Effect Handlers in Multicore OCaml

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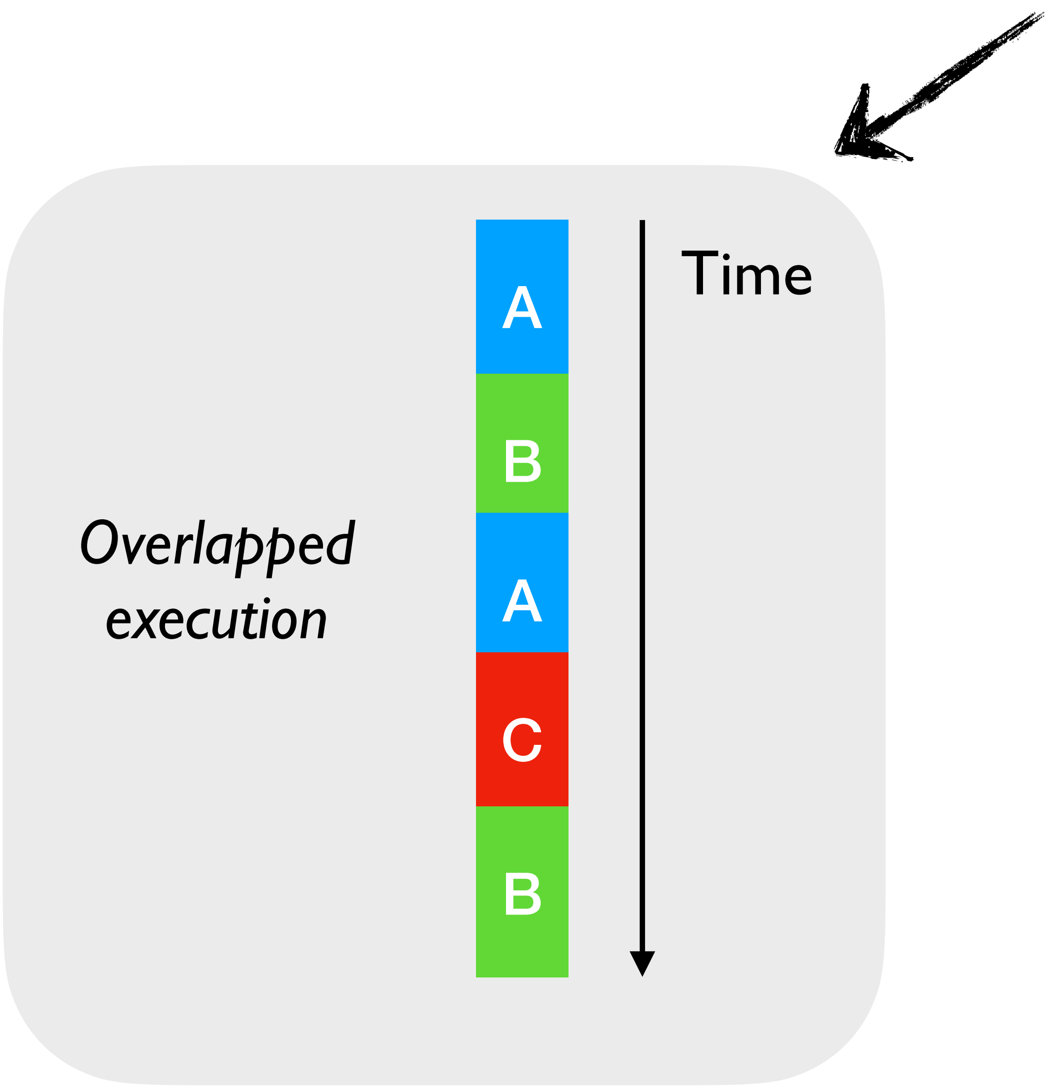

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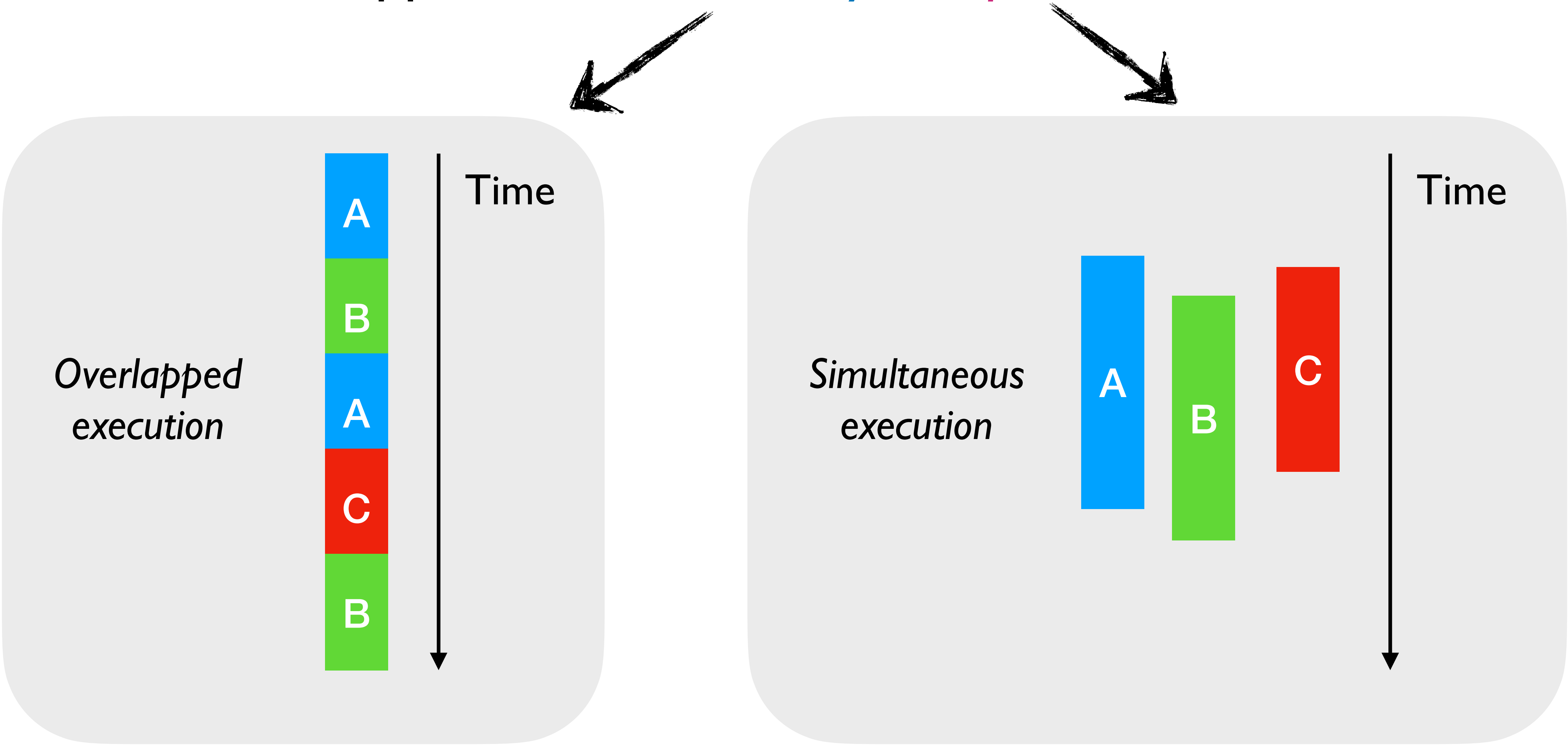

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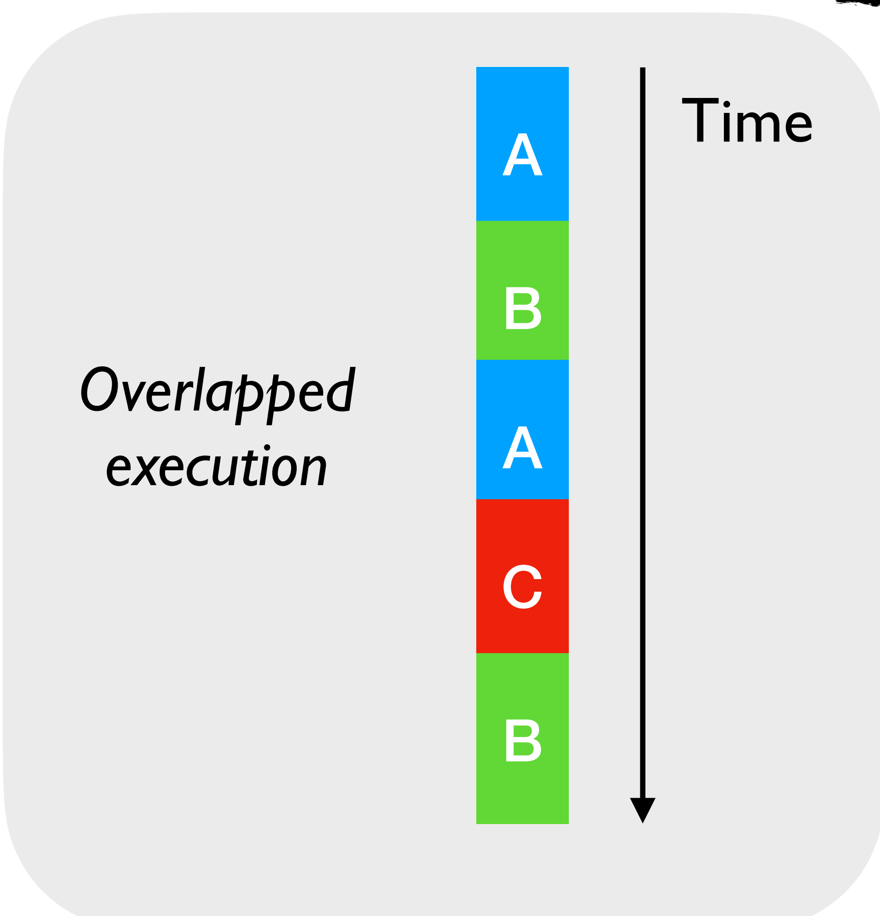

