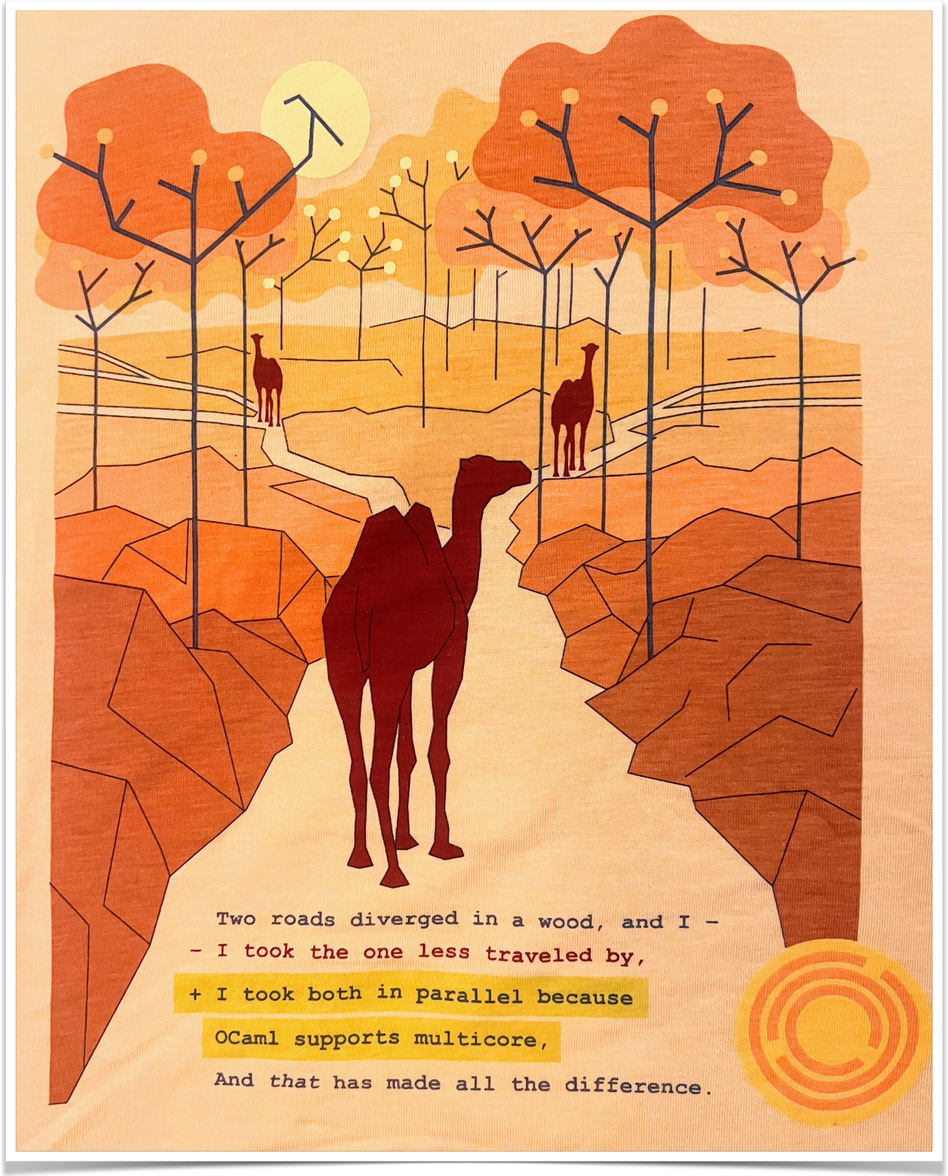
Concurrent Programming with OCaml 5

“KC” Sivaramakrishnan

OCaml 5

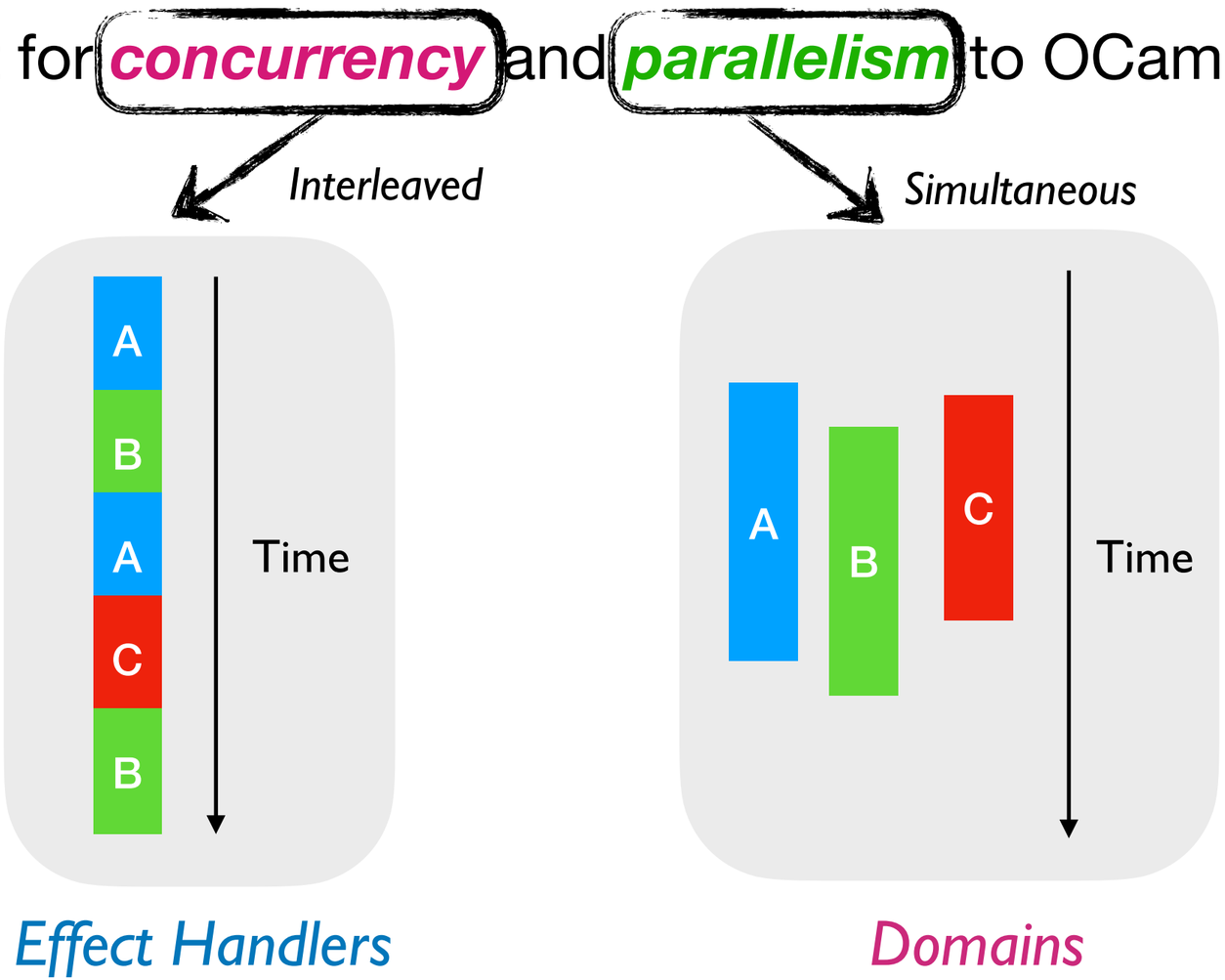
- Native-support for ***concurrency*** and ***parallelism*** to OCaml
- Started in 2014 as “Multicore OCaml” project
  - OCaml 5.0 released in Dec 2022
  - **5.1** — Sep 2023; **5.2** — May 2024; **5.3** — Jan 2025
- This talk
  - Concurrency
  - (if there is time) Experience porting from multi-process to multi-core



