

Concurrent and Parallel Programming with OCaml 5

“KC” Sivaramakrishnan

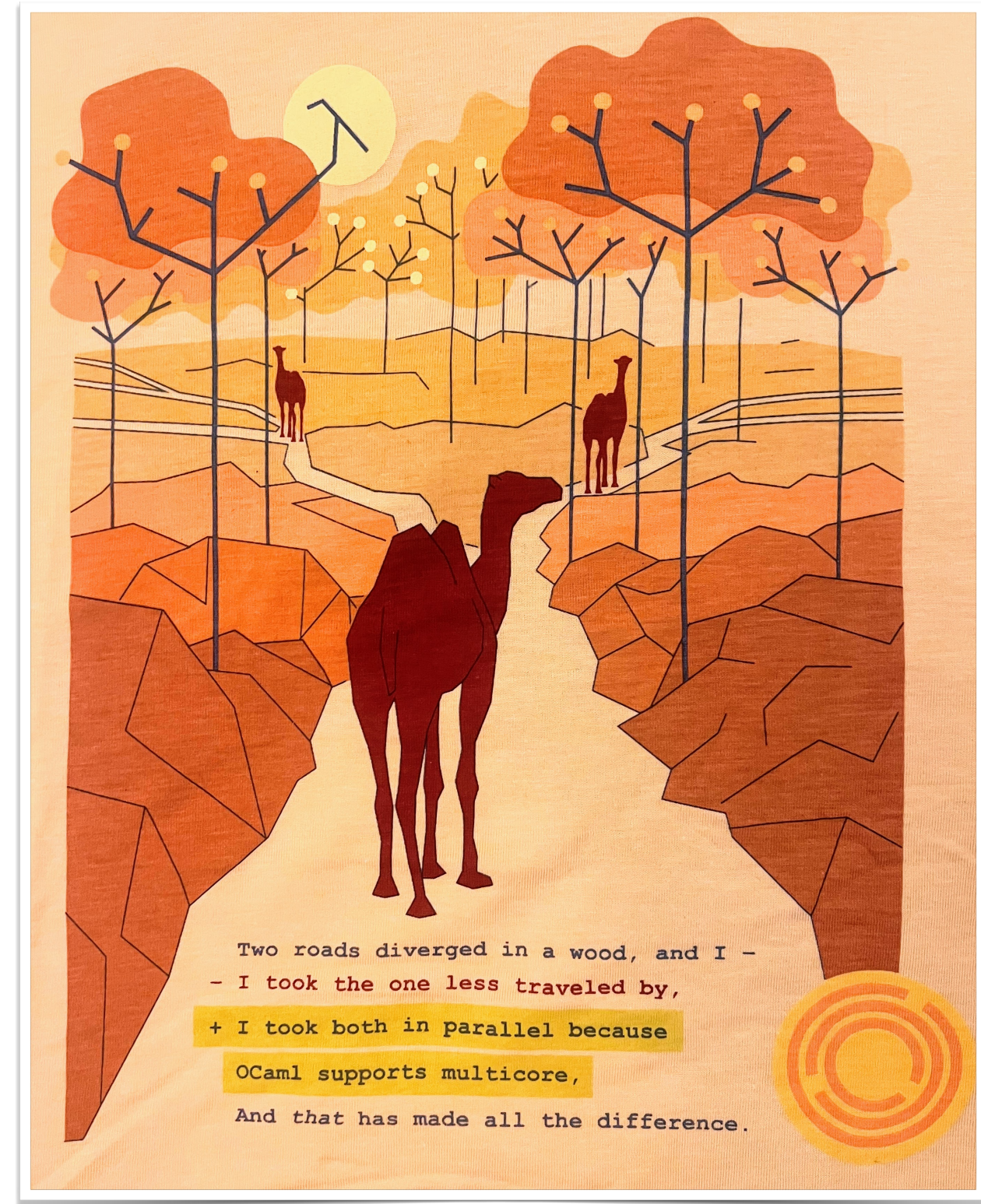
IIT
MADRAS



Tarides

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
 - Parallelism
 - Experience porting from multi-process to multi-core

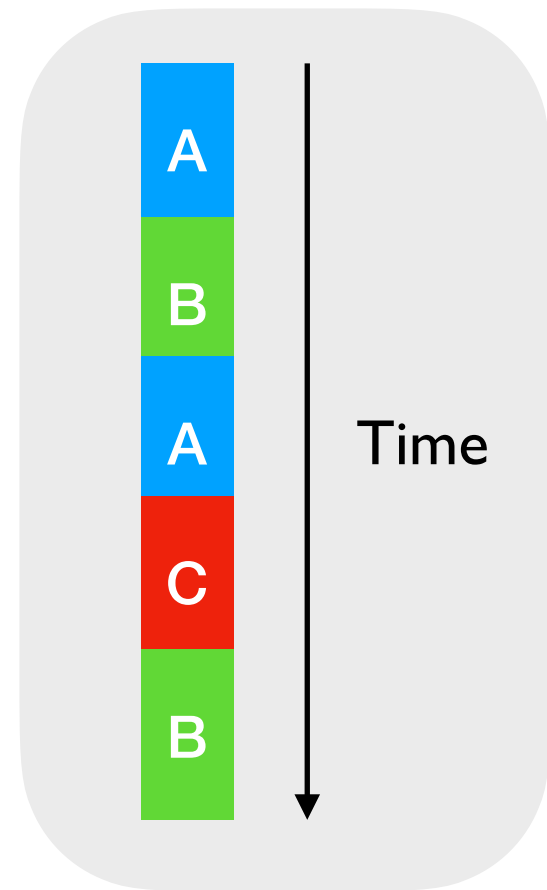


OCaml 5

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

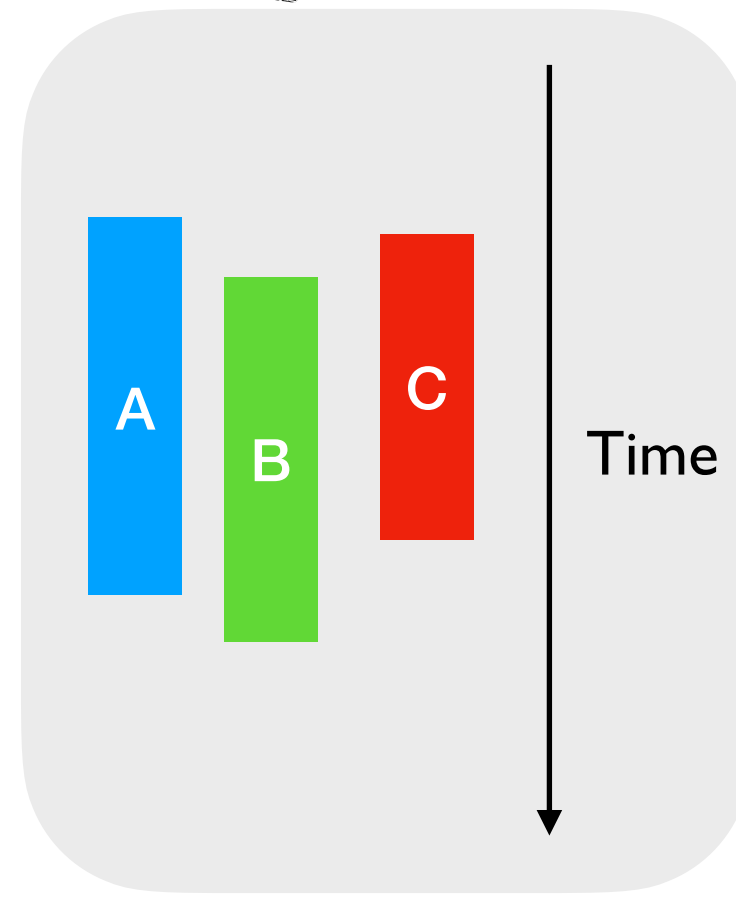
Interleaved

Simultaneous



Effect Handlers

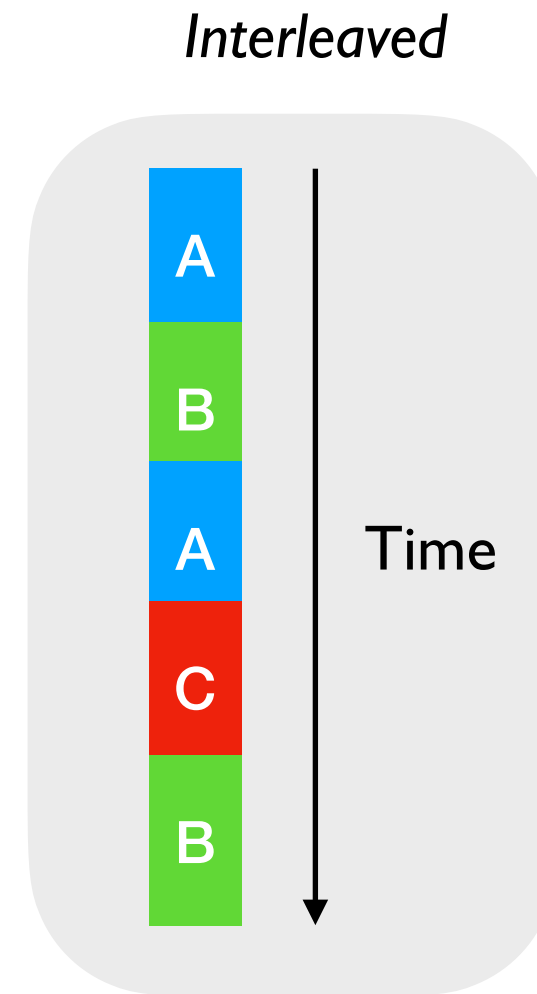
“Retrofitting Effect Handlers onto OCaml”, PLDI 2021



