Evolving the OCaml programming language

KC Sivaramakrishnan
kcsrk.info

Krea University
4th November 2025

Who am I — KC Sivaramakrishnan

- CS Prof at IIT Madras
  - Programming languages, formal verification and systems
- A core maintainer of the ***OCaml*** programming language
- CTO at Tarides
  - Building functional systems using ***OCaml***
  - Maintainers of the OCaml compiler and platform tools

File Edit Search Run Compile Debug Project Options Window Help

NONAME00.CPP

- Turbo C++ IDE
  - Learnt to program C here
- Believed the C language was "perfect & final"
  - ...like mountains and oceans
- Grew up and realised neither was!
- This talk is about the evolution of programming languages
  - Specifically, OCaml

1:1

F1 Help F2 Save F3 Open Alt-F9 Compile F9 Make F10 Menu

OCaml

📜 Language

- Functional-first but multi-paradigm (imperative, OO)
- Static-type system with Hindley-Milner type inference
- Advanced features — powerful module system, GADTs, Polymorphic variants
- Multicore support and ***effect handlers***

⚙️ Platform

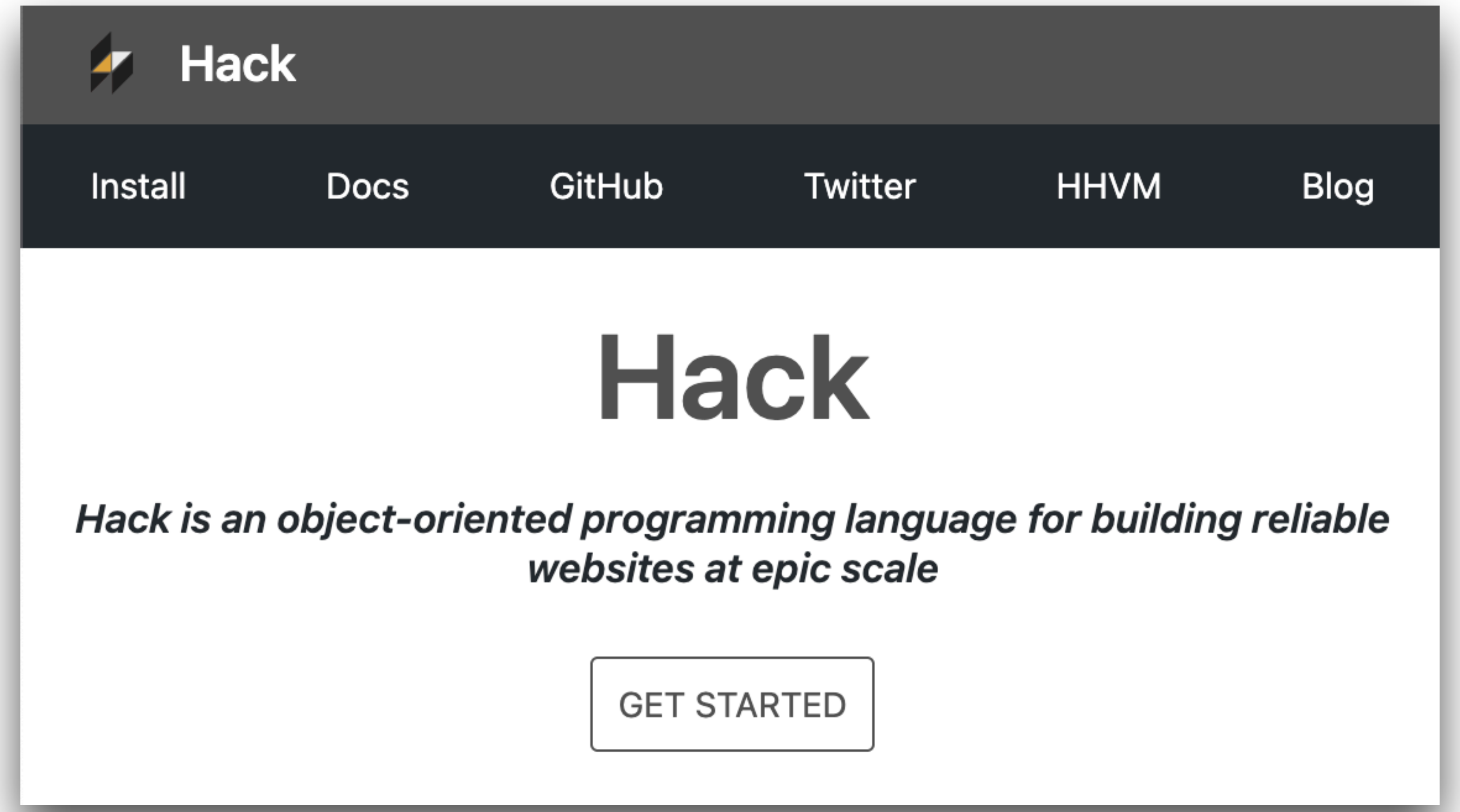
- Fast, native code— x86, ARM, RISC-V, etc.
- JavaScript and WebAssembly (using ***WasmGC***) compilation
- **Platform tools** — editor (LSP), build system (dune), package manager (opam), docs generator (odoc), etc.

🌐 Ecosystem

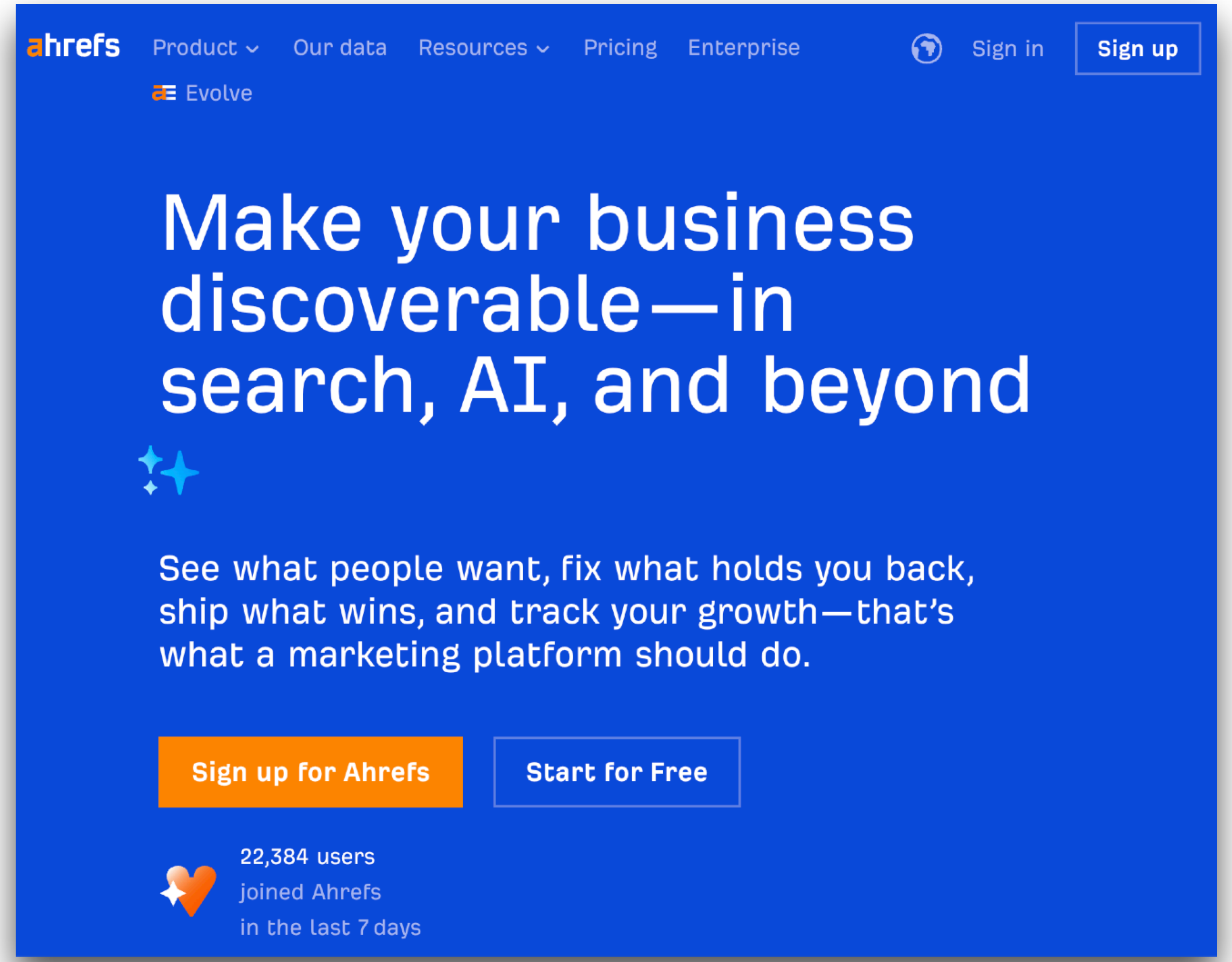
- Opam repository — small but mature package ecosystem
- Notable Industrial users — Jane Street, Meta, Microsoft, Ahrefs, Citrix, Tezos, Bloomberg, Docker

High dynamic range

From scripts to scalable systems, research prototypes to production infrastructure



Compilers



Web Frontend

High dynamic range

From scripts to scalable systems, research prototypes to production infrastructure

Functional Networking for Millions of Docker Desktops (Experience Report)

ANIL MADHAVAPEDDY, University of Cambridge, United Kingdom
DAVID J. SCOTT, Docker, Inc., United Kingdom
PATRICK FERRIS, University of Cambridge, United Kingdom
RYAN T. GIBB, University of Cambridge, United Kingdom
THOMAS GAZAGNAIRE, Tarides, France

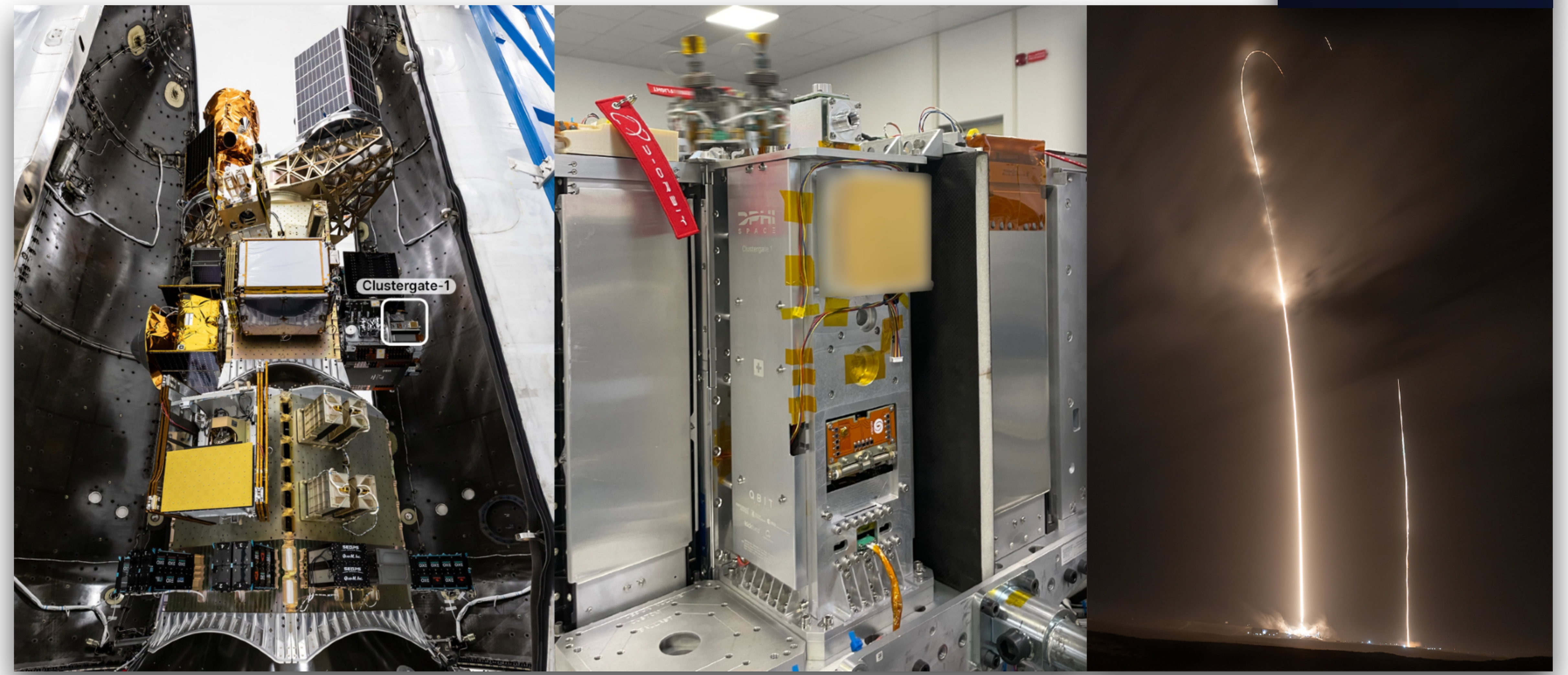
docker

Docker is a developer tool used by millions of developers to build, share and run software stacks. The Docker Desktop clients for Mac and Windows have long used a novel combination of virtualisation and OCaml unikernels to seamlessly run Linux containers on these non-Linux hosts. We reflect on a decade of shipping this functional OCaml code into production across hundreds of millions of developer desktops, and discuss the lessons learnt from our experiences in integrating OCaml deeply into the container architecture that now drives much of the global cloud. We conclude by observing just how good a fit for systems programming that the unikernel approach has been, particularly when combined with the OCaml module and type system.

