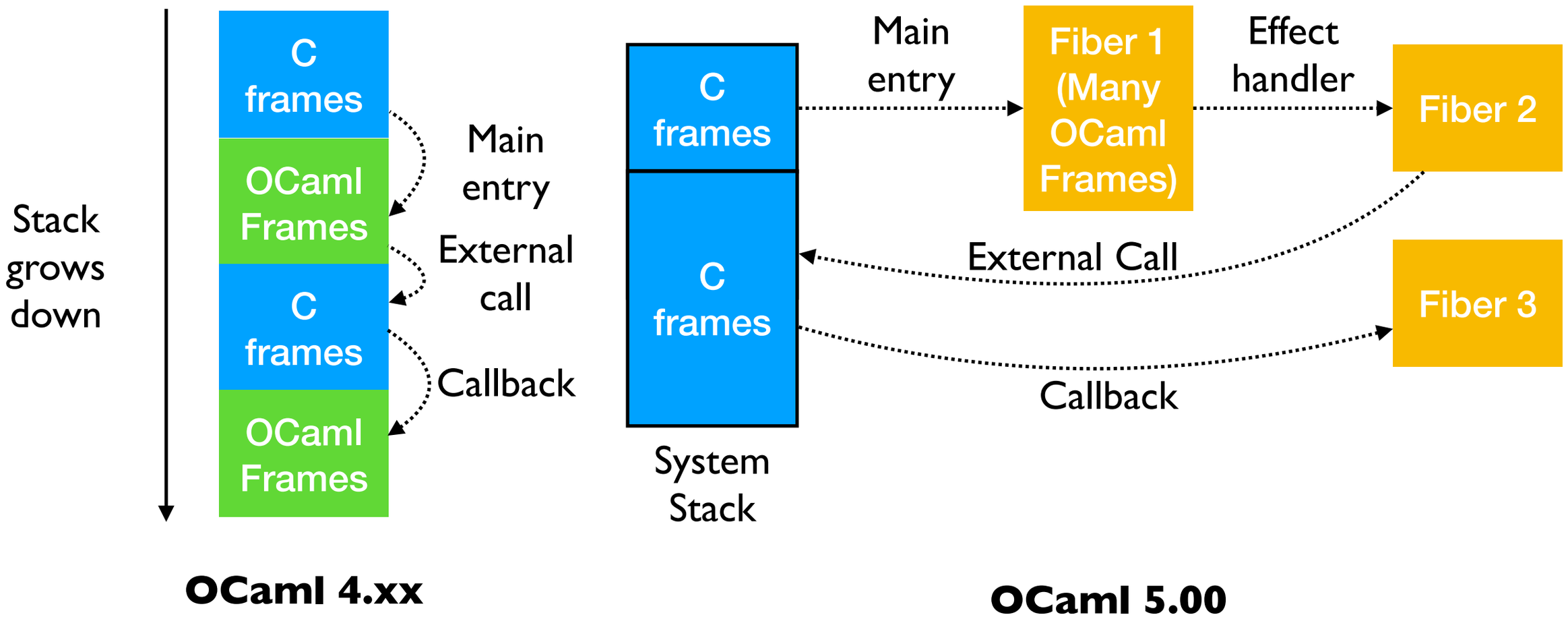

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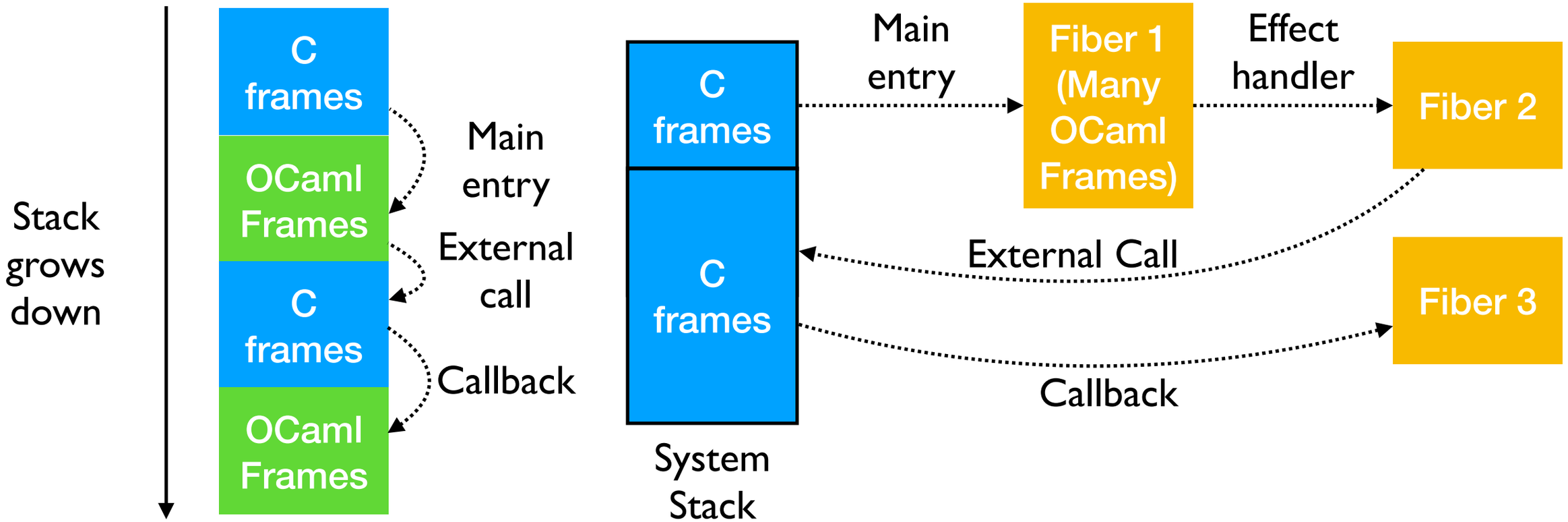
Formal Semantics in PLDI'21 paper



Switching stacks fast

- *One-shot* — capture and resumption does not involve copying frames

Switching stacks fast

- *One-shot* — capture and resumption does not involve copying frames
- No callee-saved registers in OCaml
  - ✦ Switching between stacks need not save & restore register state