OCaml 5

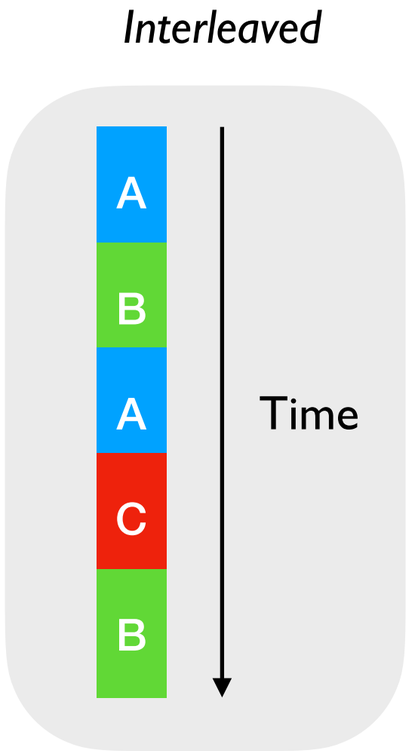
- Native-support for *concurrency* and *parallelism* to OCaml

"Retrofitting Effect Handlers onto OCaml", PLDI 2021



"Retrofitting Parallelism onto OCaml", ICFP 2020

Concurrency

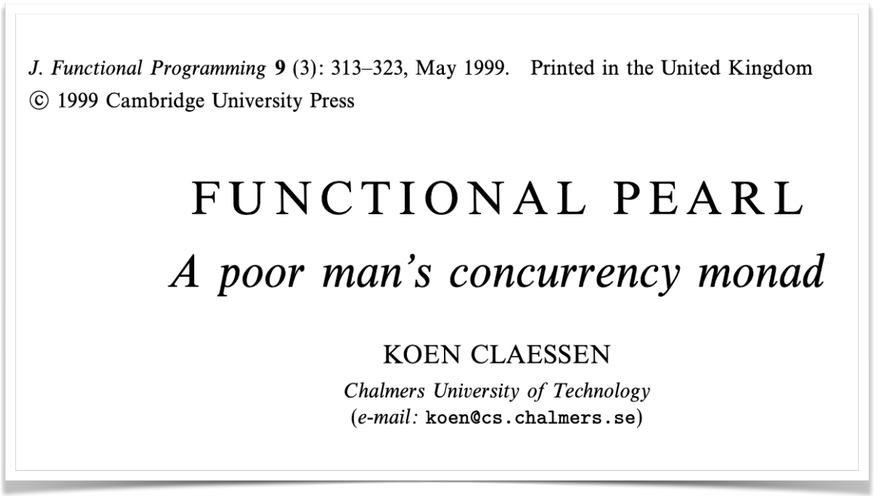


Concurrent Programming

- Computations may be *suspended* and *resumed* later
- Many languages provide concurrent programming mechanisms as *primitives*
  - **async/await** — JavaScript, Python, Rust, C# 5.0, F#, Swift, …
  - **generators** — Python, Javascript, …
  - **coroutines** — C++, Kotlin, Lua, …
  - **futures & promises** — JavaScript, Swift, …
  - **Lightweight threads/processes** — Haskell, Go, Erlang
- *Often include many different primitives in the same language!*
  - JavaScript has async/await, generators, promises, and callbacks

Concurrent Programming in OCaml 4

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



J. Functional Programming **9** (3): 313–323, May 1999. Printed in the United Kingdom

FUNCTIONAL PEARL

A poor man's concurrency monad

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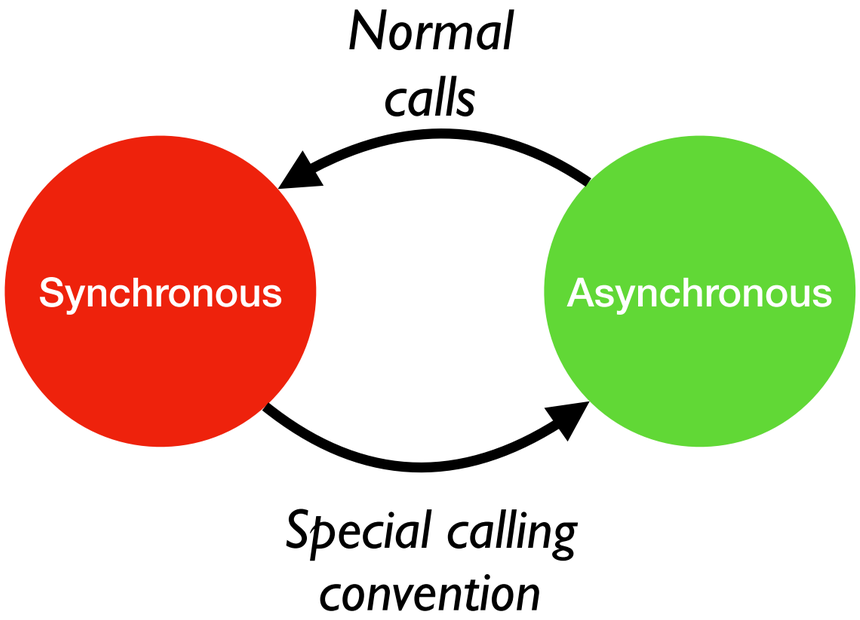
Concurrent Programming in OCaml 4

- No *primitive* support for concurrent programming
- **Lwt** and **Async** - concurrent programming *libraries* in OCaml
  - Callback-oriented programming with *monadic* syntax
- Suffers the pitfalls of callback-orinted programming
  - Incomprehensible (*"callback hell"*), no backtraces, poor performance, function colouring



What Color is Your Function?