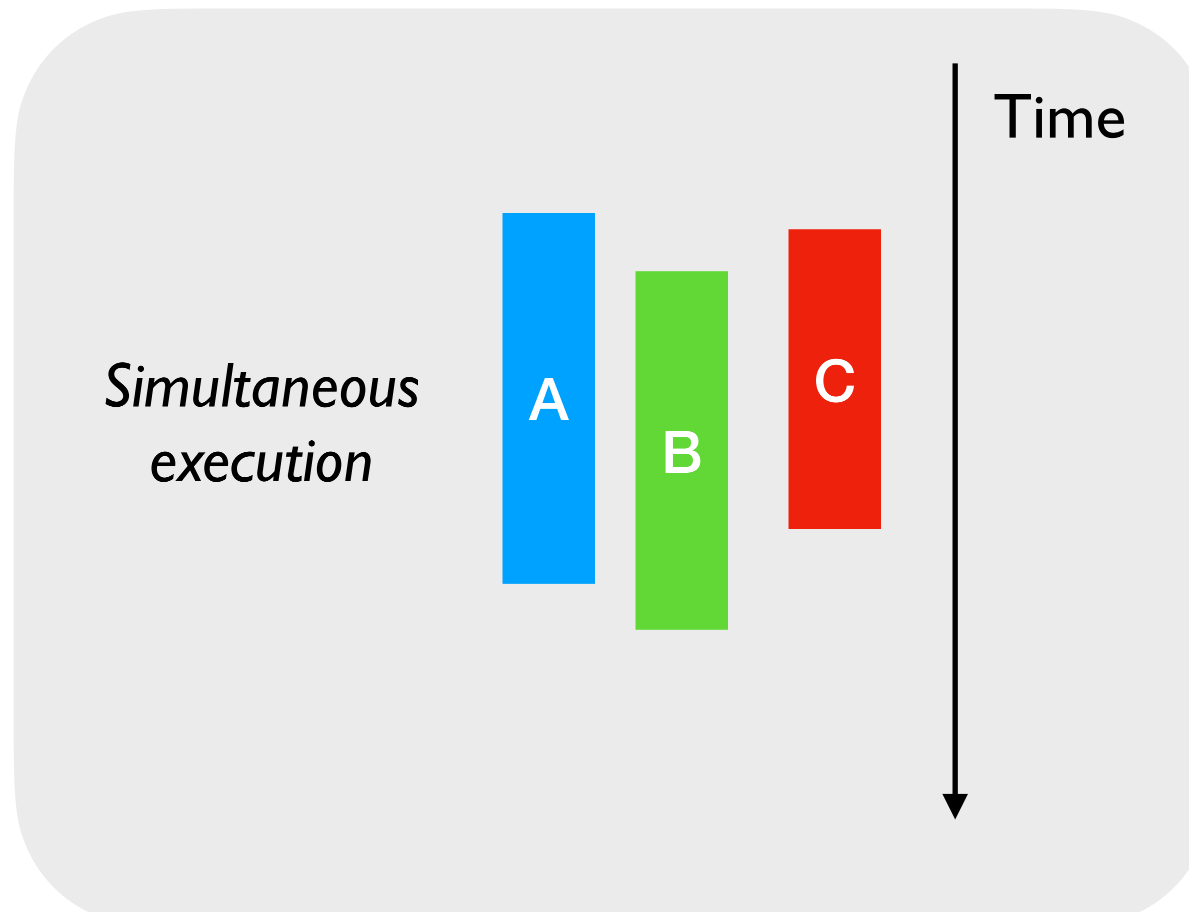

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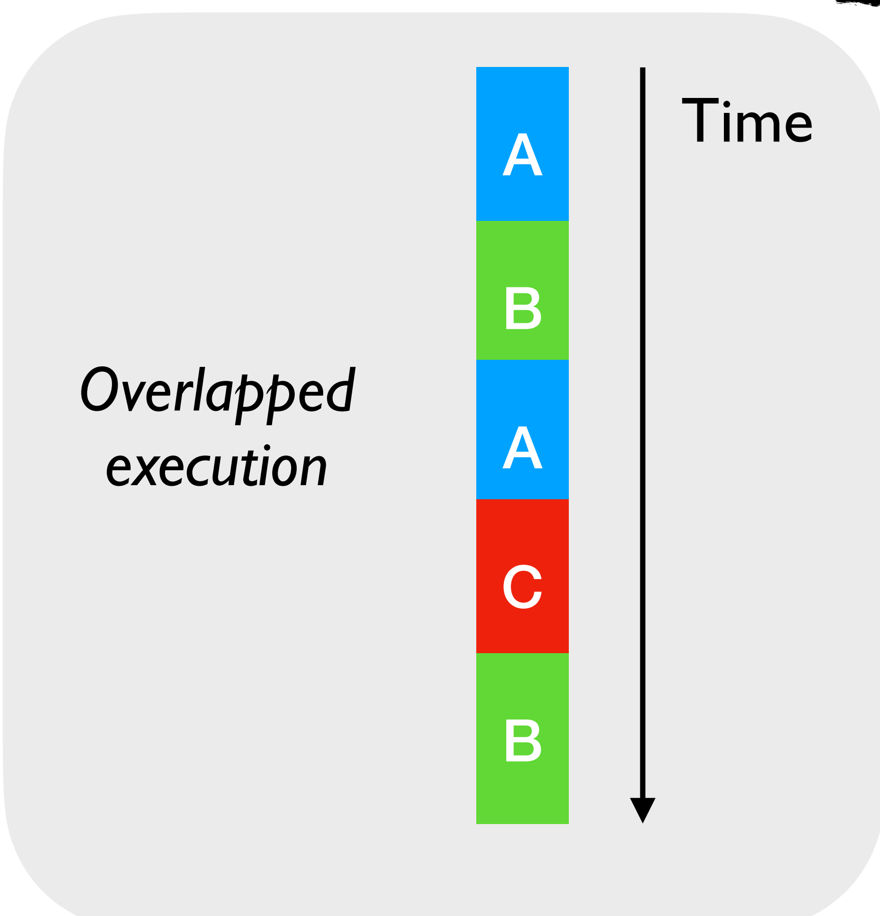

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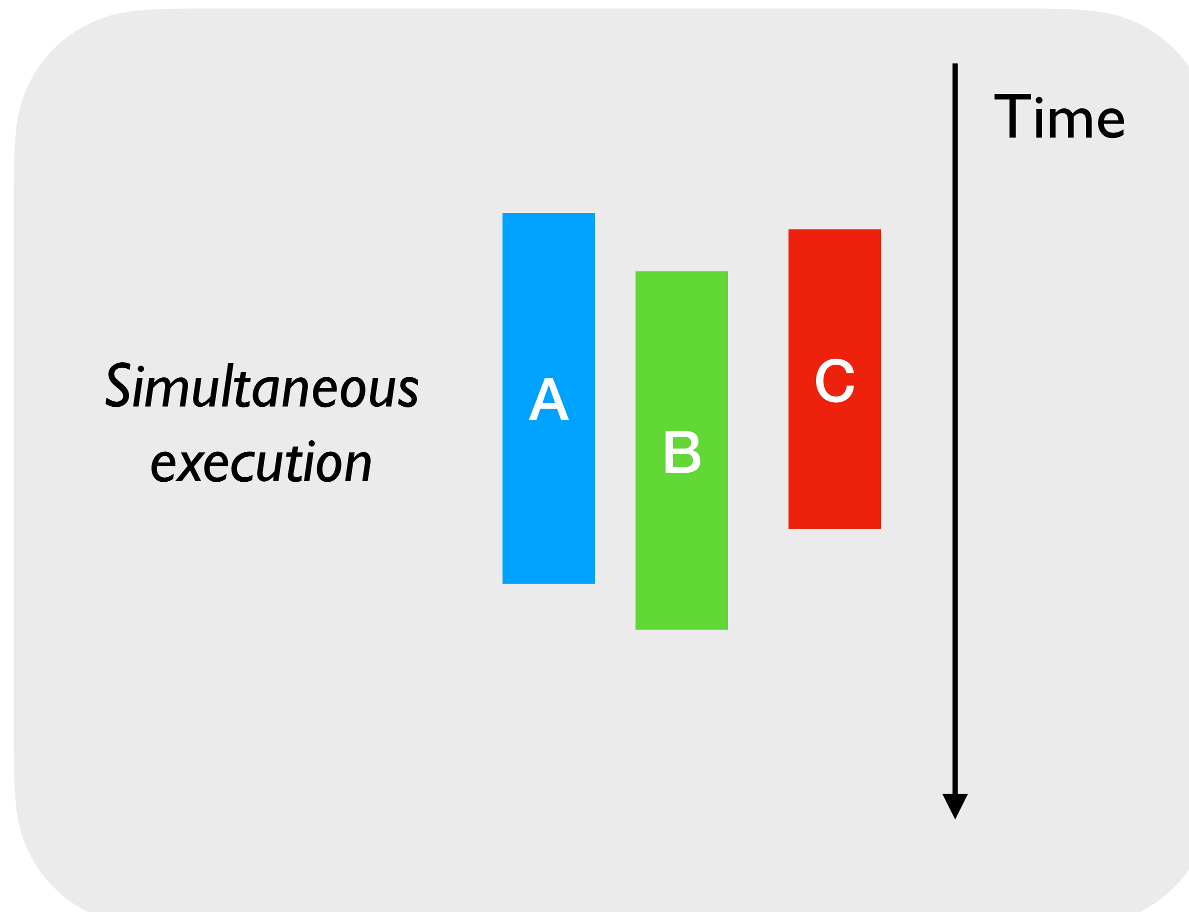

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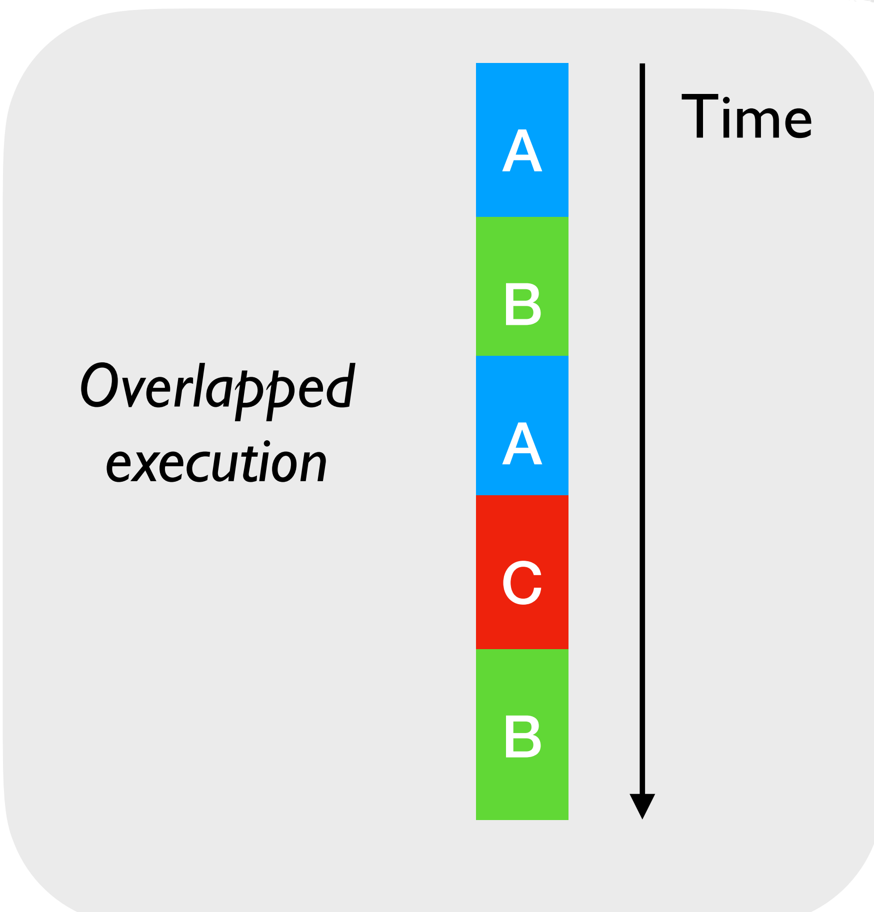

Effect Handlers

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Parallelism is a performance hack

whereas

concurrency is a program structuring mechanism

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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!!

Concurrent Programming in OCaml

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Should we add lightweight threads to OCaml?

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resume suspended computation

Stepping through the example

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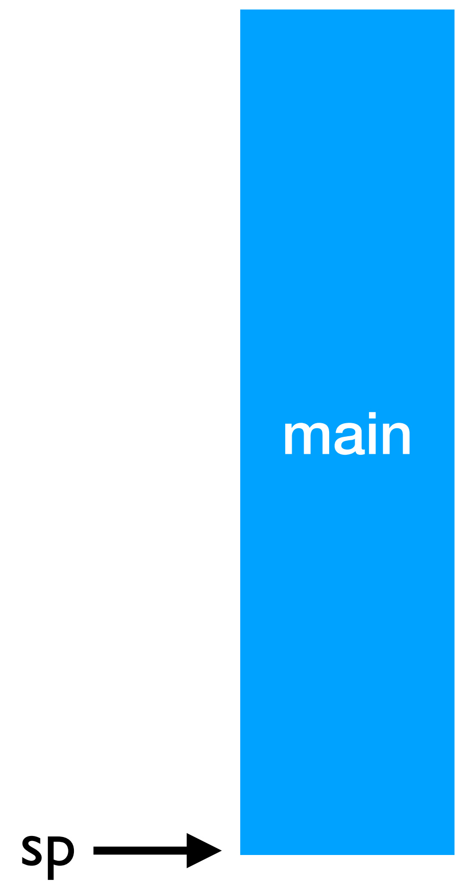

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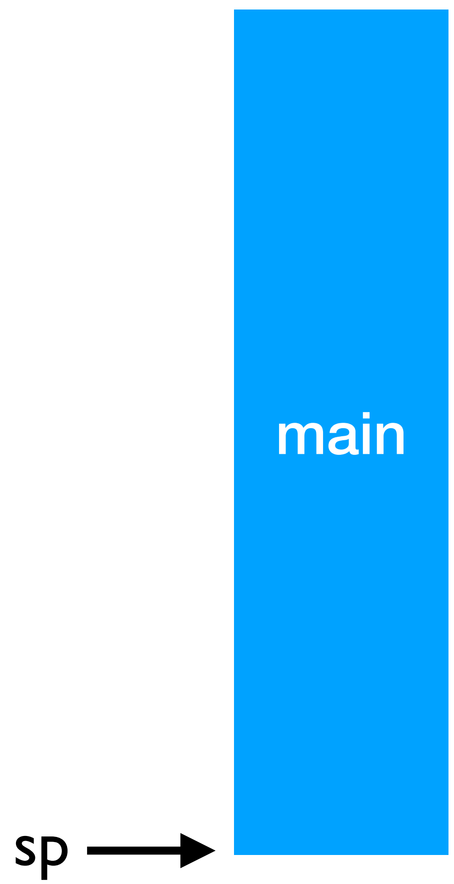

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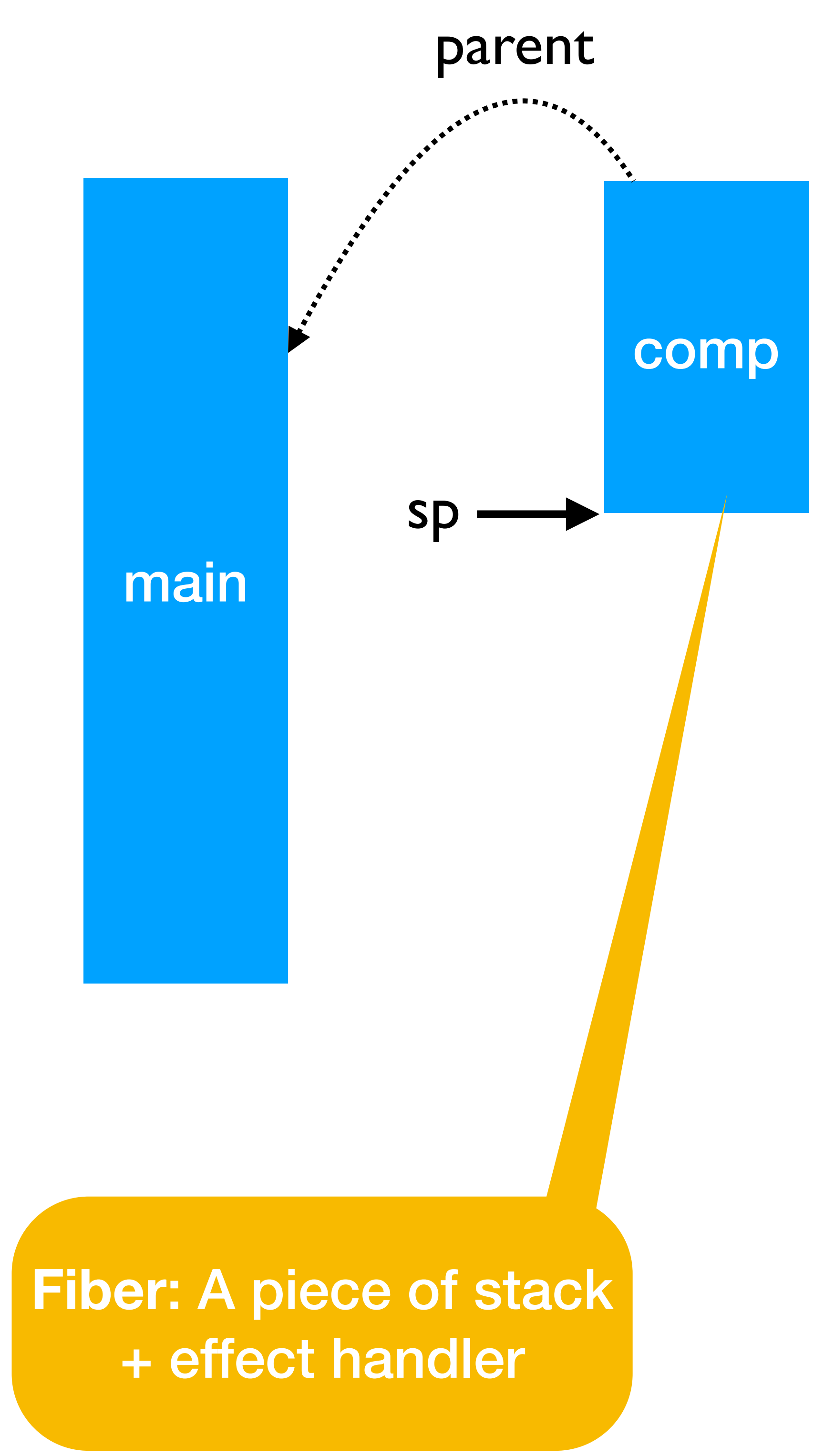