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We would like to make this code transparently asynchronous

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effect In_line : in_channel -> string
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let run_aio f = match f () with
| v -> v
| effect (In_line chan) k ->
    register_async_input_line chan k;
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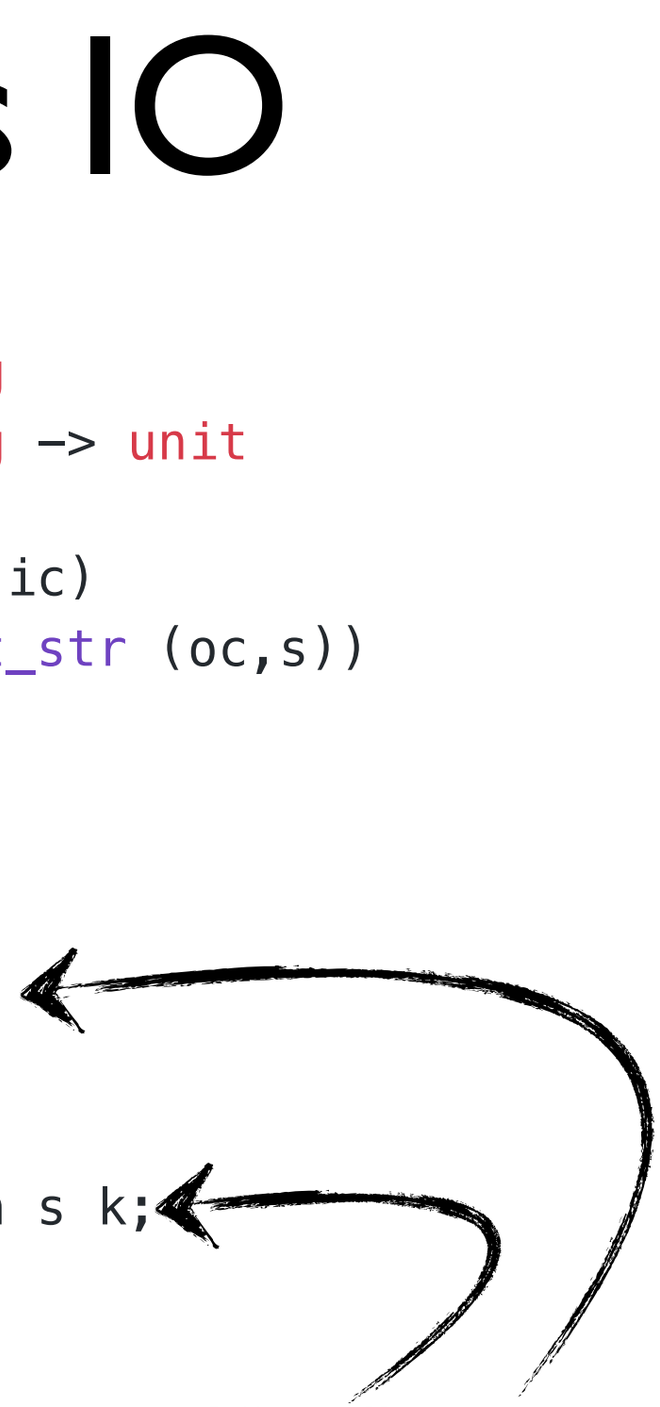