CCS Concepts: • **Software and its engineering** → *Software system structures*; **Functional languages**; • **Computer systems organization** → **Cloud computing**.

OCaml in Space 🚀

Parsimoni



Virtualisation and Networking

High dynamic range

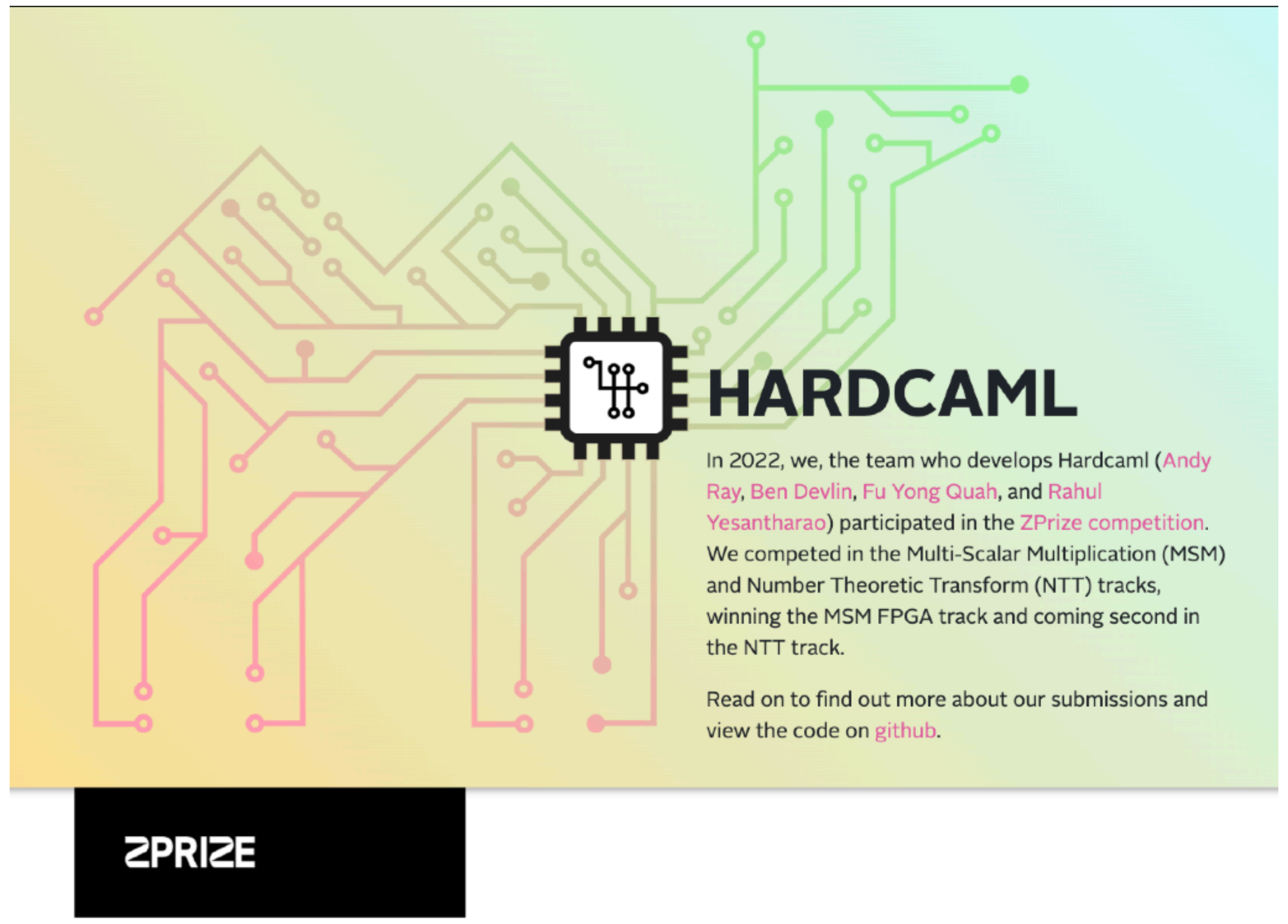
From scripts to scalable systems, research prototypes to production infrastructure

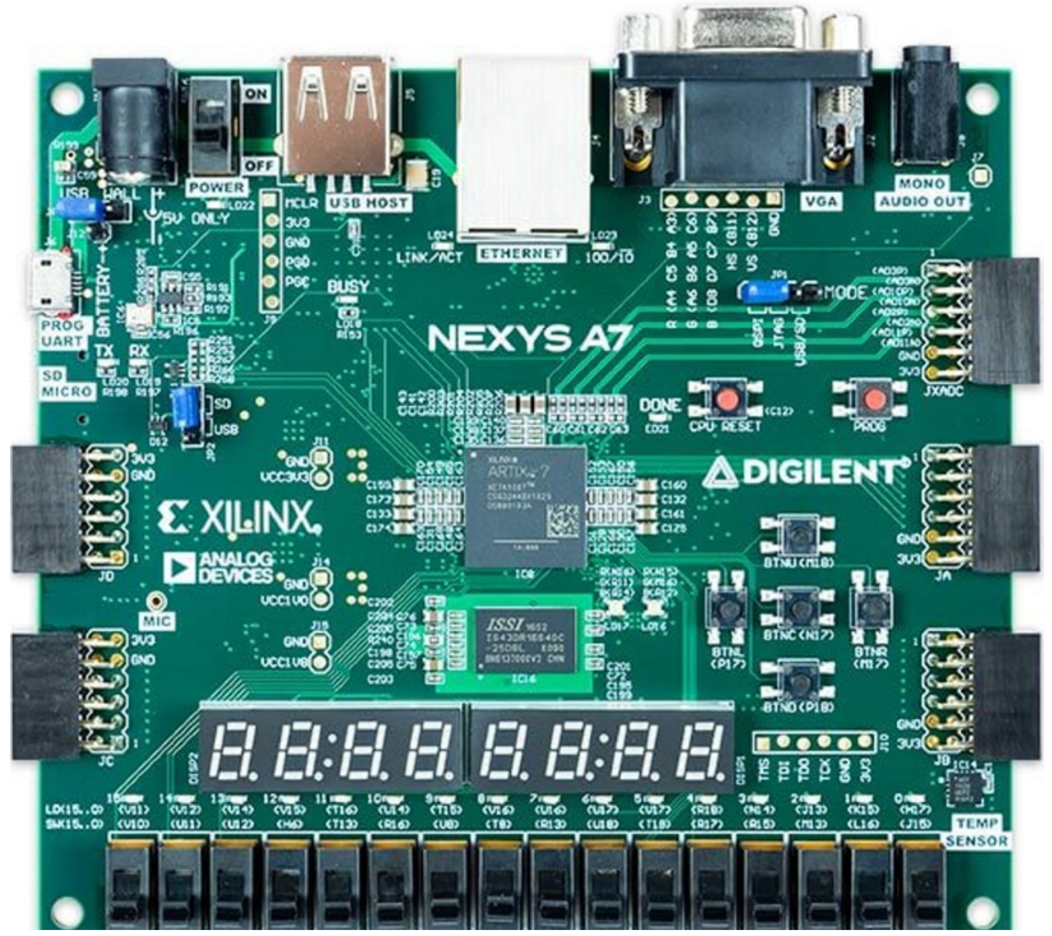
60+M lines of OCaml code!

Jane Street

Bloomberg

Finance





Hardware design

OCaml

29 years old!

Steady evolution over ***50+*** years

1973 — Robin Milner's "ML" for LCF

Type system, type inference

1985 — Guy Cousineau & co's CAML

Categorical abstract machine (CAM) as IR

1996 — OCaml 1.0

Object system, low-latency GC, fast native backend, module system

2012 — OCaml 4.0

Generalized Algebraic Data types (GADTs)

2022 — OCaml 5.0

Multicore parallelism, effect handlers

2025

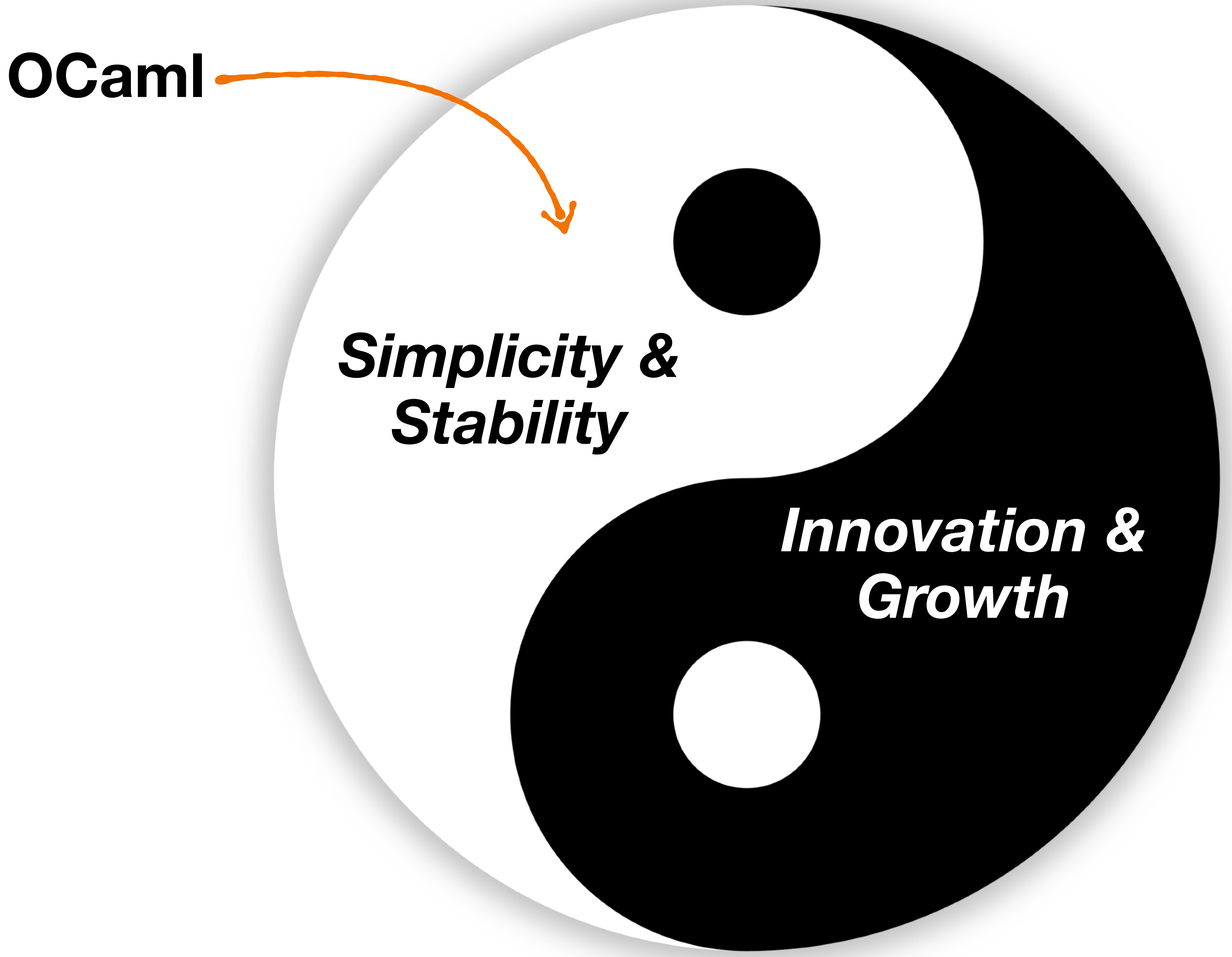
How to thrive not just survive after ~30 years?

Simplicity and ***stability***

Xavier Leroy, 2023 SIGPLAN programming languages software award! 🏆

> What made that possible? Not just fancy types and nice modules – even though systems programmers value type safety and modularity highly – but also basic properties of OCaml:
>
> - a language with a simple cost model, where it's easy to track how much time and how much space is used;
> - a compiler that produces efficient code that looks like the source code, with only predictable optimizations;
> - a low-latency garbage collector, usable for soft real-time applications.