Domains

“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

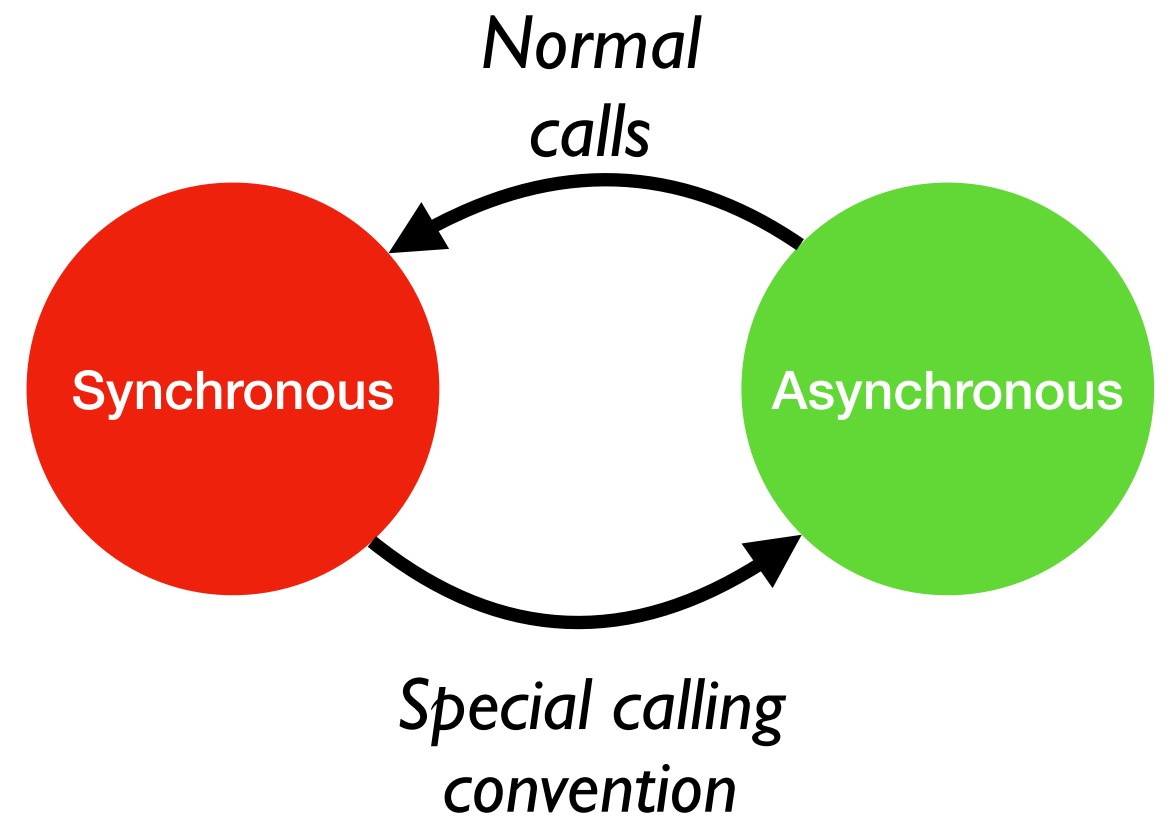
J. Functional Programming 9 (3): 313–323, May 1999. Printed in the United Kingdom
© 1999 Cambridge University Press

FUNCTIONAL PEARL
A poor man's concurrency monad

KOEN CLAESSEN
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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-oriented 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?

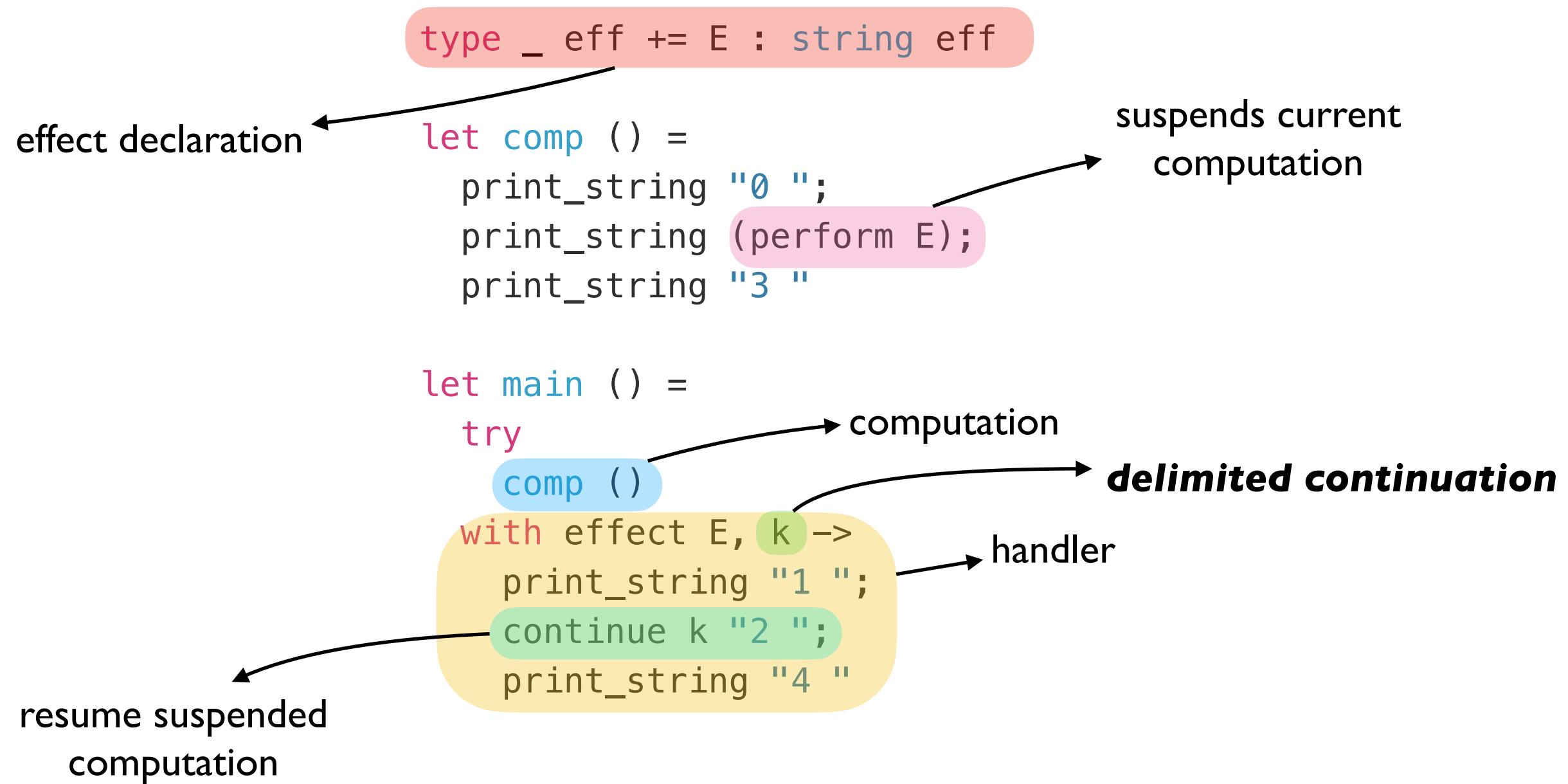
Effect handlers

- 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 \sim *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