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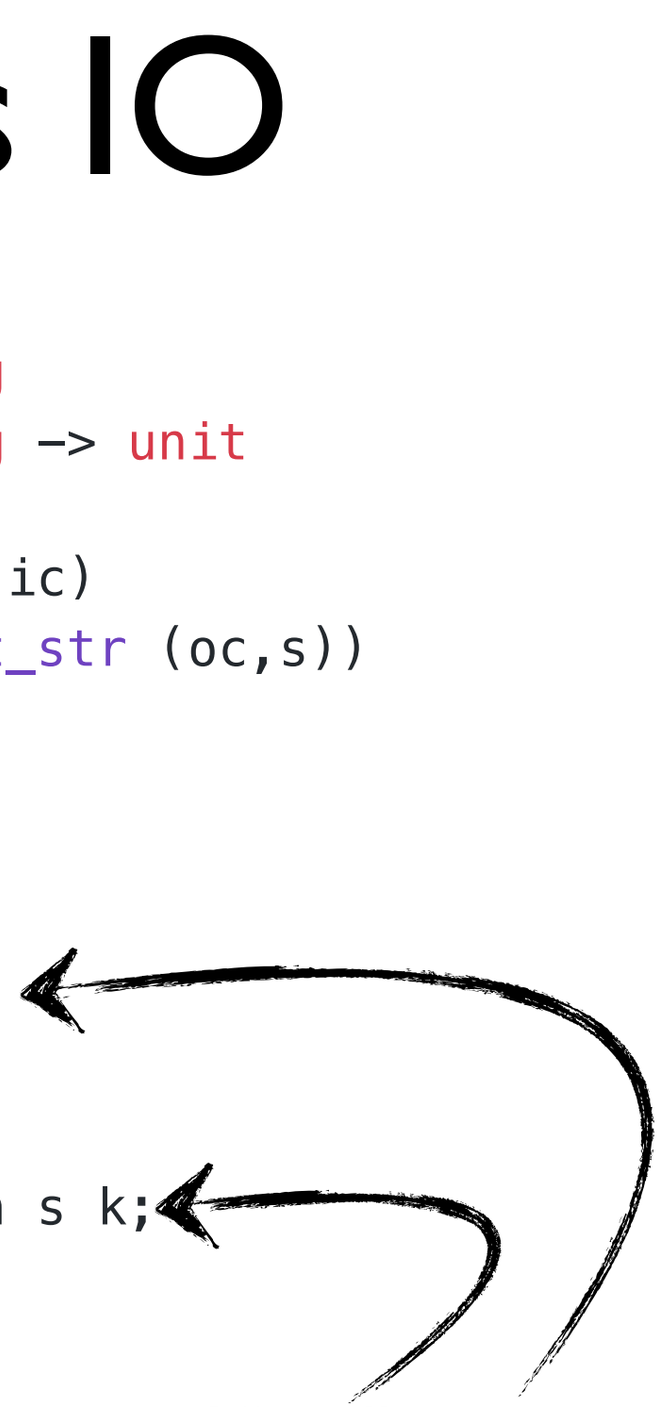