- Bob Nystrom

FEBRUARY 01, 2015 CODE DART GO JAVASCRIPT LANGUAGE LUA

I don't know about you, but nothing gets me going in the morning quite like a good old fashioned programming language rant. It stirs the blood to see someone skewer one of those "blub" languages the plebians use, muddling through their day with it between furtive visits to StackOverflow.

Don’t want a *zoo* of primitives but want *expressivity*

What’s the *smallest* primitive that expresses *many* concurrency patterns?

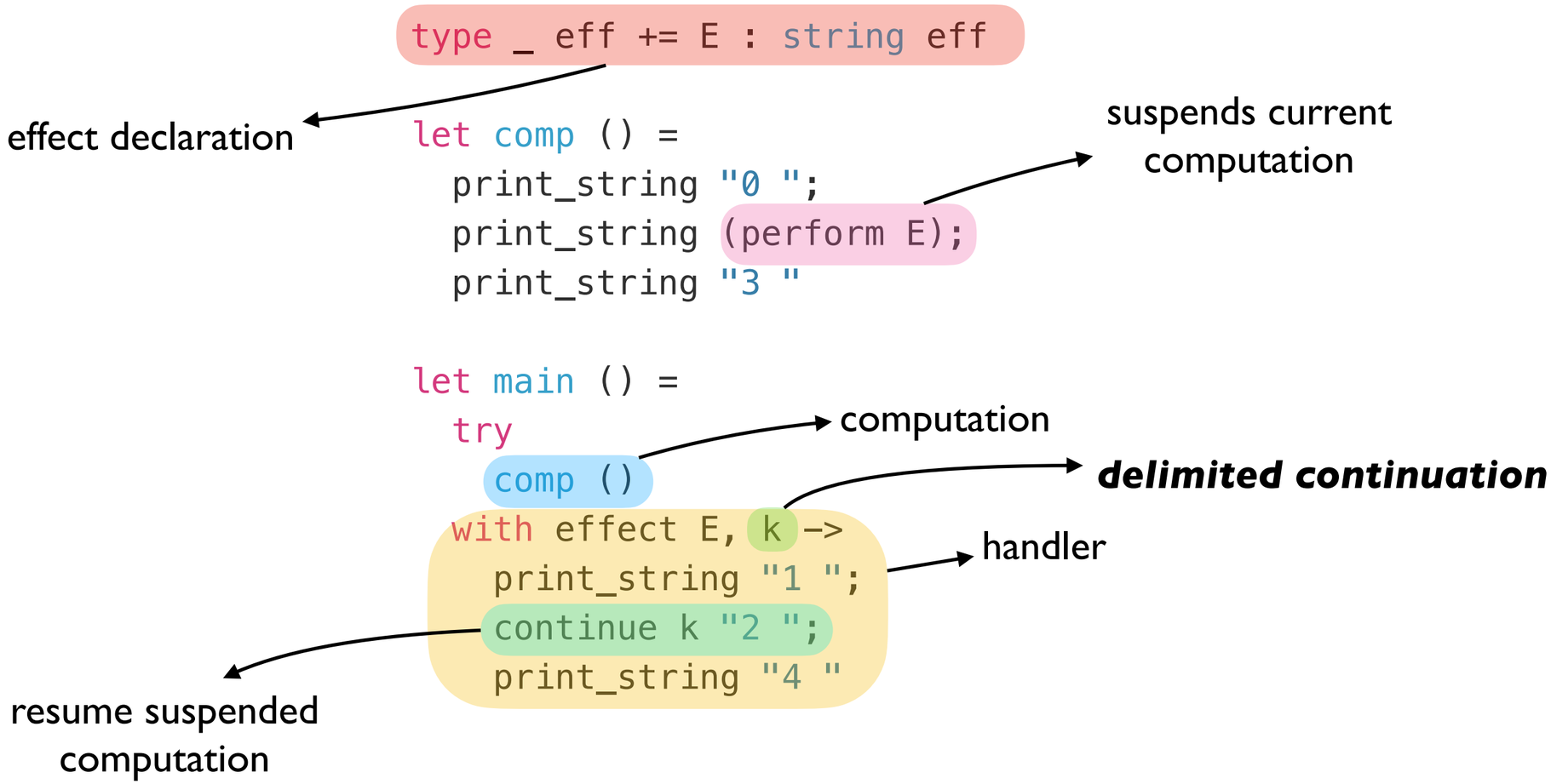
Effect handlers

- A mechanism for programming with *user-defined effects*
- *Modular* and *composable* basis of non-local control-flow mechanisms
  - ✦ Exceptions, generators, lightweight threads, promises, asynchronous IO, coroutines as *libraries*
- Effect handlers ~= *first-class, restartable exceptions*
  - ✦ Structured programming with *delimited continuations*