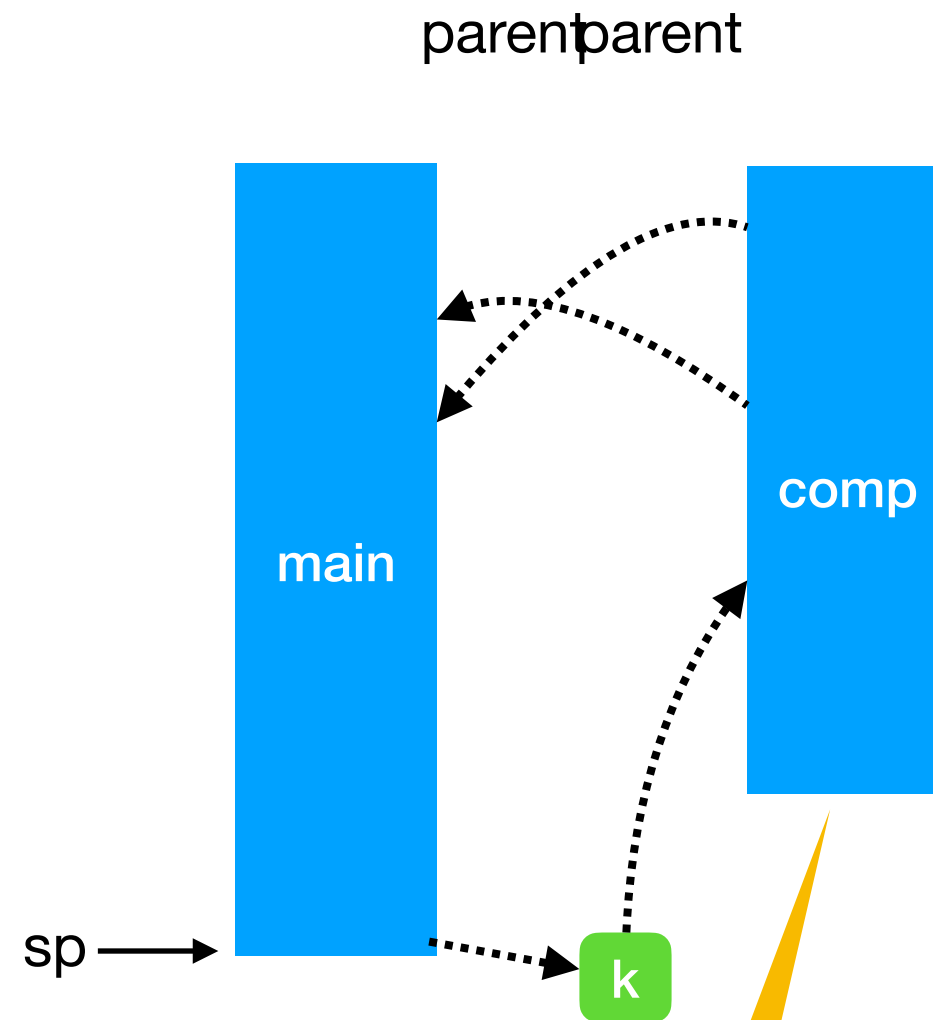
Stepping through the example

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

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

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

0 1 2 3 4



Fiber: A piece of stack + effect handler

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
```

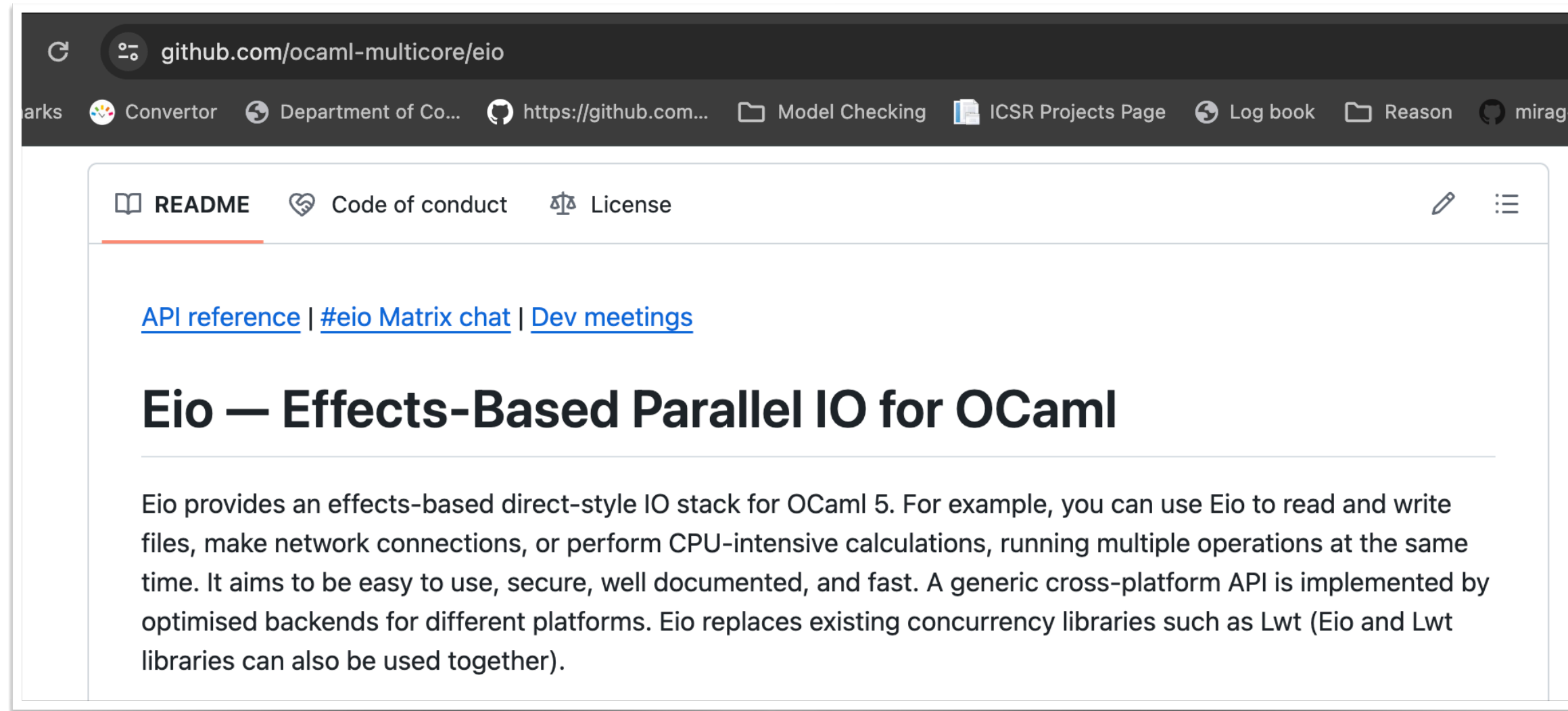
Ability to specialise
scheduler
unlike GHC Haskell / Go

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

- 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*)

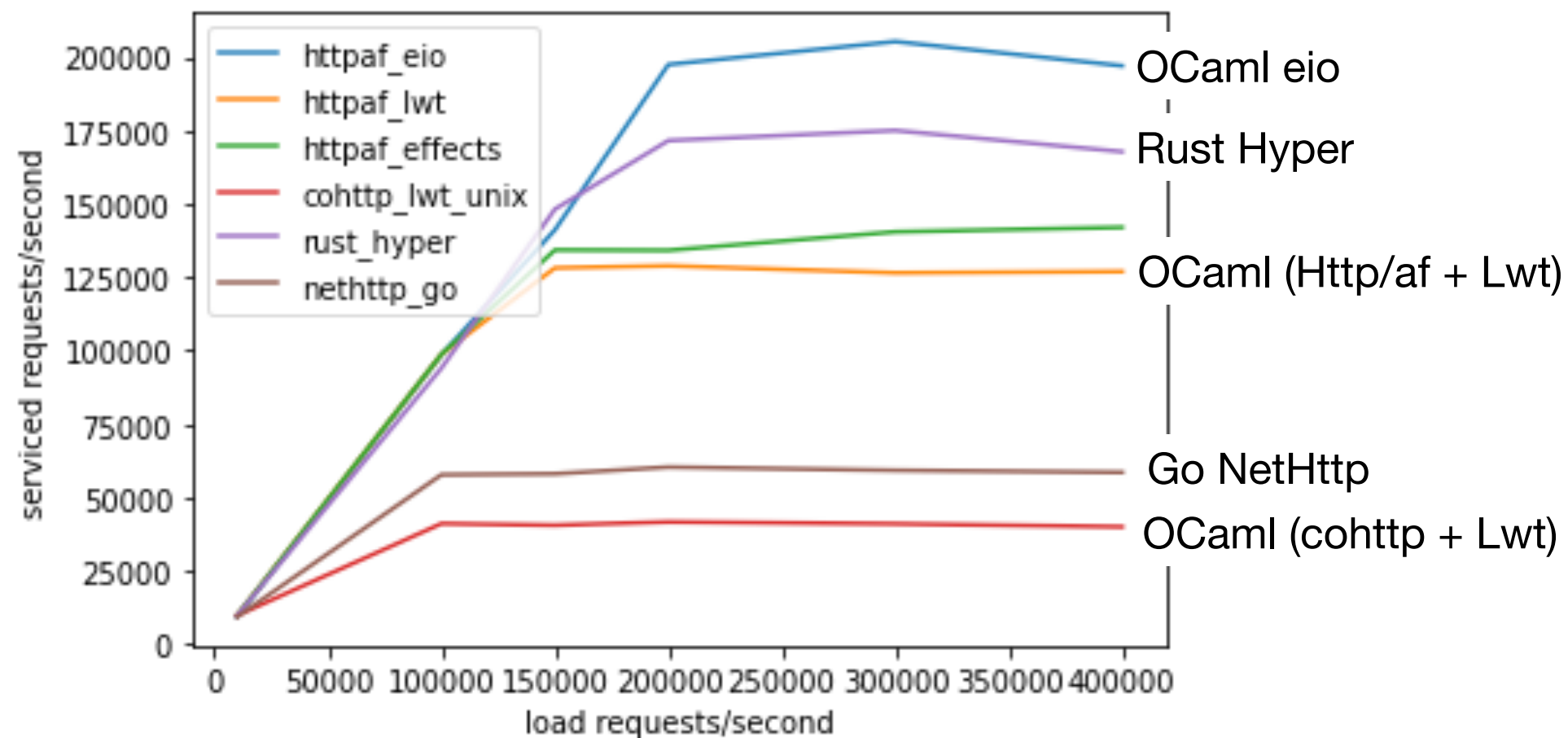


The screenshot shows a web browser window displaying the GitHub repository page for `ocaml-multicore/eio`. The browser's address bar shows the URL `github.com/ocaml-multicore/eio`. The page content includes a navigation bar with links for `README`, `Code of conduct`, and `License`. Below the navigation bar, there are links for `API reference`, `#eio Matrix chat`, and `Dev meetings`. The main heading is `Eio — Effects-Based Parallel IO for OCaml`. The introductory text states: "Eio provides an effects-based direct-style IO stack for OCaml 5. For example, you can use Eio to read and write files, make network connections, or perform CPU-intensive calculations, running multiple operations at the same time. It