- If you take OCaml from 20 years ago, the code will likely ***continue to work!***
- No recent releases for some popular packages
  - They are ***good enough***, and continue to be so.
  - Nothing to be done to keep it working!


OCaml
Simplicity & Stability
Innovation & Growth

OCaml Maintainers

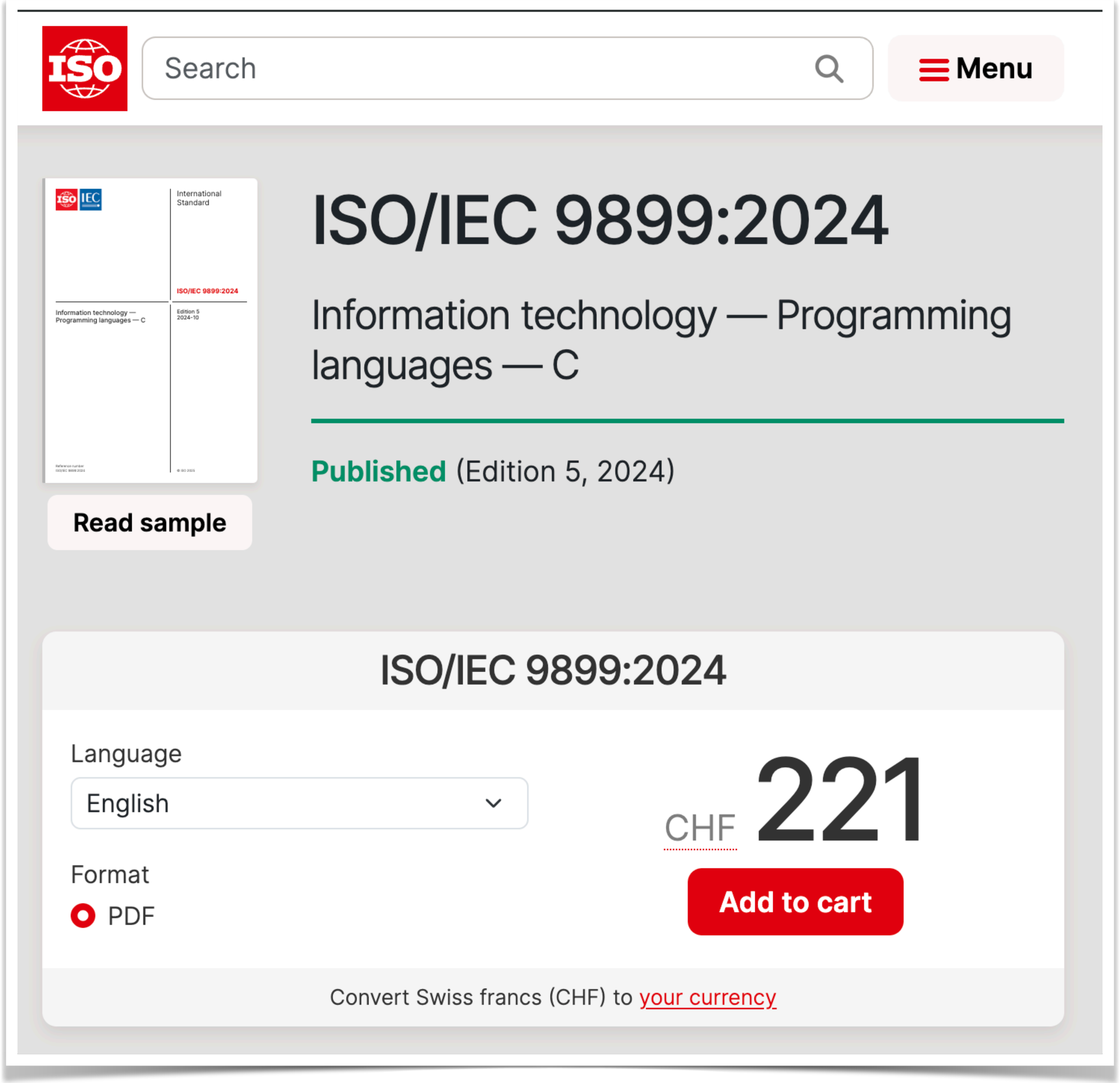
Abigael
Alain Frisch
Armaël Guéneau
Anil Madhavapeddy
Pierre Chambart
Damien Doligez
David Allsopp
Jacques Garrigue
Gabriel Scherer
Richard Eisenberg
Jacques-Henri Jourdan
KC Sivaramakrishnan
Frédéric Bour
Leo White
Vincent Laviron
Luc Maranget
Mark Shinwell
Nick Barnes
Nicolás Ojeda Bär
Florian Angeletti
Olivier Nicole
Sadiq Jaffer
Sébastien Hinderer
Stephen Dolan
Thomas Refis
Xavier Leroy
Jeremy Yallop

- 27 maintainers from France, UK, Japan, India and USA, across industry and academia.
- Custodians of the compiler
  - ***Not the ones deciding how the language should evolve!***

Who decides how OCaml evolves?

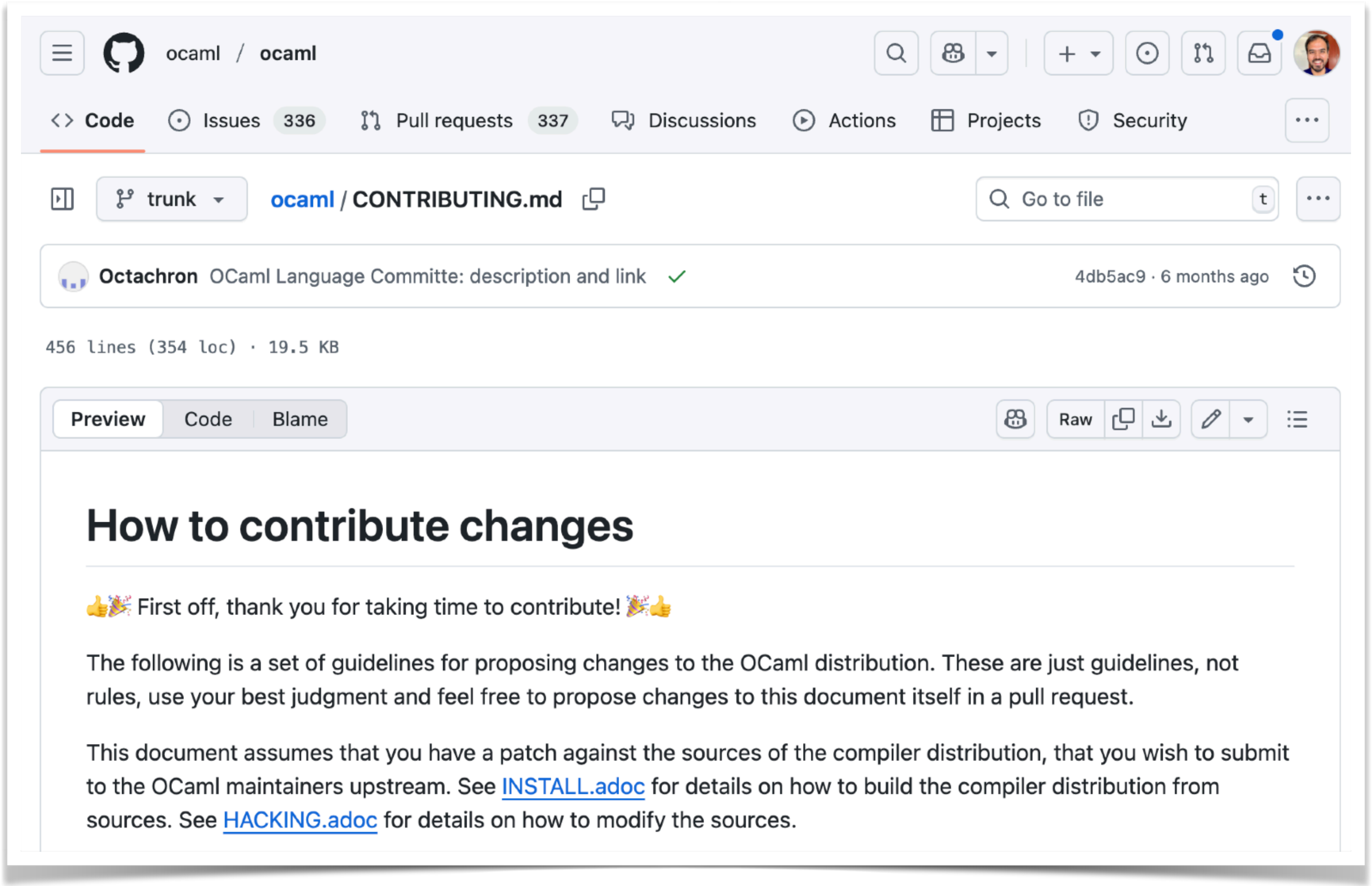
Who decides how OCaml evolves?

- Evolution
  - **User-driven:** OCaml, Python
  - **Committee-driven:** ISO/IEC evolving C and C++
  - **Vendor-driven consensus:** WebAssembly
- **Language** and **compiler** aren't distinct
  - OCaml compiler implementation ***IS*** the language.
    - Unlike C, Wasm, JavaScript
  - *Bar is lower to change the language*

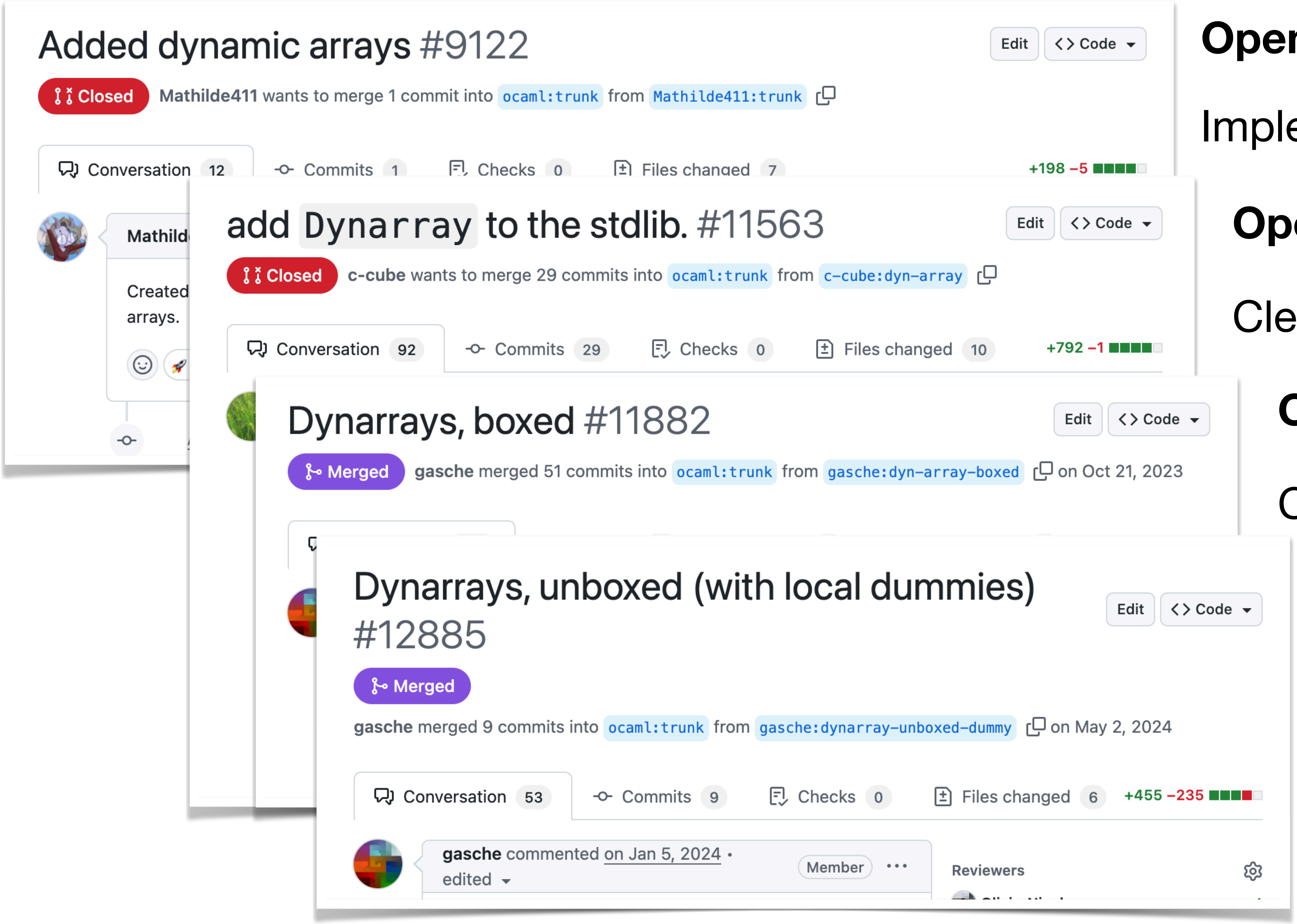


Evolving OCaml

- Open process
  - OCaml compiler is maintained on GitHub
  - All discussions are public in the PRs, Issues and RFCs on GitHub
- Multi-speed model
  - **Small fixes/features** → Make an issue (“feature request”), open a PR, discuss and get that merged
    - Every PR needs a maintainer's approval before merging
  - **Large features** → Bespoke based on the features
    - May need publishing papers, extensive performance evaluation, formalised/mechanised soundness results, etc.
- ***Often, presumably small feature requests take a life of their own!***