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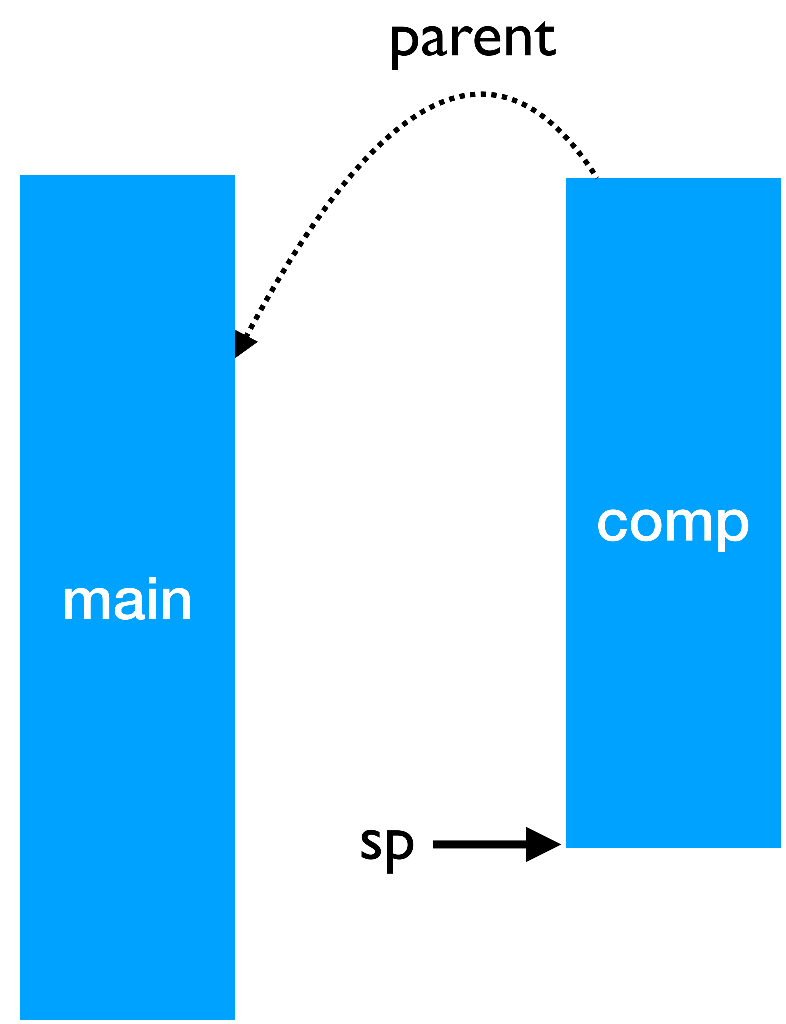

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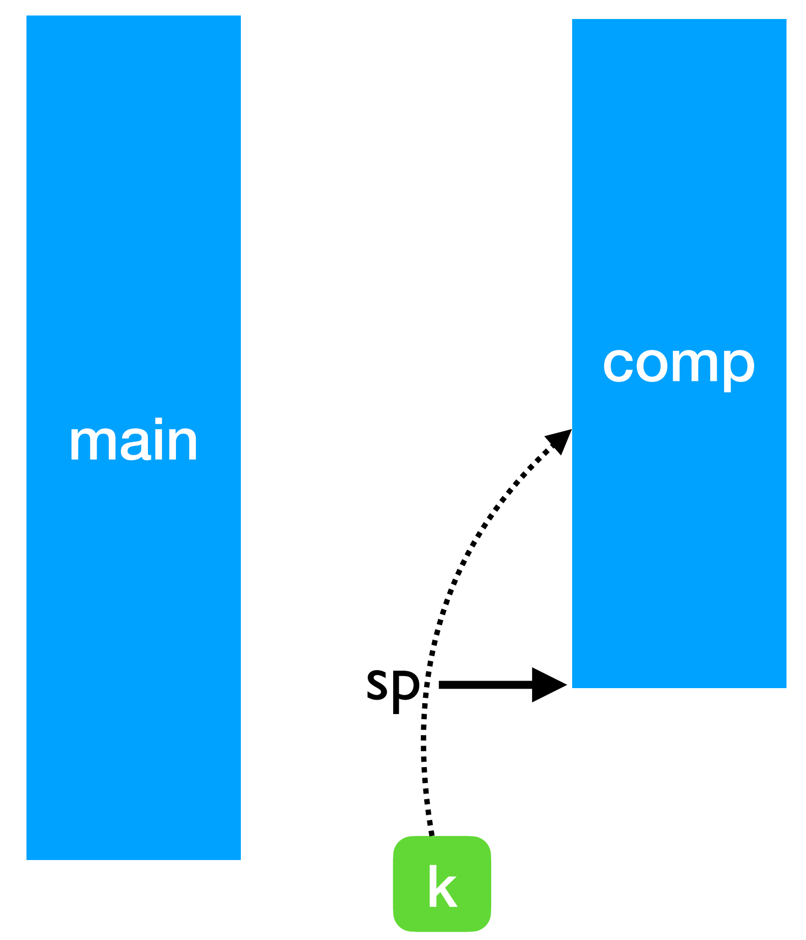

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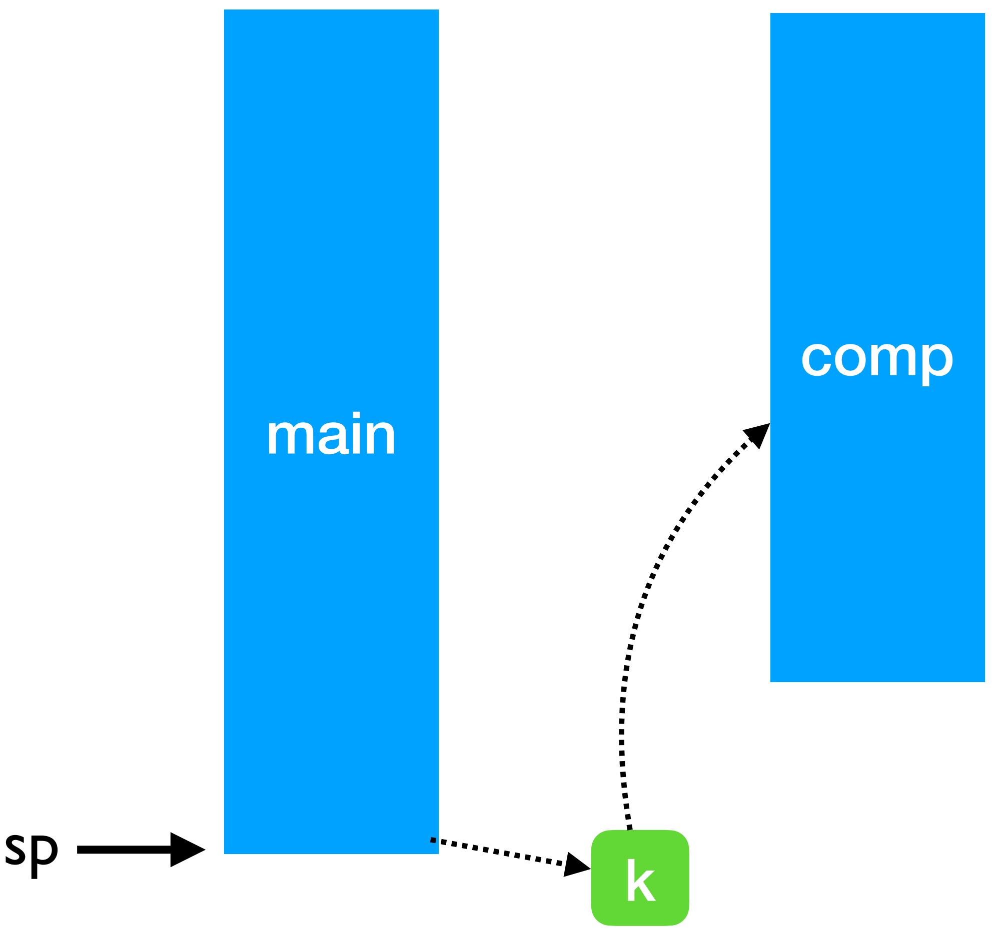

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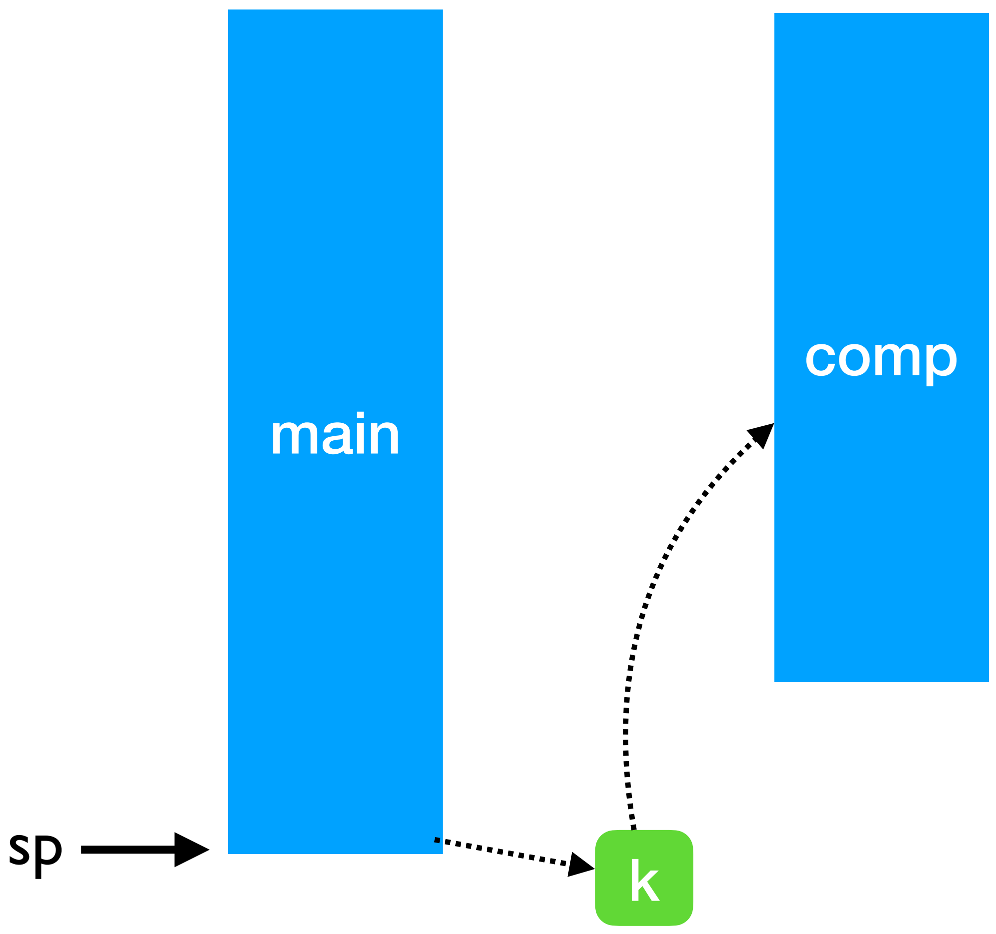