aims to be easy to use, secure, well documented, and fast. A generic cross-platform API is implemented by optimised backends for different platforms. Eio replaces existing concurrency libraries such as Lwt (Eio and Lwt libraries can also be used together)."

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

Industrial-strength concurrency

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



100 open connections, 60 seconds w/ io_uring

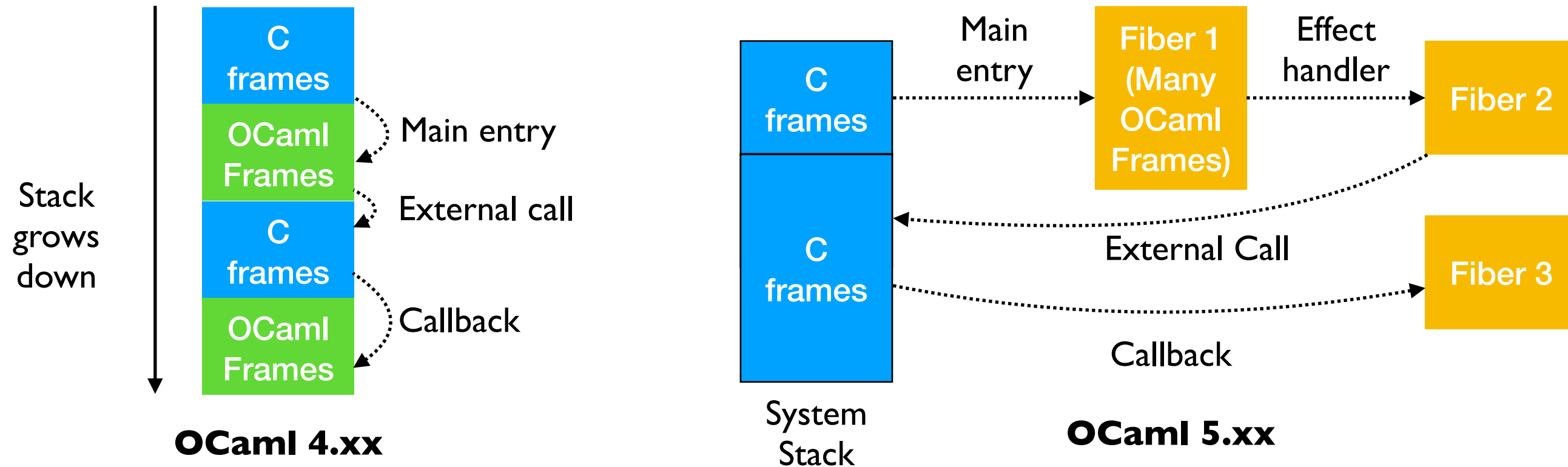
<https://github.com/ocaml-multicore/eio>

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!

Summary — Effect Handlers

- Effect handlers brings *simple*, *fast*, *backwards compatible* native concurrency to OCaml
- Support for
 - ▶ Integration with GDB (DWARF backtraces)
 - ▶ frame-pointers (perf, eBPF)
- No static type system
 - ▶ Unhandled effects are runtime errors (just like exceptions)!

☰ The OCaml language

The OCaml language
◆ Language extensions

Chapter 12 Language extensions

24 Effect handlers

24.1 Basics

24.2 Concurrency

24.3 User-level threads

24.4 Control inversion

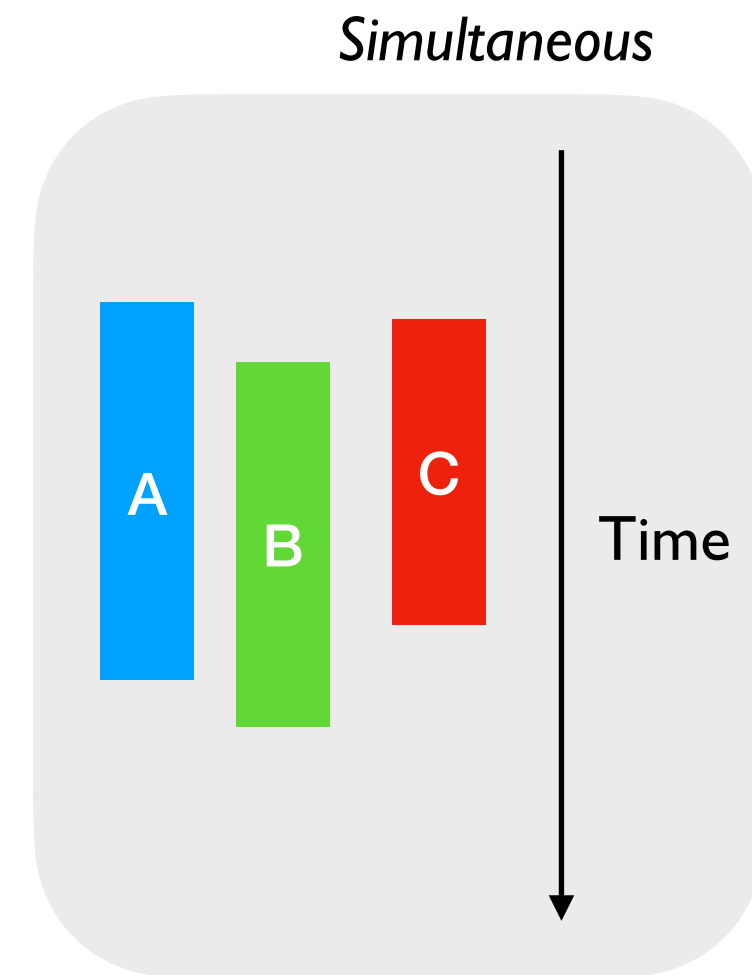
24.5 Semantics

24.6 Shallow handlers

(Introduced in 5.0)

