Effective Programming in OCaml

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OCaml Labs

IIT MADRAS

Multicore OCaml

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

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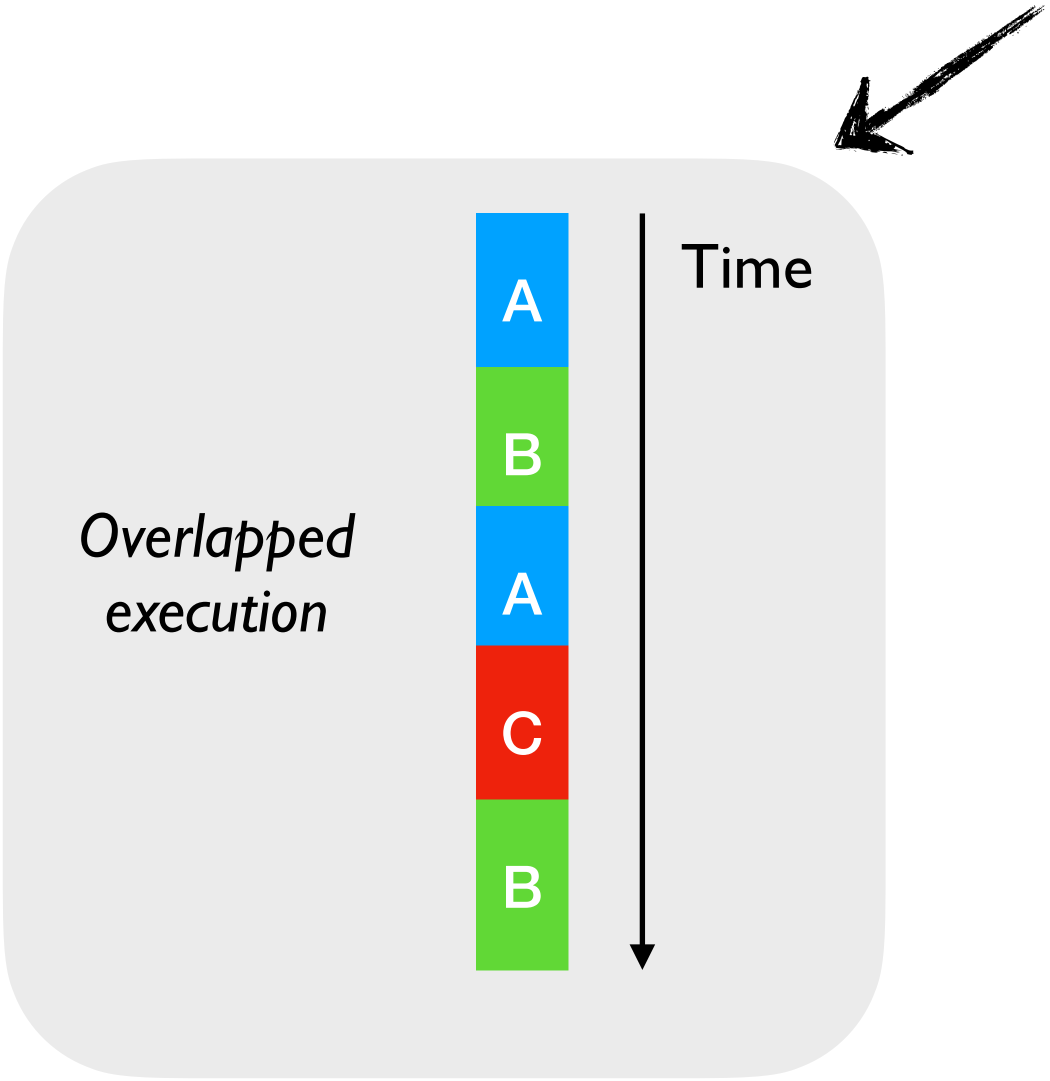

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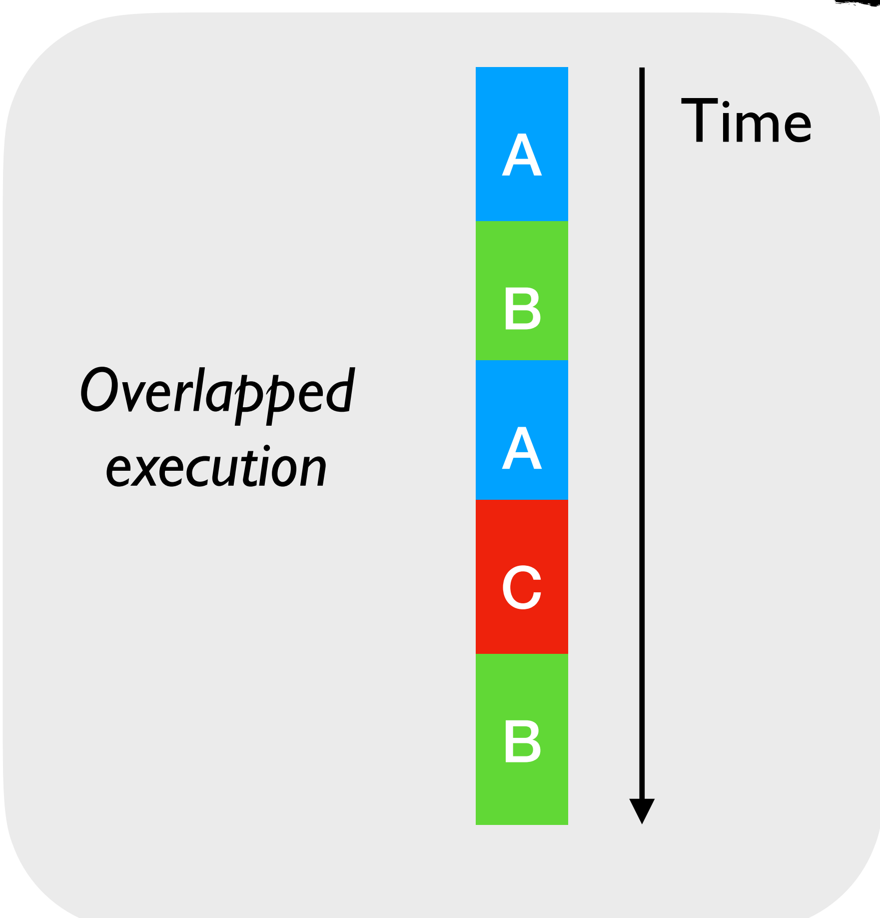

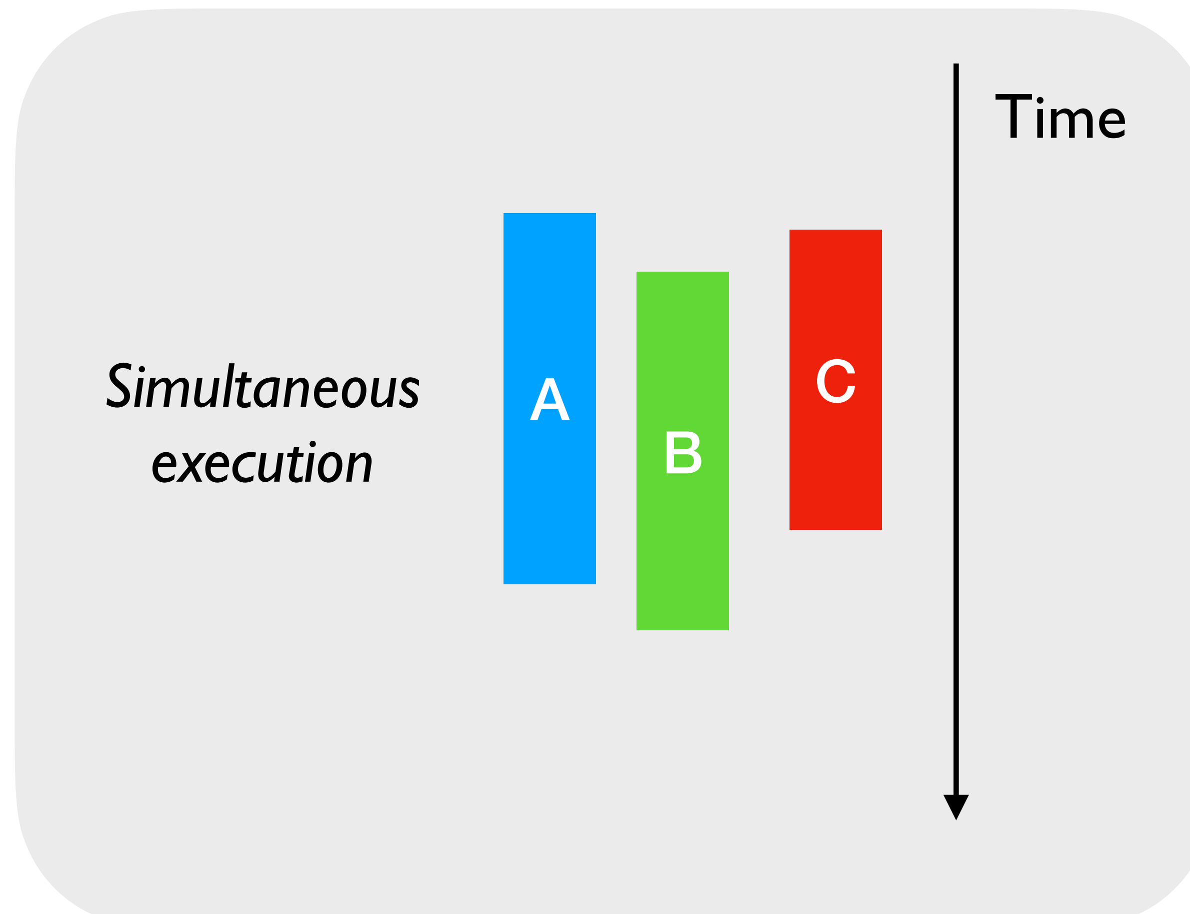

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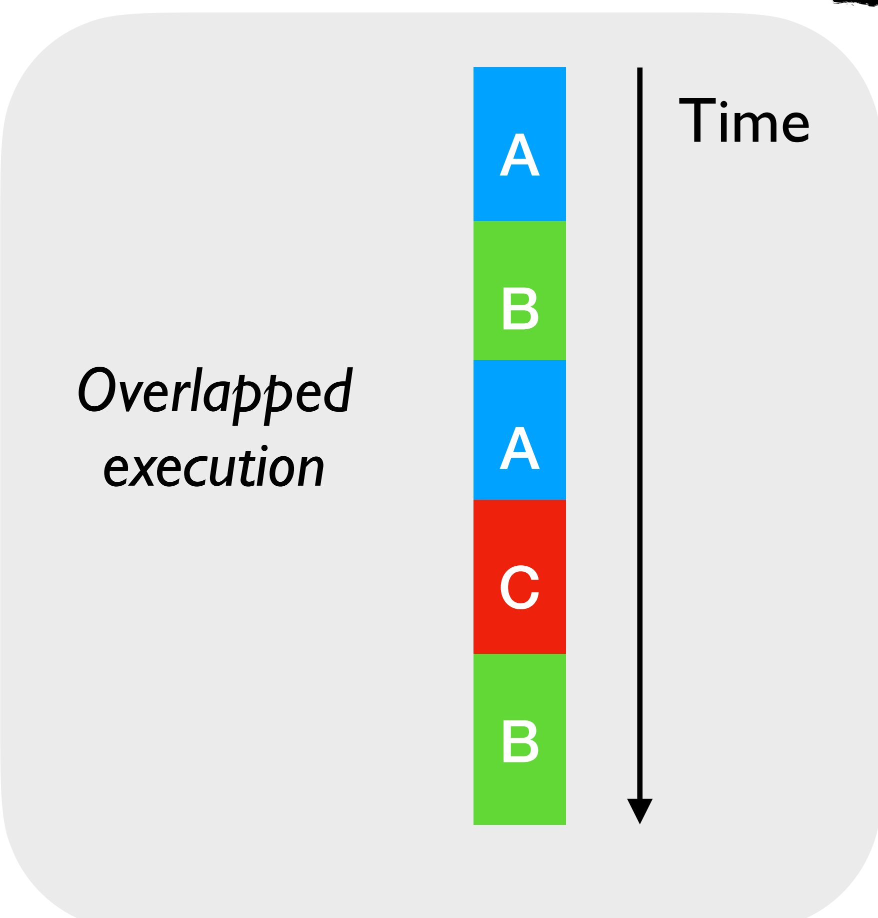