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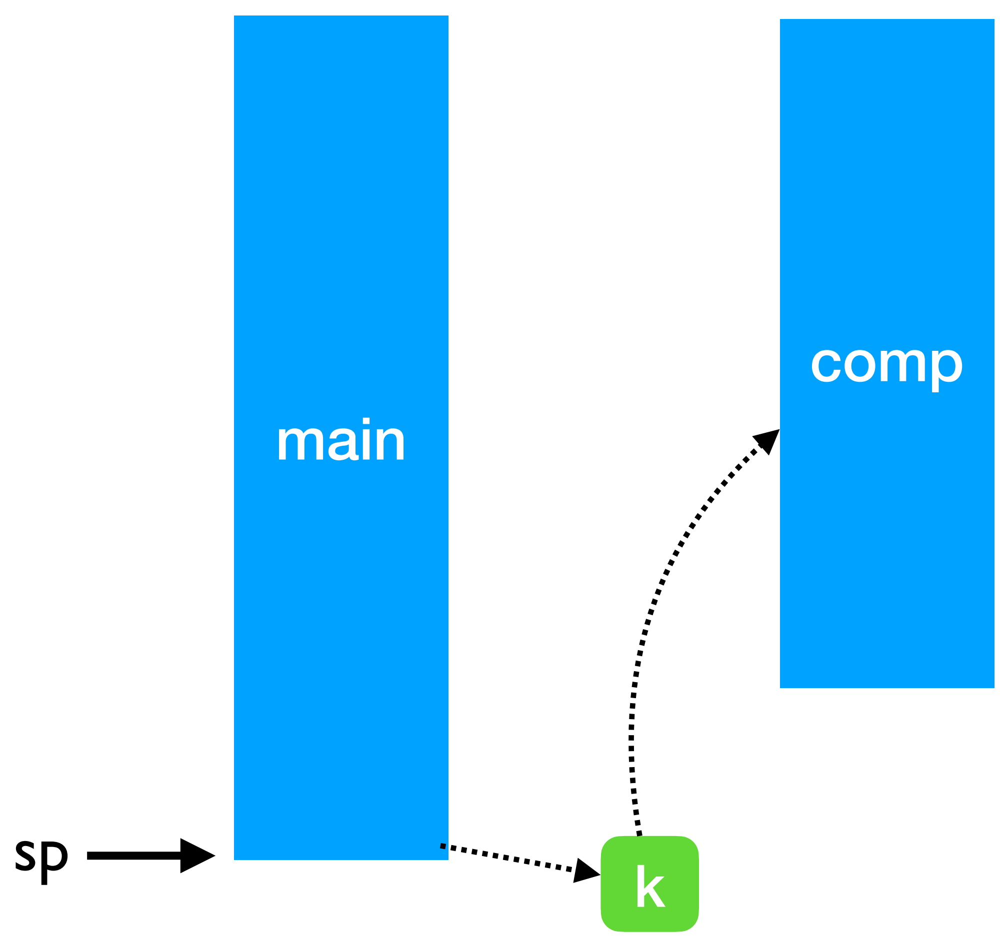

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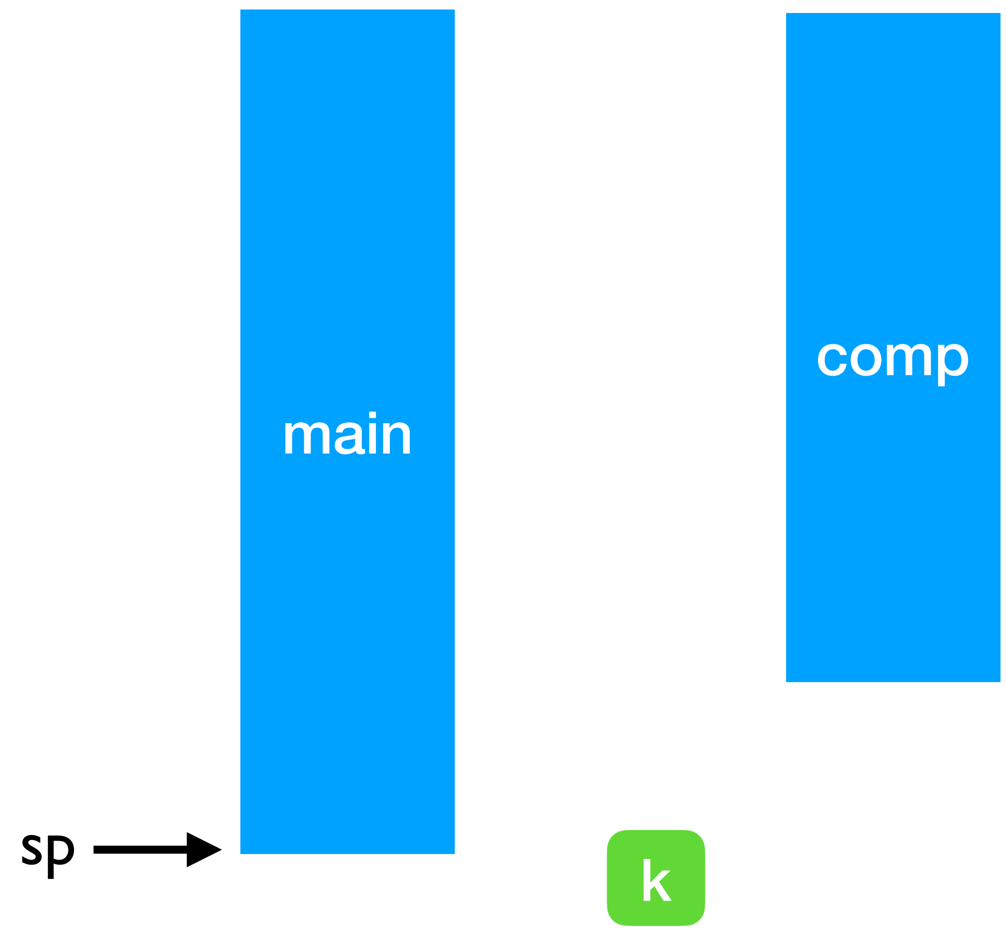

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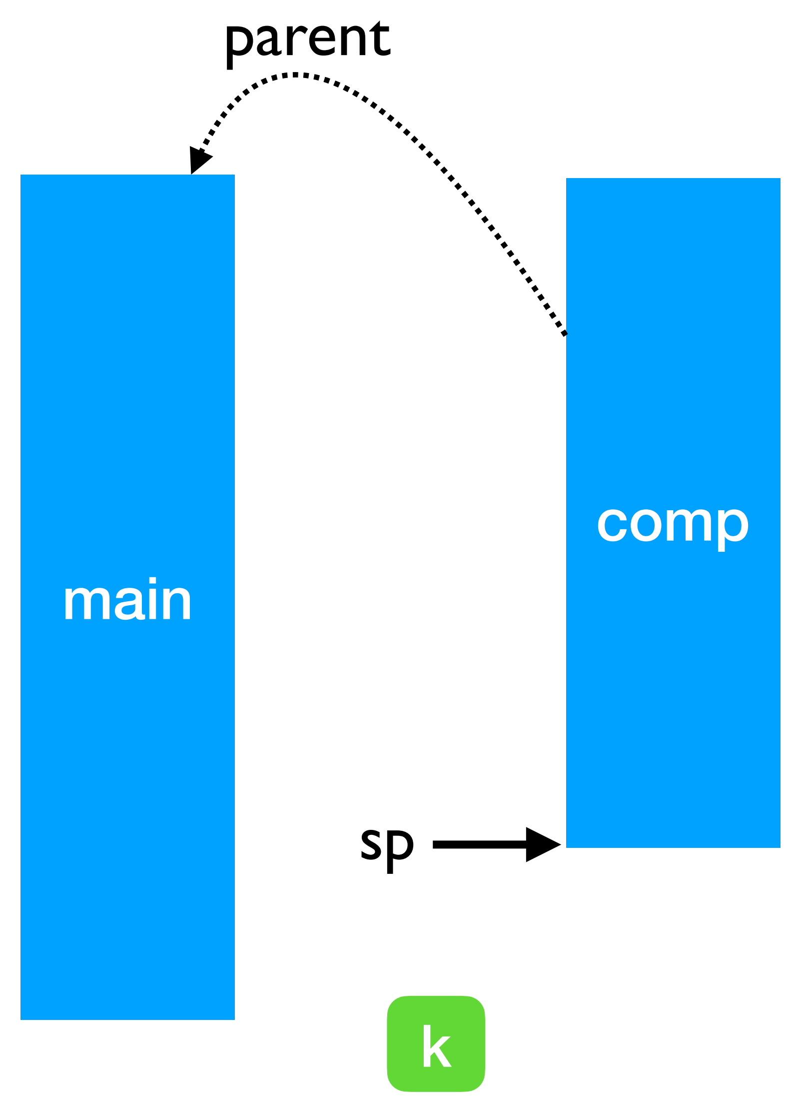

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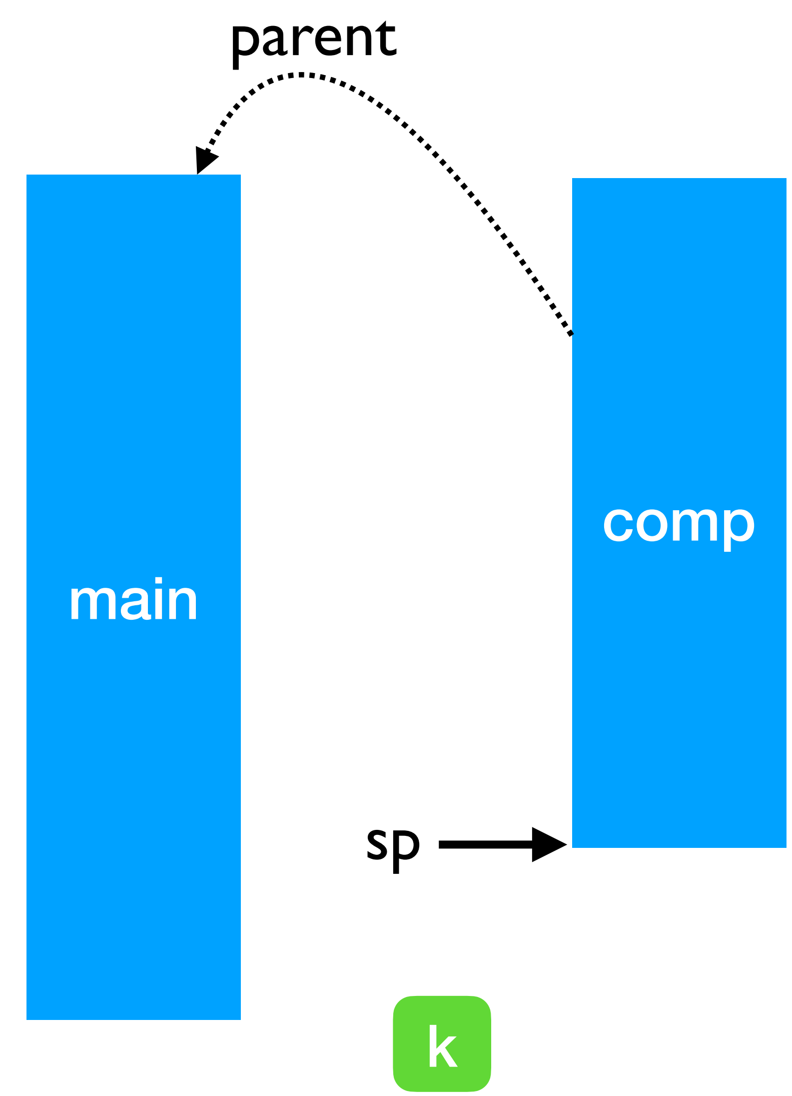

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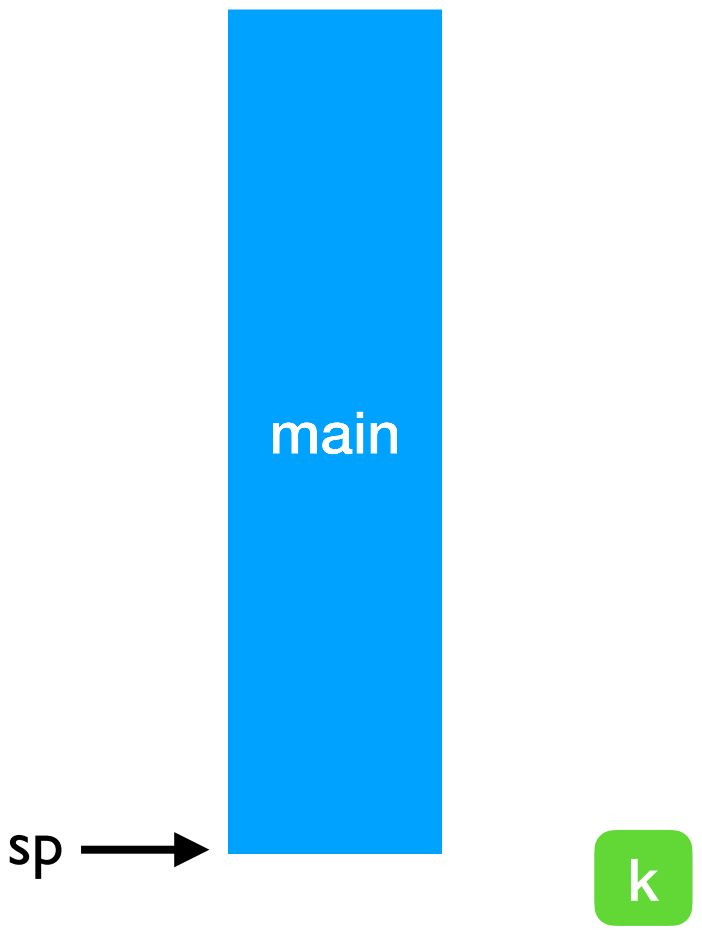