Effect handlers are a mechanism for modular programming with user-defined effects. Effect handlers allow the programmers to describe *computations* that *perform* effectful *operations*, whose meaning is described by *handlers* that enclose the computations. Effect handlers are a generalization of exception handlers and enable non-local control-flow mechanisms such as resumable exceptions, lightweight threads, coroutines, generators and asynchronous I/O to be composably expressed. In this tutorial, we shall see how some of these mechanisms can be built using effect handlers.

Parallelism



Domains

- A unit of parallelism
- **Heavyweight** — maps onto an OS thread
 - Aim to have 1 domain per physical core
- Stdlib exposes
 - Spawn & join, Mutex, Condition, domain-local storage
 - Atomic references
- Relaxed memory model
 - Data-race-free programs have sequential consistency
 - *Programs with data races are type/memory safe!*
 - Unlike C++, unsafe Rust
 - Important when porting sequential code to be made parallel

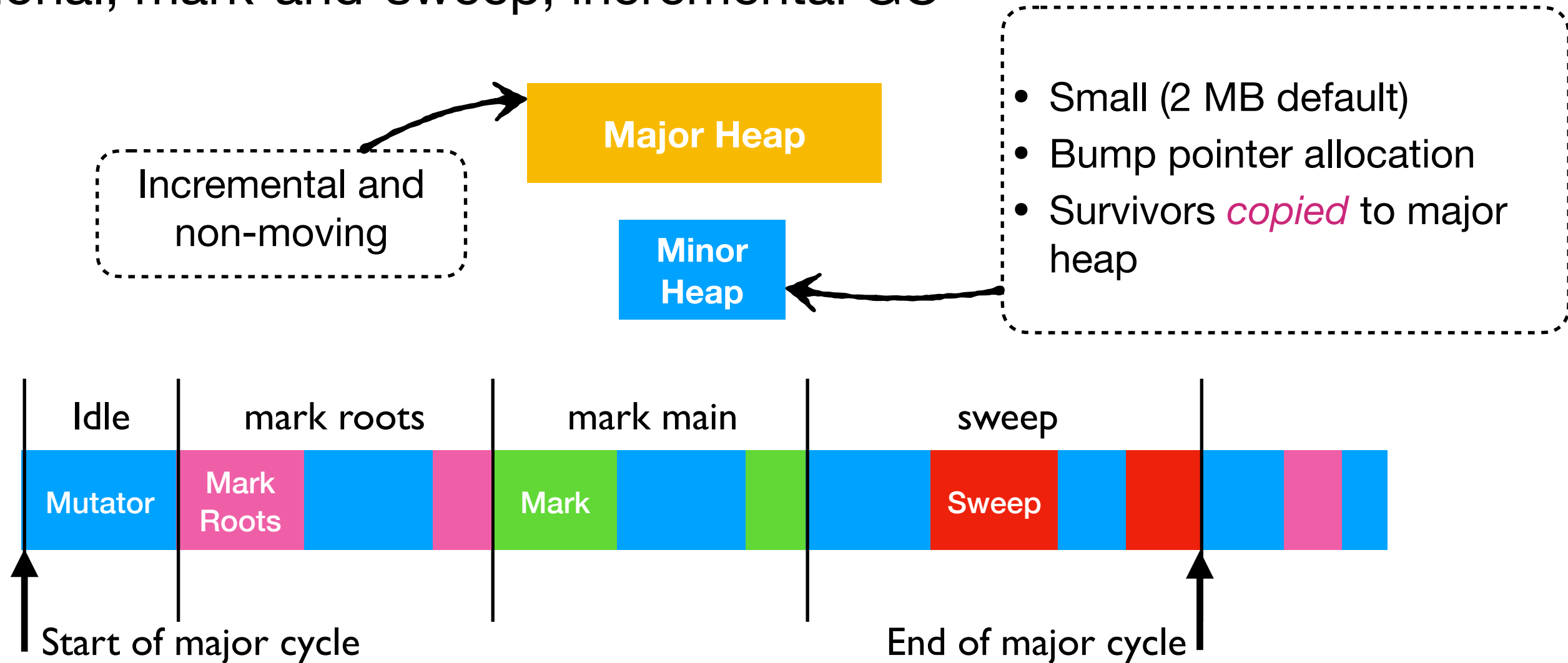
Chapter 10 Memory model: The hard bits

This chapter describes the details of OCaml relaxed memory model. The relaxed memory model describes what values an OCaml program is allowed to witness when reading a memory location. If you are interested in high-level parallel programming in OCaml, please have a look at the parallel programming chapter 9.