A small(?) change — Dynamic Arrays



Opened: Nov 15, 2019, **Closed:** Nov 15 2019

Implementation rather naive, room for improvements

Opened: Sep 25, 2022, **Closed:** Jan 18, 2023

Clean API, ***but*** multicore safety, performance

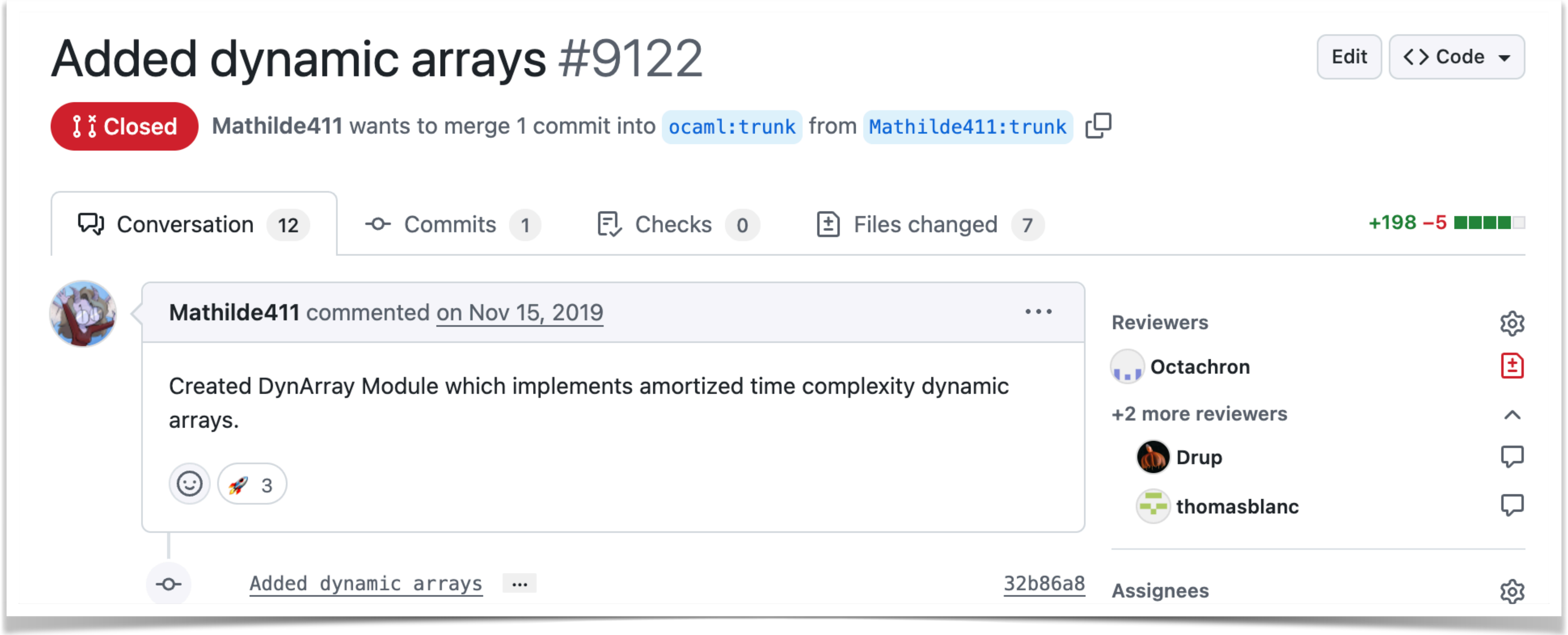
Opened: Jan 11, 2023, **Merged:** Oct 21, 2023

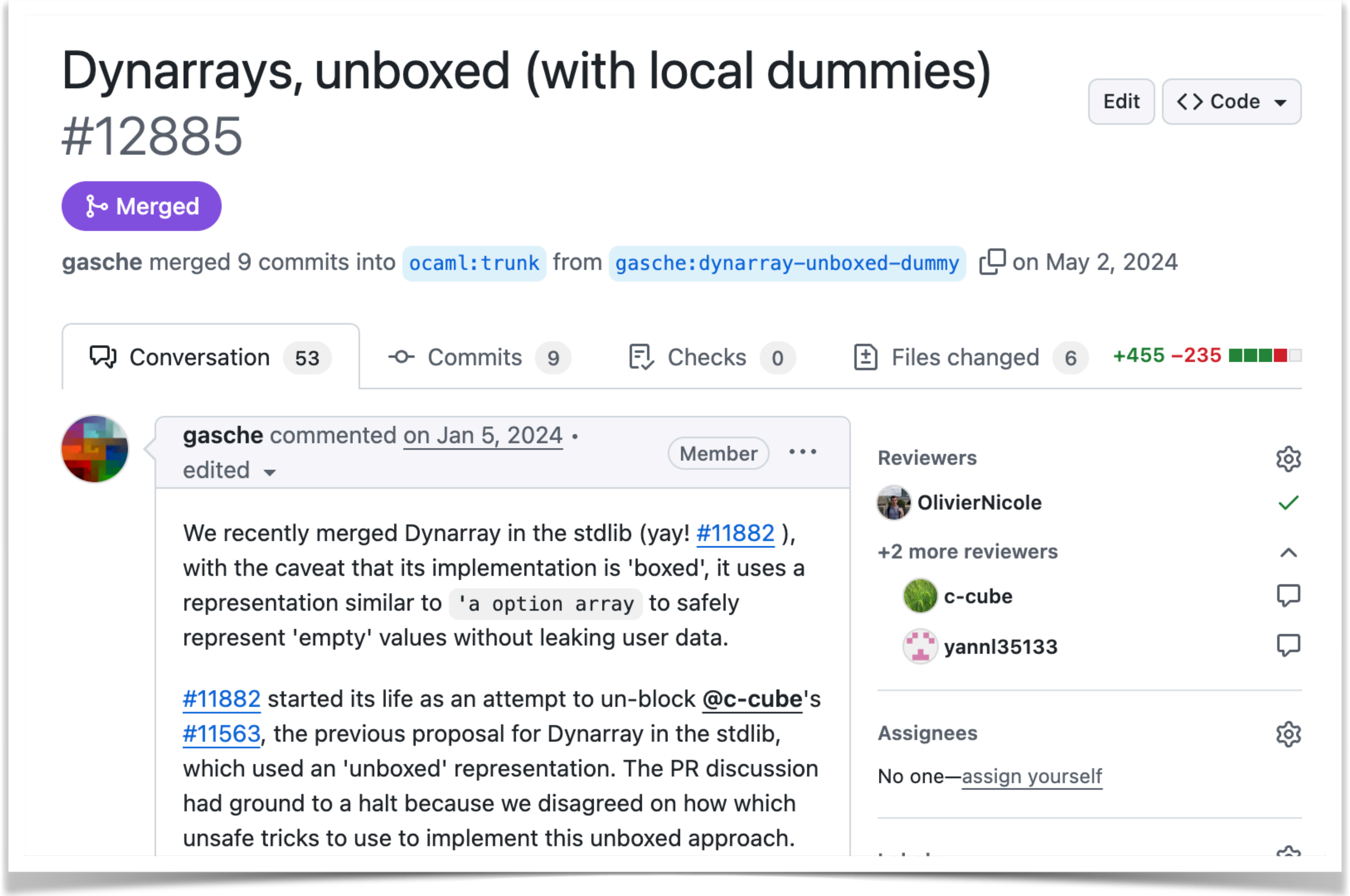
Clean API ***and*** simple implementation

Opened: Jan 5, 2024, **Merged:** May 2, 2024

Clean API and ***optimised*** implementation

Dynamic Arrays



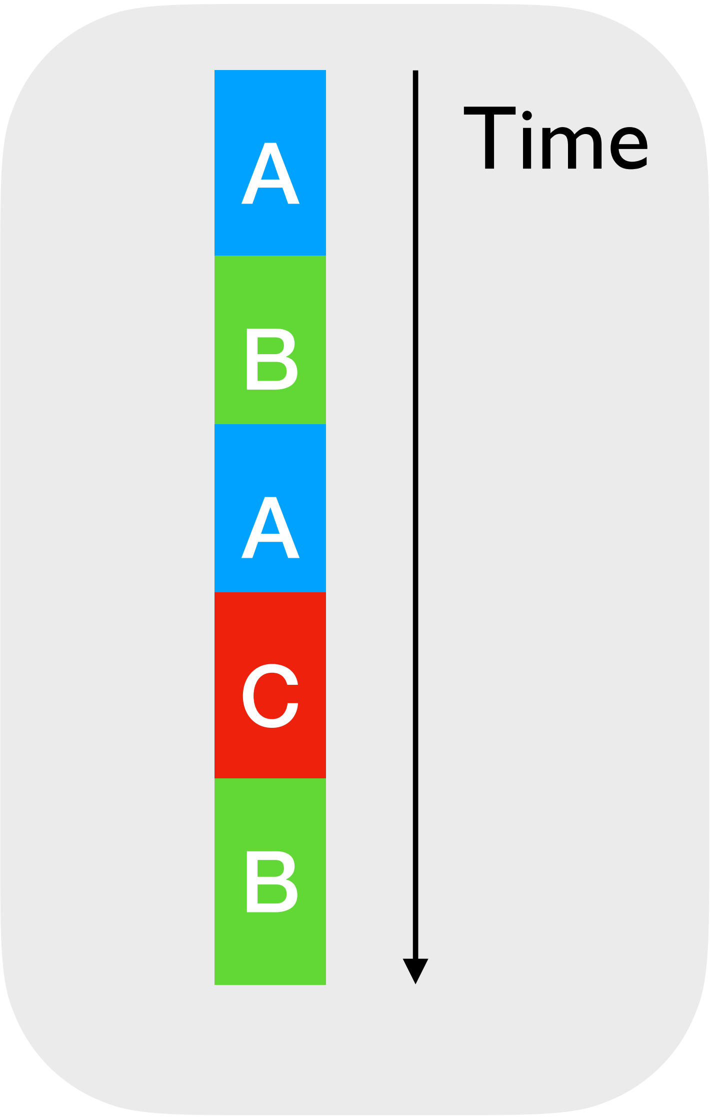


- **Summary**
  - Proposed — Nov 2019, Merged — (PR#1) Jan 2024; (PR#2) May 2024
  - Initially — 198 loc, finally — ~2500 loc
  - 500+ comments in the various PRs
- **Worth it?**
  - ***Yes!*** Should work for the next couple of decades.
  - Harder to undo changes after the release.