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Handlers can be nested

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pc →   perform A

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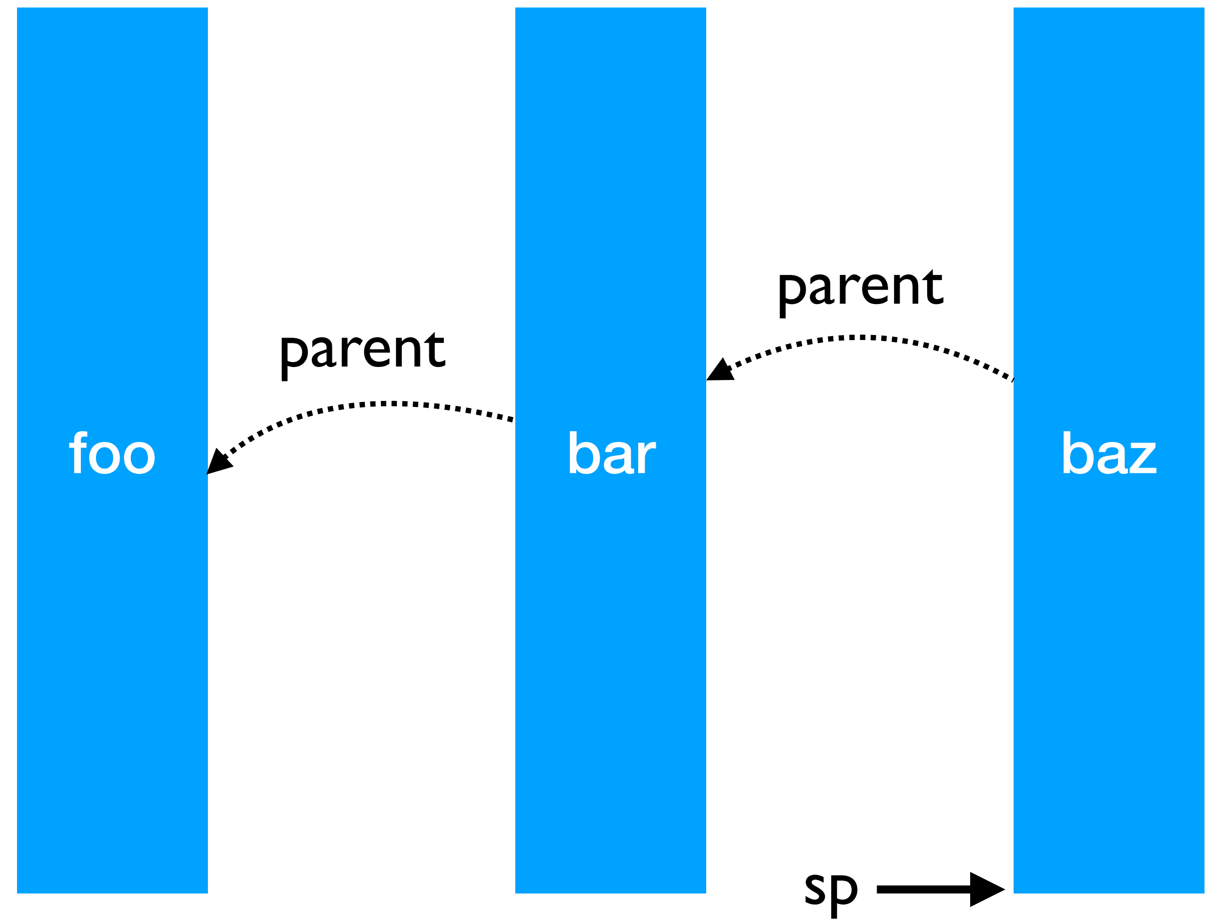

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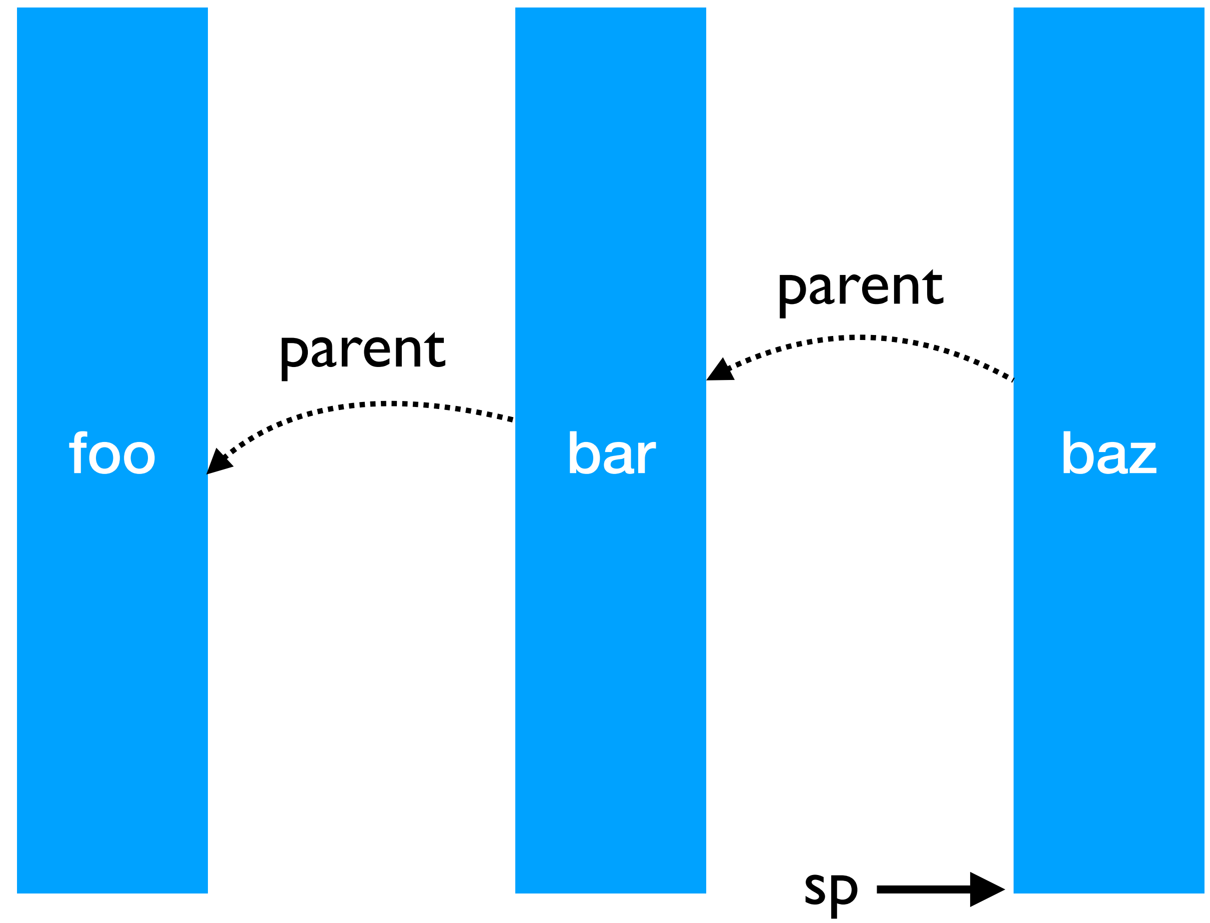

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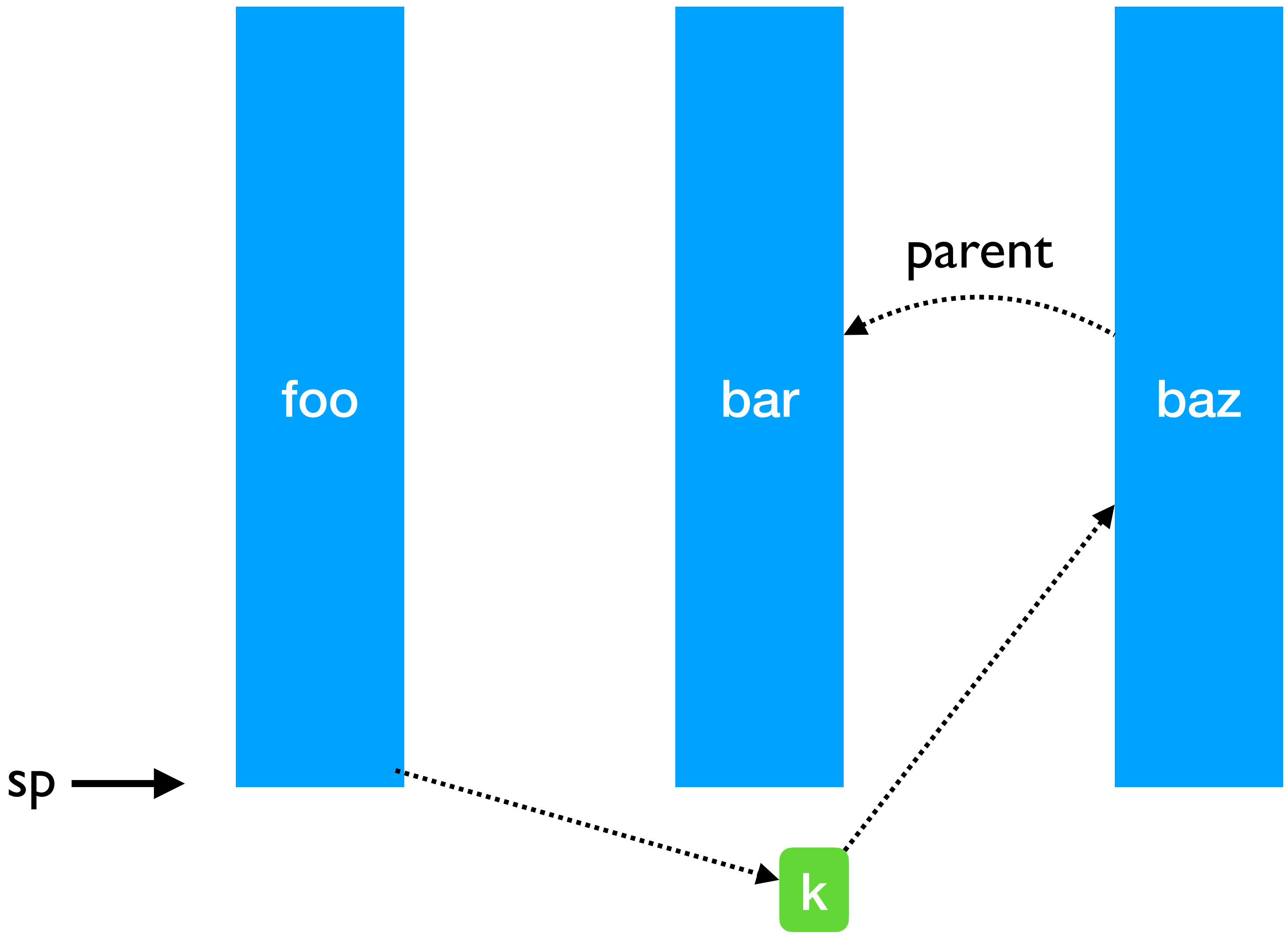

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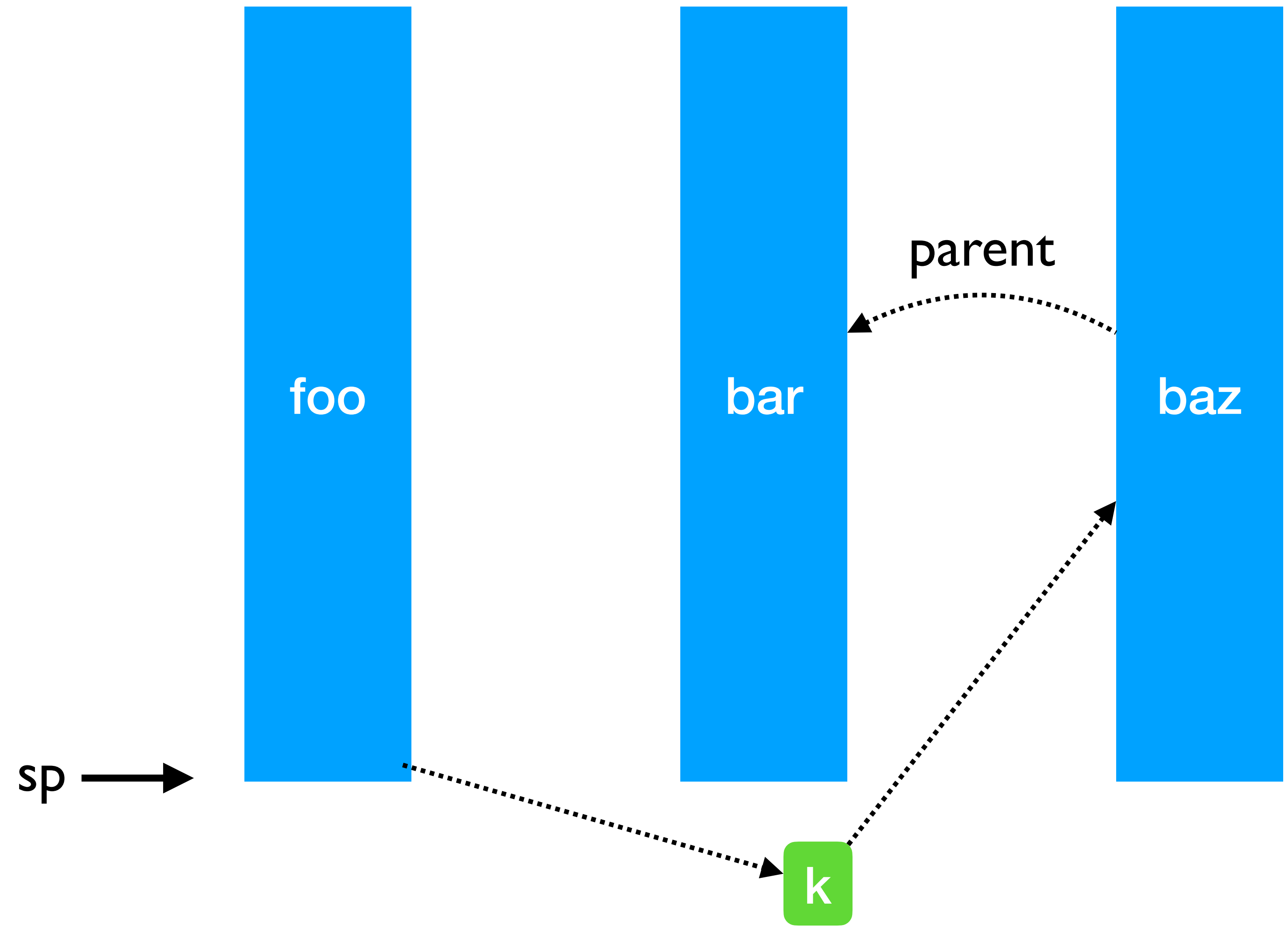