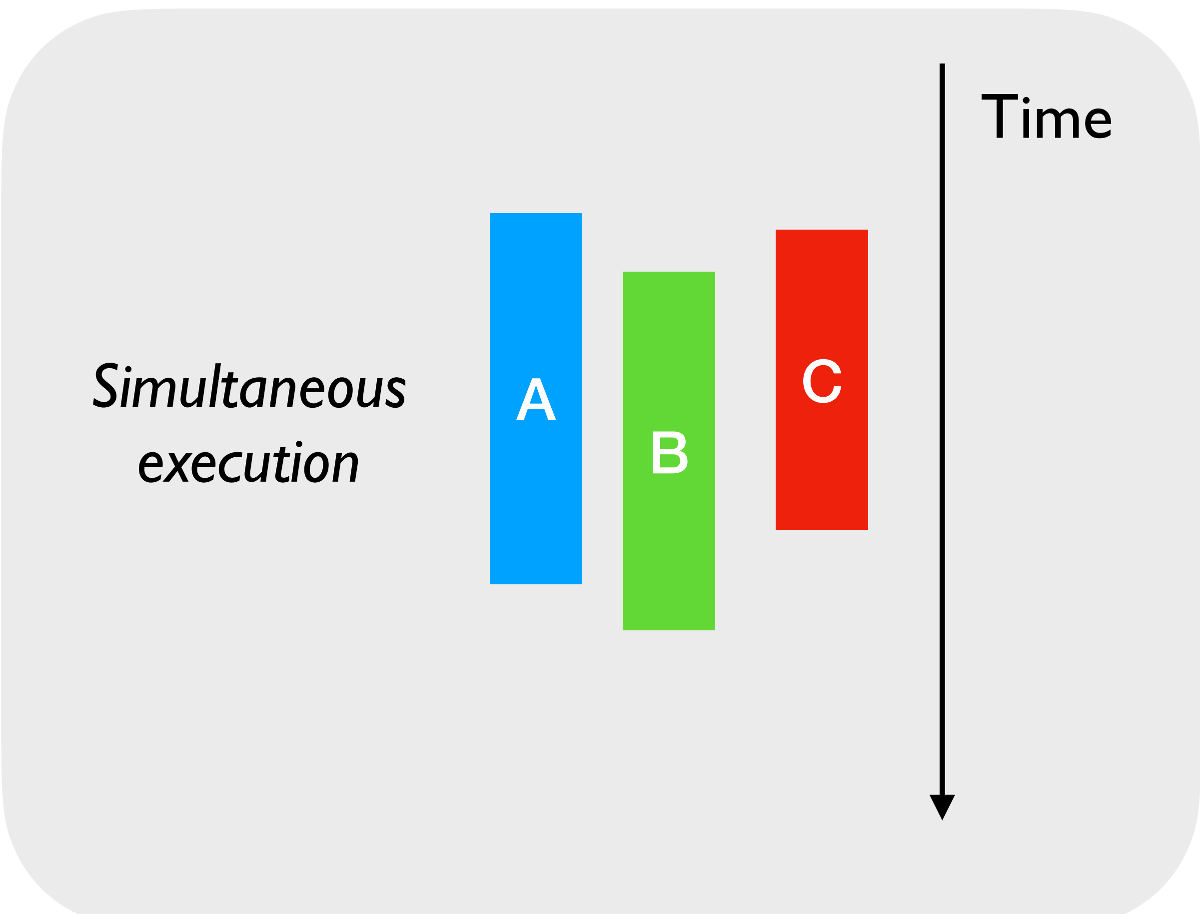

Effect Handlers

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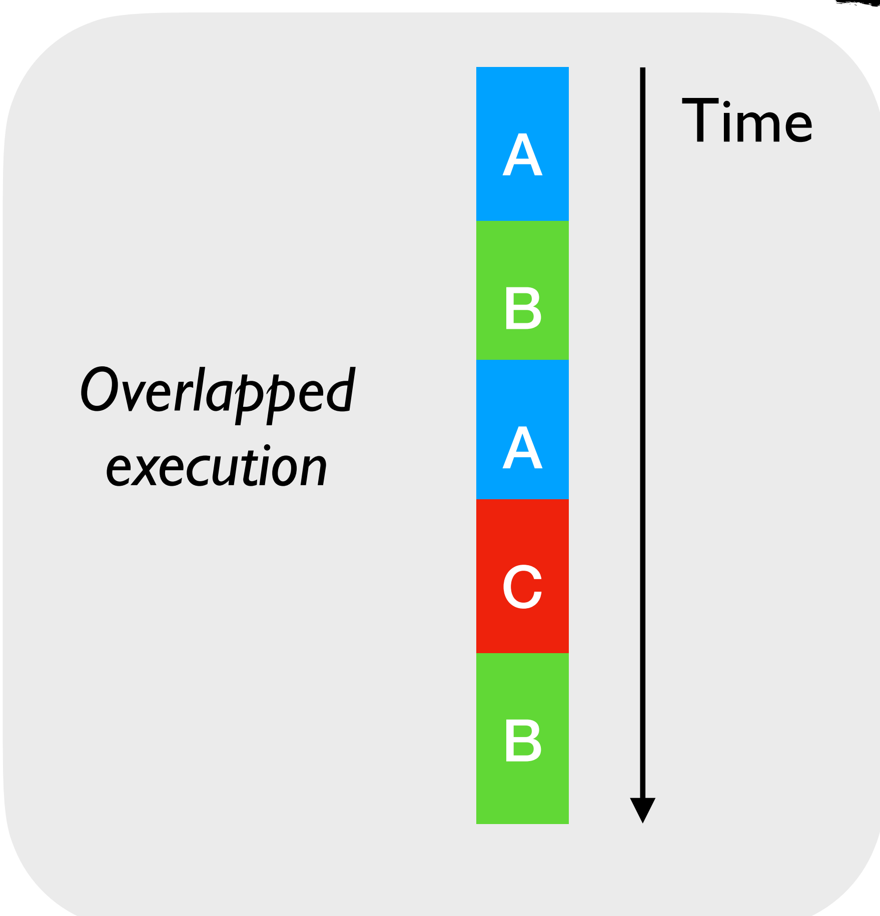

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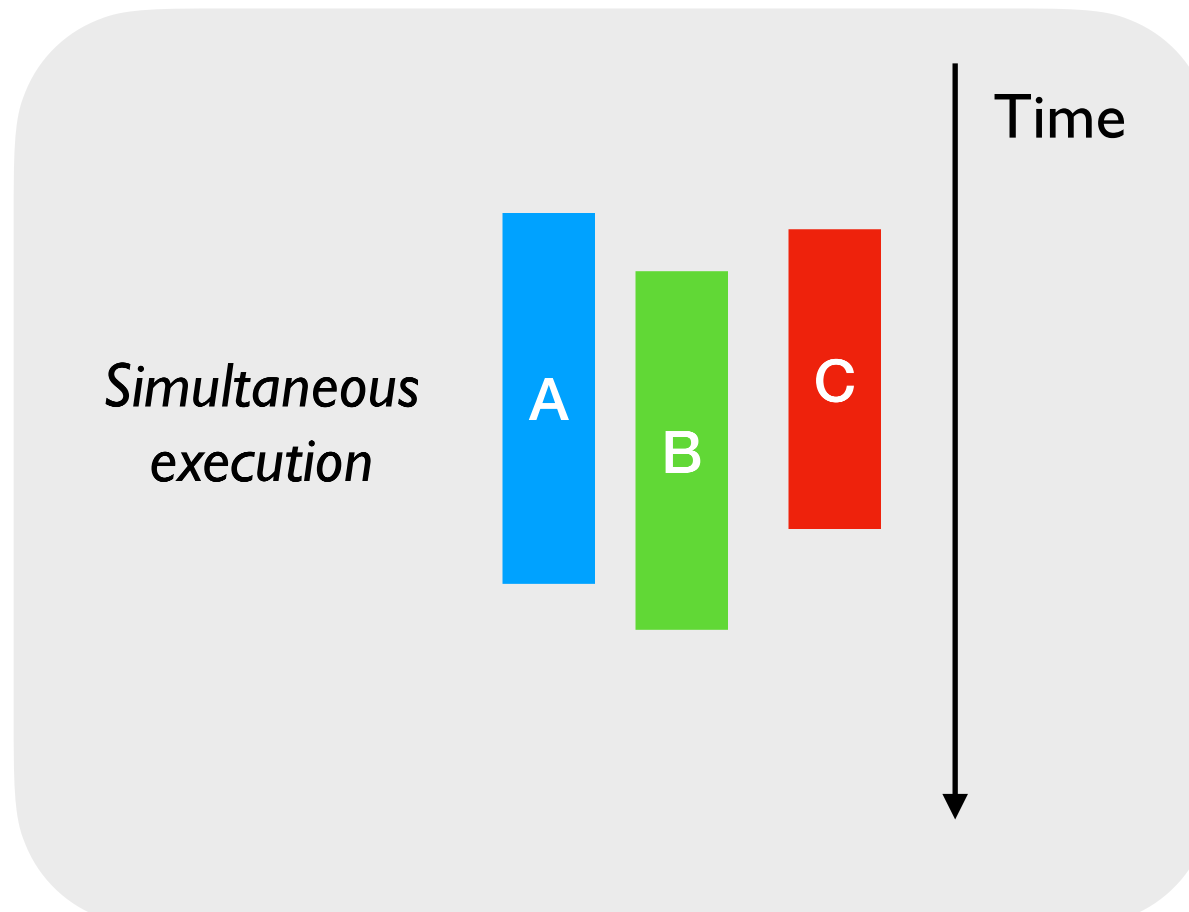

Domains

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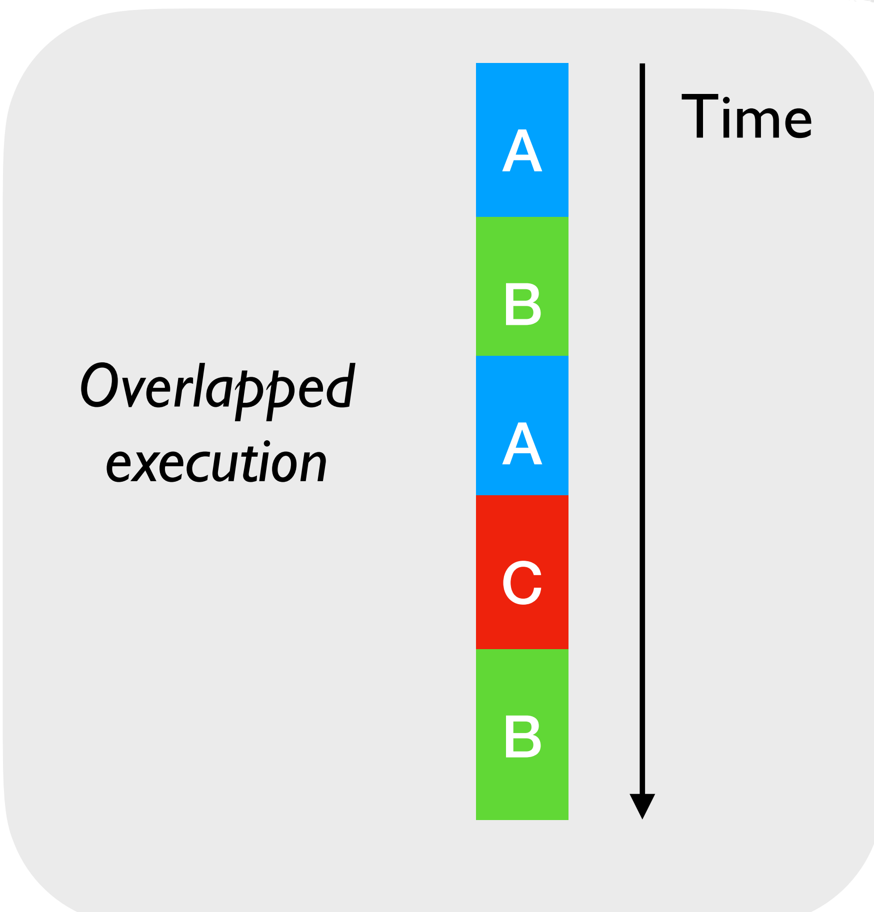

Effect Handlers

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Concurrency is not parallelism

Parallelism is a performance hack

whereas

concurrency is a program structuring mechanism

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- OS threads give you parallelism and concurrency
  - ✦ Too heavy weight for concurrent programming
  - ✦ Http server with 1 OS thread per request is a terrible idea

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- Programming languages provide concurrent programming mechanisms as *primitives*
  - ✦ async/await, generators, coroutines, etc.
- Often include different primitives for concurrent programming
  - ✦ JavaScript has async/await, generators, promises, and callbacks!!

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Should we add lightweight threads to OCaml?

Effect Handlers

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- A mechanism for programming with *user-defined effects*
- Modular basis of non-local control-flow mechanisms
  - ✦ Exceptions, generators, lightweight threads, promises, asynchronous IO, coroutines
- Effect handlers ~= *first-class, restartable exceptions*
  - ✦ Similar to exceptions, *performing* an effect separate from *handling* it