This chapter is aimed at experts who would like to understand the details of the OCaml memory model from a practitioner's perspective. For a formal definition of the OCaml memory model, its guarantees and the compilation to hardware memory models, please have a look at the PLDI 2018 paper on [Bounding Data Races in Space and Time](#). The memory model presented in this chapter is an extension of the one presented in the PLDI 2018 paper. This chapter also covers some pragmatic aspects of the memory model that are not covered in the paper.

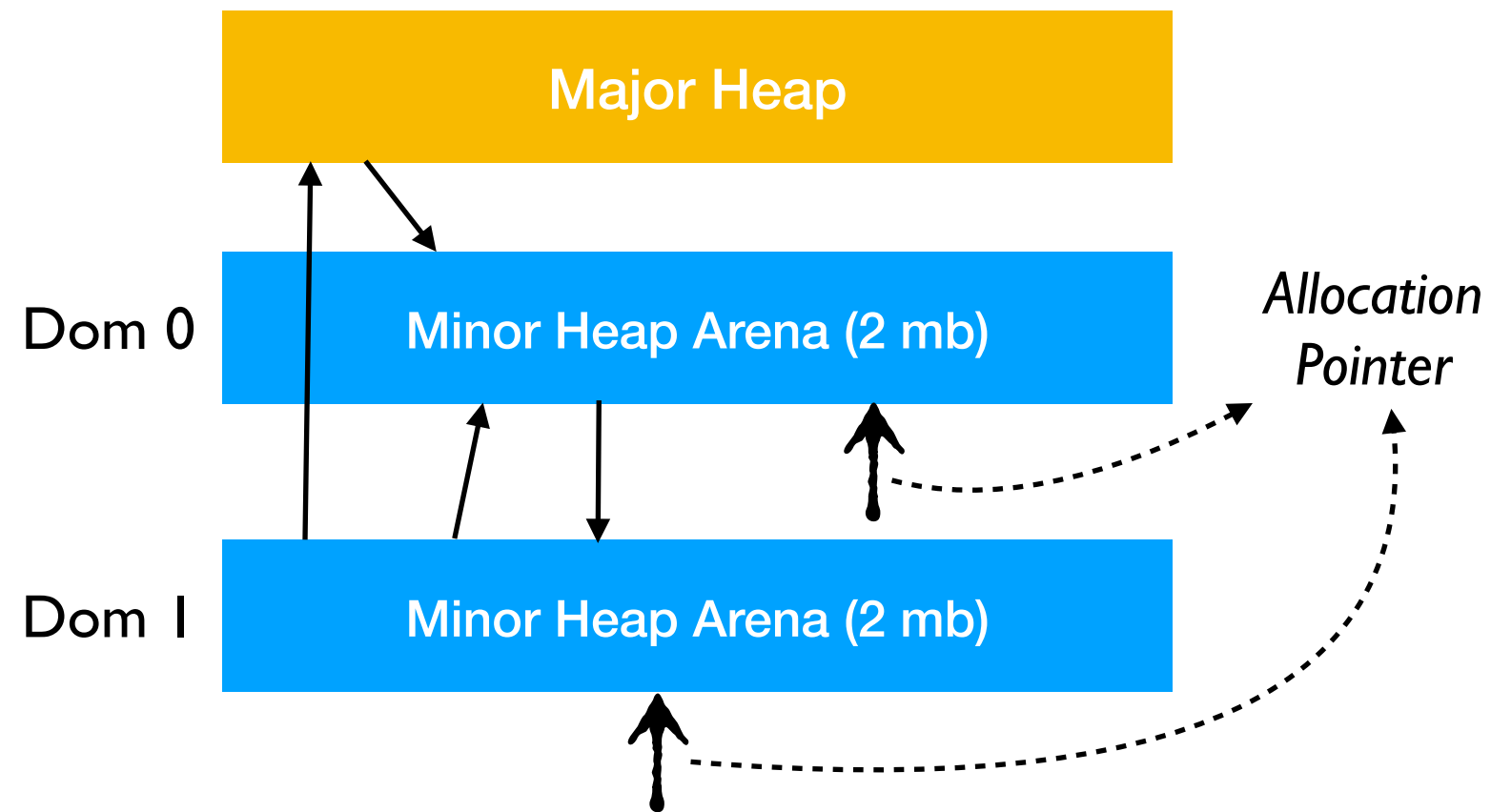
OCaml 4 GC

- Generational, mark-and-sweep, incremental GC



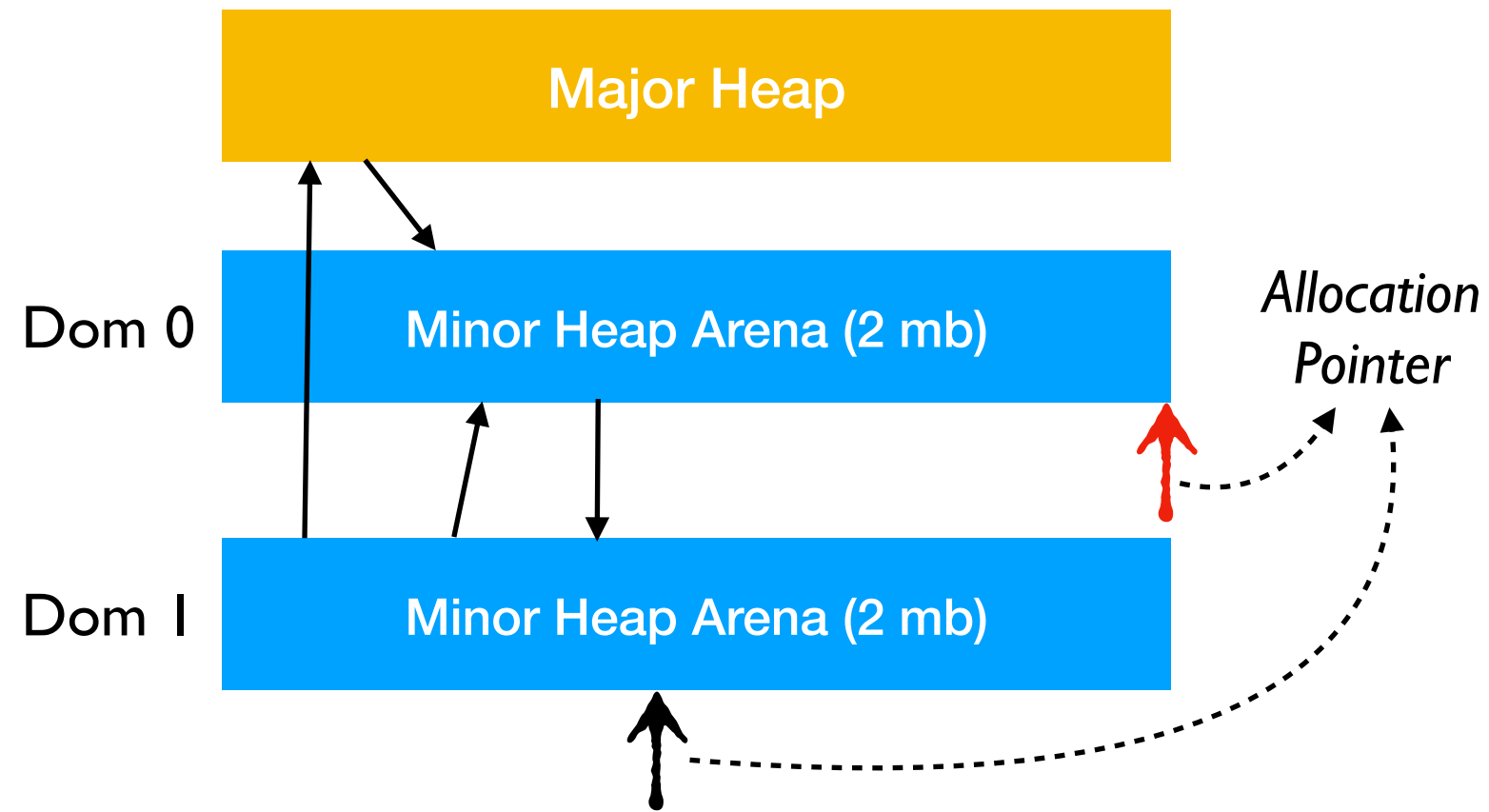
- Fast local allocations
- Max GC latency **< 10 ms**, 99th percentile latency **< 1 ms**

OCaml 5 minor GC



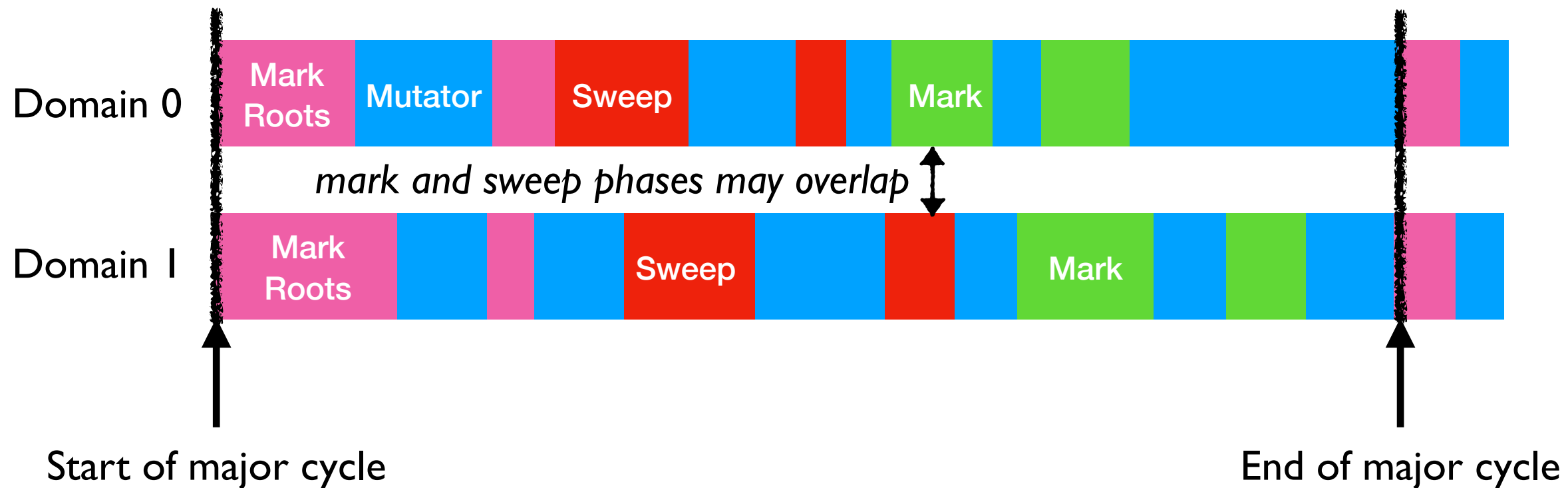
- Private minor heap arenas per domain
 - *Fast allocations without synchronisation*
- No restrictions on pointers between minor heap arenas and major heap

OCaml 5 minor GC



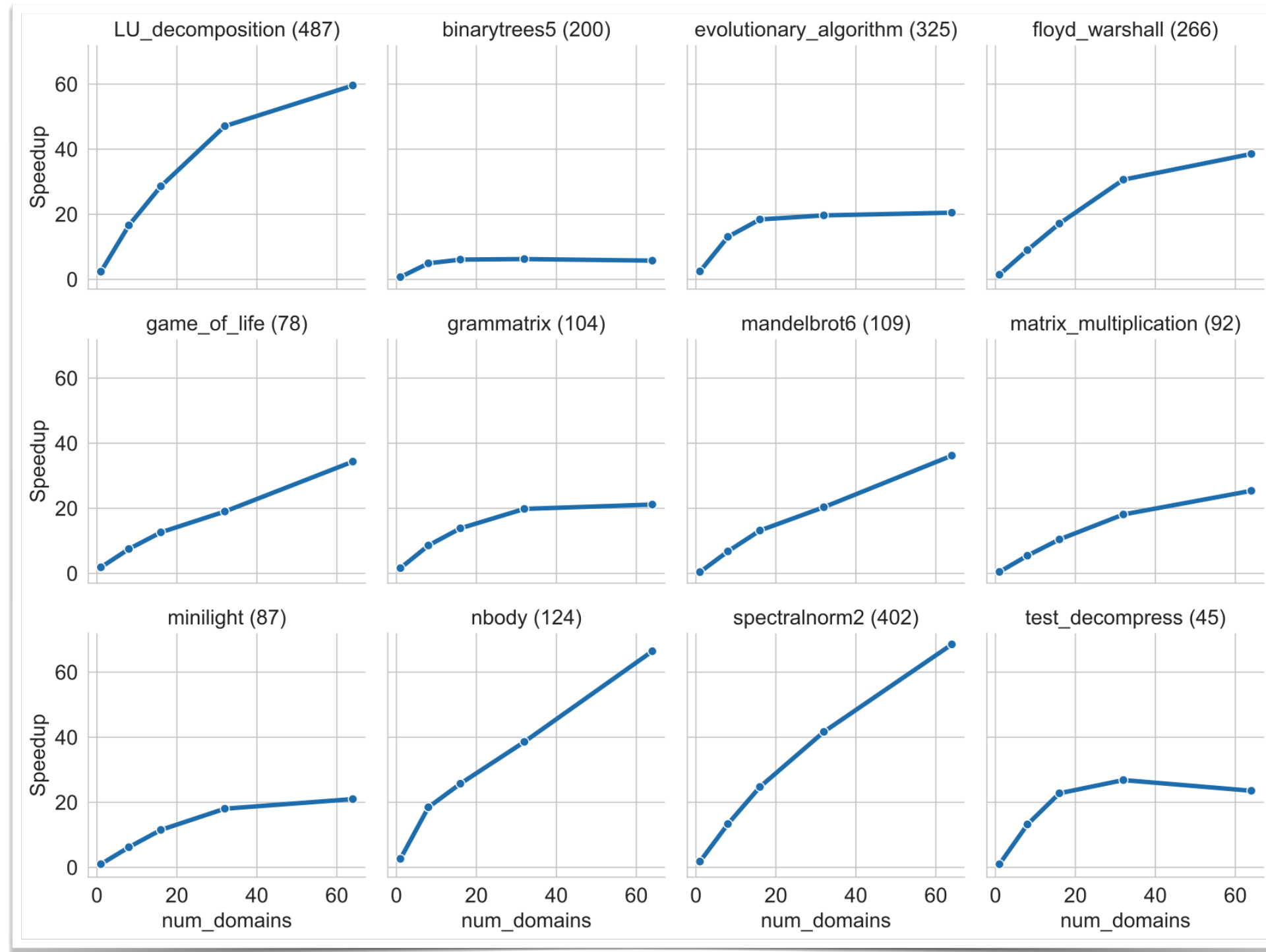
- *Stop-the-world parallel* collection for minor heaps
 - 2 barriers / minor gc; (some) work sharing between gc threads
- On 24 cores, w/ default heap size (2MB / arena), **< 10 ms** pause for completing minor GC

OCaml 5 major GC



- Mostly concurrent mark-and-sweep GC