- Linear search through handlers
  - *Handler stacks shallow in practice*

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
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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
```

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

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

```
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Generators

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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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Generators: effect handlers

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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
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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)
```

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
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end)
```

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

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   tree of depth [n] *)
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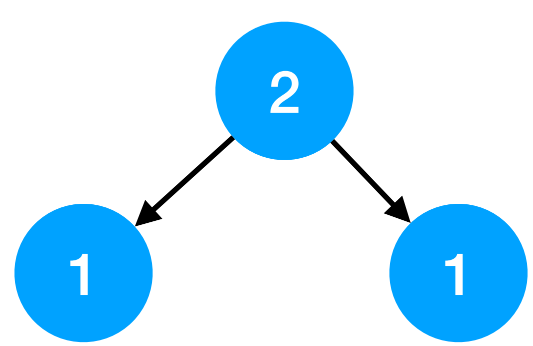
         in Node (t,n,t)

let t = make 2

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



Static Semantics

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- No *effect safety*
  - No static guarantee that all the effects performed are handled (c.f. exceptions)
  - `perform E` at the top-level raises `Unhandled` exception

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

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

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```

Syntax is still in the works

- Today, Multicore OCaml effect handler static semantics is simple

Static Semantics

```
(* OCaml extensible variant type *)
type 'a eff = ..
```

The declaration

```
effect E : string -> int
```

gets translated to

```
type _ eff = E : string -> int eff
```

Static Semantics

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

argument type

result type

```
val perform: 'a eff -> 'a
val continue: ('a,'b) continuation -> 'a -> 'b
```

Static Semantics

```
match e with
| None -> false
| Some b -> b
| effect (E s) k1 -> e1
| effect (F f) k2 -> e2
```

compiled to

```
match_with (fun () -> e)
{ retc = (function None -> false
                  | Some b -> b);
  effc = (function
  | (E s) -> (fun k1 -> e1)
  | (F f) -> (fun k2 -> e2)
  | e -> (fun k -> continue k (perform e)); }
```

assuming we have

```
(* Internal API *)
type 'a comp = unit -> ‘a

type ('a,'b) handler = {
 retc: 'a -> 'b; (* value case *)
 effc: 'c.'c eff -> ('c,'b) continuation -> 'b; (* effect case *)
}

val match_with: 'a comp -> ('a,'b) handler -> ‘b
```

Comparison to shift/reset

- Effect handlers equivalent in expressive power to other delimited control operators
  - Forster et al, *"On the expressive power of user-defined effects: Effect handlers, monadic reflection, delimited control"*, JFP 2019
  - Macro-expressible to each other (ignoring types)

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  - Macro-expressible to each other (ignoring types)
- Nicer to program with thanks to the handler syntax

goto : while loop :: shift/reset : effect handlers

- Andrej Bauer

Retrofitting Challenges

- Millions of lines of legacy code
  - Written without *non-local control-flow* in mind
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Backwards compatibility
before
fancy new features

Defensive Programming

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```ocaml
let copy ic oc =
  let rec loop () =
    let l = input_line ic in
    output_string oc (l ^ "\n");
    loop ()
  in
  try loop () with
  | End_of_file  -> close_in ic; close_out oc
  | e -> close_in ic; close_out oc; raise e
```

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```

raise `Sys_error` when channel is closed

We would like to make this code transparently asynchronous

Asynchronous IO

```
effect In_line : in_channel -> string
effect Out_str : out_channel * string -> unit

let input_line ic = perform (In_line ic)
let output_string oc s = perform (Out_str (oc,s))

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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```

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```

- Continue with appropriate value when the asynchronous IO call returns
- But what about termination identified by `End_of_file` and `Sys_error` exceptions?

Discontinue

```
val discontinue: ('a,'b) continuation -> exn -> 'b
```

- 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

Linearity

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- Resources such as sockets, file descriptors, channels and buffers are *linear* resources
    - Created and destroyed *exactly once*

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    - ✦ Created and destroyed *exactly once*
- When calling an OCaml function, the caller expects the callee to return *exactly once* either with a value or an exception
    - ✦ Defensive programming already guards against exceptional return cases

Linearity

- With effect handlers if the captured continuation is dropped on the floor, then any function call may only return *at-most once*
  - This breaks resource-safe legacy code

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  - This breaks resource-safe legacy code

```
effect E : unit
let foo () = perform E

let bar () =
  let ic = open_in "input.txt" in
  match foo () with
  | v -> close_in ic
  | exception e -> close_in ic; raise e

let baz () =
  try bar () with
  | effect E _ -> () (* leak *)
```

Linearity

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  - *Someone please add linear types to OCaml :-)*

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  - No need for Scheme `dynamic-wind`

Linearity

- We *assume* that well-formed programs resume captured continuations exactly once either using continue or discontinue
  - *Someone please add linear types to OCaml :-)*
- Linear use of continuations ensures that non-local control-flow and resources work well together
  - No need for Scheme `dynamic-wind`
- **Core** and **Base** provide `unwind-protect` implemented using exceptions
  - Backwards compatibility of resourceful code ensured thanks to linearity and defensive programming

Foreign-function interface

```
(* meander.ml *)
external ocaml_to_c : unit -> int = "ocaml_to_c"

exception E1
exception E2

let c_to_ocaml () = raise E1;;
Callback.register "c_to_ocaml" c_to_ocaml;;

let omain () =
  try (* h1 *)
    try (* h2 *)
      ocaml_to_c ()
    with E2 -> -42
  with E1 -> 42;;

assert (omain () = 42)


/* meander.c */
#include <caml/mlvalues.h>
#include <caml/callback.h

value ocaml_to_c (value unit) {
  caml_callback(*caml_named_value("c_to_ocaml"), Val_unit);
  return Val_int(0);
}
```

Stack Management

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exception E1
exception E2

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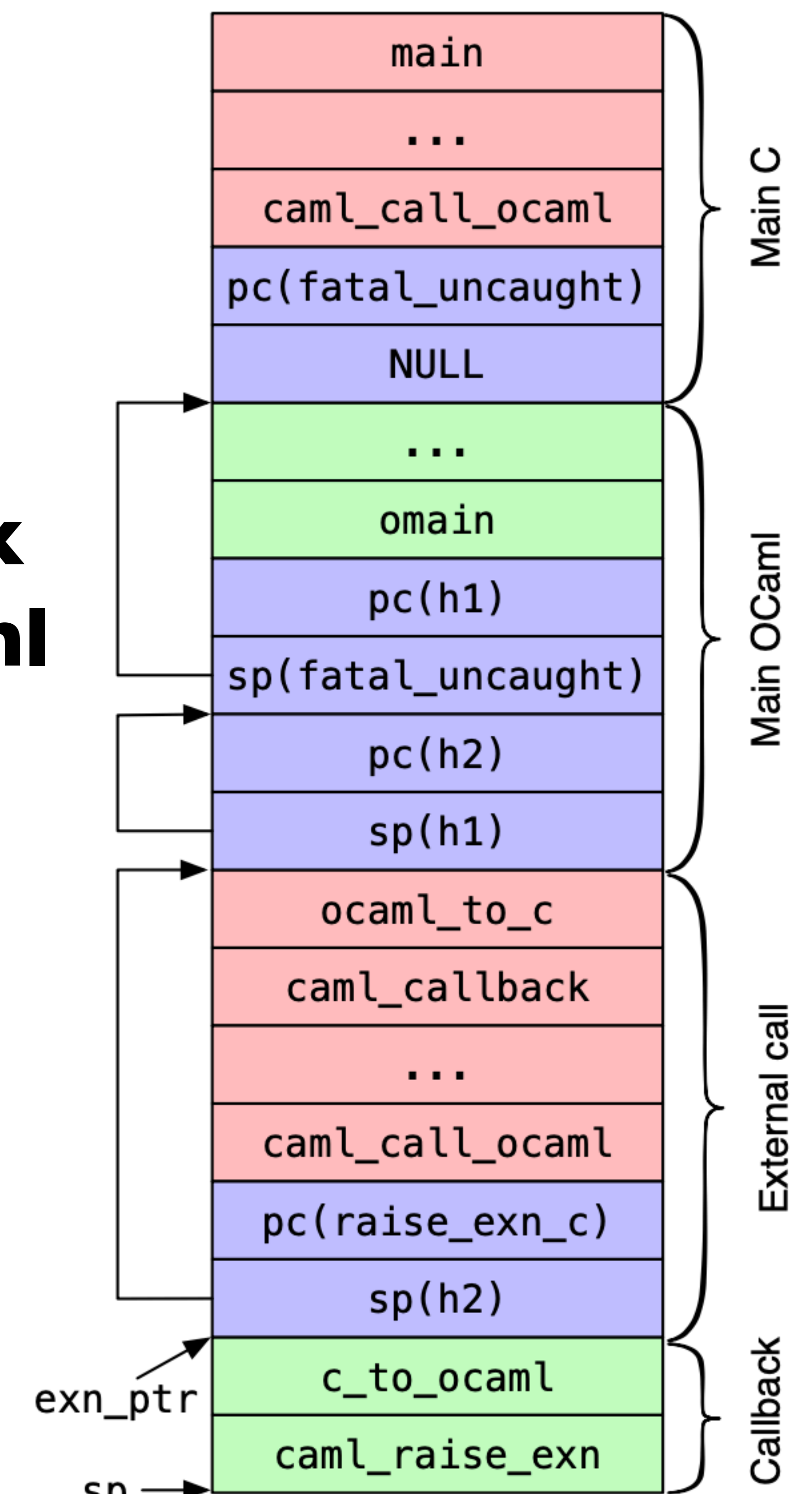
Stock OCaml



Stack Management

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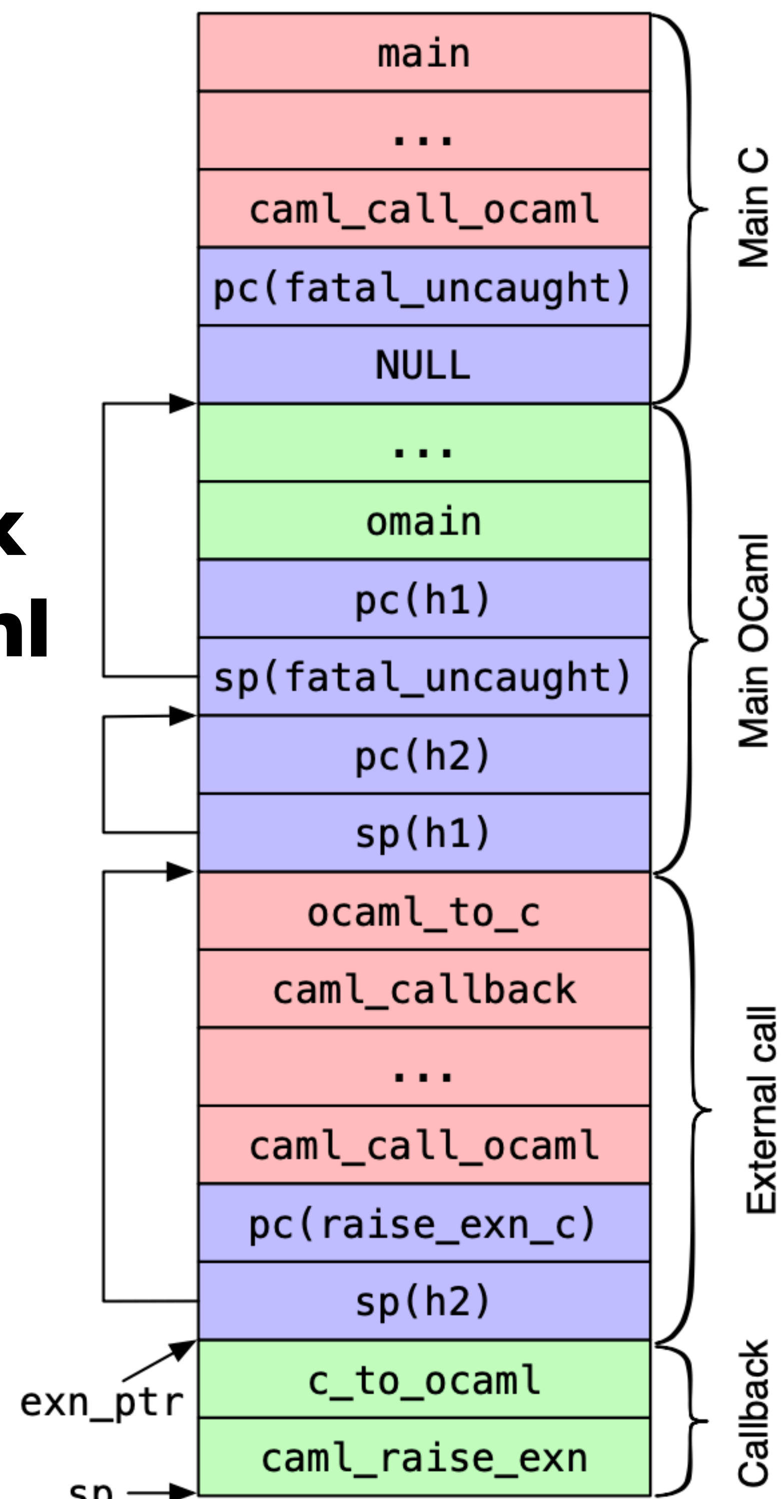
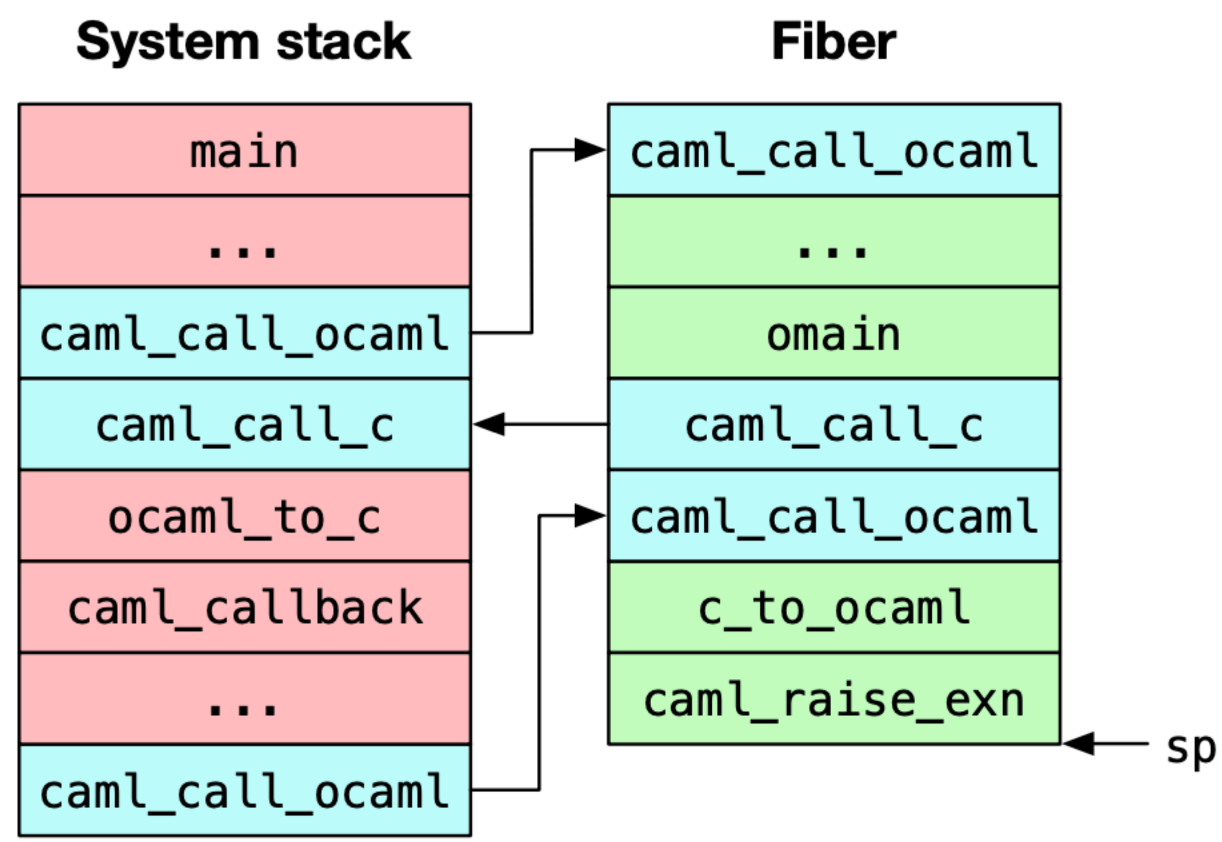