An example

```
effect E : string

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

let main () =
  try
    comp ()
  with effect E k ->
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resume suspended computation

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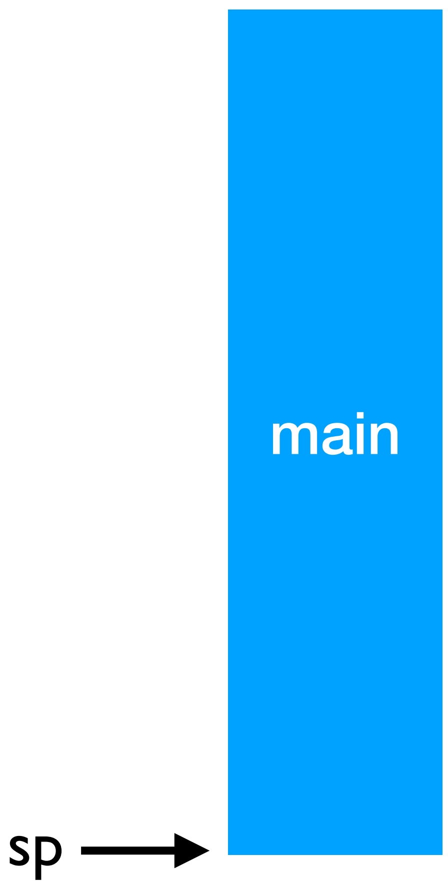

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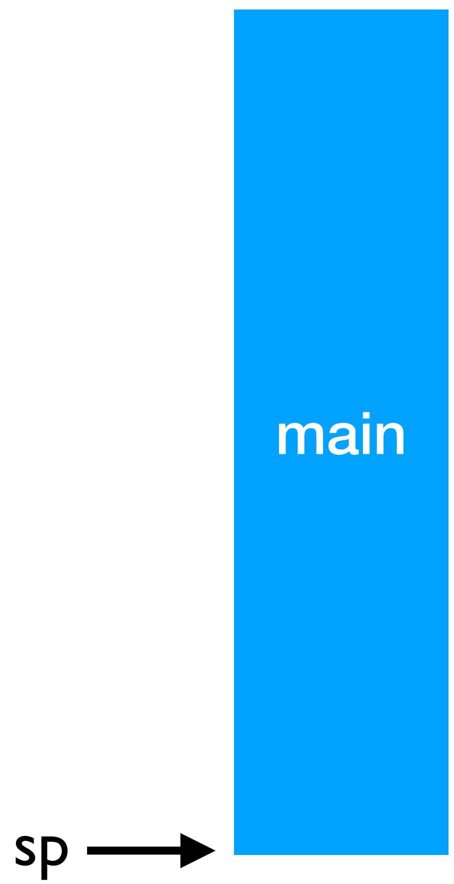

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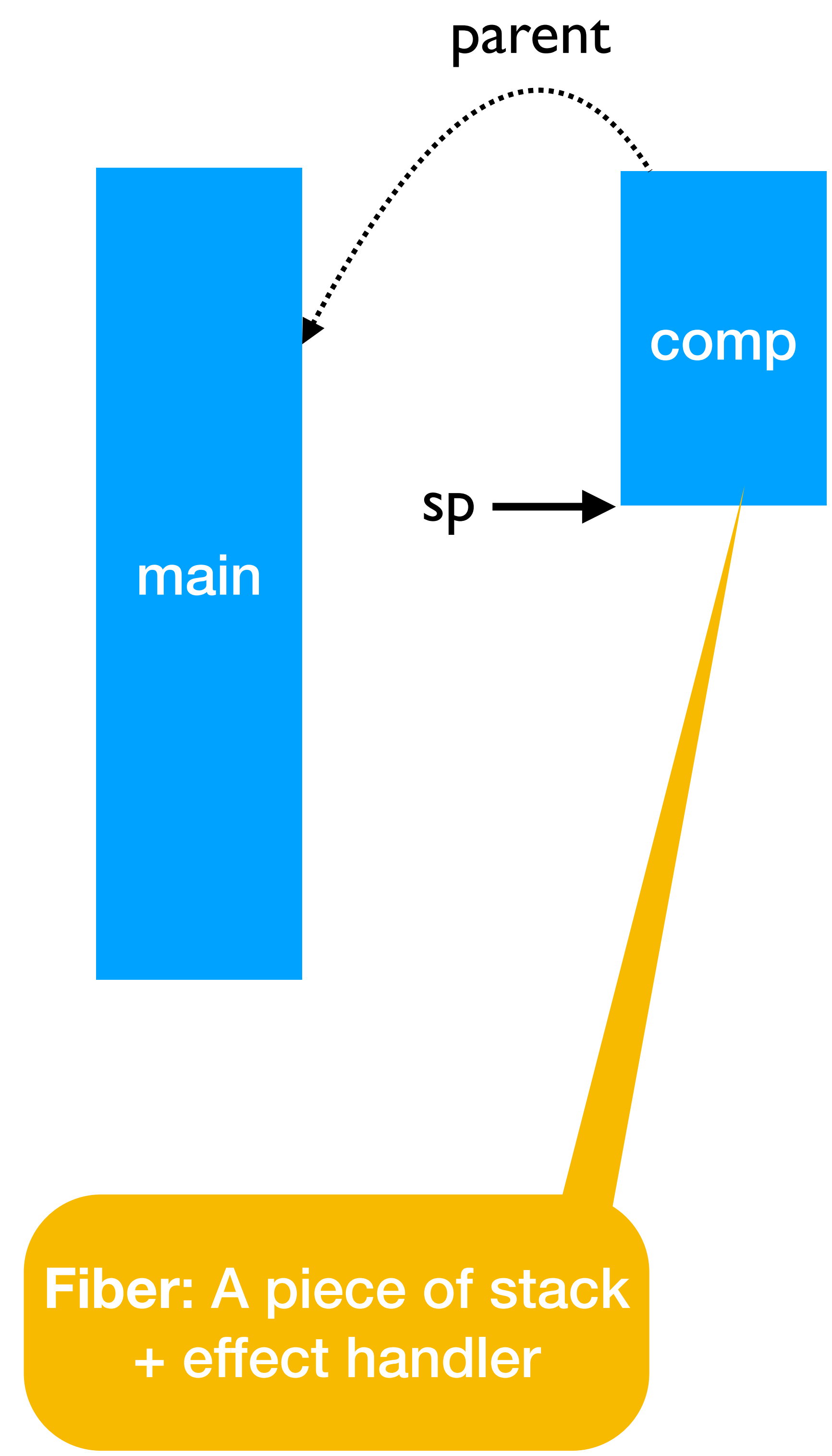

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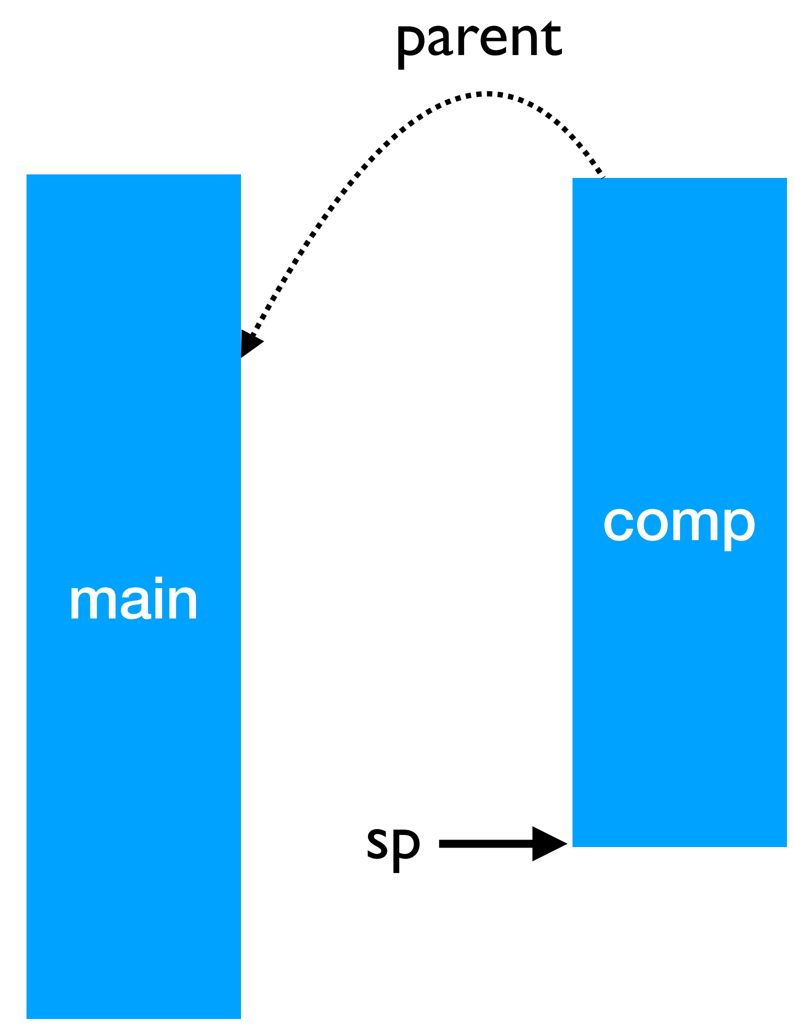

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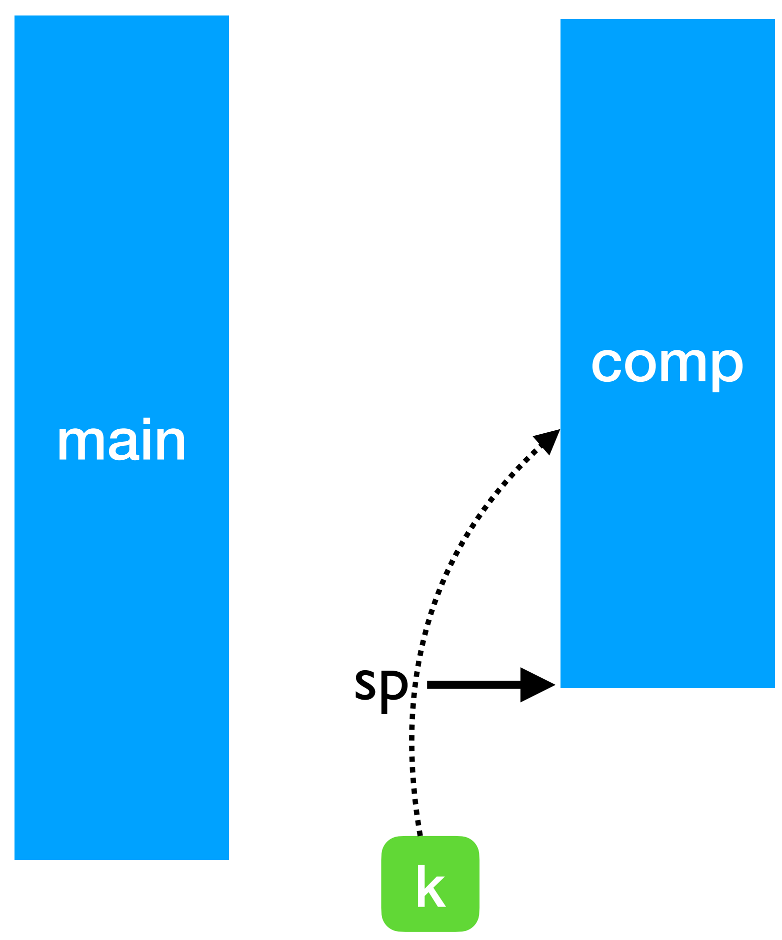

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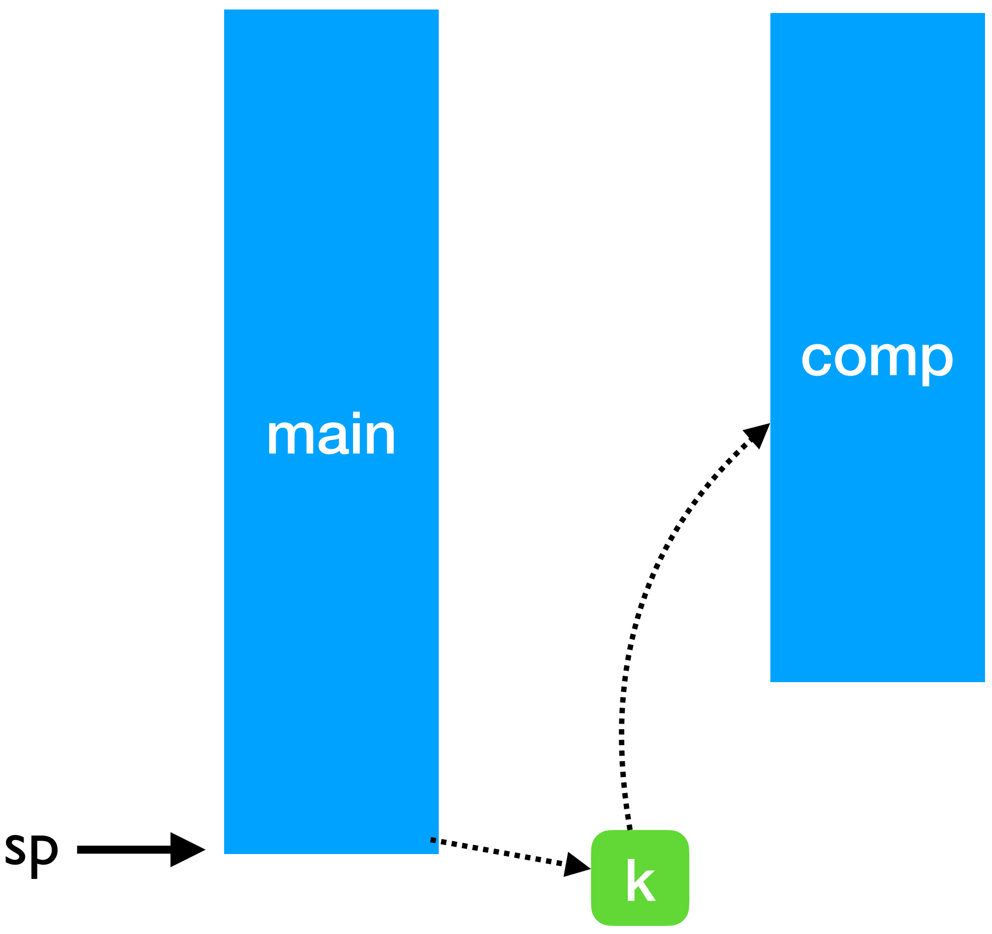