A large change — Multicore OCaml

- Native support for concurrency and parallelism to OCaml

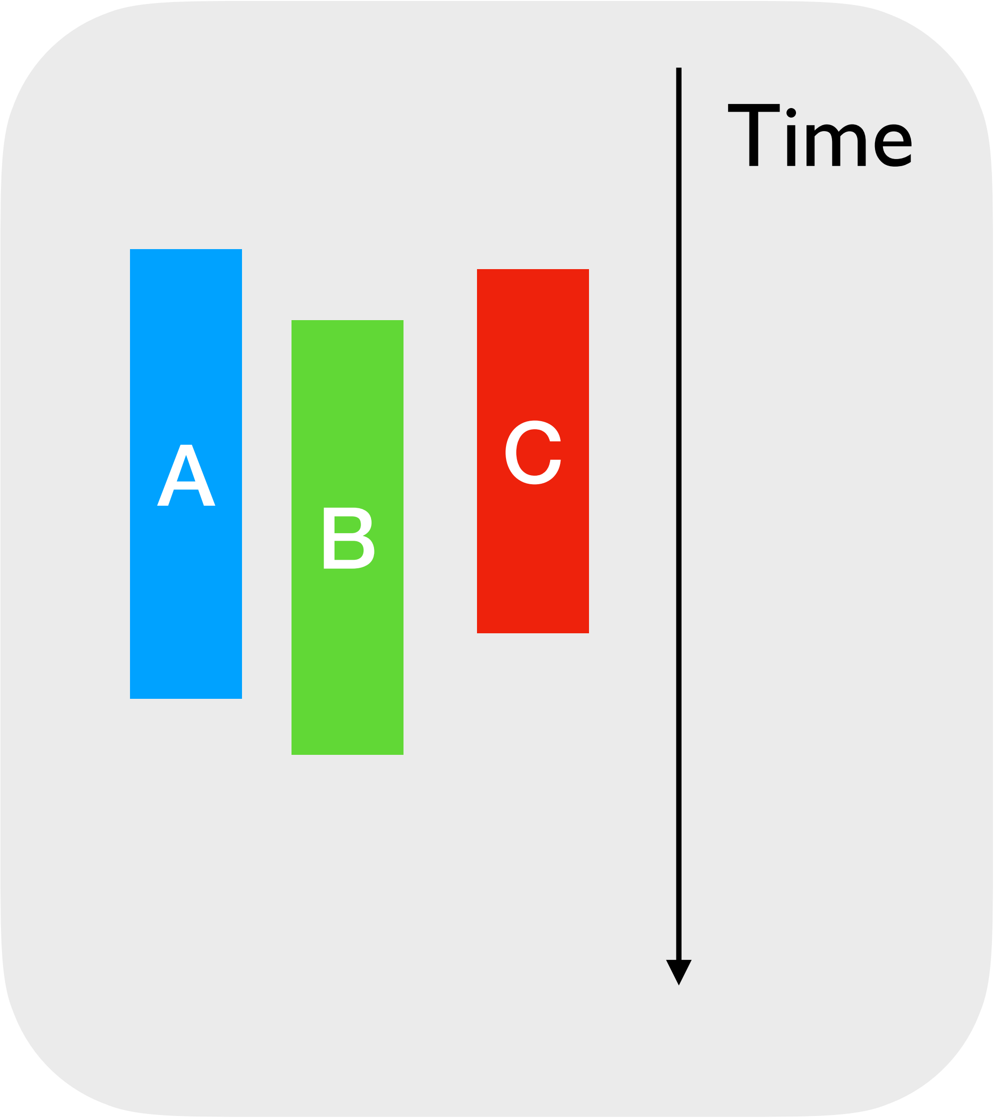
Concurrency



Interleaved execution

Effect Handlers

Parallelism



Simultaneous execution

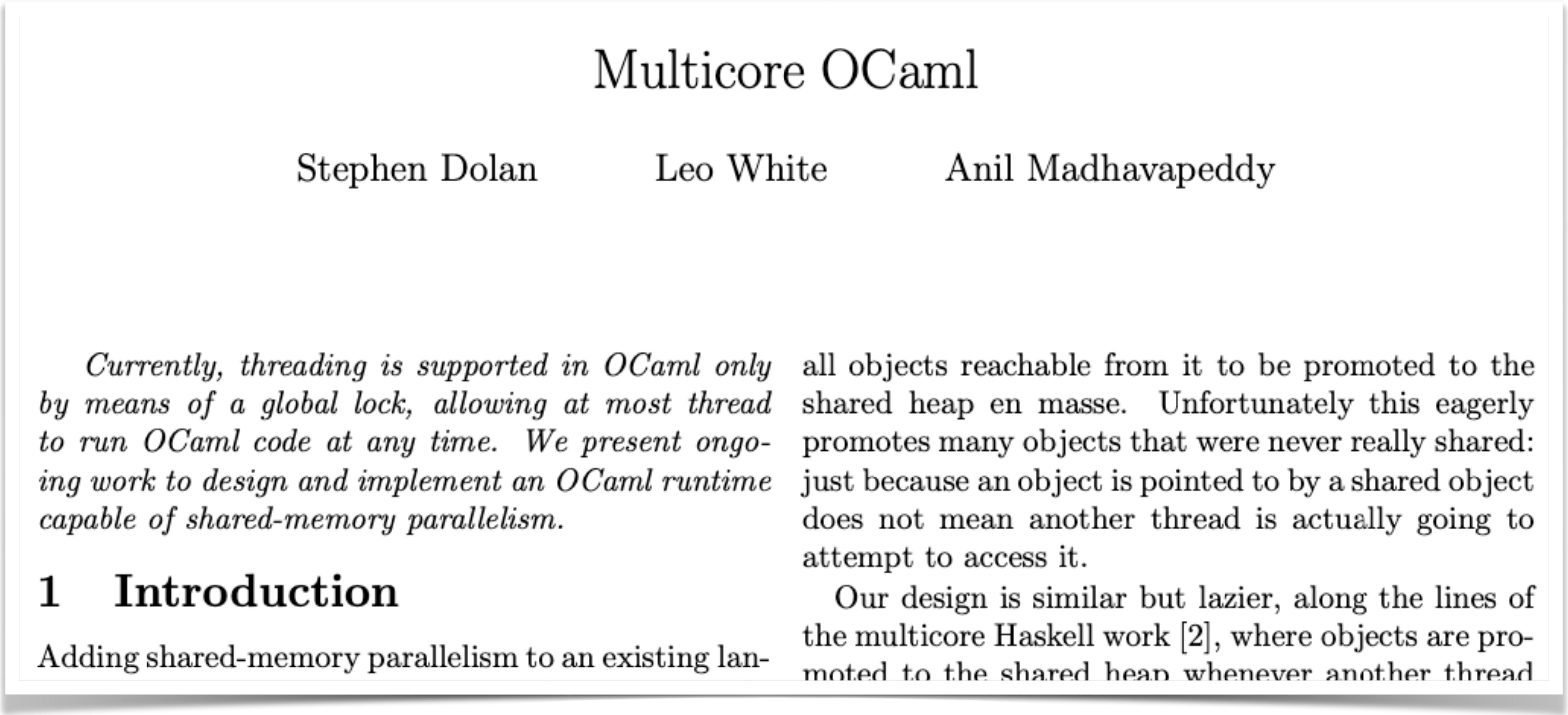
Domains

Challenges

- A new multicore garbage collector and multicore runtime system
  - *Replacing a car engine with a new one!*
- Make the language itself thread-safe
  - OCaml is a safe language! (Unlike C/C++, Go)
- Maintain feature and performance backwards compatibility!
  - Most OCaml programs will continue to remain single-threaded

Build credibility by ***publishing key results*** and ***rigorous evaluation***

Starting out



Multicore OCaml

Stephen Dolan Leo White Anil Madhavapeddy

Currently, threading is supported in OCaml only by means of a global lock, allowing at most thread to run OCaml code at any time. We present ongoing work to design and implement an OCaml runtime capable of shared-memory parallelism.

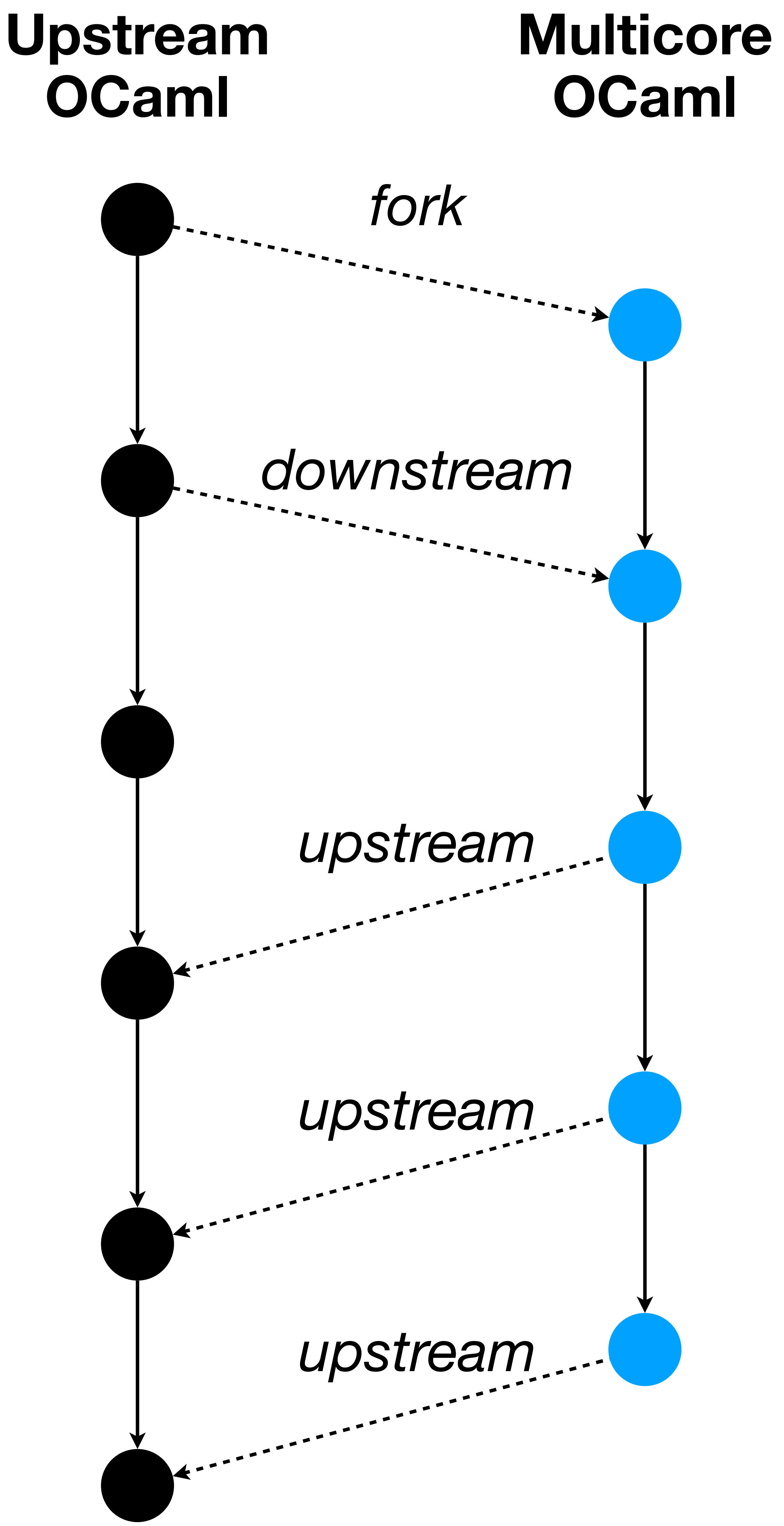
1 Introduction

Adding shared-memory parallelism to an existing lan-

all objects reachable from it to be promoted to the shared heap en masse. Unfortunately this eagerly promotes many objects that were never really shared: just because an object is pointed to by a shared object does not mean another thread is actually going to attempt to access it.

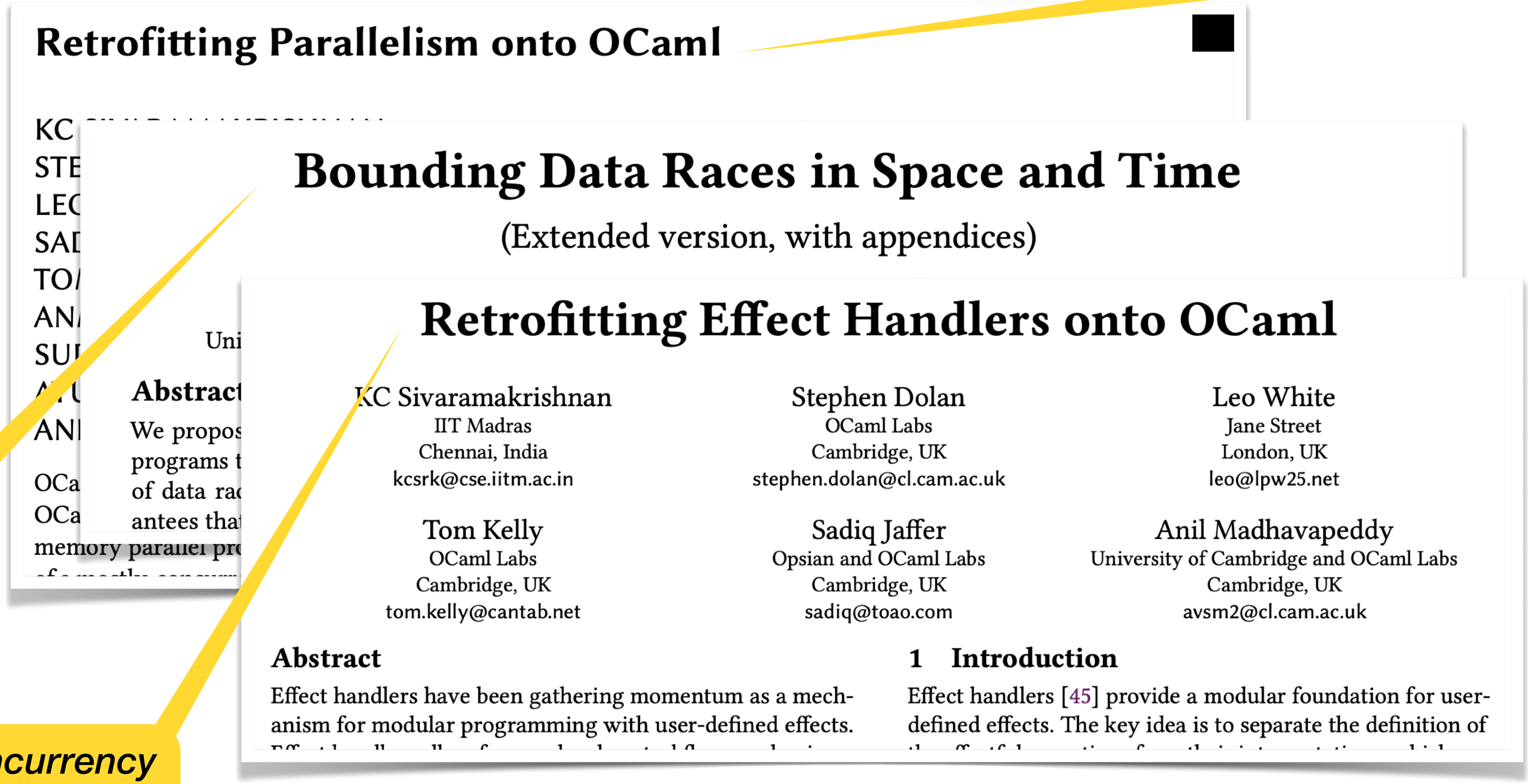
Our design is similar but lazier, along the lines of the multicore Haskell work [2], where objects are promoted to the shared heap whenever another thread