- 3 barriers / cycle (when not using ephemerons)
 - 1 each at the end of mark, finalise_first, finalise_last phases
- On 24 cores, **< 5 ms** pauses at barriers
 - Only to agree that the phase has ended

Scalability



Backwards compatibility

- Both effect handlers and GC designed for *backwards compatibility*
 - Performance, tooling support, features (almost all of them)
- **Performance**
 - OCaml 5 is designed to run sequential programs as well as OCaml 4
 - *Any significant performance regressions (5%+) is a bug!*



Backwards compatibility

- **Feature set**
 - All of the language including finalisers, weak references, ephemerons, systhreads supported
 - Compaction (manual) is manual, no naked pointers
- **Programs with data races are *type and memory safe!***
 - Racy use of Stdlib may yield surprising results, but *will not crash!*
 - think Queue, Hashtbl, Lazy, Unix, etc.
- **Existing tools continue to work**
 - GDB, perf, eBFP, statmemprof



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

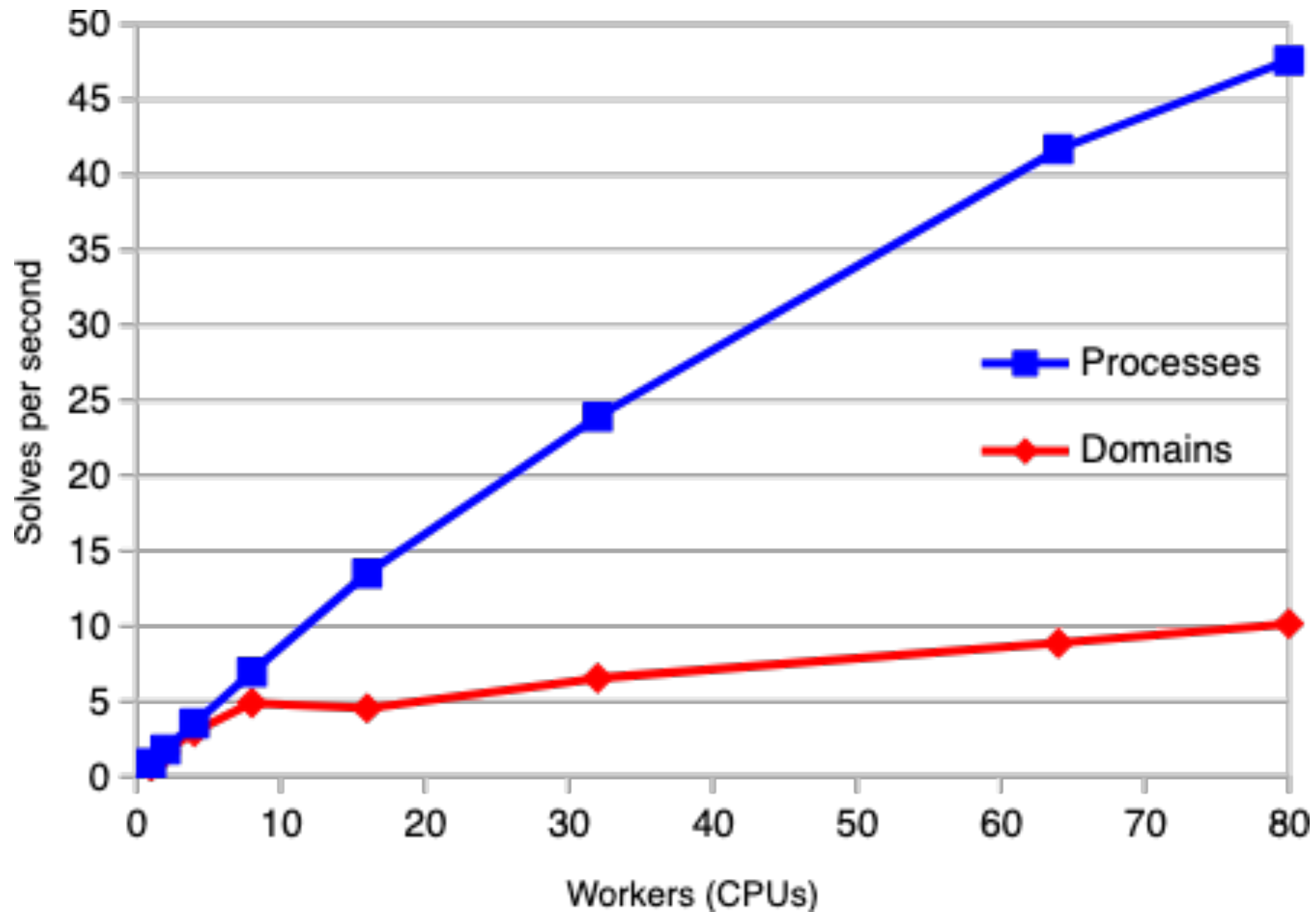
```
=====
1 let a = ref 0 and b = ref 0
2
3 let d1 () =
4   a := 1;
5   !b
6
7 let d2 () =
8   b := 1;
9   !a
10
11 let () =
12   let h = Domain.spawn d2 in
13   let r1 = d1 () in
14   let r2 = Domain.join h in
15   assert (not (r1 = 0 && r2 = 0)) [...]
```