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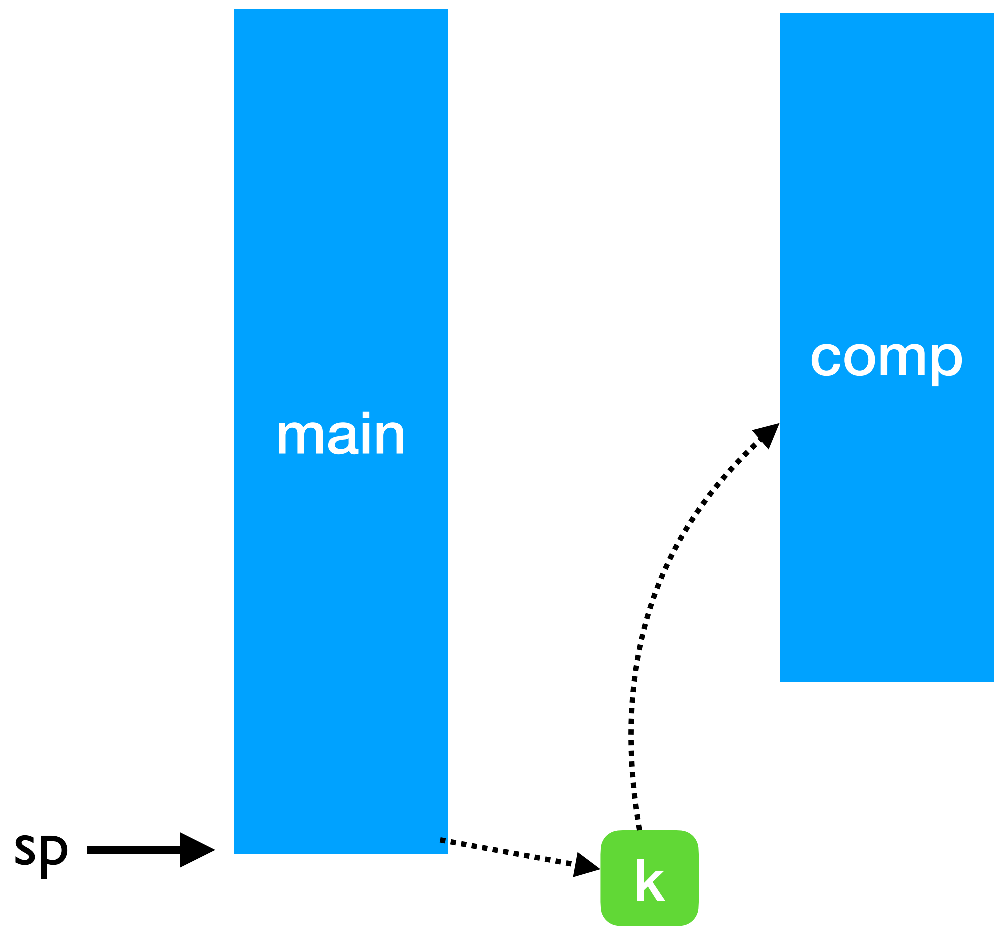
pc → (at `print_string "1 ";`)



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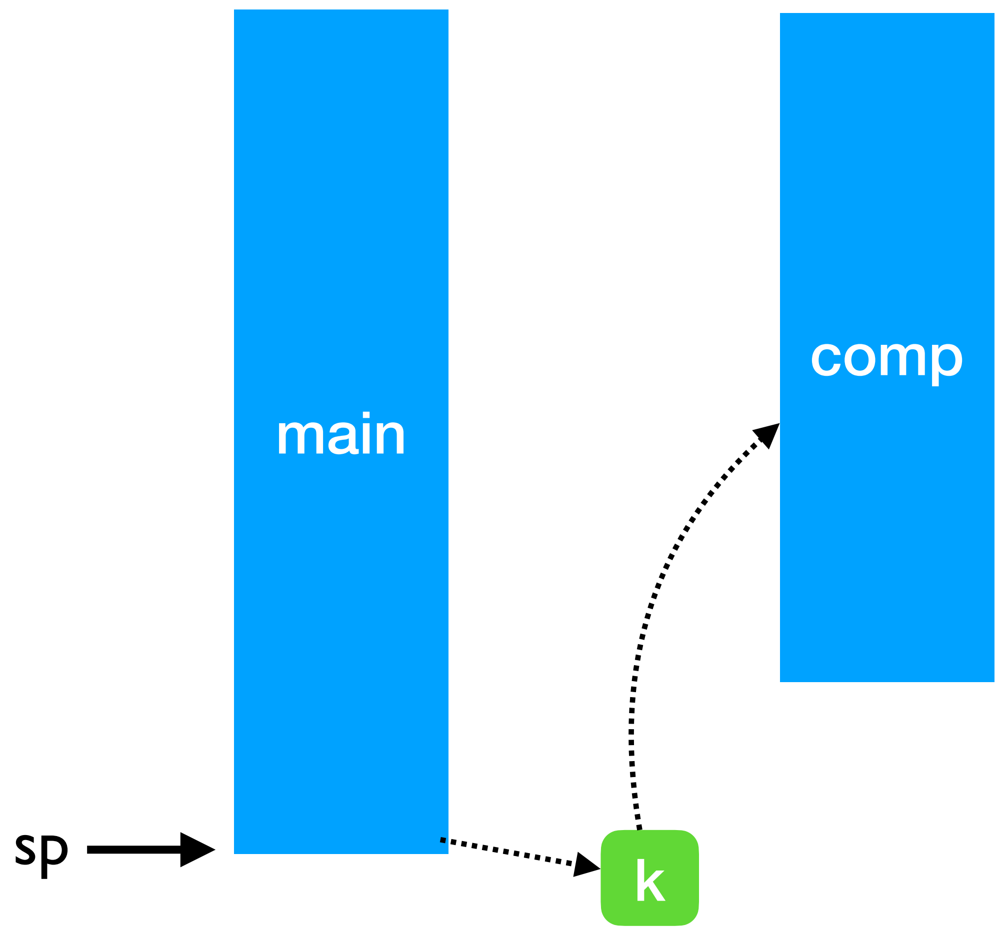

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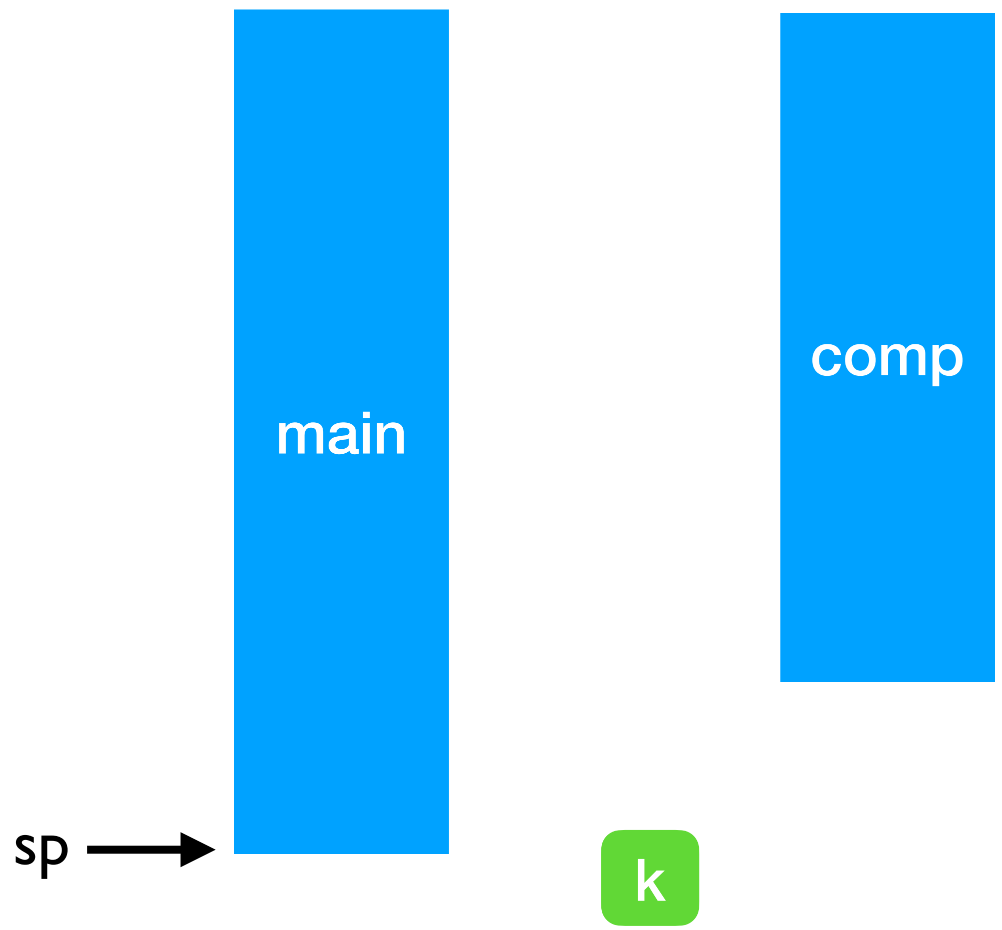

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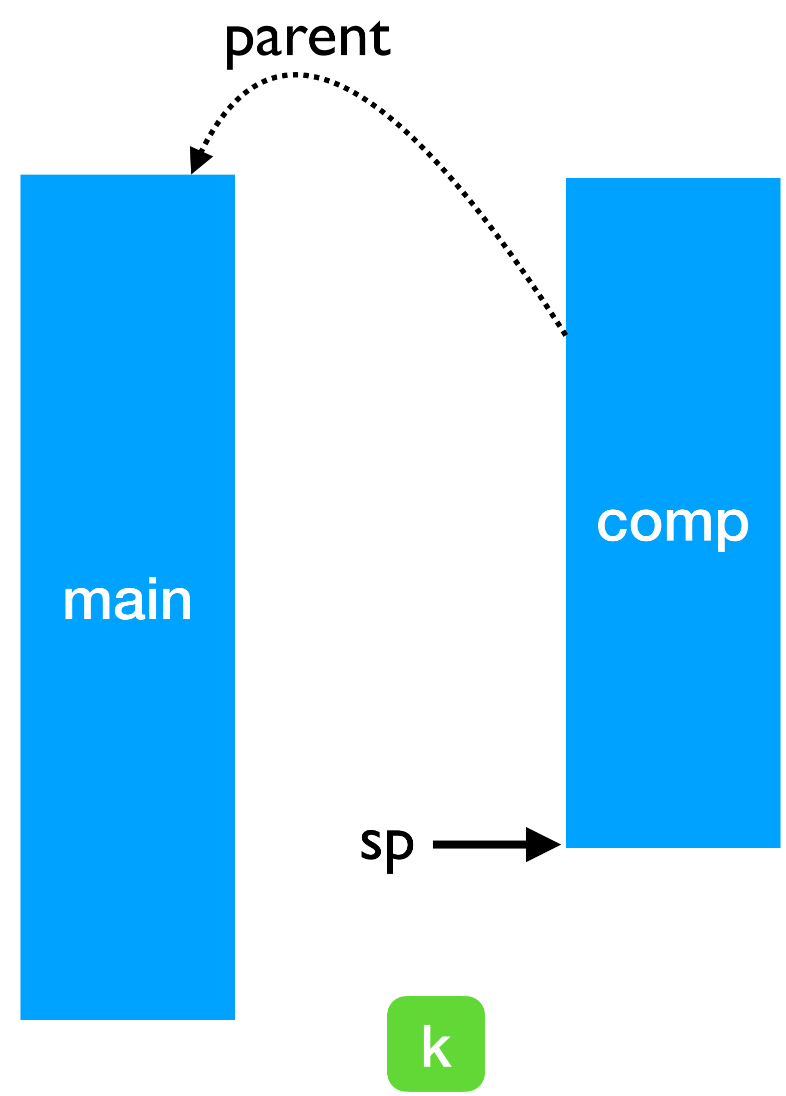

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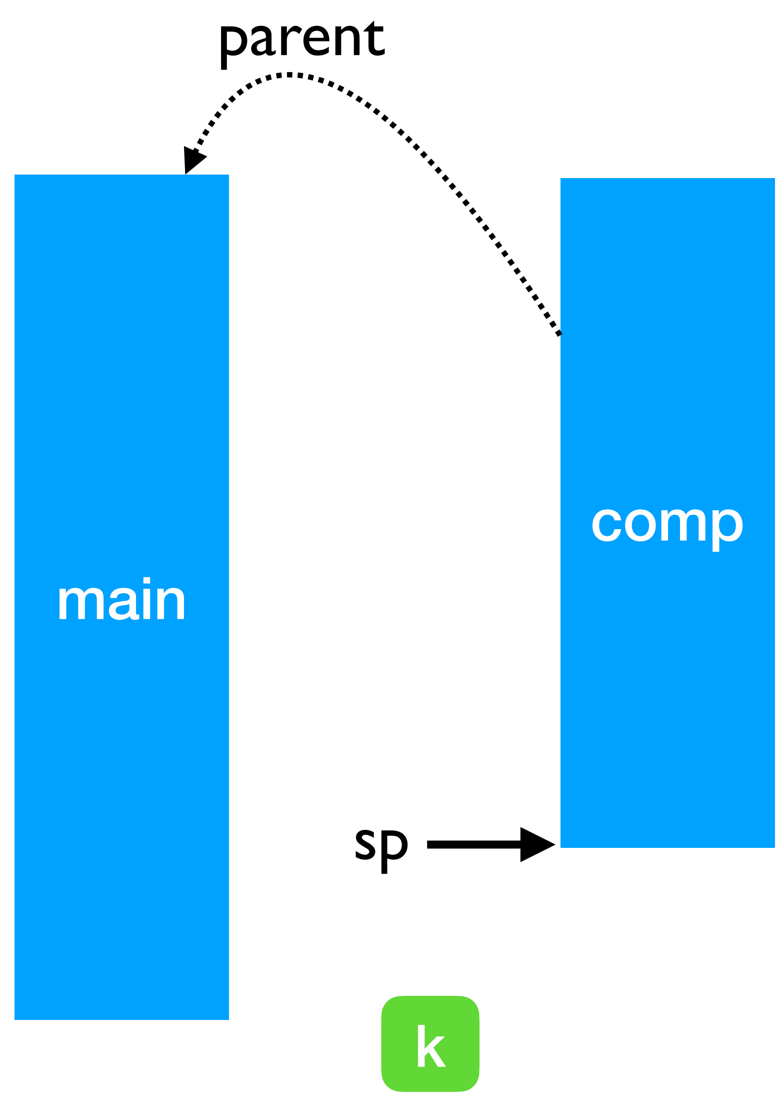

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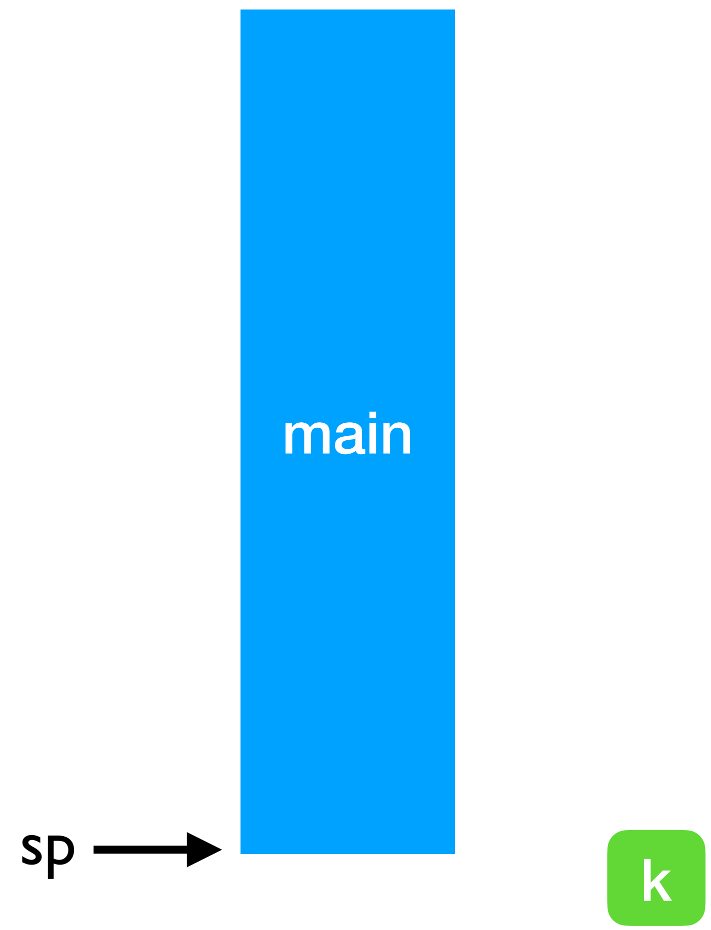

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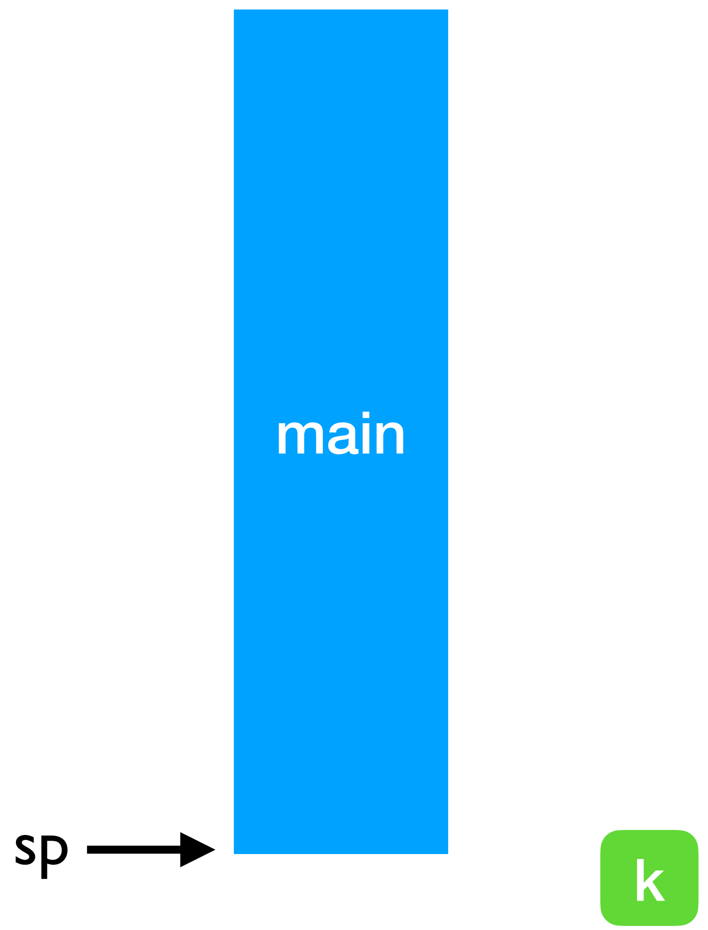

0 1 2 3 4

Handlers can be nested