- Continue with appropriate *value* when the asynchronous IO call returns
- But what about termination? — `End_of_file` and `Sys_error` *exceptional* cases.

Discontinue

```
discontinue k End_of_file
```

- We add a discontinue primitive to resume a continuation by raising an exception
- On `End_of_file` and `Sys_error`, the asynchronous IO scheduler uses discontinue to raise the appropriate exception

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- With effect handlers, functions may return *at-most once* if continuation not resumed
  - ✦ This breaks resource-safe legacy code

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We *assume* that captured continuations are resumed *exactly once*
either using `continue` or `discontinue`

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- Sivaramakrishnan et al, "*Retrofitting Effect Handlers onto OCaml*", PLDI 2021
  - ✦ Static semantics and compilation scheme
  - ✦ DWARF Backtrace support (gdb, lldb, perf)
  - ✦ Lot of benchmarks!

Nothing to see here…

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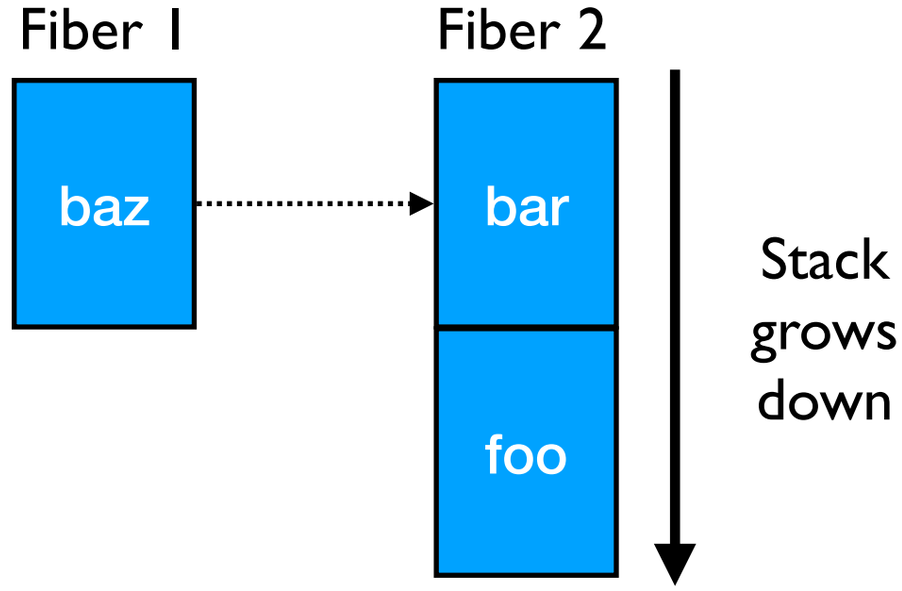