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

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

Effect handlers



Stepping through the example

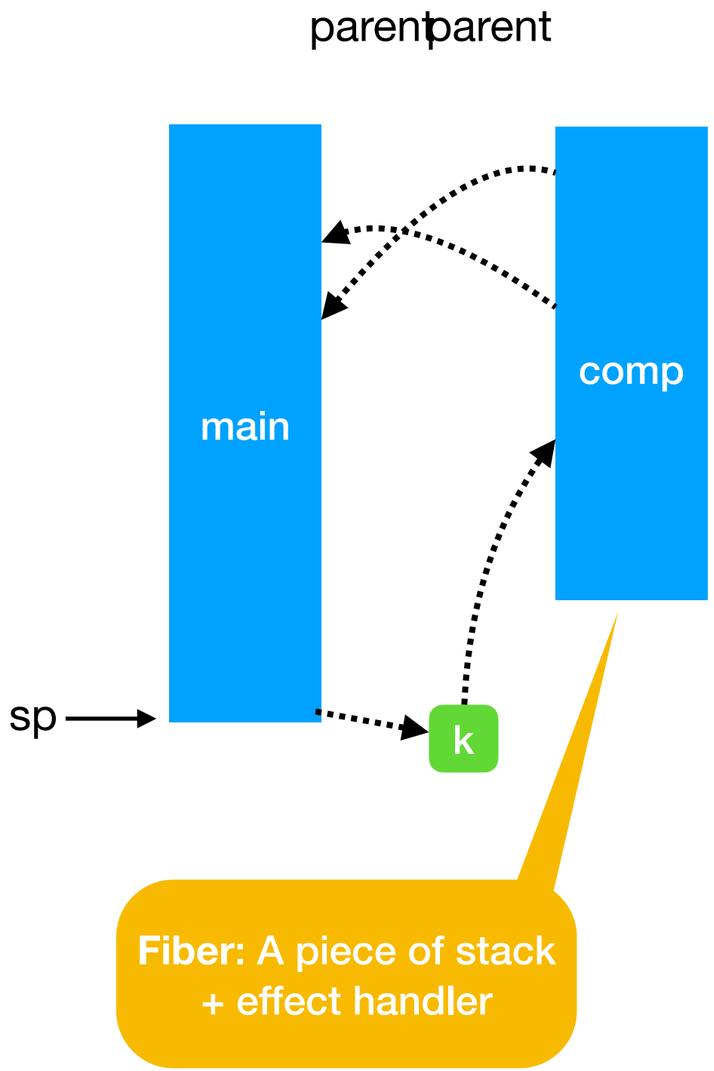
```
type 'a eff += E : string eff

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 "
```

pc →

0 1 2 3 4



Handlers can be nested

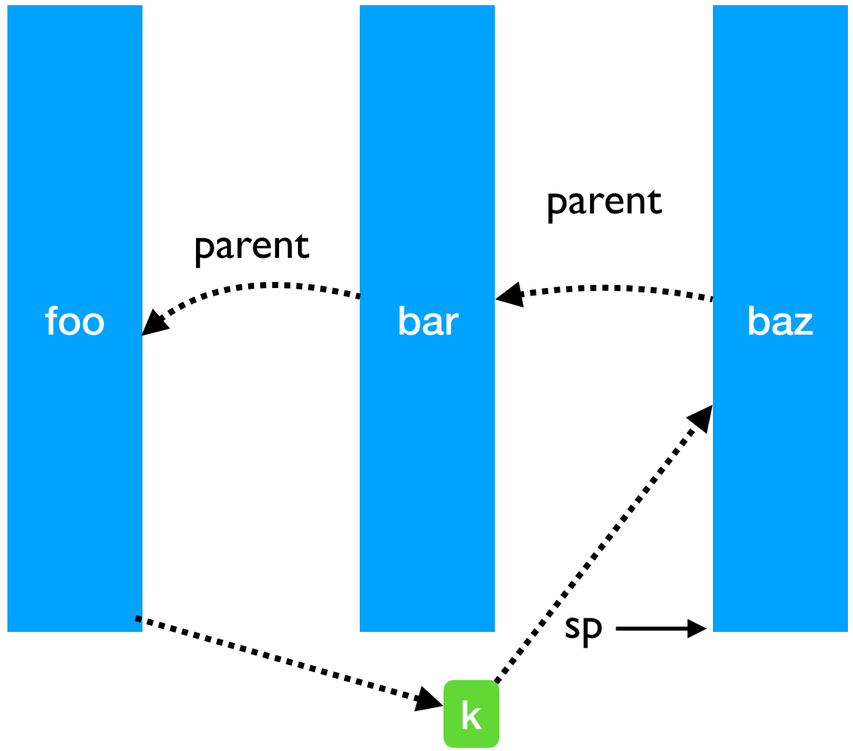
```
type _ eff += A : unit eff
           | B : unit eff

let baz () =
  perform A

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

let foo () =
  try
    bar ()
  with effect A, k ->
    continue k ()
```

pc →



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

Lightweight threading

```
type _ eff += Fork  : (unit -> unit) -> unit eff
            | Yield : unit eff

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

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

Effect Handler

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
```