OCaml Workshop 2014



Building confidence — Papers

Multicore GC and runtime system



Retrofitting Parallelism onto OCaml

Bounding Data Races in Space and Time

(Extended version, with appendices)

Retrofitting Effect Handlers onto OCaml

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Anil Madhavapeddy
University of Cambridge and OCaml Labs
Cambridge, UK
avsm2@cl.cam.ac.uk

Abstract

Effect handlers have been gathering momentum as a mechanism for modular programming with user-defined effects.

1 Introduction

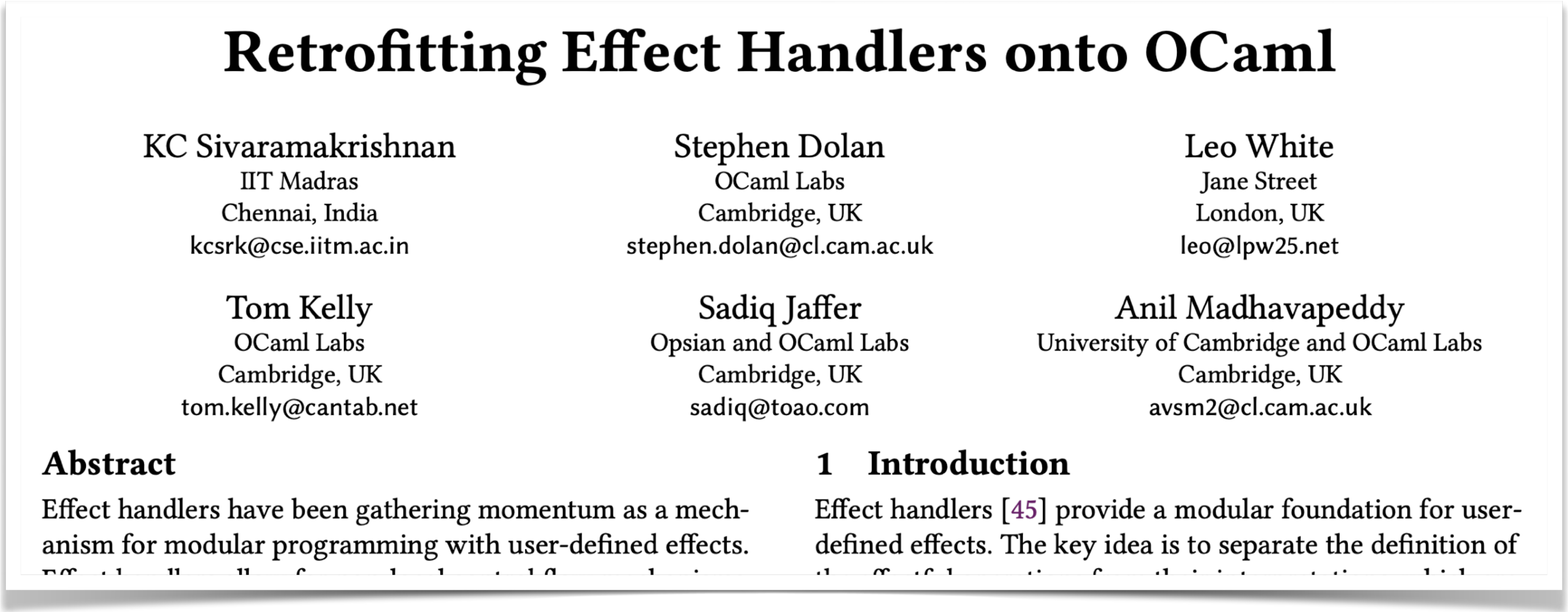
Effect handlers [45] provide a modular foundation for user-defined effects. The key idea is to separate the definition of

Relaxed Memory Model

Concurrency story

Peer-reviewed ideas build confidence

Diving deeper — Concurrency



Retrofitting Effect Handlers onto OCaml

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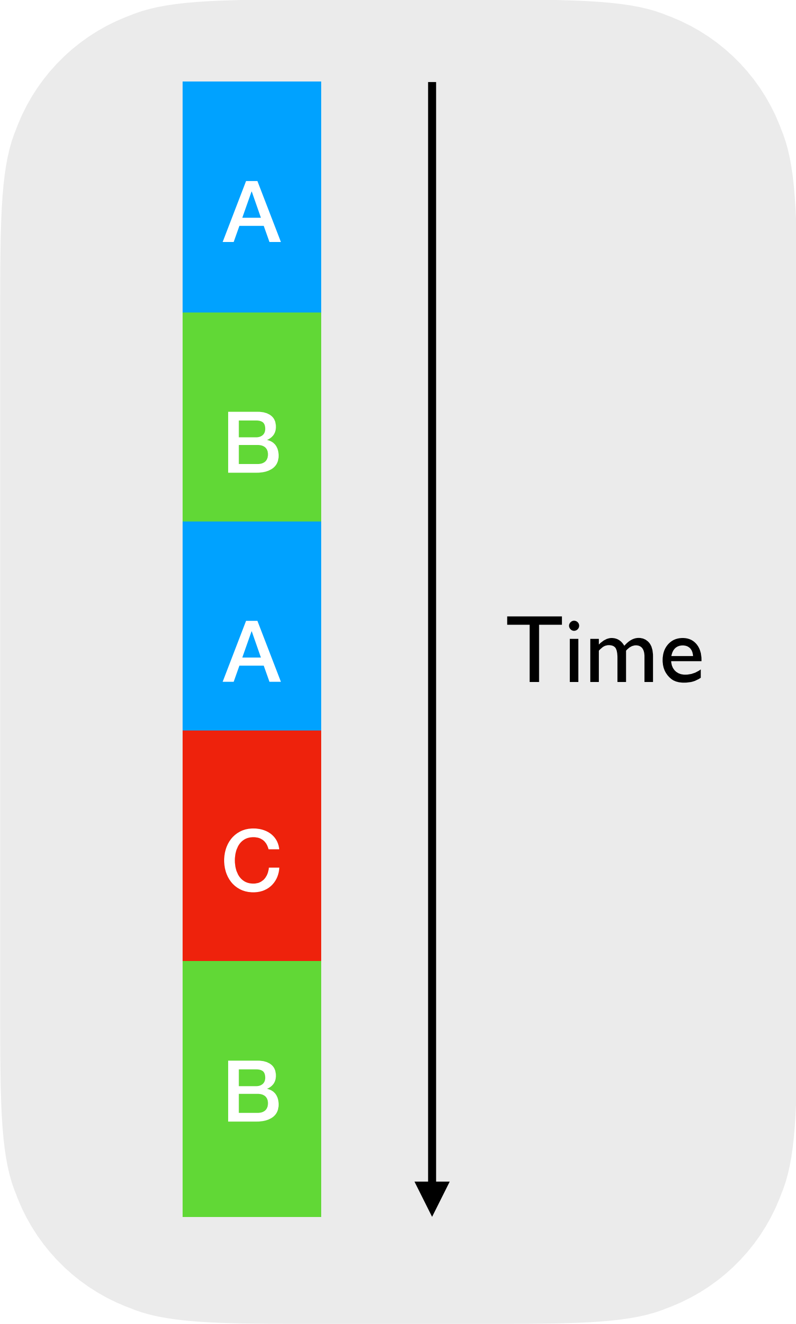
Abstract

Effect handlers have been gathering momentum as a mechanism for modular programming with user-defined effects.

1 Introduction

Effect handlers [45] provide a modular foundation for user-defined effects. The key idea is to separate the definition of

Interleaved



Concurrent Programming

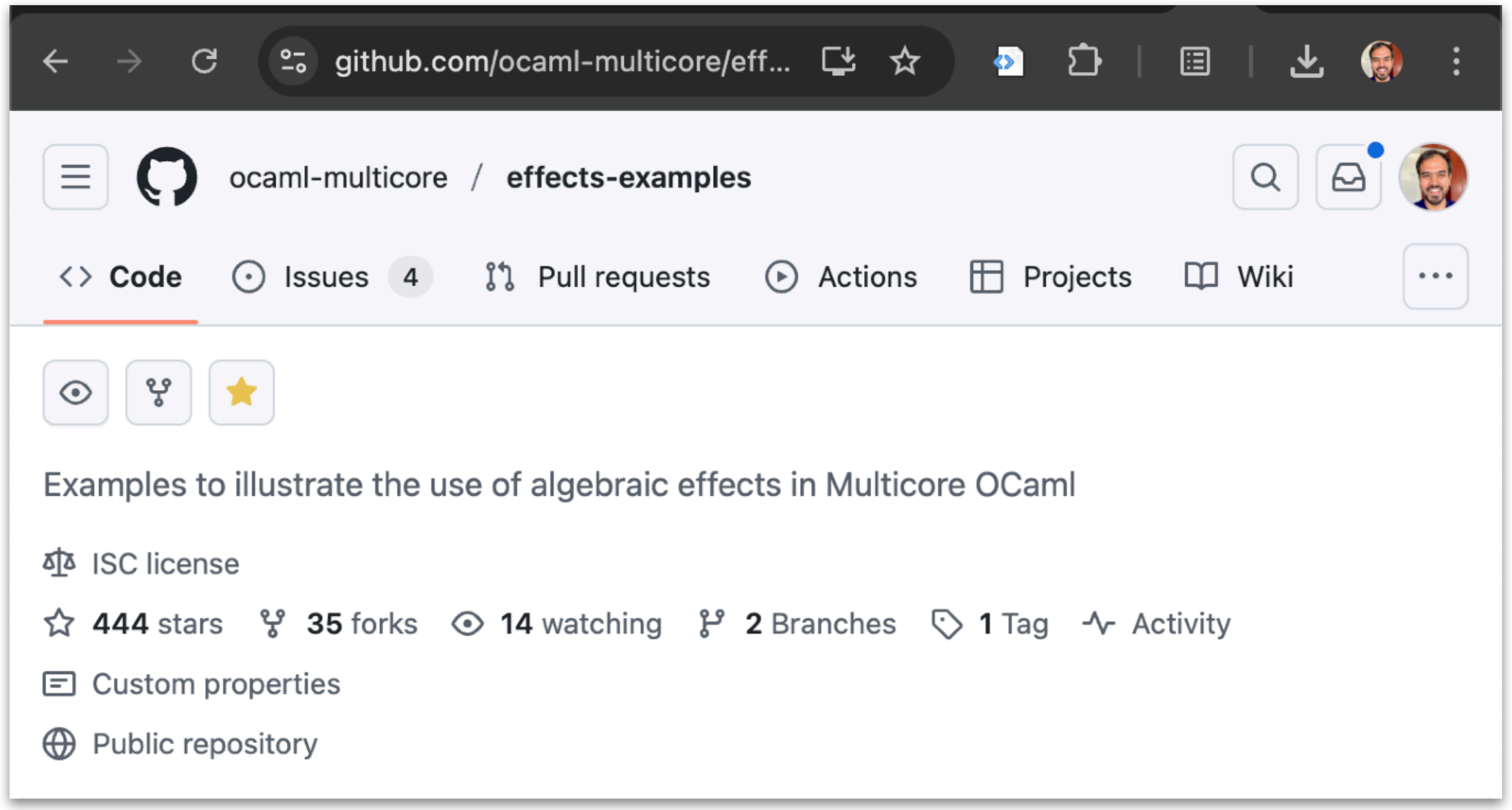
- Computations may be *suspended* and *resumed* later
- Many languages provide concurrent programming mechanisms as *primitives*
  - ✦ **async/await** — JavaScript, Python, Rust, C# 5.0, F#, Swift, …
  - ✦ **generators** — Python, Javascript, …
  - ✦ **coroutines** — C++, Kotlin, Lua, …
  - ✦ **futures & 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