```
effect A : unit
effect B : unit

let baz () =
  perform A

let bar () =
  try
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  with effect B k ->
    continue k ()

let foo () =
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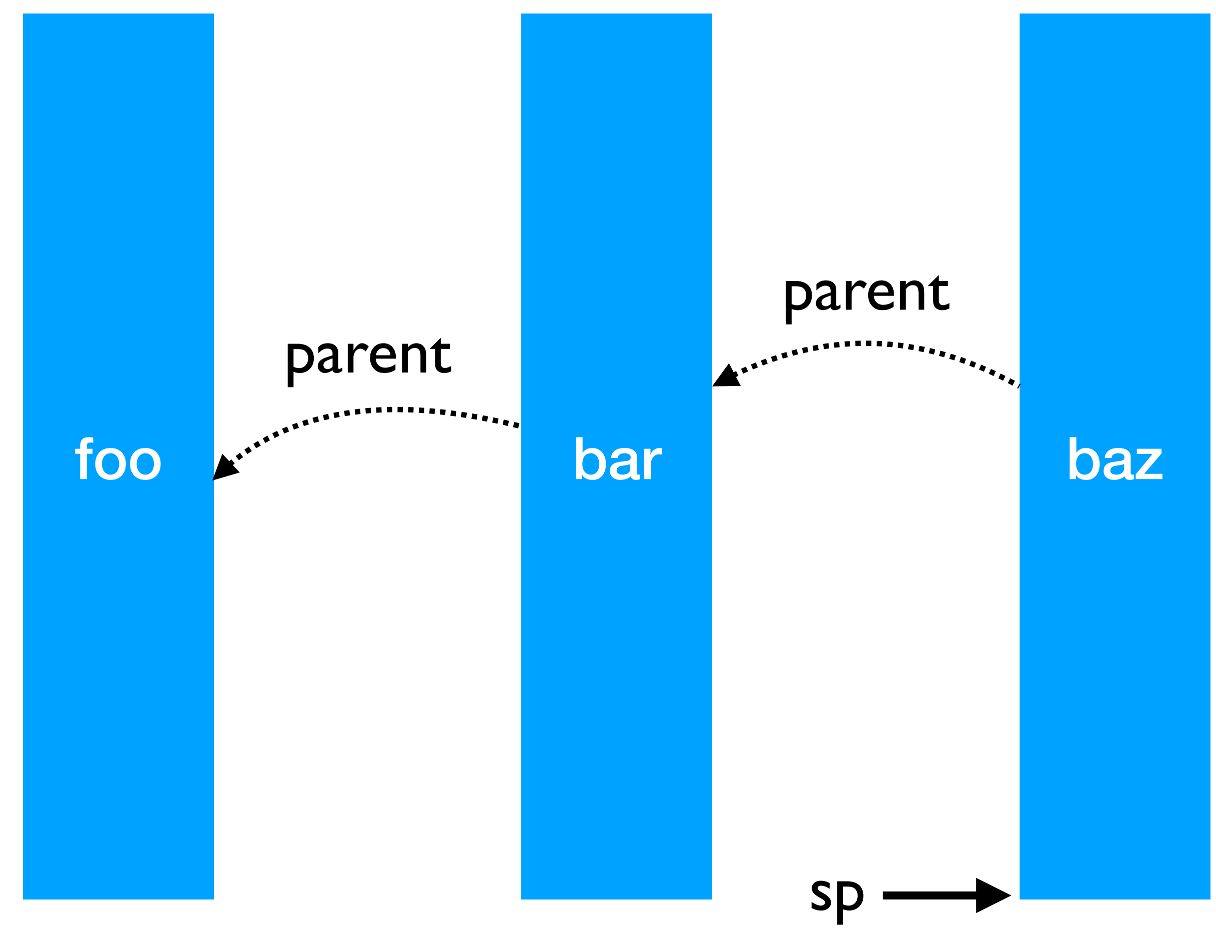
```

pc → perform A



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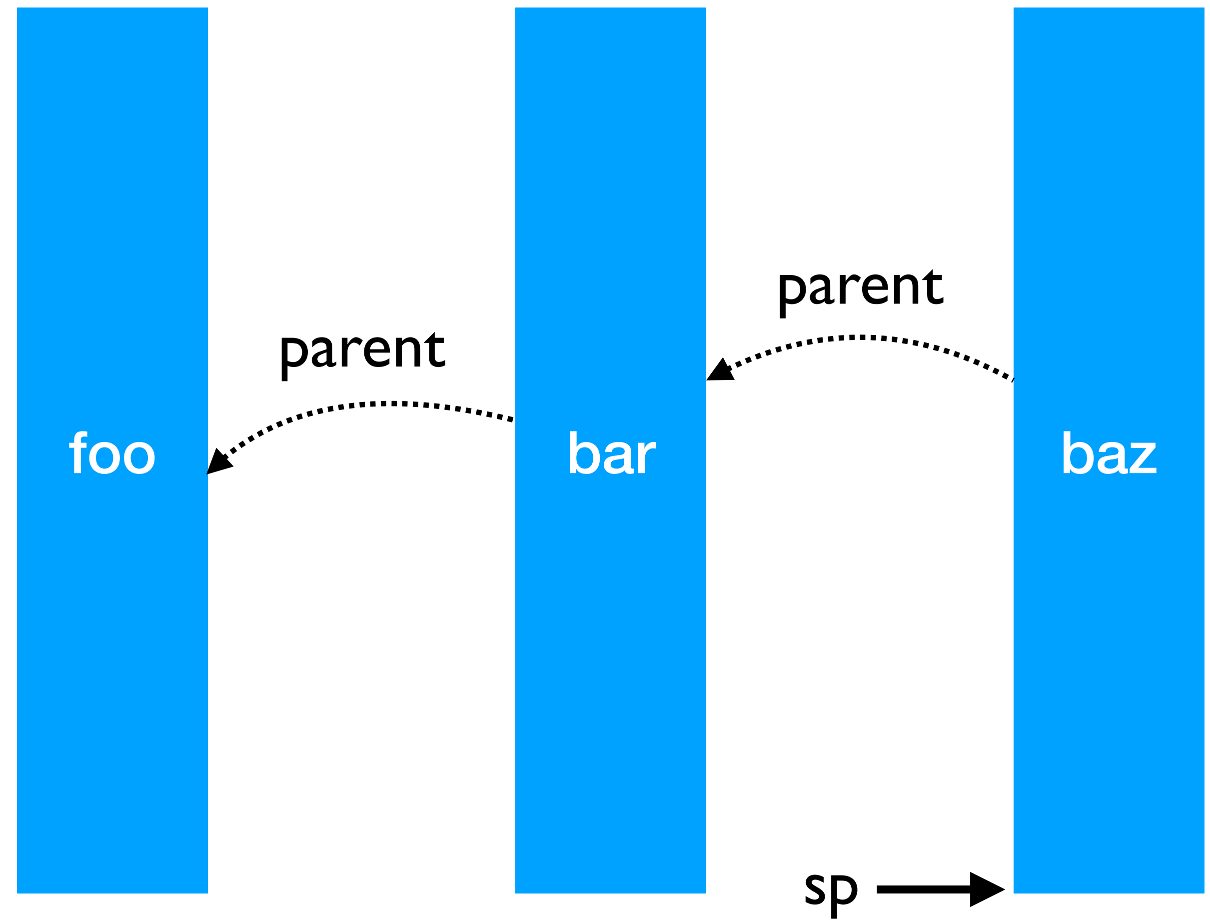

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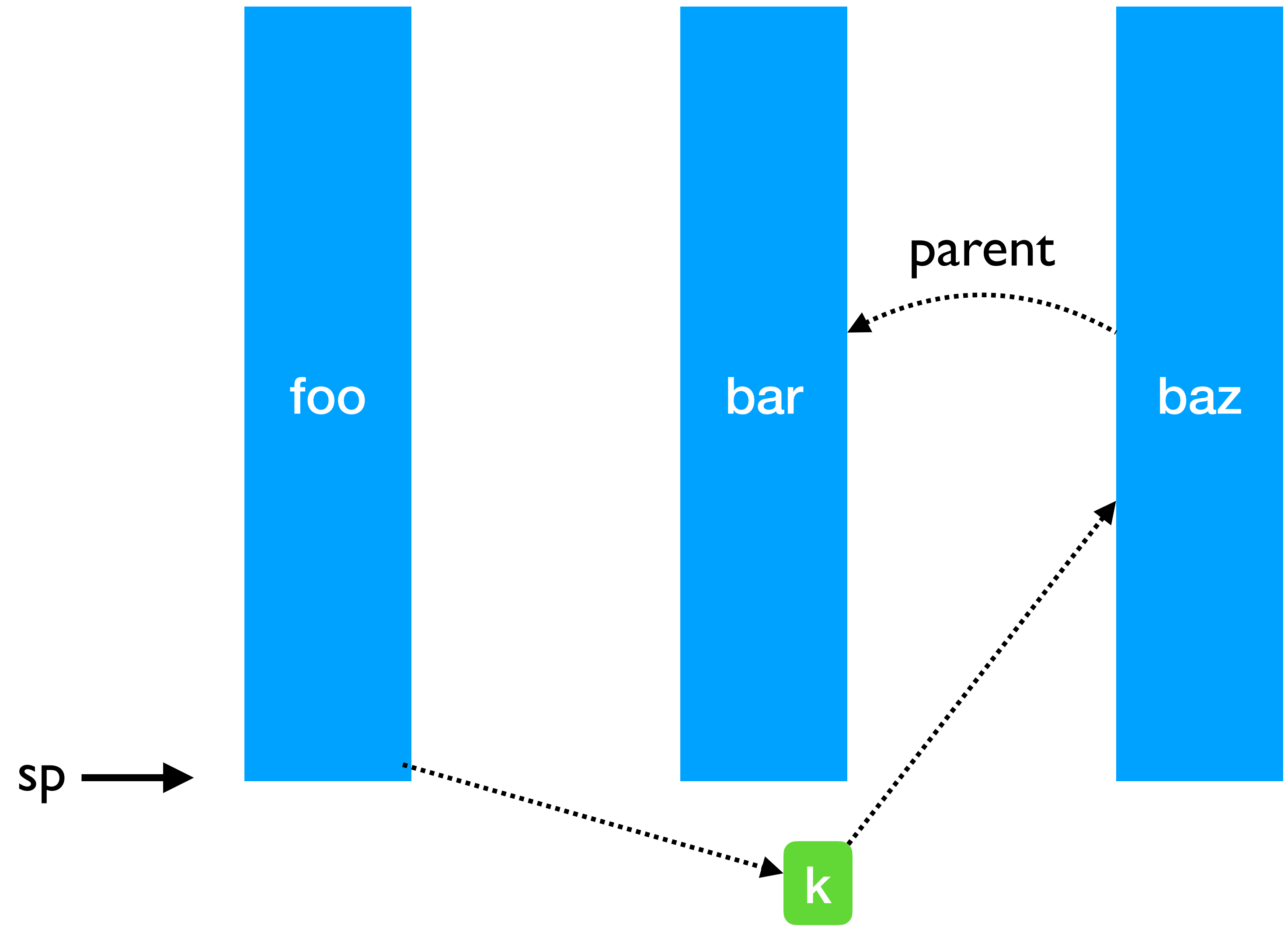

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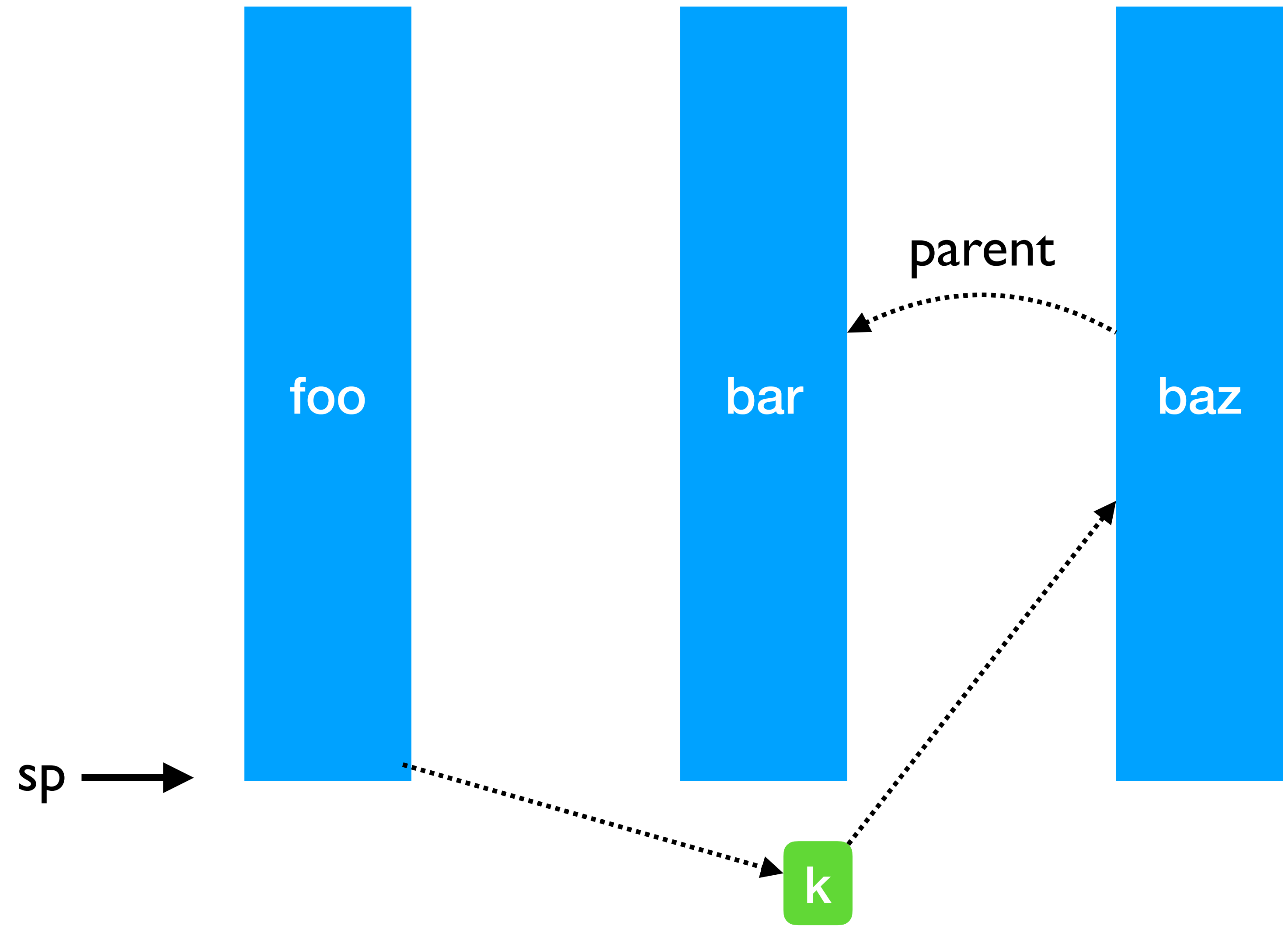

- Linear search through handlers
  - *Handler stacks shallow in practice*

Lightweight Threading