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

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
```

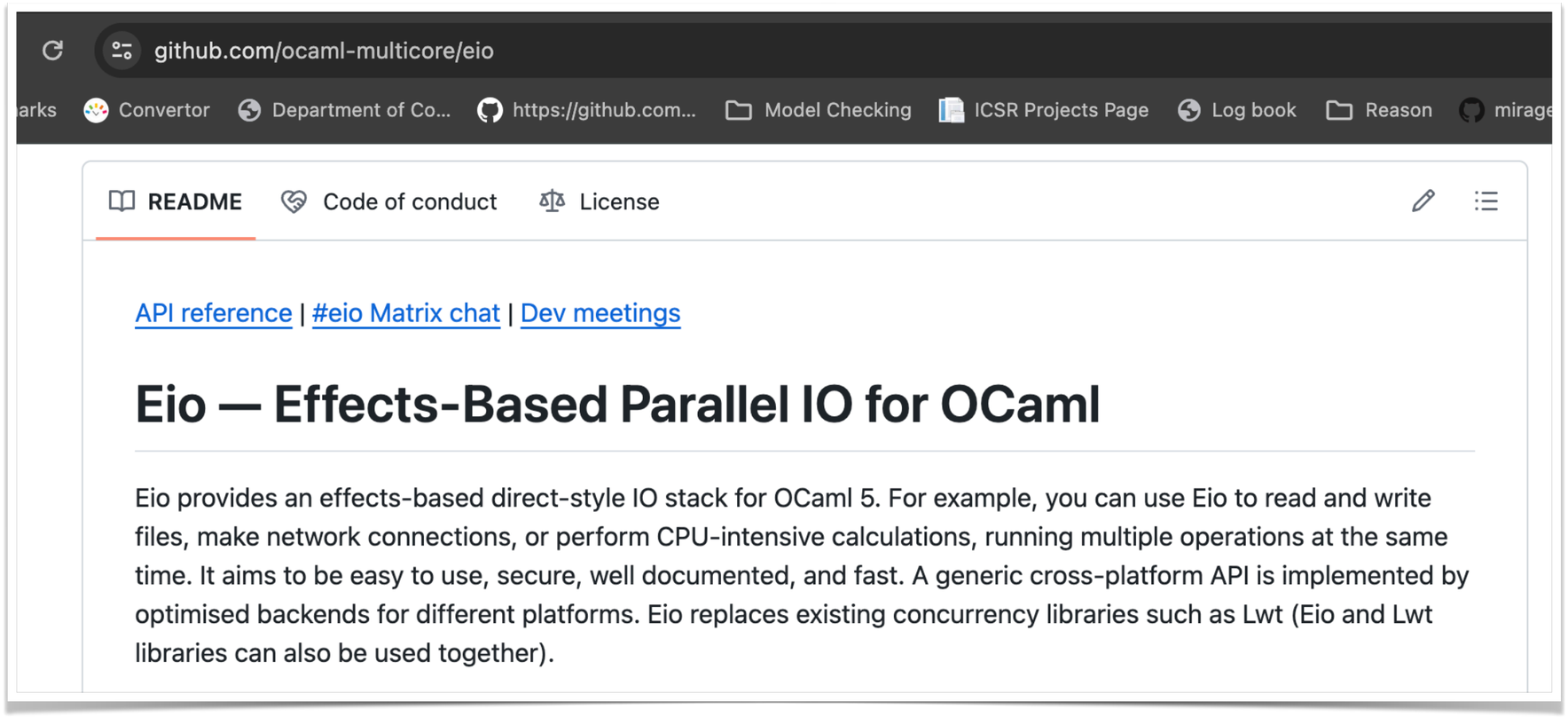
```
1.a
2.a
1.b
2.b
```

Ability to specialise scheduler
unlike GHC Haskell / Go

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

Industrial-strength concurrency

- **eio**: effects-based direct-style I/O
  - ✦ Multiple backends — epoll, select, ***io_uring*** *(new async io in Linux kernel)*



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

Industrial-strength concurrency

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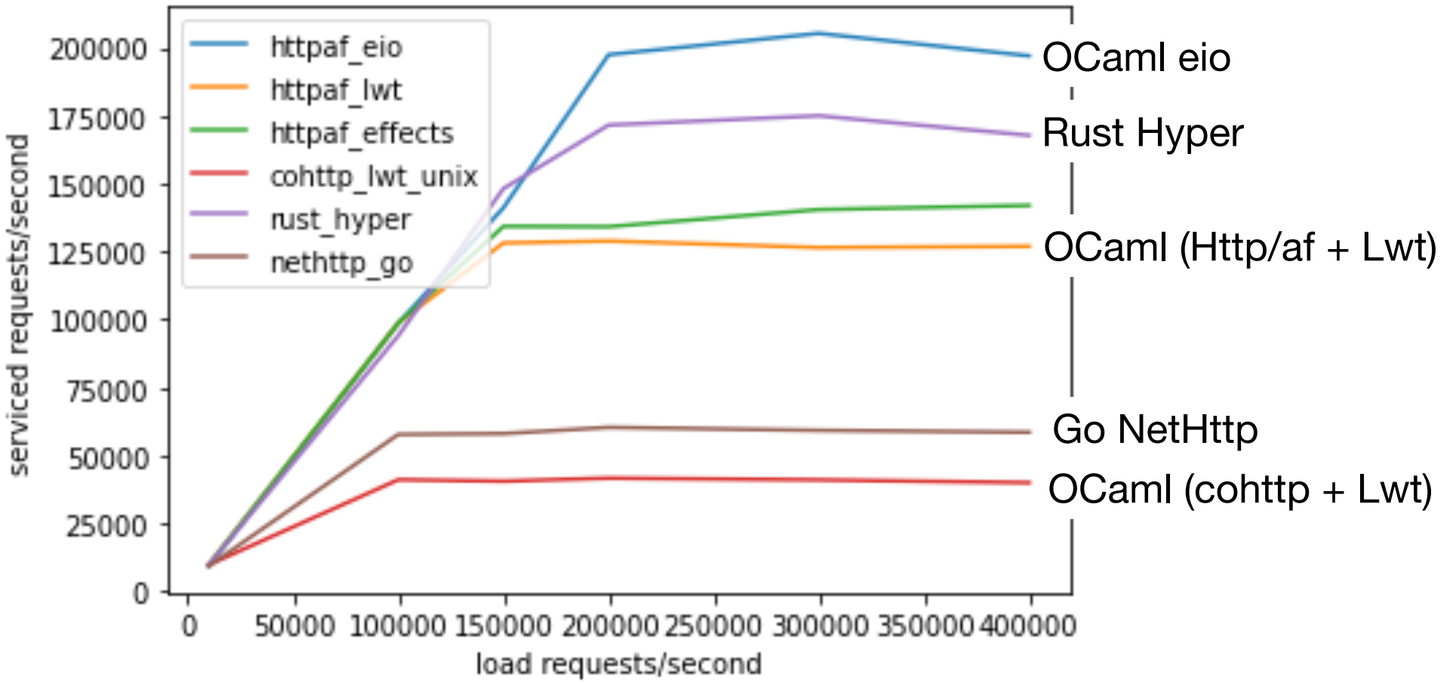


100 open connections, 60 seconds w/ io_uring

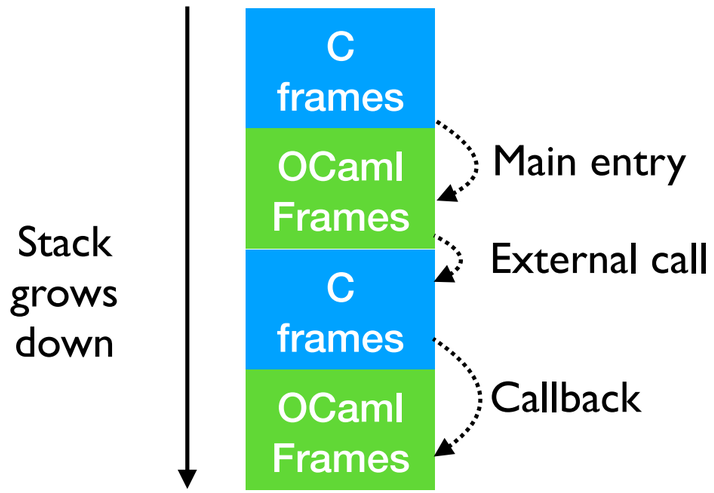
https://github.com/ocaml-multicore/eio

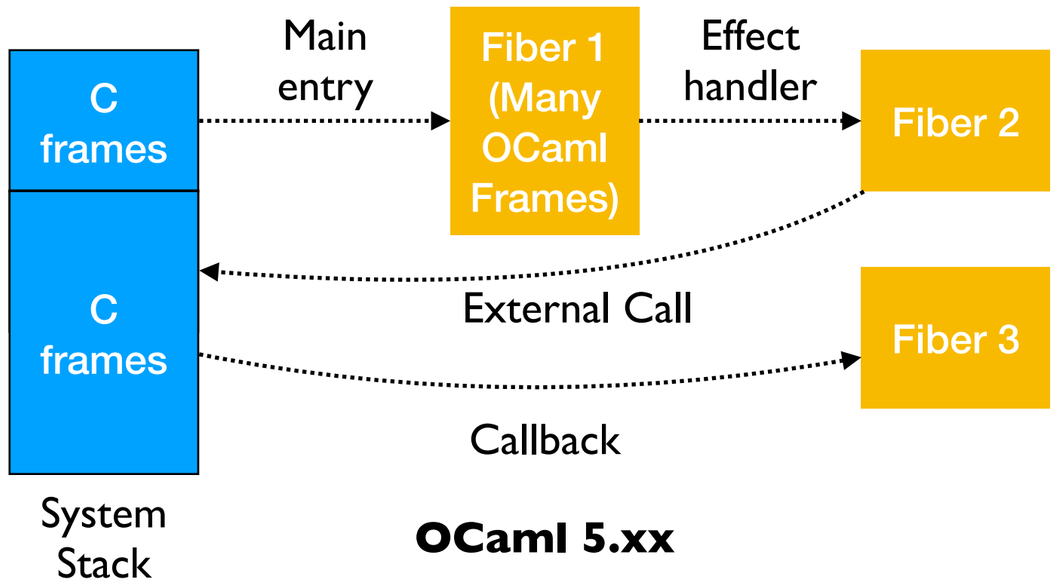
Representing Stack & Continuations

- Program stack is a stack of runtime-managed *dynamically growing* fibers
  - No pointers into the OCaml stack ➔ reallocate fibers on stack overflow
- Stack switching is ***fast!!***
  - One shot continuations ➔ No copying of frames
  - No callee-saved registers in OCaml ➔ No registers to save and restore at switches
  - *Few 10s of instructions; 5 to 10ns for stack switch*
- Need *stack overflow checks* in OCaml function prologue
  - Branch predictor correctly predicts almost always

Representing Stack & Continuations

- No stack overflow checks in C code
  - *Need to perform C calls on system stack!*





Made fast enough to be not noticable!

Porting Applications to OCaml 5

Based on work done by Thomas Leonard @ Tarides