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

Previous read of size 8 at 0x8febe0 by main thread (mutexes: read M90)
#0 camlSimple_race.d1_271 simple_race.ml:5 (simple_race.exe+0x47cf37)
#1 camlSimple_race.entry_simple_race.ml:13 (simple_race.exe+0x47cf37)
#2 caml_program <null> (simple_race.exe+0x41ffb9)
#3 caml_start_program <null> (simple_race.exe+0x47cf37)

Eio solver service performance

- ... was underwhelminginitially

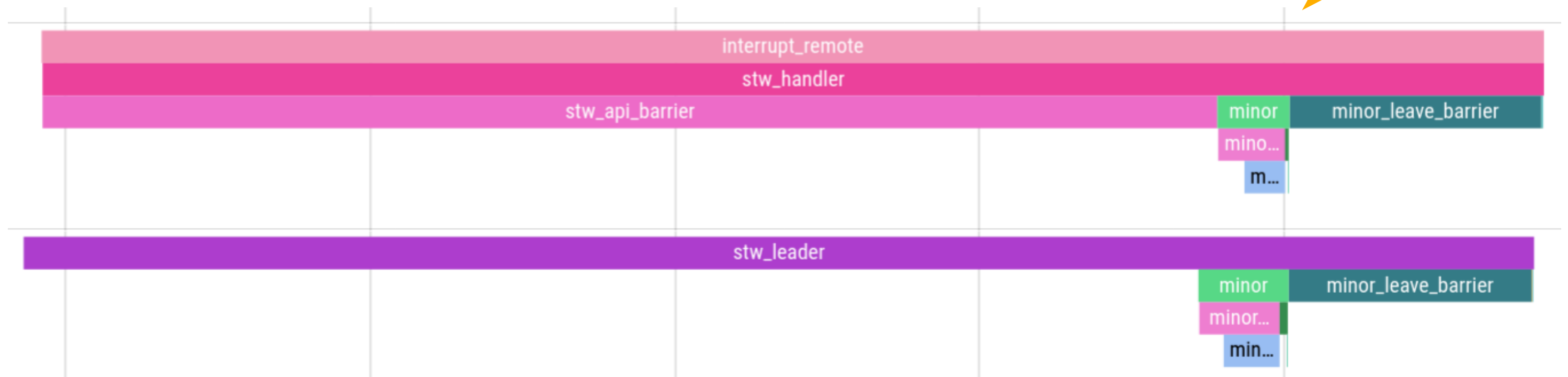


Performance analysis

- perf (incl. call graph), eBPF 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

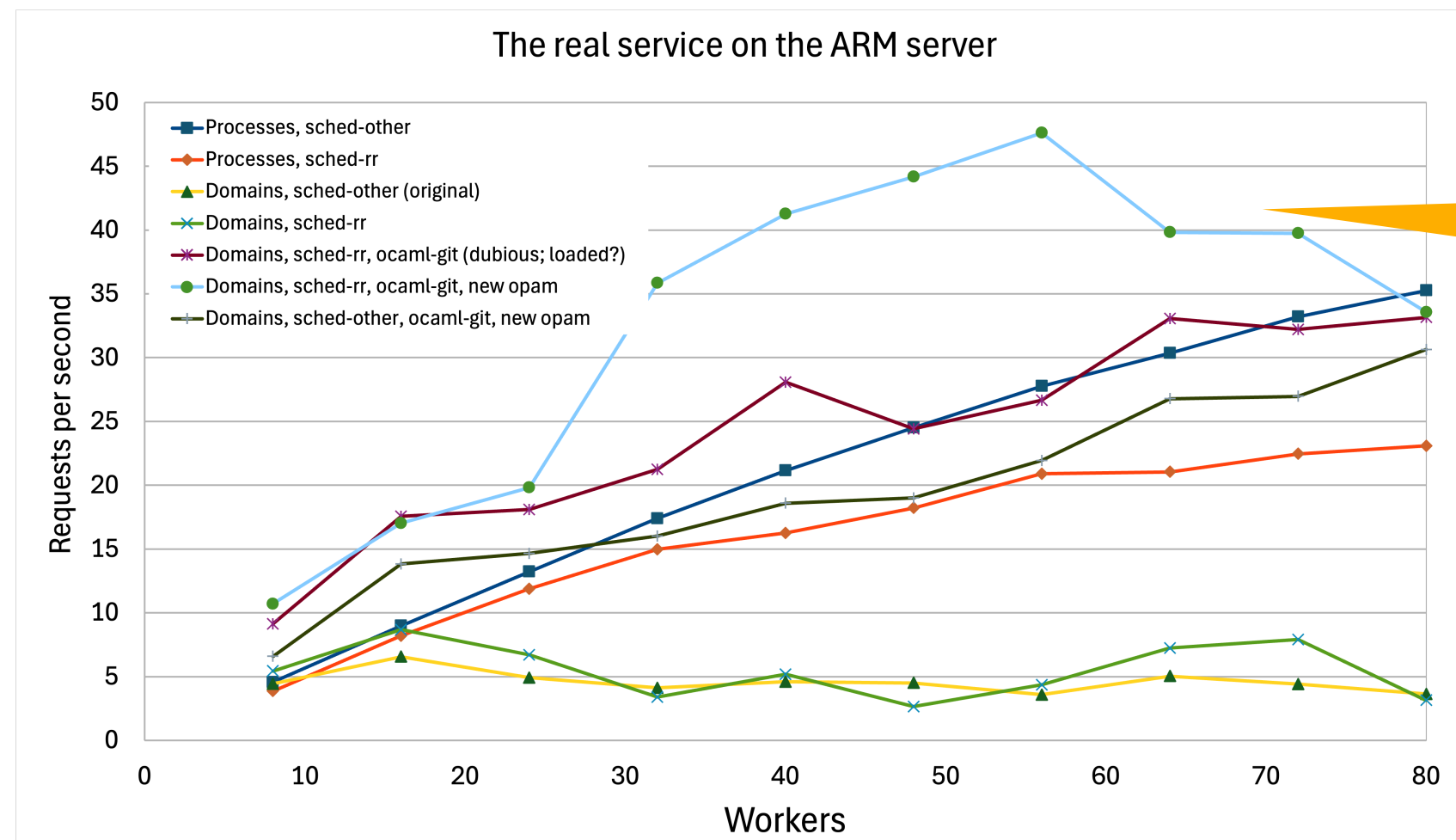
```
$ olly trace foo.trace foo.exe
```

<https://perfetto.dev/>



Problem indentified

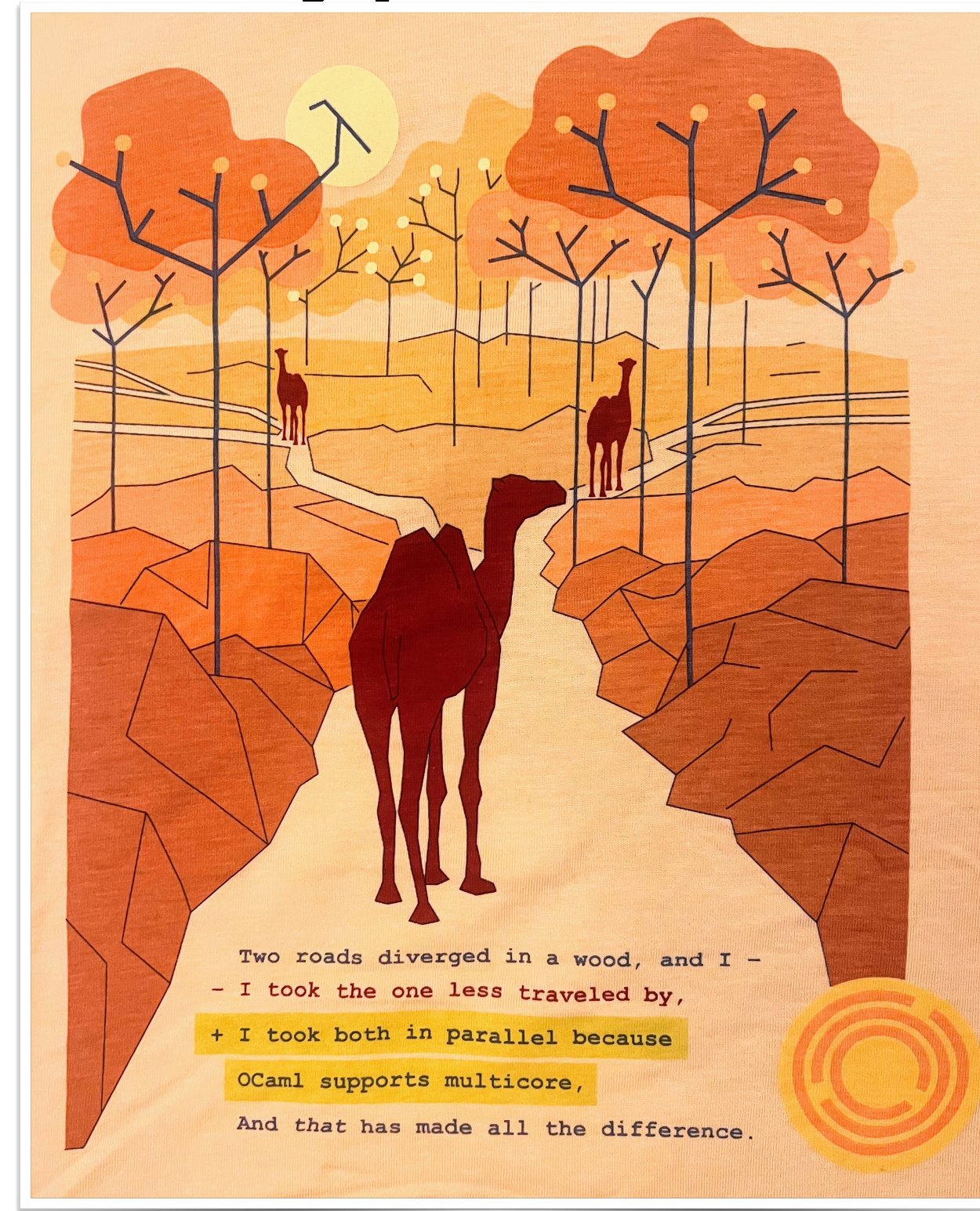
- Switch from `sched_other` to `sched_rr`
- `git log` for each solve to find earliest commit
 - 50ms penalty for STW subprocess spawn
 - Avoid by implementing it in OCaml



Still some work to do

Takeaways for introducing shared-memory parallelism

- 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

A Mechanically Verified Garbage Collector for OCaml

JAR 2025

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Data Race

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

We present DRE
threaded OCaml

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.