```
effect Fork  : (unit -> unit) -> unit
effect Yield : unit
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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
   in
   spawn main
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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
```

Lightweight threading

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```
1.a
2.a
1.b
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```

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run main
```

- Direct-style (no monads)
- User-code need not be aware of effects

```
1.a
2.a
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```
function* generator(i) {
  yield i;
  yield i + 10;
}
const gen = generator(10);

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

console.log(gen.next().value);
// expected output: 20
```

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```

- Can be *derived automatically* from any iterator using effect handlers

Generators: effect handlers

```
module MkGen (S :sig
  type 'a t
  val iter : ('a -> unit) -> 'a t -> unit
end) : sig
  val gen : 'a S.t -> (unit -> 'a option)
end = struct
```

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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 ()
end
```

Generators: List

```
module L = MkGen (struct
  type 'a t = 'a list
  let iter = List.iter
end)
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module L = MkGen (struct
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```

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

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

module T = MkGen(struct
  type 'a t = 'a tree
  let iter = iter
end)
```

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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)
         in Node (t,n,t)
```

Generators: Tree

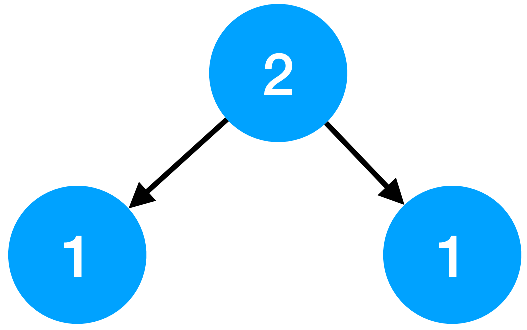
```
type 'a tree =
| Leaf
| Node of 'a tree * 'a * 'a tree

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

module T = MkGen(struct
  type 'a t = 'a tree
  let iter = iter
end)
```

```
(* Make a complete binary tree of
   depth [n] using [O(n)] space *)
let rec make = function
  | 0 -> Leaf
  | n -> let t = make (n-1)
         in Node (t,n,t)

let t = make 2
```



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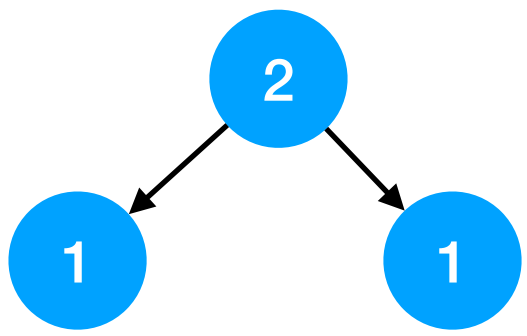
let next = T.gen t
next() (* Some 1 *)
next() (* Some 2 *)
next() (* Some 1 *)
next() (* None *)
```



Retrofitting Challenges

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- Millions of lines of legacy code
  - Written without *non-local control-flow* in mind
  - Cost of refactoring sequential code itself is *prohibitive*

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Backwards compatibility
before
fancy new features

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let copy ic oc =
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    output_string oc (l ^ "\n");
    loop ()
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We would like to make this code transparently asynchronous

Asynchronous IO

```
effect In_line : in_channel -> string
effect Out_str : out_channel * string -> unit
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let run_aio f = match f () with
| v -> v
| effect (In_line chan) k ->
    register_async_input_line chan k;
    run_next ()
| effect (Out_str (chan, s)) k ->
    register_async_output_string chan s k;
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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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- OCaml functions return *exactly once* with *value* or *exception*
  - ✦ Defensive programming already guards against exceptional return cases
- With effect handlers, functions may return *at-most once* if continuation not resumed
  - ✦ This breaks resource-safe legacy code