https://roscidus.com/blog/blog/2024/07/22/performance-2/

Solver service

- ocaml-ci — CI for OCaml projects
  - Free to use for the OCaml community
  - Build and run tests on a matrix of platforms on *every commit*
    - **OCaml compilers** (4.02 — 5.2), **architectures** (32- and 64-bit x86, ARM, PPC64, s390x), **OSes** (Alpine, Debian, Fedora, FreeBSD, macOS, OpenSUSE and Ubuntu, in multiple versions)
- Select compatible versions of its dependencies
  - ~1s per solve; 132 solver runs per commit!
- Solves are done by solver-service
  - 160-core ARM machine
  - Lwt-based; sub-process based parallelism for solves
- *Port it to OCaml 5 to take advantage of better concurrency and shared-memory parallelism*

Solver service in OCaml 5

- Used Eio to port from *multi-process* parallel to *shared-memory* parallel
  - Support for asynchronous IO (incl ***io_uring***!) and parallelism
  - *Structured concurrency* and *switches* for resource management
- Outcome
  - Simple code, more stable (switches), removal of lots of IPC logic
  - No function colouring!
    - Reclaim the use of `try…with`, `for` and `while` loops!
- Used TSan to ensure that data races are removed

ThreadSanitizer (since 5.2)

- Detect data races dynamically
- Part of the LLVM project — C++, Go, Swift

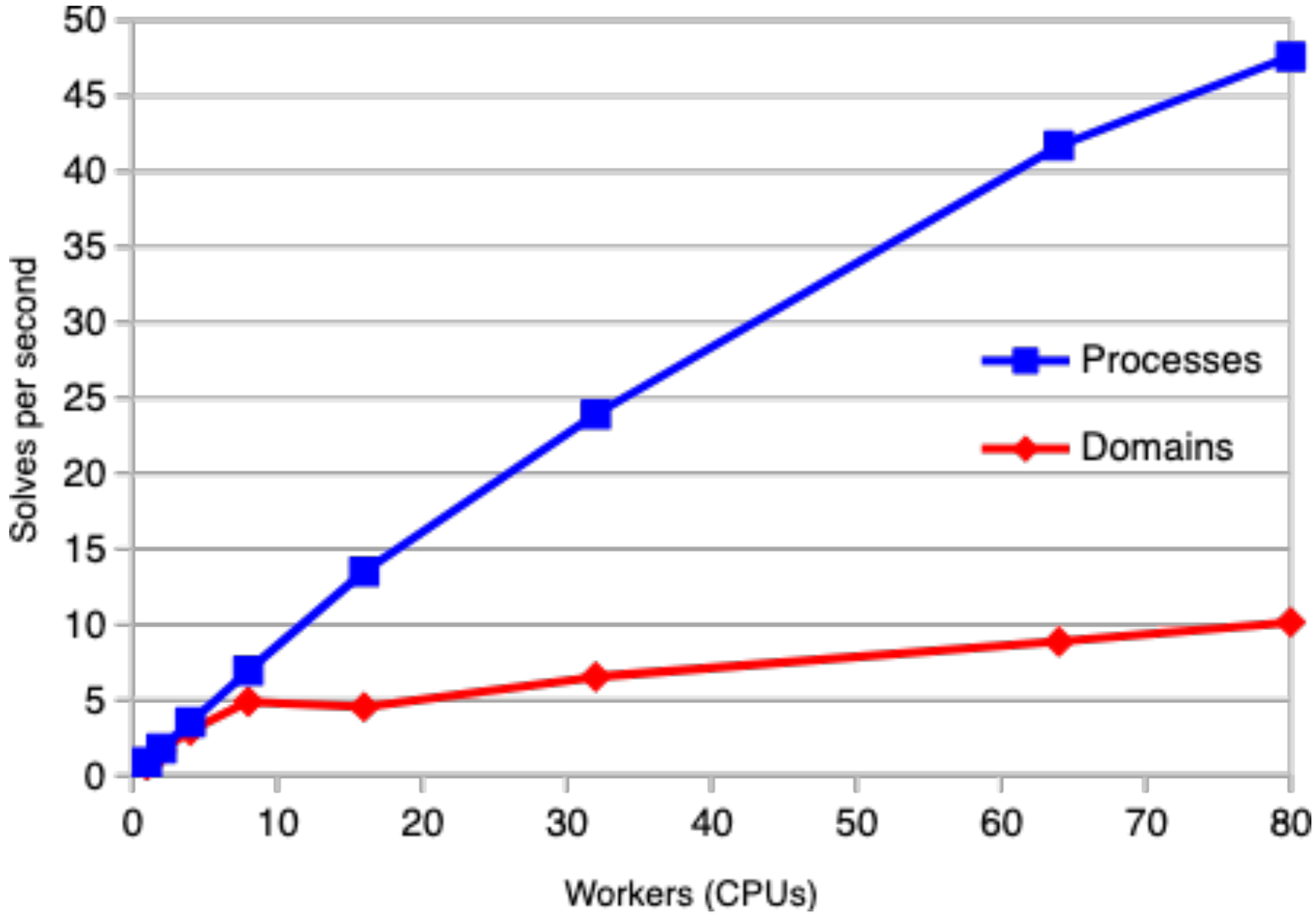
```
1  let a = ref 0 and b = ref 0
2
3  let d1 () =
4    a := 1;
5    !b
6
7  let d2 () =
8    b := 1;
9    !a
10
11 let () =
12   let h = Domain.spawn d2 in
13   let r1 = d1 () in
14   let r2 = Domain.join h in
15   assert (not (r1 = 0 && r2 = 0))
```