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*



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

Effect handlers

```
type _ 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 "
```

effect declaration

suspends current computation

computation

delimited continuation

handler

resume suspended computation

Stepping through the example

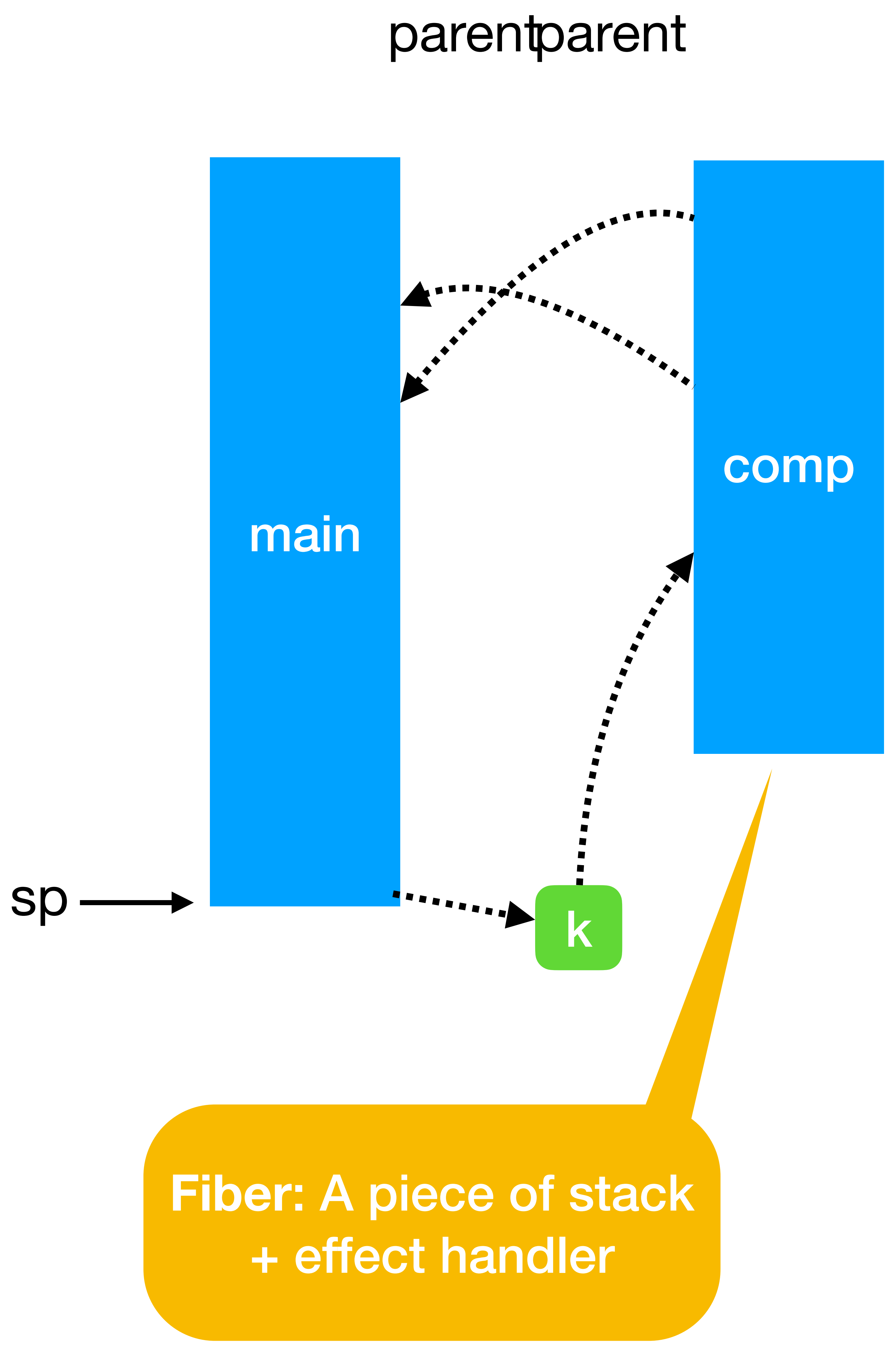
```
type 'a eff += E : string eff

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



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
```

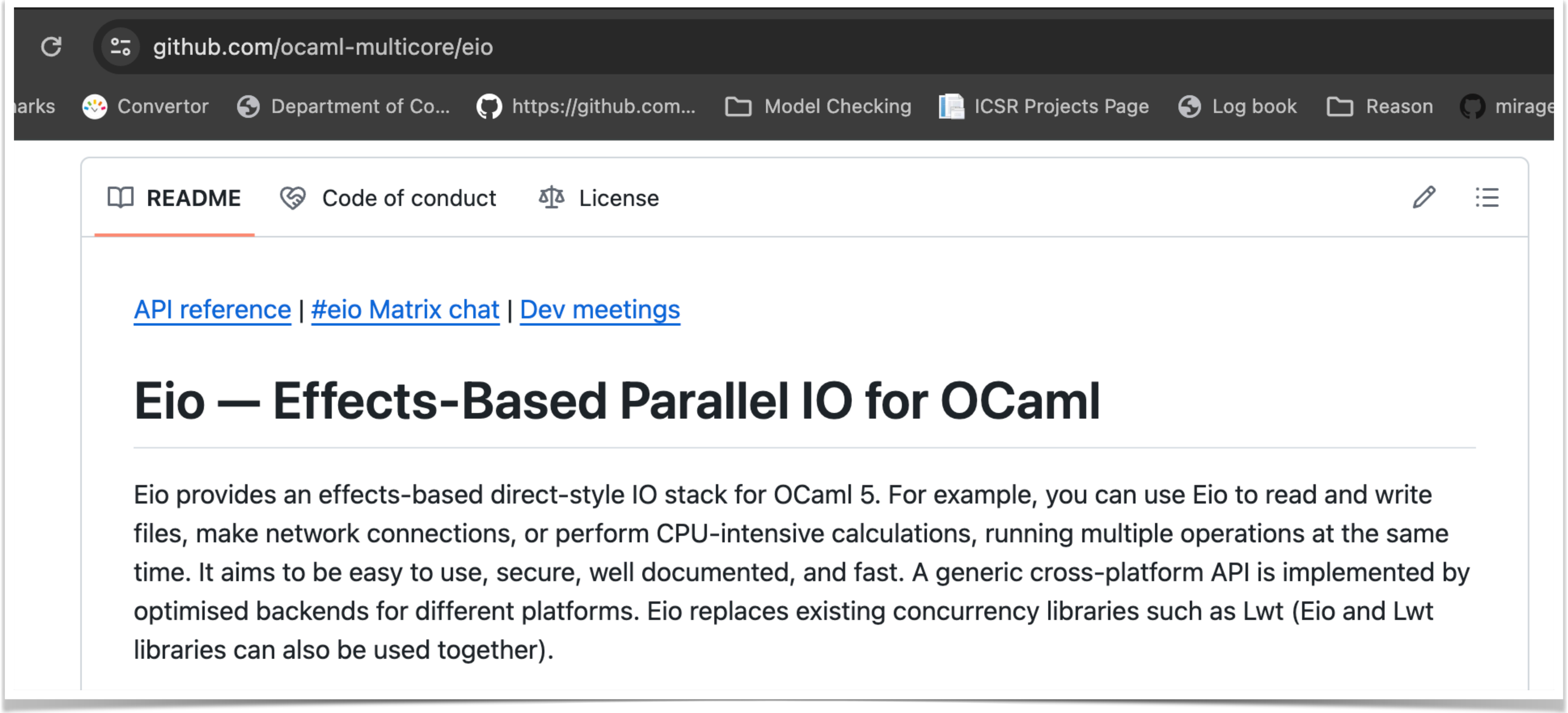
Ability to specialise scheduler
unlike GHC Haskell / Go

User-code need not be aware of effects

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

Industrial-strength concurrency

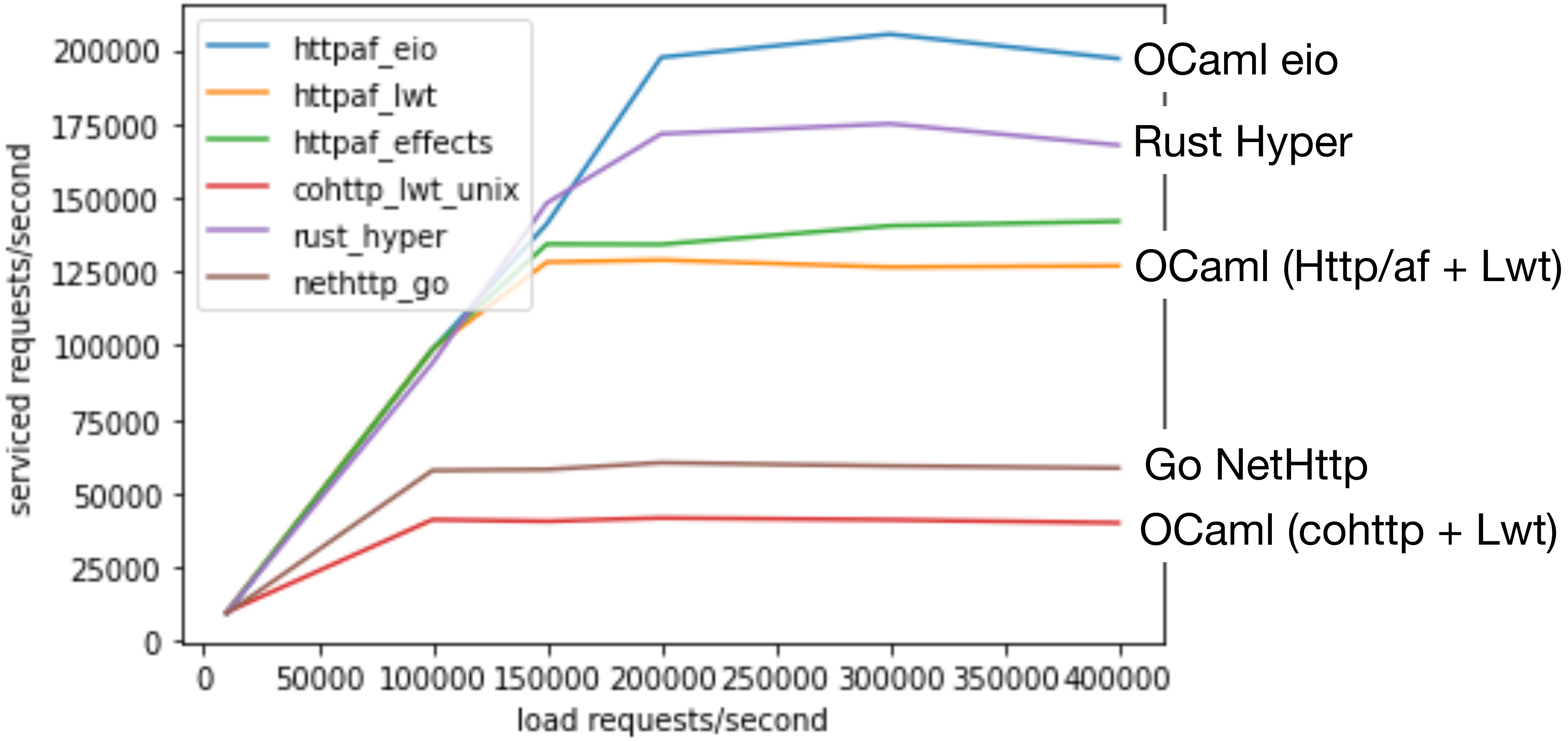
- **eio**: effects-based direct-style I/O
  - Multiple backends — epoll, select, ***io_uring*** *(new async io in Linux kernel)*



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

Industrial-strength concurrency

- **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

Further reading

Control structures in programming languages: from goto to algebraic effects

Xavier Leroy

This book is a journey through the design space and history of programming languages from the perspective of control structures: the language mechanisms that enable programs to control their execution flows. Starting with the "goto" jumps of early programming languages and the emergence of structured programming in the 1960s, the book explores advanced control structures for imperative languages such as generators and coroutines, then develops alternate views of control in functional languages, first as continuations and their control operators, then as algebraic effects and effect handlers. Blending history, code examples, and theory, the book offers an original, comparative perspective on programming languages, as well as an extensive introduction to algebraic effects and other contemporary research topics in P.L.

Publication history

To be published by Cambridge University Press.