Linearity

```
effect E : unit
let foo () = perform E
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We *assume* that captured continuations are resumed *exactly once* either using `continue` or `discontinue`

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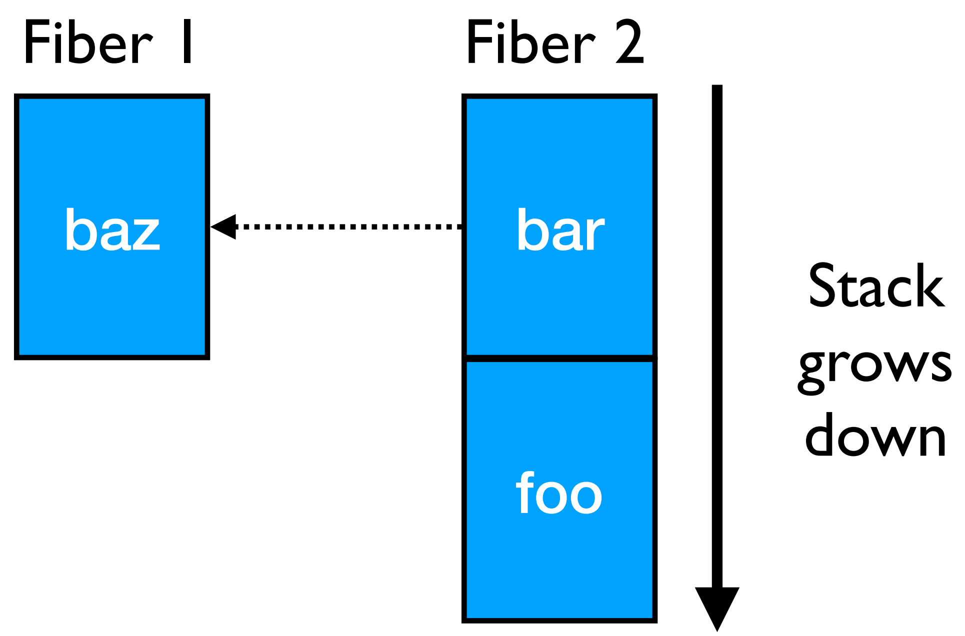

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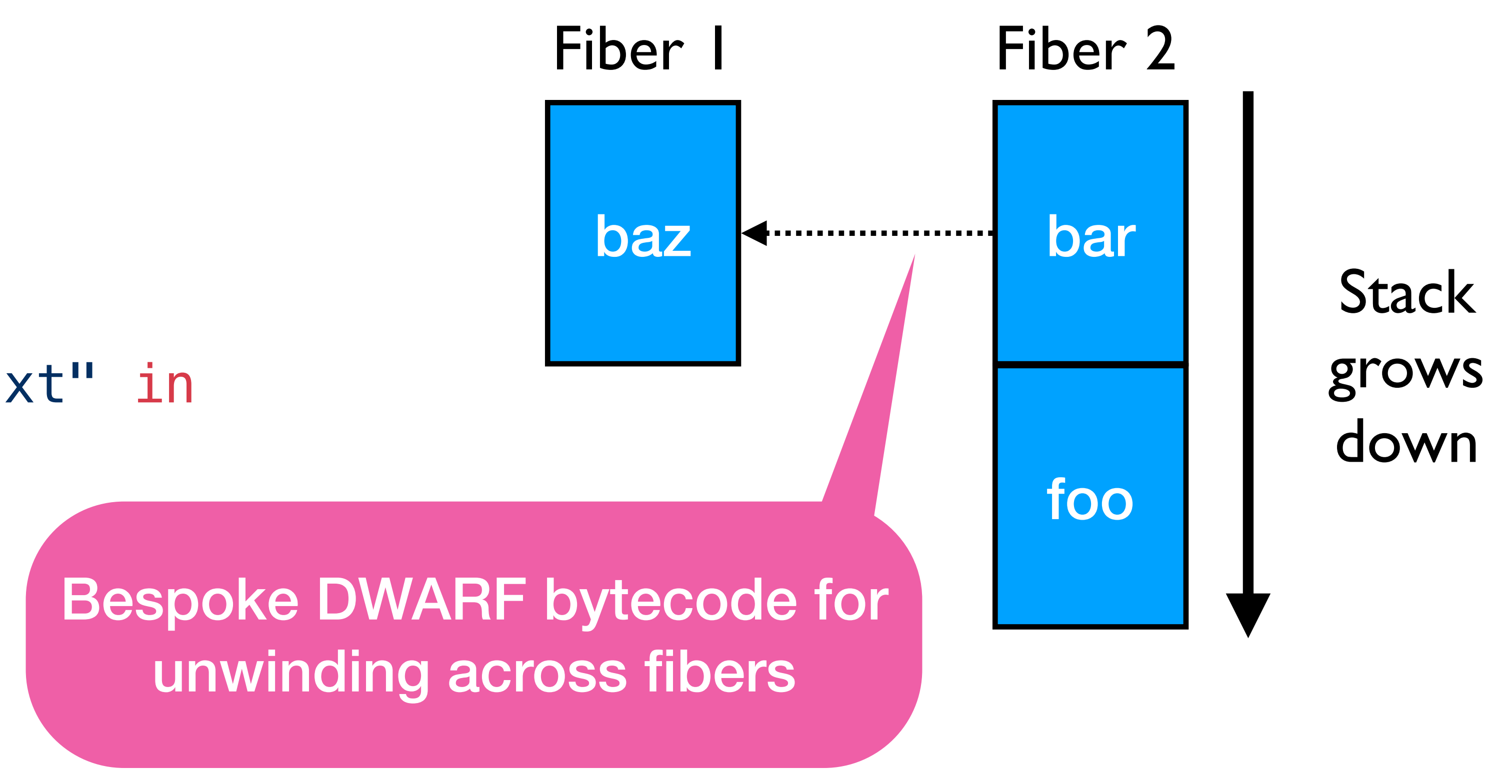

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```
(lldb) bt
* thread #1, name = 'a.out', stop reason = …
  * #0: 0x58b208 caml_perform
    #1: 0x56aa5d camlTest__foo_83 at test.ml:4
    #2: 0x56aae2 camlTest__bar_85 at test.ml:9
    #3: 0x56a9fc camlTest__fun_199 at test.ml:14
    #4: 0x58b322 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 is still in the works

Dynamic Semantics

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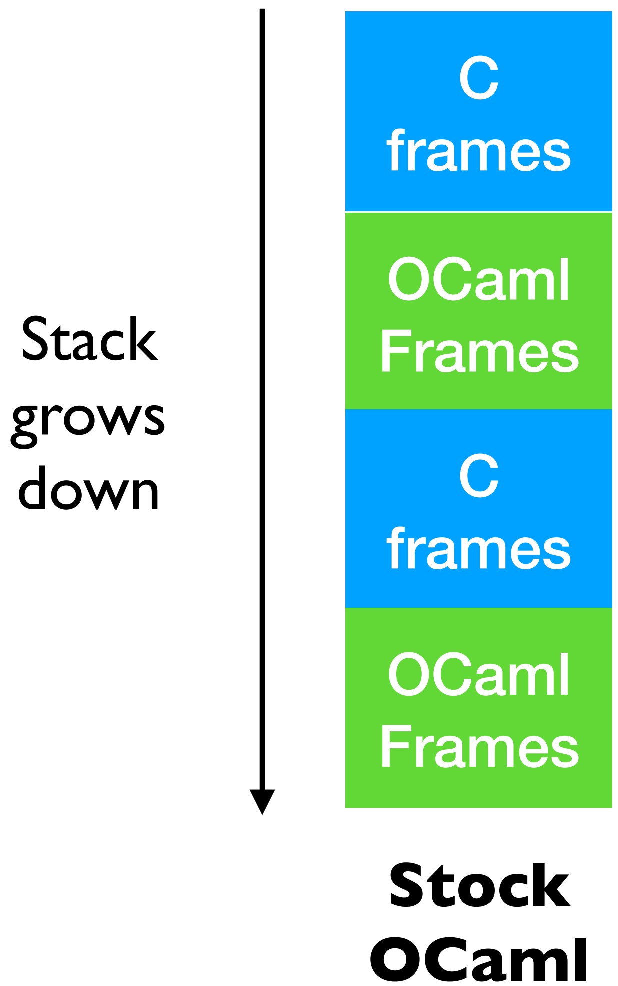

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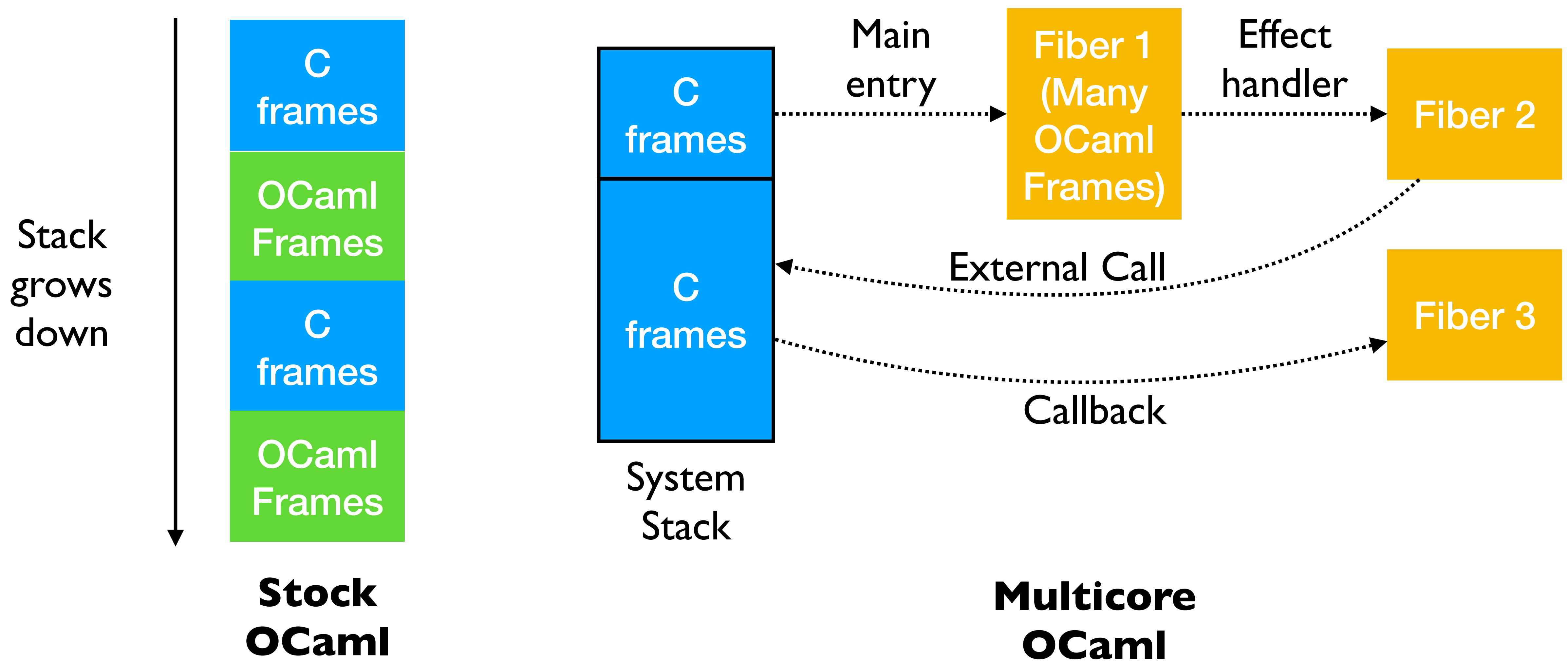
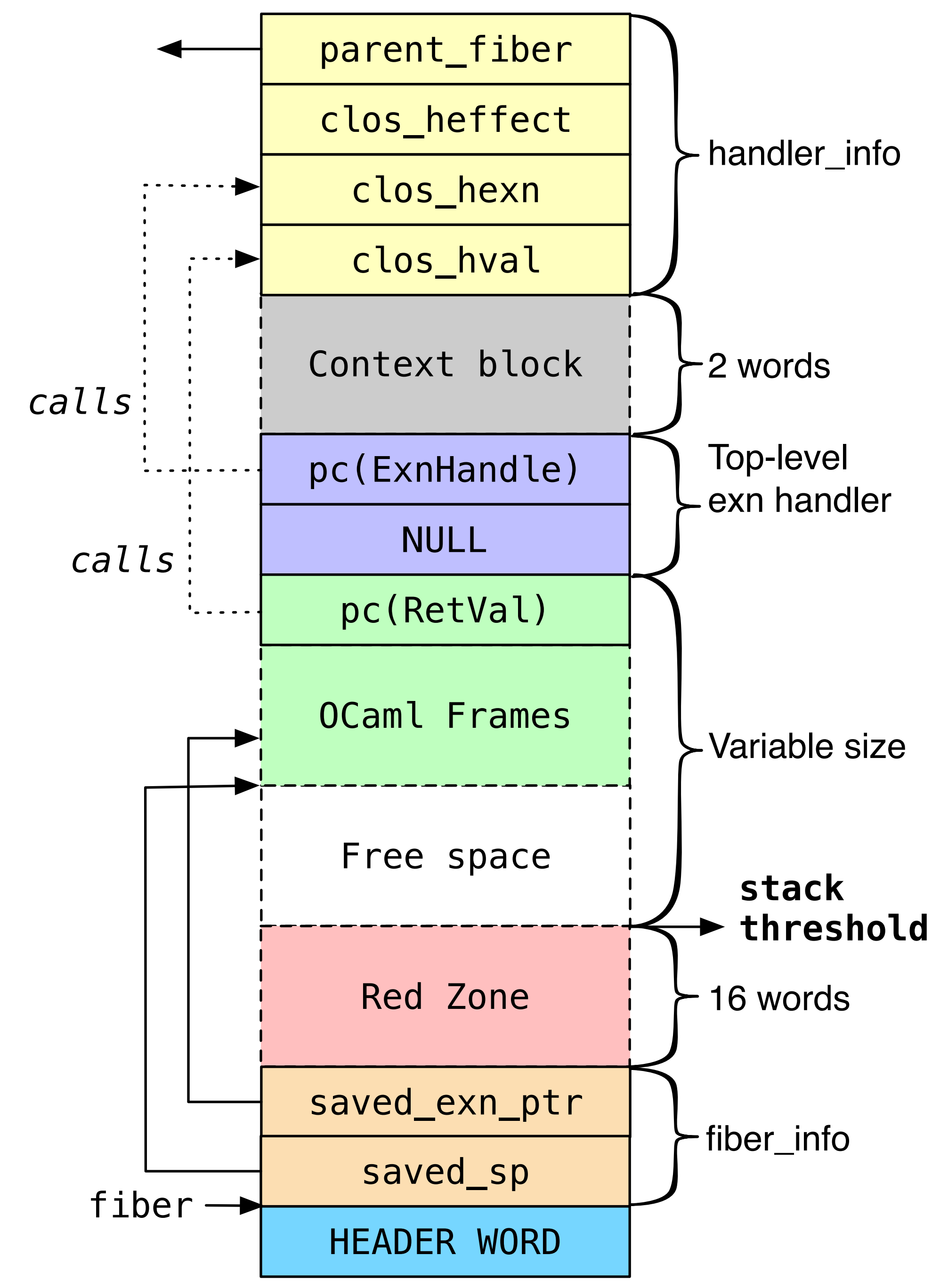


Dynamic Semantics

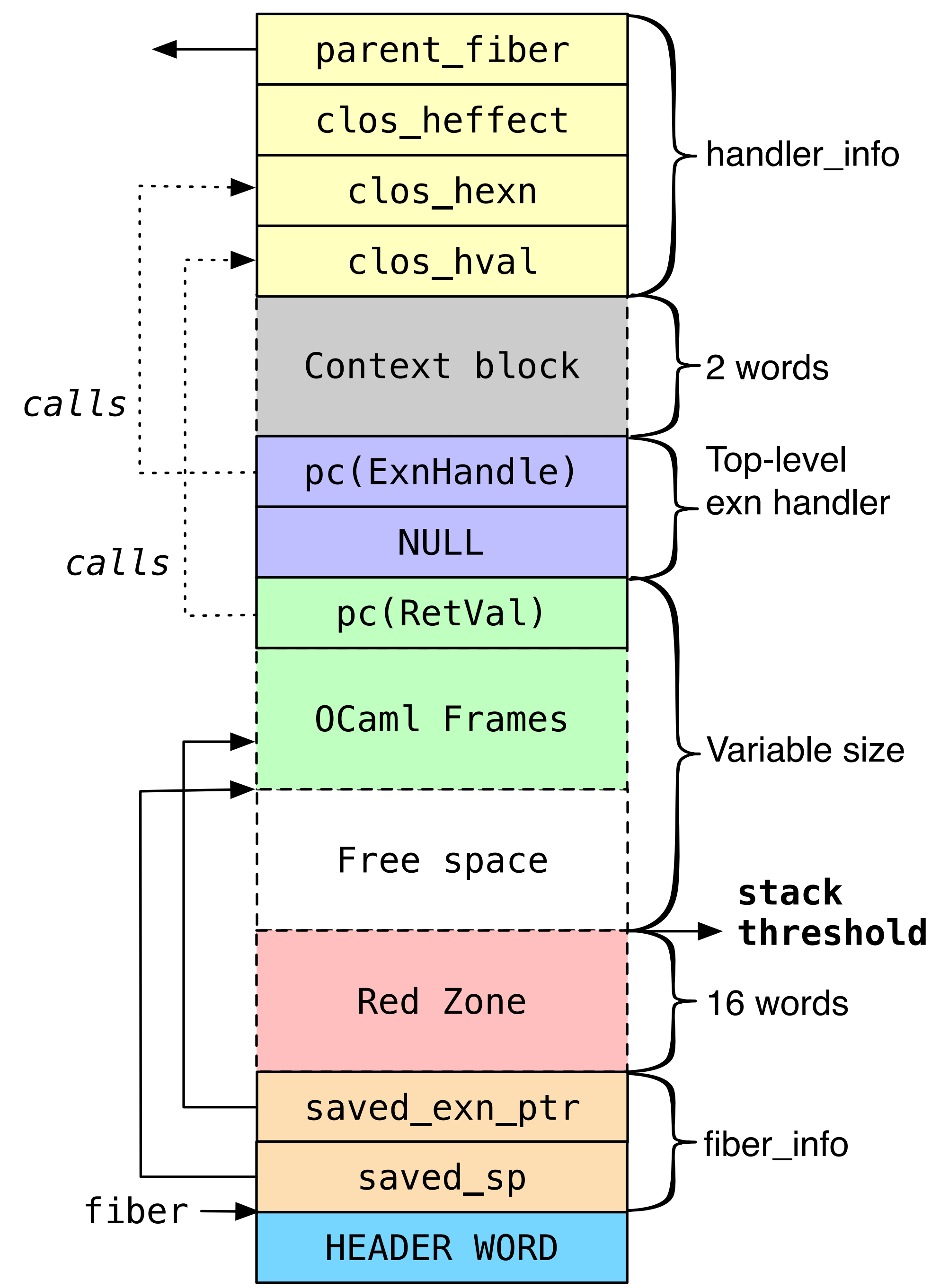
Deep dive

Fiber Layout



Fiber Layout

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



No effects micro benchmarks

	exnval	exnraise	extcall	callback	ack	fib	motzkin	sudan	tak
Time	+0.0	-1.9	+17	+65	+5.3	+2.2	+10	+0.0	+4.2
Instr	+0.0	+0.0	+10	+72	+16	+24	+16	+14	+17

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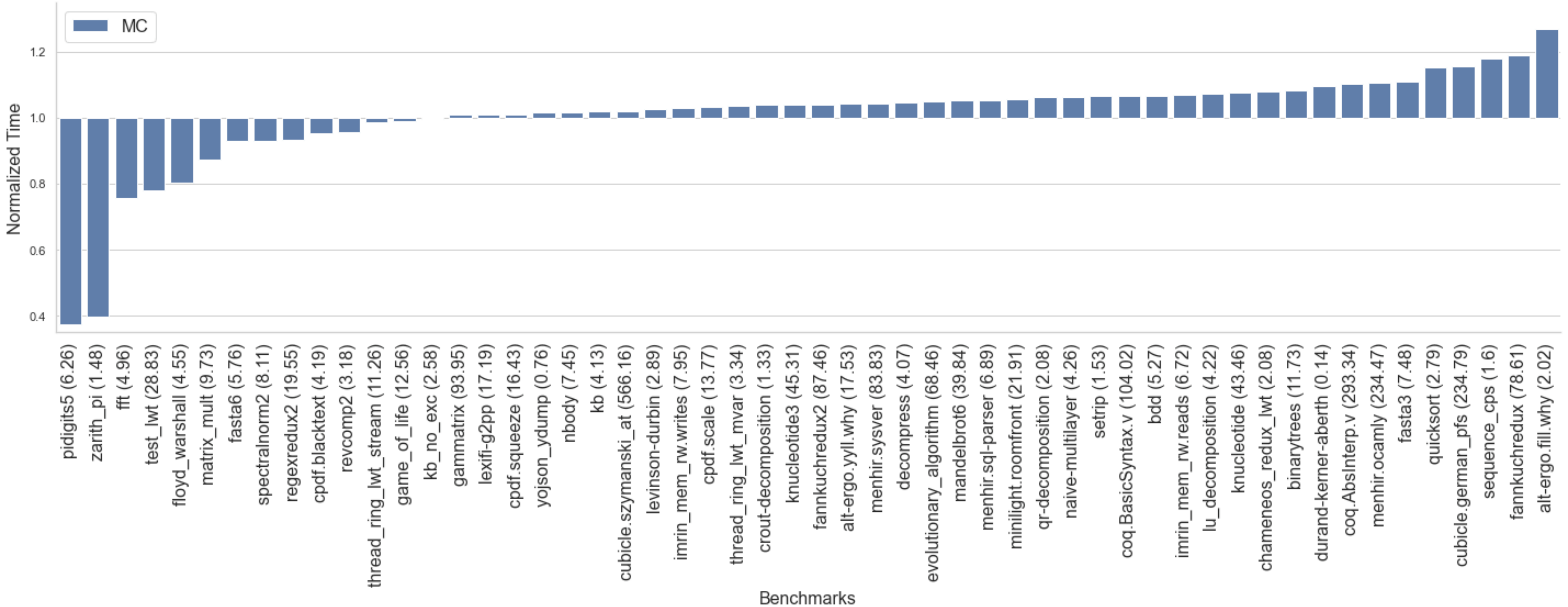

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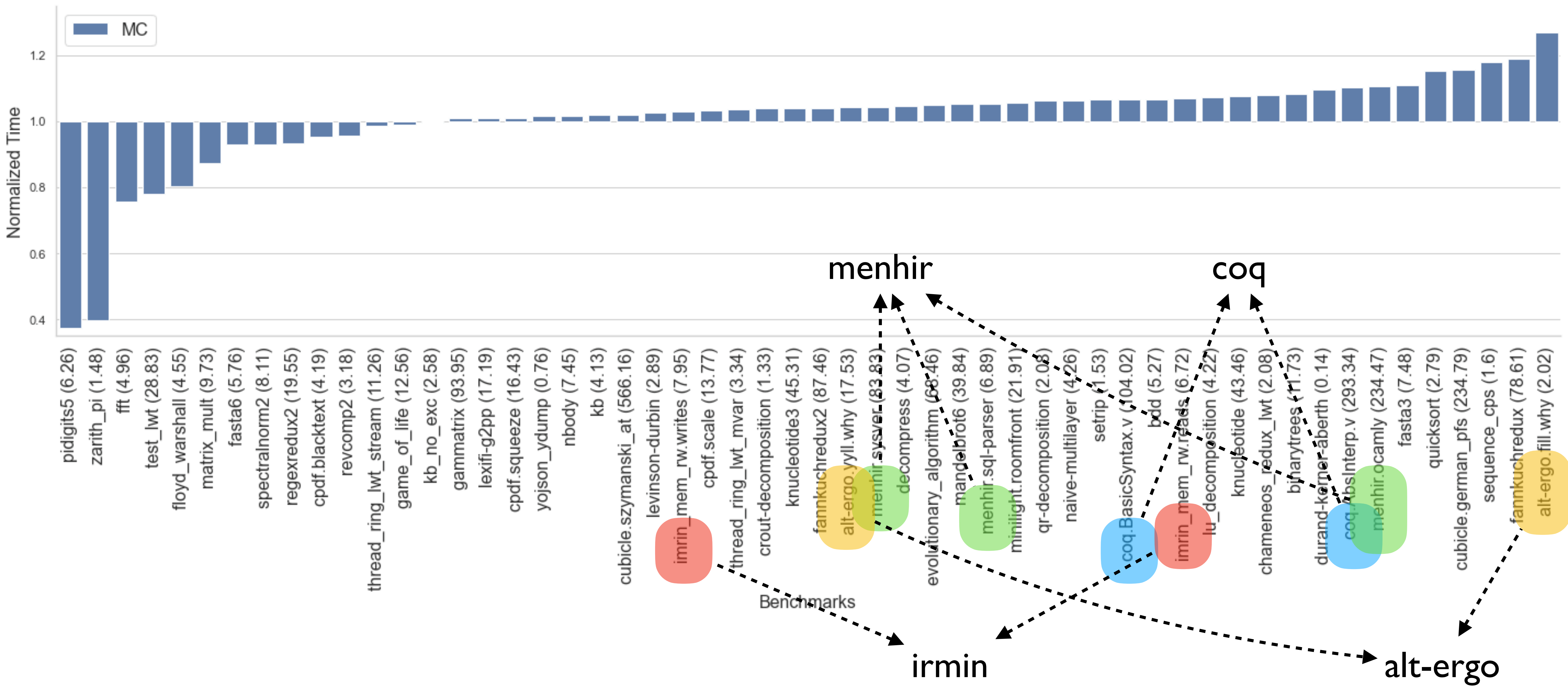

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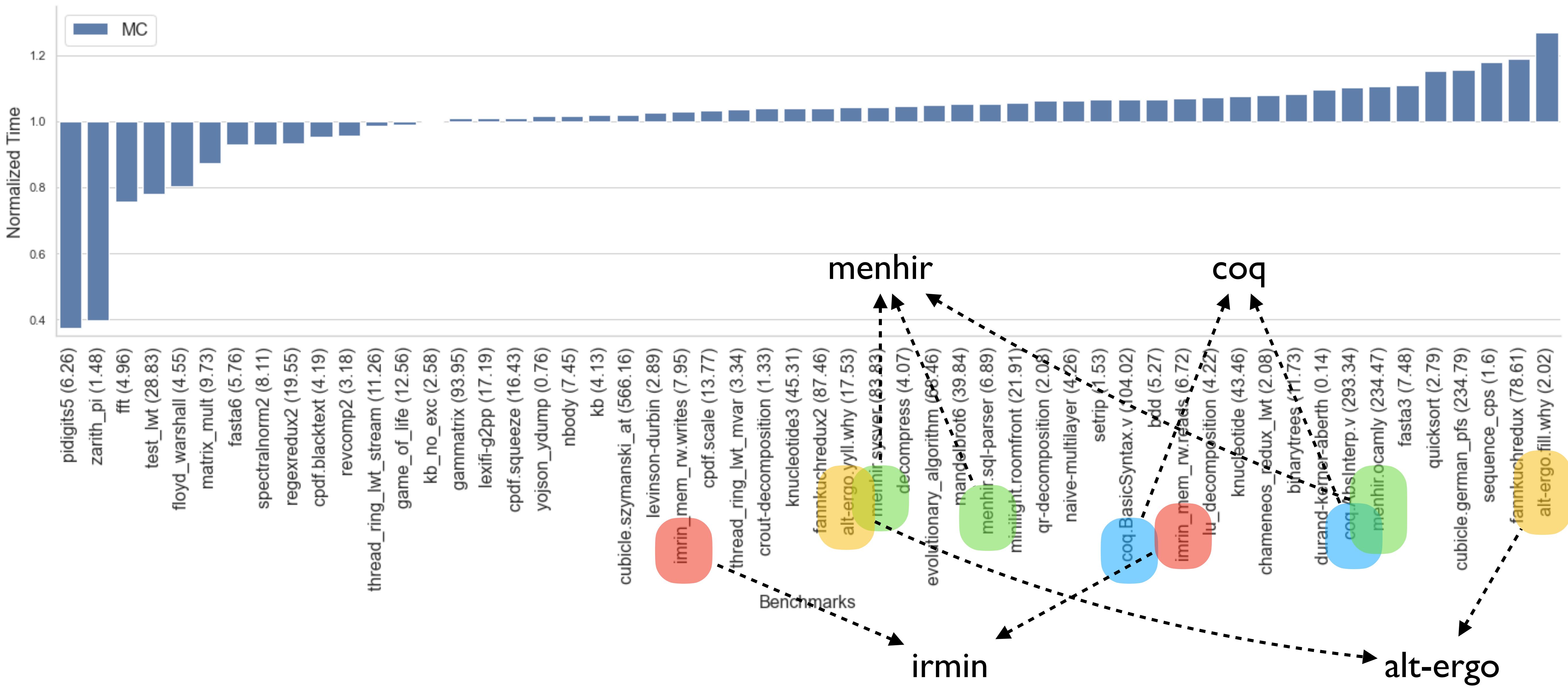

- ~1% faster than stock (geomean of normalised running times)
  - ✦ Difference under measurement noise mostly
  - ✦ Outliers due to difference in allocators

Effect handler — Nano benchmark

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