```
==================
WARNING: ThreadSanitizer: data race (pid=3808831)
  Write of size 8 at 0x8febe0 by thread T1 (mutexes: write M90
    #0 caml_Simple_race.d2_274 simple_race.ml:8 (simple_race.ex
    #1 caml_Domain.body_706 stdlib/domain.ml:211 (simple_race.e
    #2 caml_start_program <null> (simple_race.exe+0x47cf37)
    #3 caml_callback_exn runtime/callback.c:197 (simple_race.e
    #4 domain_thread_func runtime/domain.c:1167 (simple_race.e

  Previous read of size 8 at 0x8febe0 by main thread (mutexes
    #0 caml_Simple_race.d1_271 simple_race.ml:5 (simple_race.ex
    #1 caml_Simple_race.entry simple_race.ml:13 (simple_race.ex
    #2 caml_program <null> (simple_race.exe+0x41ffb9)
    #3 caml_start_program <null> (simple_race.exe+0x47cf37)
[...]
```

Eio solver service performance

- … was underwhelming ….initially

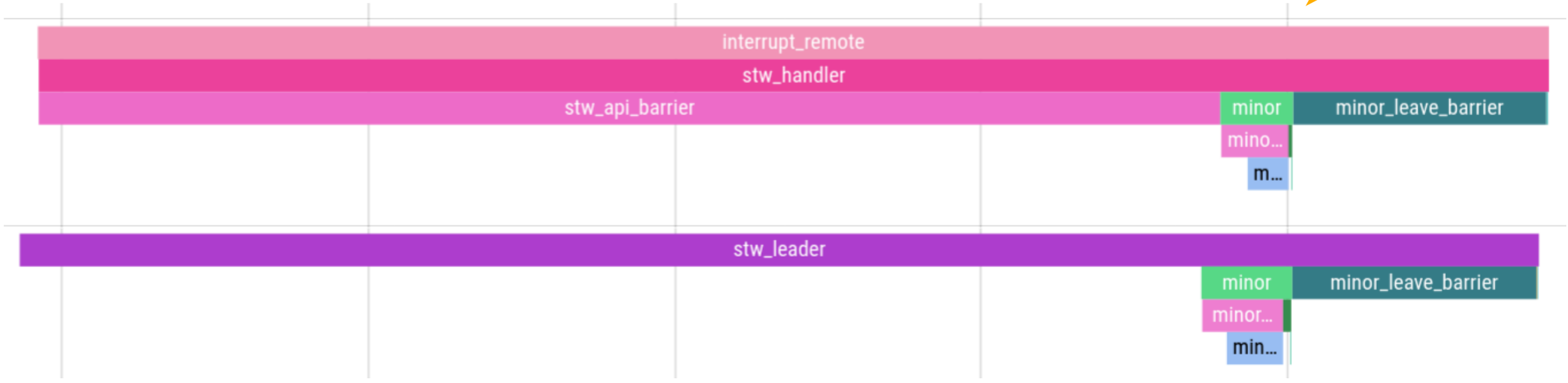


Performance analysis

- perf (incl. call graph), eBFP works
  - Frame-pointers across effect handlers!
- Runtime Events
  - *Every OCaml 5 program has tracing support built-in*
  - Events are written to a shared ring buffer that can be read by an external process

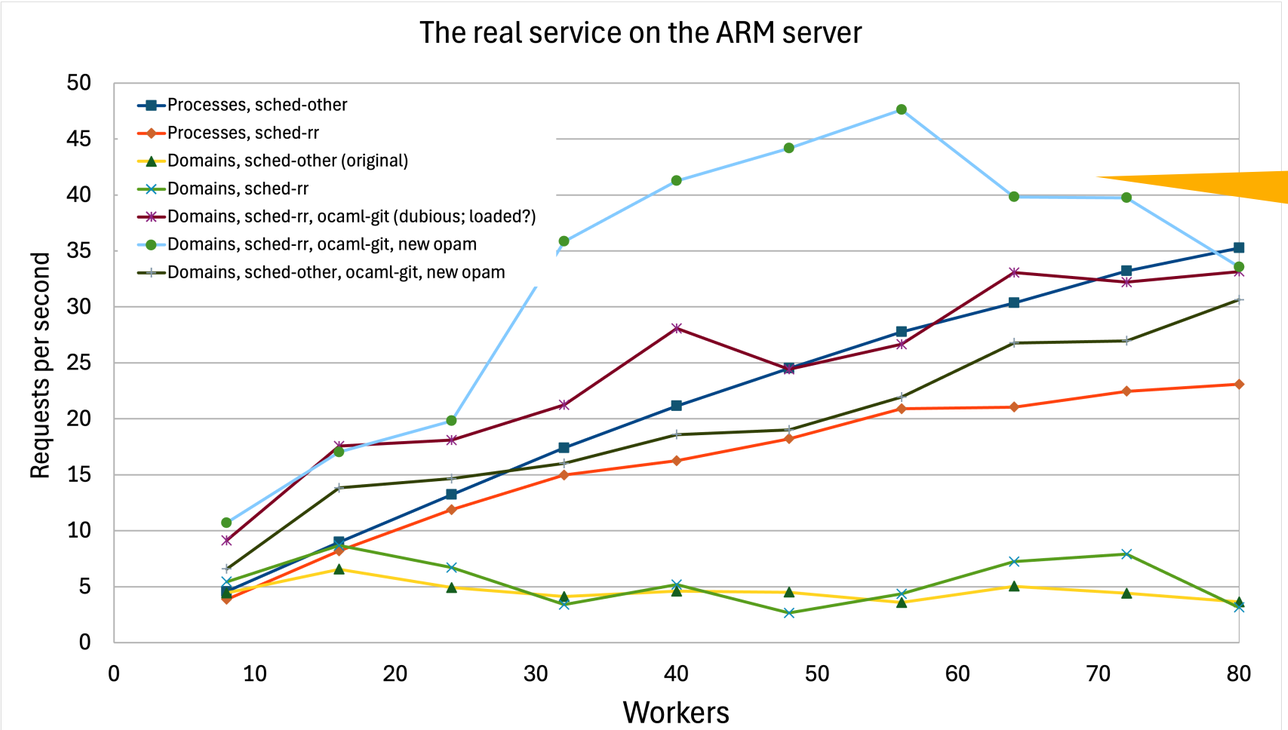
```
$ olly trace foo.trace foo.exe
```

https://perfetto.dev/



Problem indentified

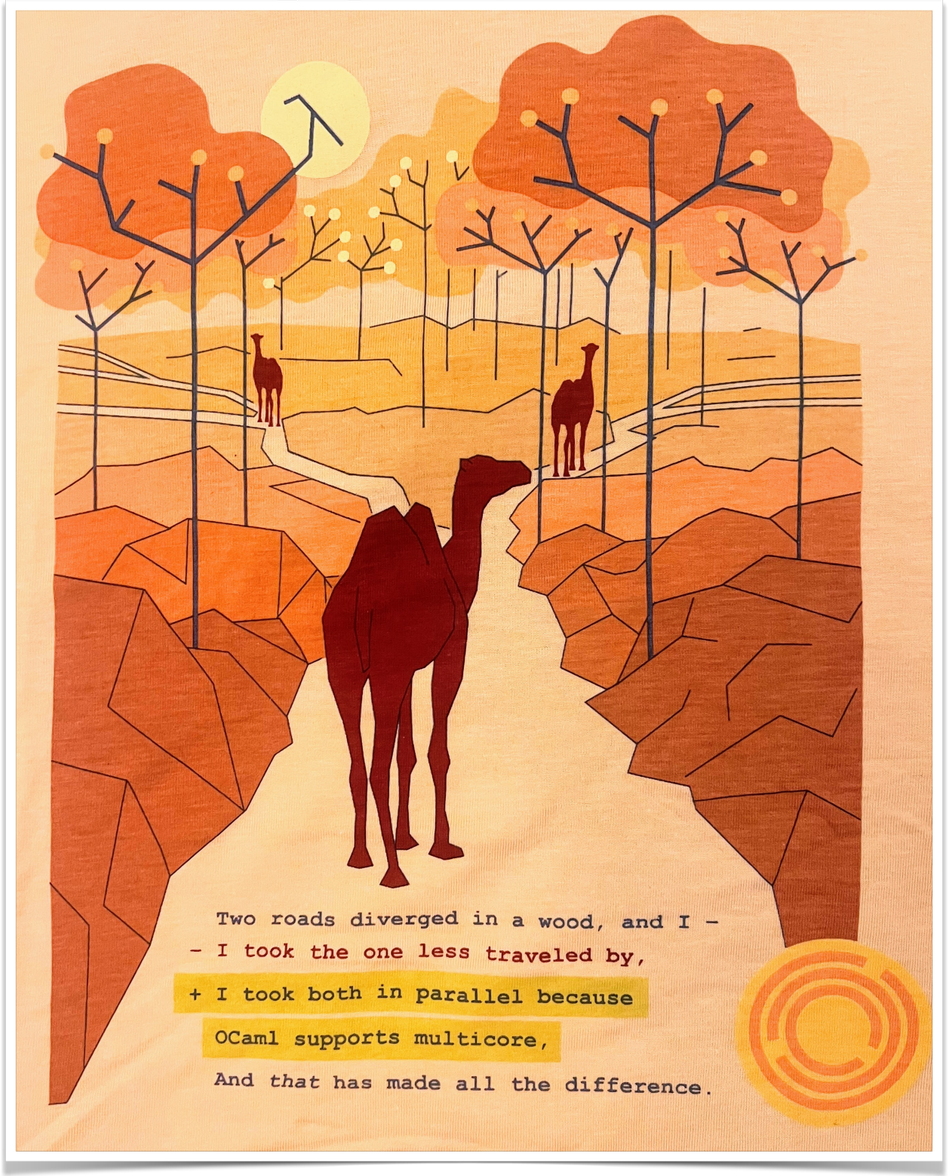
- Switch from `sched_other` to `sched_rr`
- `git log` for each solve to find earliest commit
  - 50ms penalty for STW subprocess spawn