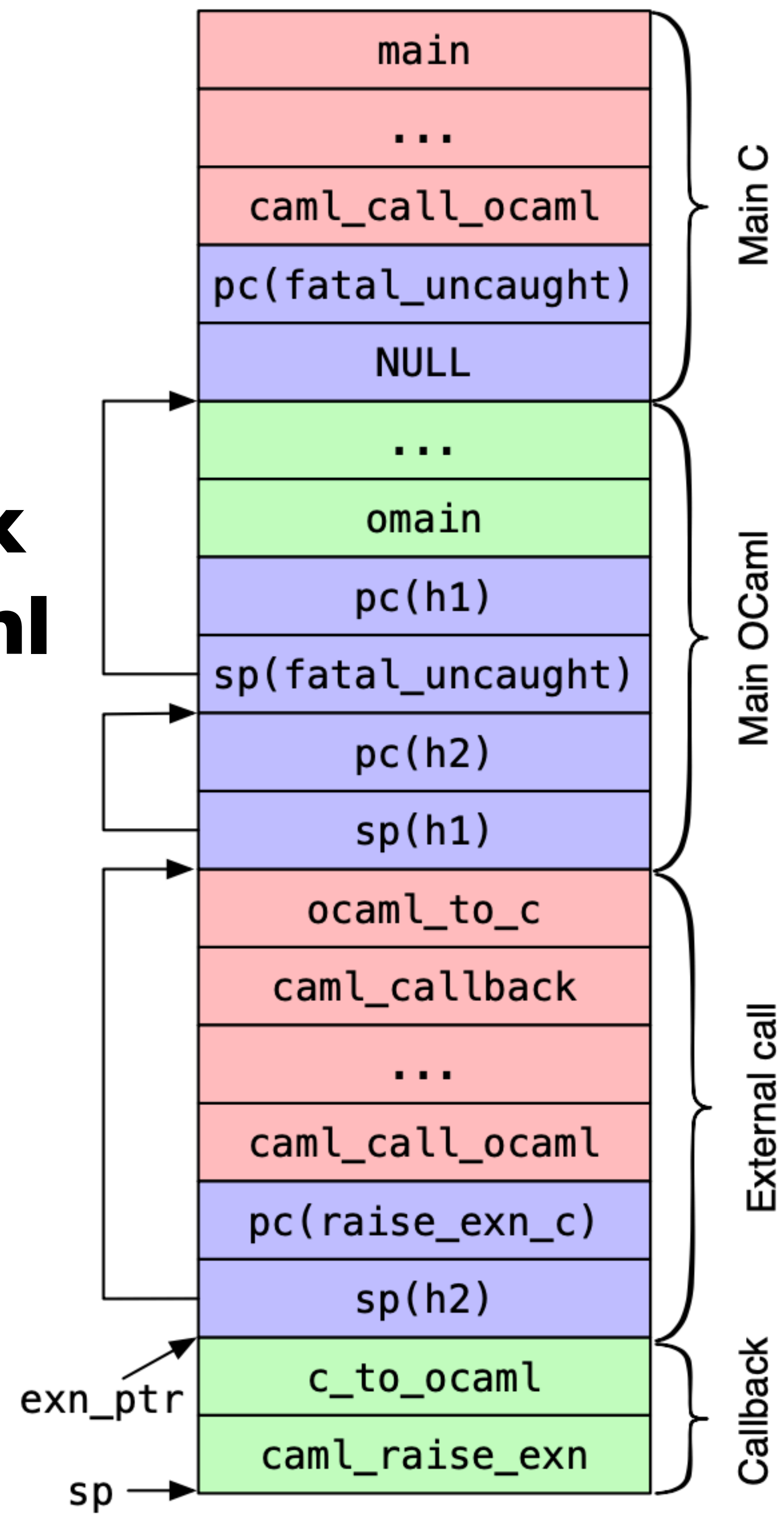
Multicore OCaml



- Stack overflow checks
  - ✦ Reallocate with 2x stack space
- FFI requires stack switch

DWARF stack unwinding

Stock OCaml




```
#0  0x925dc in caml_raise_exn ()
#1  0x6fd3e in camlMeander__c_to_ocaml_83 () at
     meander.ml:5
#2  0x925a4 in caml_call_ocaml ()
#3  0x8a84a in caml_callback_exn (...) at
     callback.c:145
#4  caml_callback (...) at callback.c:199
#5  0x76e0a in ocaml_to_c (unit=1) at meander.c:5
#6  0x6fd77 in camlMeander__omain_88 () at
     meander.ml:10
#7  0x6fe92 in camlMeander__entry () at
     meander.ml:13
#8  0x6f719 in caml_program ()
#9  0x925a4 in caml_call_ocaml ()
#10 0x92e4c in caml_startup_common (...) at
     startup_nat.c:162
#11 0x92eab in caml_startup_exn (...) at
     startup_nat.c:167
#12 caml_startup (...) at startup_nat.c:172
#13 0x6f55c in main (...) at main.c:44
```

DWARF stack unwinding

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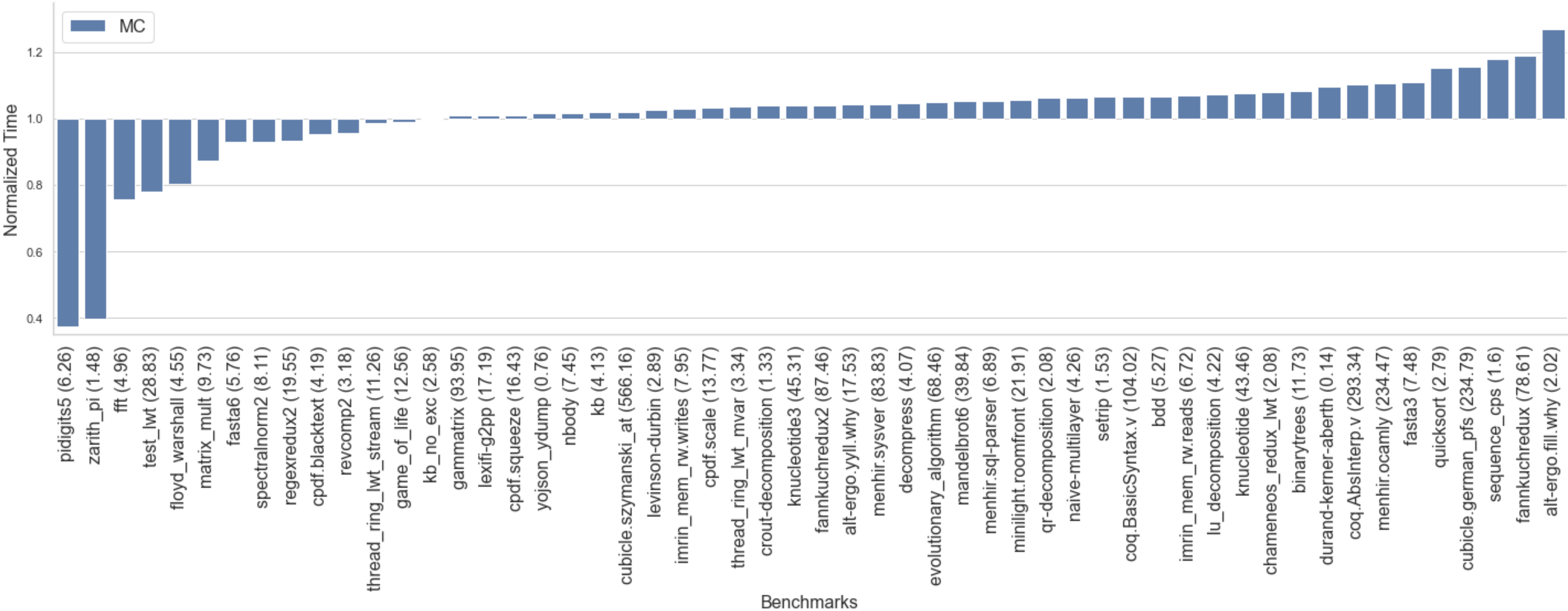
- In Multicore OCaml, we've encoded DWARF unwinding across callbacks, external calls and effect handlers
    - ✦ gdb, lldb, perf continue to work!

DWARF stack unwinding

- DWARF bytecode is a Turing complete language
- In Multicore OCaml, we've encoded DWARF unwinding across callbacks, external calls and effect handlers
  - ✦ gdb, lldb, perf continue to work!
- Verified that the unwind tables are correct using an automated tool
  - ✦ Basitien et al, *"Reliable and Fast DWARF-Based Stack Unwinding"*, OOPSLA 2019

No effects performance



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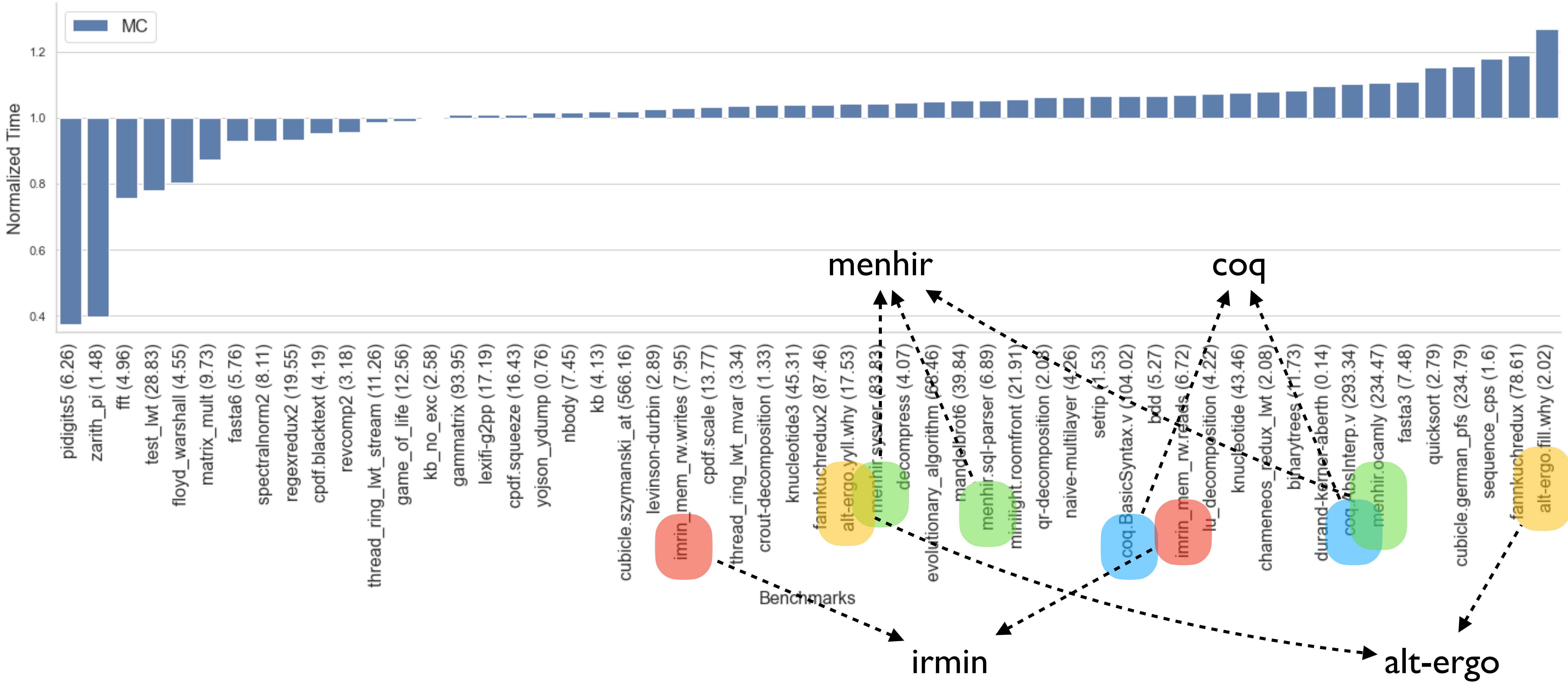