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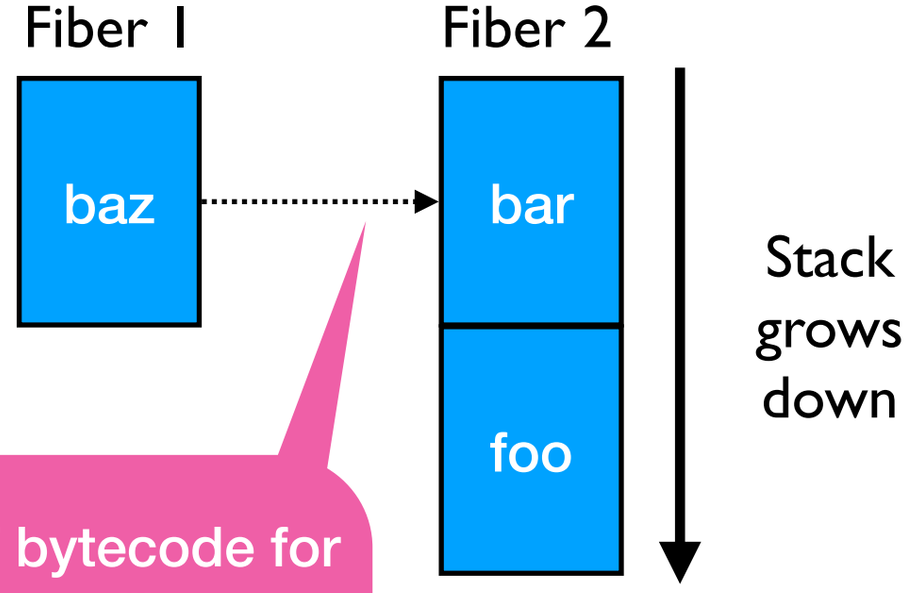

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```
(lldb) bt
* thread #1, name = 'a.out', stop reason = …
  * #0: 0x58b208 caml_perform
    #1: 0x56aa5d camlTest__foo_83 at test.ml:4
    #2: 0x56aae2 camlTest__bar_85 at test.ml:9
    #3: 0x56a9fc camlTest__fun_199 at test.ml:14
    #4: 0x58b322 caml_runstack + 70
    #5: 0x56ab99 camlTest__baz_91 at test.ml:14
    #6: 0x56ace6 camlTest__entry at test.ml:21
    #7: 0x56a41c caml_program + 60
    #8: 0x58b0b7 caml_start_program + 135
    #9: …
```

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```
let foo () = print_string "hello, world"
```

```
val foo : unit -[ io ]-> unit
```

Syntax & Semantics in the works

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effect E : string

let comp () =
  print_string "0 ";
  print_string (perform E);
  print_string "3 "

let main () =
  try
    comp ()
  with effect E k ->
    print_string "1 ";
    continue k "2 ";
    print_string “4 "
```

```
effect E : string

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  print_string "0 ";
  print_string (perform E);
  print_string "3 "

let main () =
  try_with comp ()
  { effc = fun e ->
      match e with
      | E -> Some (fun k ->
          print_string "1 ";
          continue k "2 ";
          print_string “4 “)
      | e -> None }
```

Performance

```
let foo () =
    (* a *)
  try
    (* b *)
    perform E
    (* d *)
  with effect E k ->
    (* c *)
    continue k ()
(* e *)
```

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Instruction Sequence	Significance
a to b	Create a new stack & run the computation
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- Each of the instruction sequences involves a stack switch

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- Each of the instruction sequences involves a stack switch
- Intel(R) Xeon(R) Gold 5120 CPU @ 2.20GHz
  - ✦ Cost measured using Intel PT's cycle accurate tracing
  - ✦ For calibration, memory read latency is **90 ns** (local NUMA node) and **145 ns** (remote NUMA node)

Performance

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let foo () =
    (* a *)
  try
    (* b *)
    perform E
    (* d *)
  with effect E k ->
    (* c *)
    continue k ()
(* e *)
```

Instruction Sequence	Significance	Time (ns)
a to b	Create a new stack & run the computation	23
b to c	Performing & handling an effect	5
c to d	Resuming a continuation	11
d to e	Returning from a computation & free the stack	7

- Each of the instruction sequences involves a stack switch
- Intel(R) Xeon(R) Gold 5120 CPU @ 2.20GHz
  - ✦ Cost measured using Intel PT's cycle accurate tracing
  - ✦ For calibration, memory read latency is **90 ns** (local NUMA node) and **145 ns** (remote NUMA node)

Fiber Layout

```
match f () with
| v -> ...
| exception X1 -> ...
| exception (X2 v) -> ...
| effect E1 k -> ...
| effect E2 k -> ...
```