  - Avoid by implementing it in OCaml



Still some work to do

Takeaways for introducing shared-memory parallellism

- Use Eio for concurrency and parallelism in OCaml 5
  - Makes your asynchronous IO program more reliable
- Other libraries
  - **Saturn**: Verified multicore safe data structures
  - **Kcas**: Software transactional memory for OCaml
- Use TSan to remove data races
  - Data races will not lead to crashes
- Expect that the initial performance may be underwhelming
  - Existing external tools such as perf, eBPF based profiling, statmemprof continue to work
  - New tools are available on OCaml 5 enabled through *runtime events* — Olly, eio-trace, etc.



Future

Oxidizing OCaml with Modal Memory Management

Data Rac

AÏNA LINN C
BENJAMIN P
LAILA ELBEH
LEO WHITE,
STEPHEN DO
RICHARD A.
CHRIS CASIN
FRANÇOIS P
DEREK DREY

We present DRF
threaded OCaml

A Mechanically Verified Garbage Collector for OCaml

JAR 2025

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A 2025

ational effects.
n, but using a
traditional effect system would require adding extensive effect annotations to the millions of lines of existing code in these languages. Recent proposals seek to address this problem by removing the need for explicit effect polymorphism. However, they typically rely on fragile syntactic mechanisms or on introducing a separate notion of second-class function. We introduce a novel semantic approach based on modal effect types.