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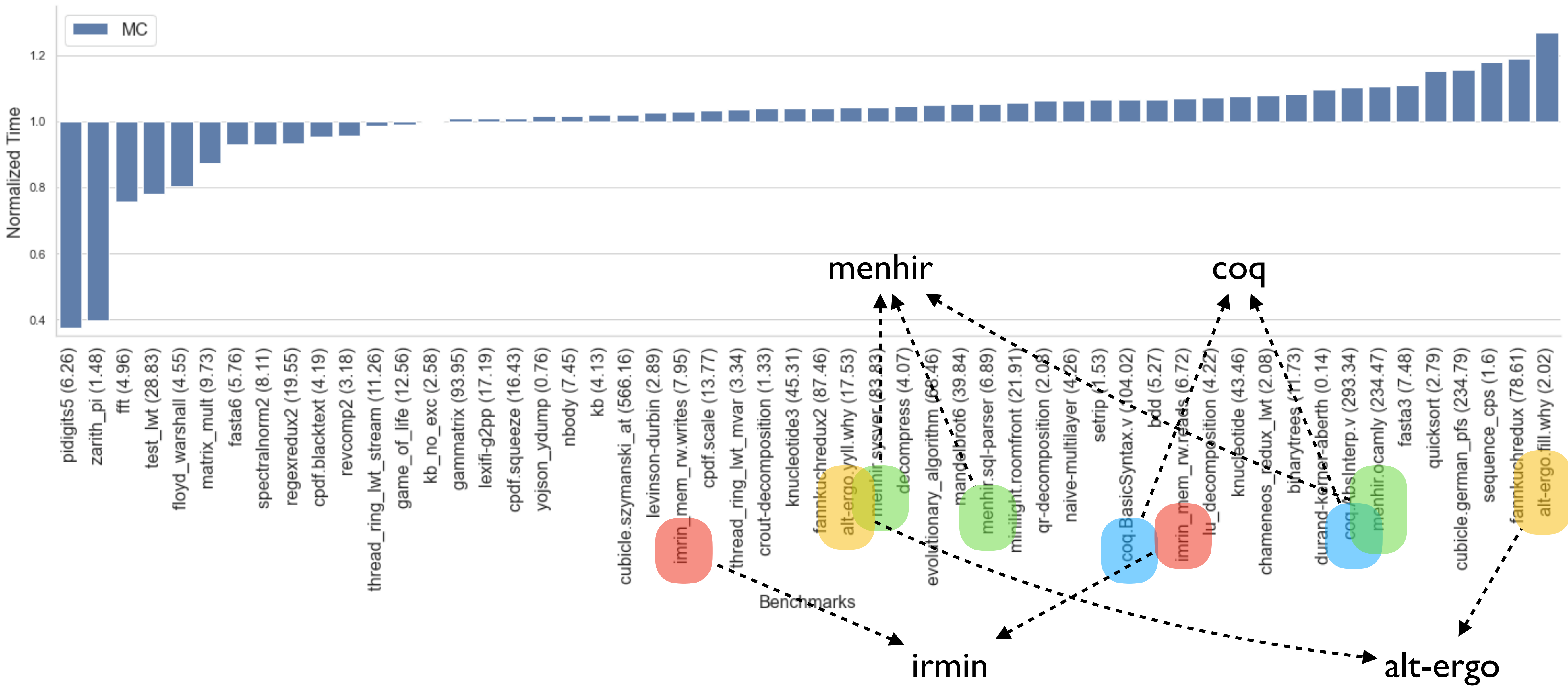

- ~1% faster than stock (geomean of normalised running times)
  - ✦ Difference under measurement noise mostly
  - ✦ Outliers due to difference in allocators

Performance

Performance

```
let foo () =
   (* a *)
  try
    (* b *)
    perform E
    (* d *)
  with effect E k ->
    (* c *)
    continue k ()
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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
- For reference, memory read latency is **90 ns** (local NUMA node) and **145 ns** (remote NUMA node)

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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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- Traverse a complete binary-tree of depth 25
  - 2^{26} stack switches

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- *Iterator* — idiomatic recursive traversal
- Generator
  - Hand-written generator (*hw-generator*)
    - CPS translation + defunctionalization to remove intermediate closure allocation
  - Generator using effect handlers (*eh-generator*)

Performance: Generators

Multicore OCaml

Variant	Time (milliseconds)
Iterator (baseline)	202
hw-generator	837 (**3.76x**)
eh-generator	1879 (**9.30x**)

Performance: Generators

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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)
  - OCaml + http/af + **Lwt** (explicit callbacks)
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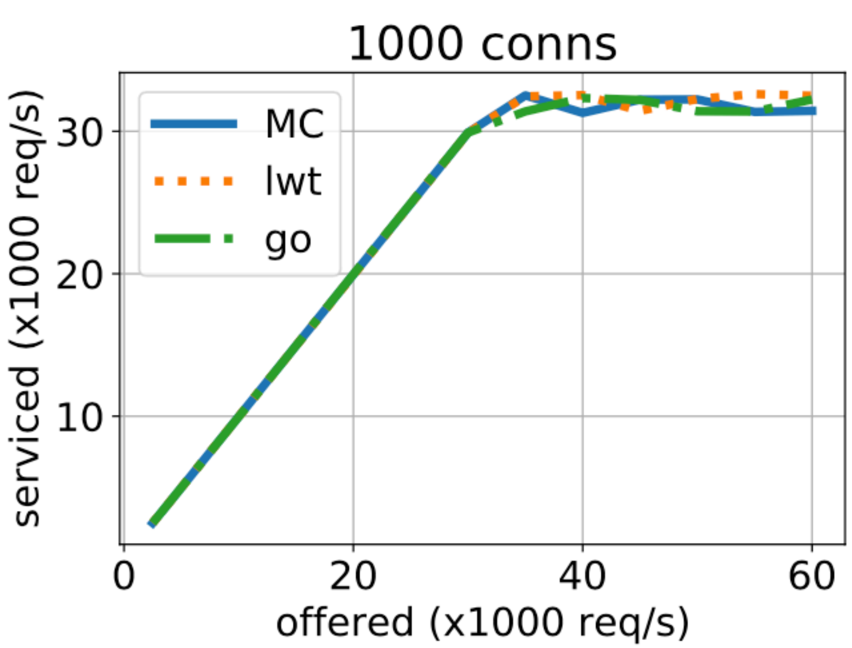
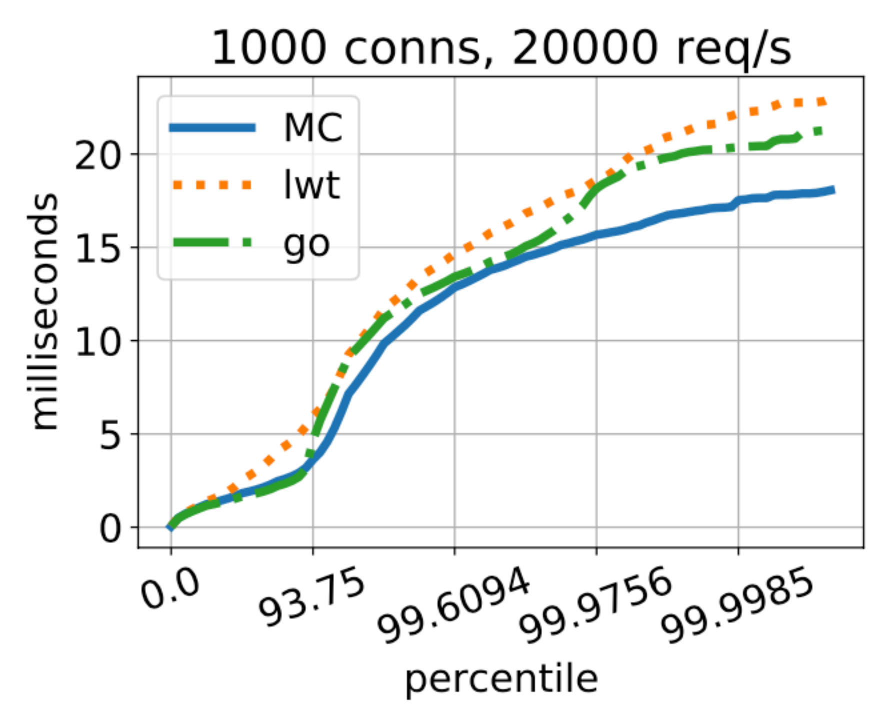


(a) Throughput



(b) Tail latency

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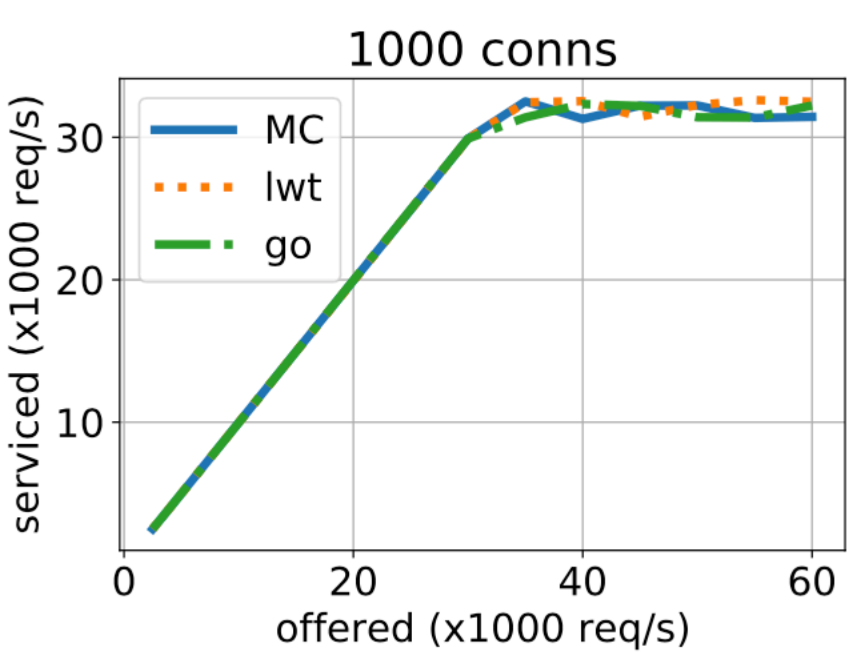
- Direct style (no monadic syntax)
- Can use OCaml exceptions!
- Backtrace per thread (request)
- gdb & perf work!



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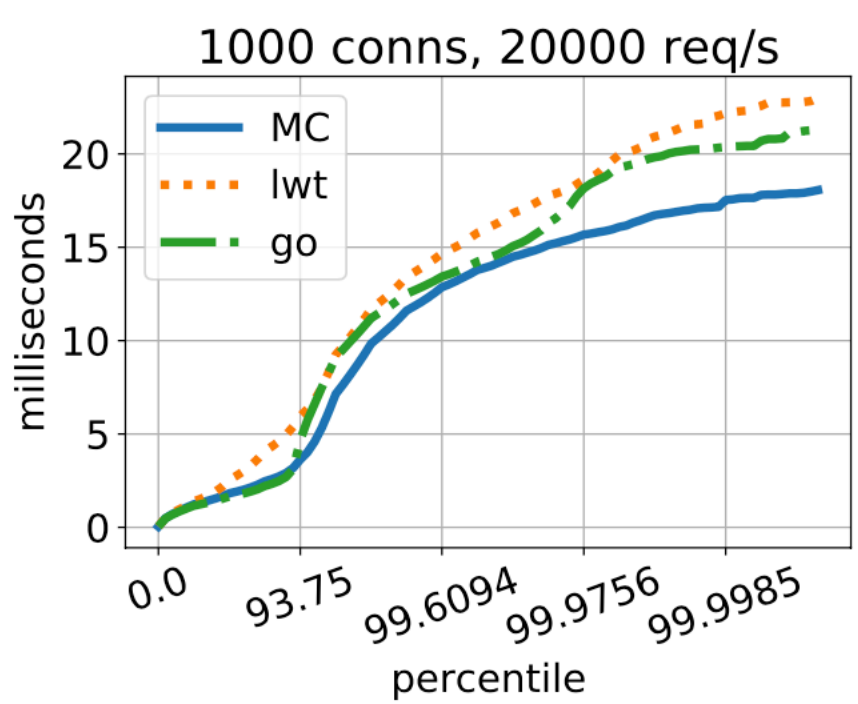

(b) Tail latency

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