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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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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

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    - CPS translation + defunctionalization to remove intermediate closure allocation
  - Generator using effect handlers (*eh-generator*)

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Multicore OCaml

Variant	Time (milliseconds)
Iterator (baseline)	202
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nodejs 14.07

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

Performance: WebServer

- Effect handlers for asynchronous I/O in direct-style
  - https://github.com/kayceesrk/ocaml-aeio/
- Variants
  - **Go** + net/http (GOMAXPROCS=1)
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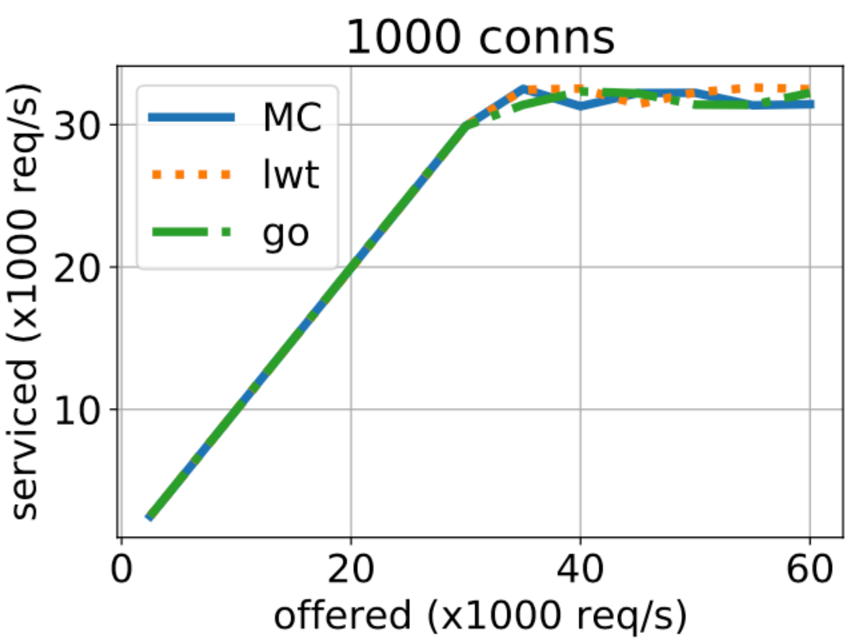
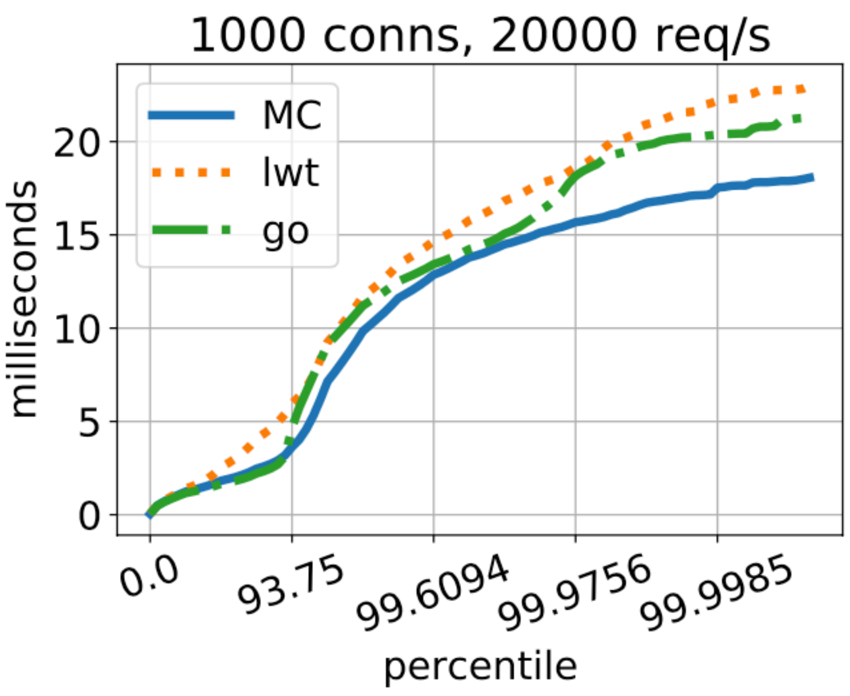


(a) Throughput



(b) Tail latency

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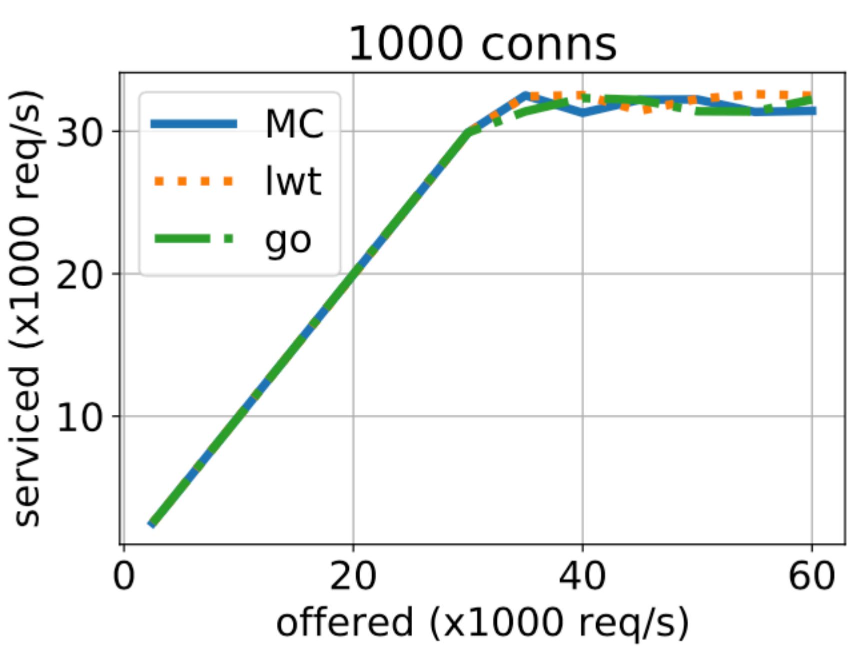
- Direct style (no monadic syntax)
- Can use OCaml exceptions!
- Backtrace per thread (request)
- gdb & perf work!



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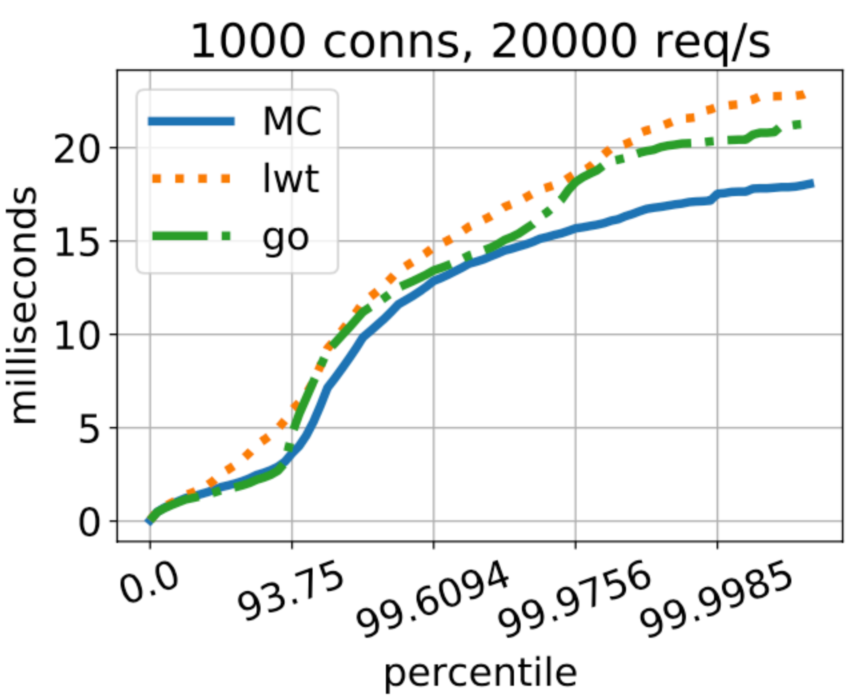

(b) Tail latency

Thanks!

Install Multicore OCaml

```
$ opam switch create 4.10.0+multicore \
    --packages=ocaml-variants.4.10.0+multicore \
    --repositories=multicore=git+https://github.com/ocaml-multicore/multicore-opam.git,default
```

- Multicore OCaml — https://github.com/ocaml-multicore/ocaml-multicore
- Effects Examples — https://github.com/ocaml-multicore/effects-examples
- Sivaramakrishnan et al, "*Retrofitting Parallelism onto OCaml*", ICFP 2020
- Dolan et al, "*Concurrent System Programming with Effect Handlers*", TFP 2017

Bonus Slides