Book preview

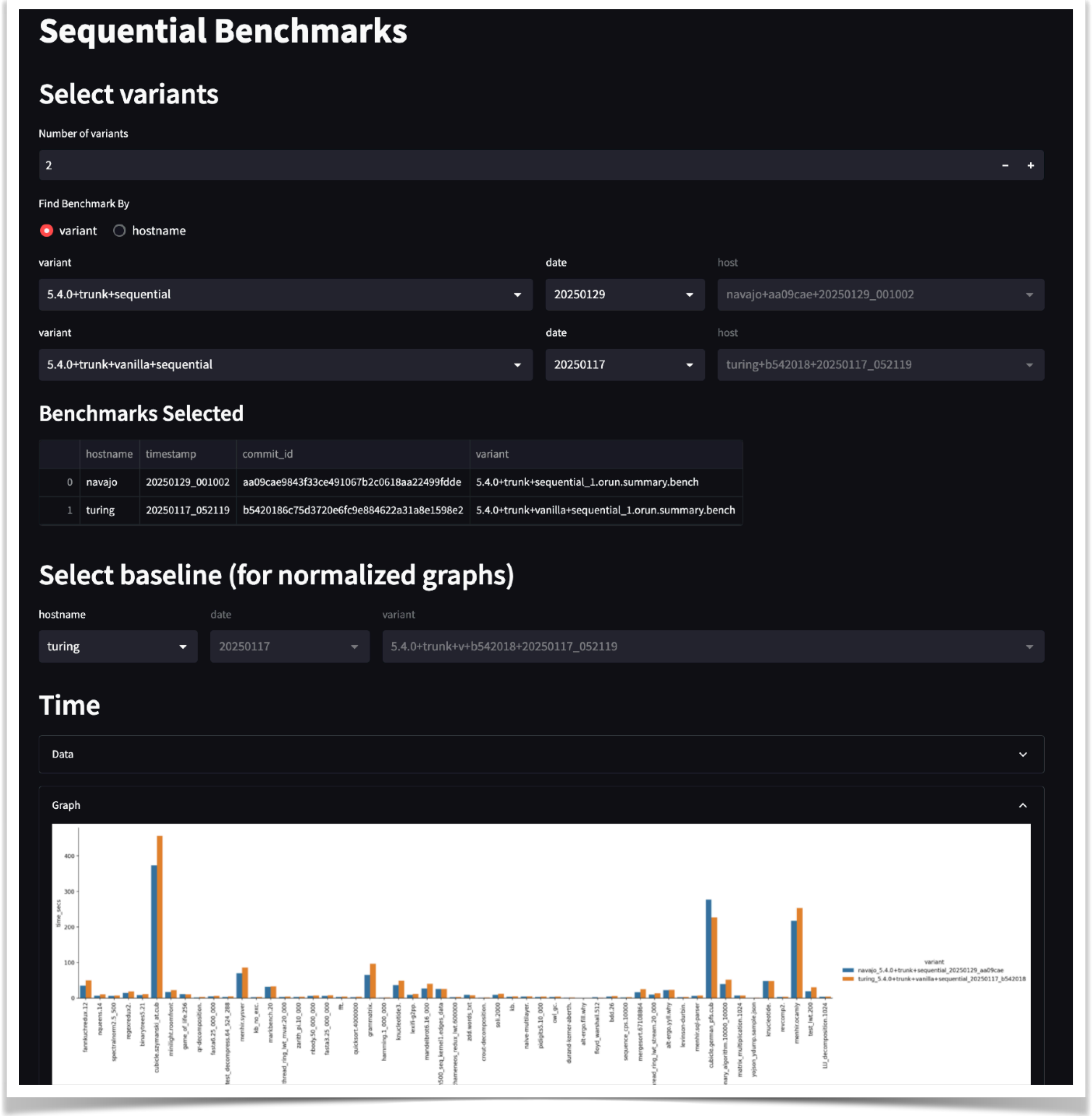
This is an HTML preview of the book, generated with Hevea. License: CC-BY-NC-ND 4.0.

- Table of contents
- Introduction

https://xavierleroy.org/control-structures/

Building confidence — Benchmarking

- ***Rigorous***, ***continuous*** benchmarking on ***real-world programs***
- sandmark.tarides.com — Benchmark suite, Infra and runners



Building confidence — CI for package universe

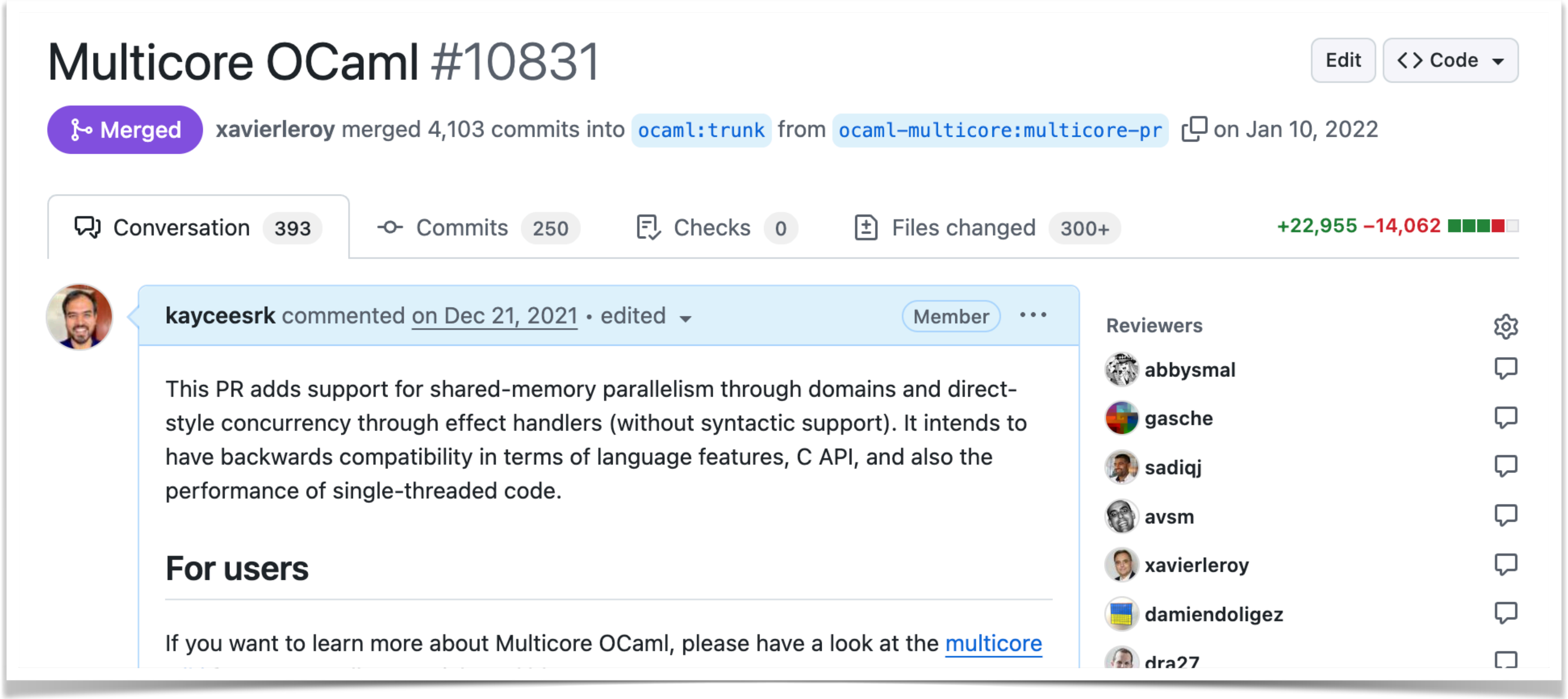
- ***Can the new compiler build the existing universe?***
  - Build the OPAM universe of packages against ***upstream*** and ***multicore*** compilers

	4.14	5.0+alpha-repo	number of revdeps
0install.2.18	☑	☒	1
BetterErrors.0.0.1	☑	☒	7
TCSLib.0.3	☑	☒	1
absolute.0.1	☑	☒	0
acgtk.1.5.3	☑	☒	0
advi.2.0.0	☑	☒	0
aez.0.3	☑	☒	0
ahrocksdb.0.2.2	☒	☒	0
aio.0.0.3	☑	☒	0
alt-ergo-free.2.2.0	☑	☒	7
amqp-client-async.2.2.2	☑	☒	0
amqp-client-lwt.2.2.2	☑	☒	0
ancient.0.9.1	☑	☒	0
apron.v0.9.13	☑	☒	17

You can contribute to the compiler development without hacking on the compiler

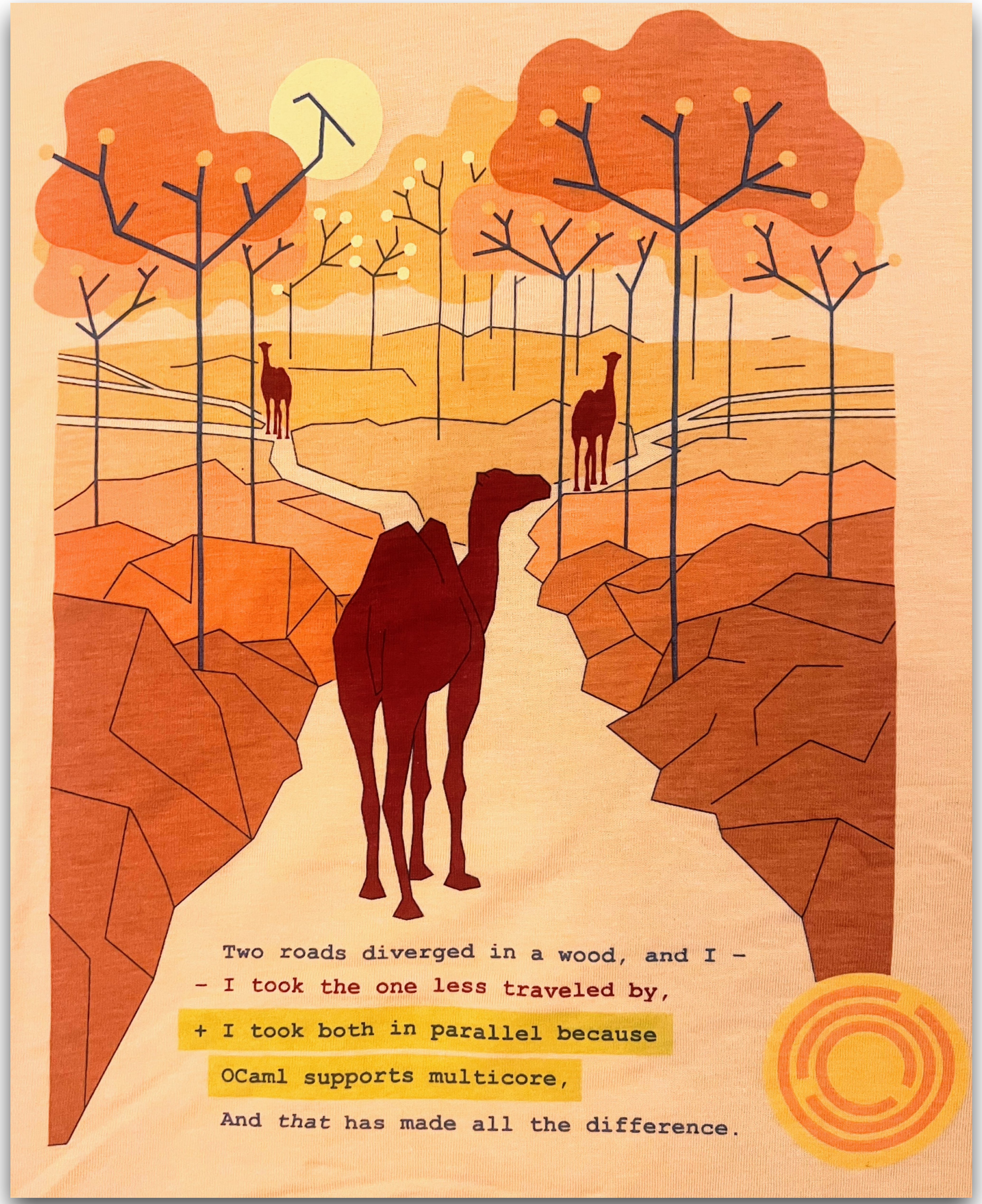
Release and Long Tail

- **Opened** — Dec 2021, **Merged** — Jan 2022
    - *….A few months of iteration to fix design issues and bugs….*



Release and Long Tail

- **Opened** — Dec 2021, **Merged** — Jan 2022
  - *….A few months of iteration to fix design issues and bugs….*
- **Released** — Dec 16 2022, as OCaml 5.0
- **Long tail** of adding missing features, bug fixes and performance improvements
  - 5.1 — Sep 2023
  - 5.2 — May 2024
  - 5.3 — Jan 2025
  - 5.4 — Sep 2025

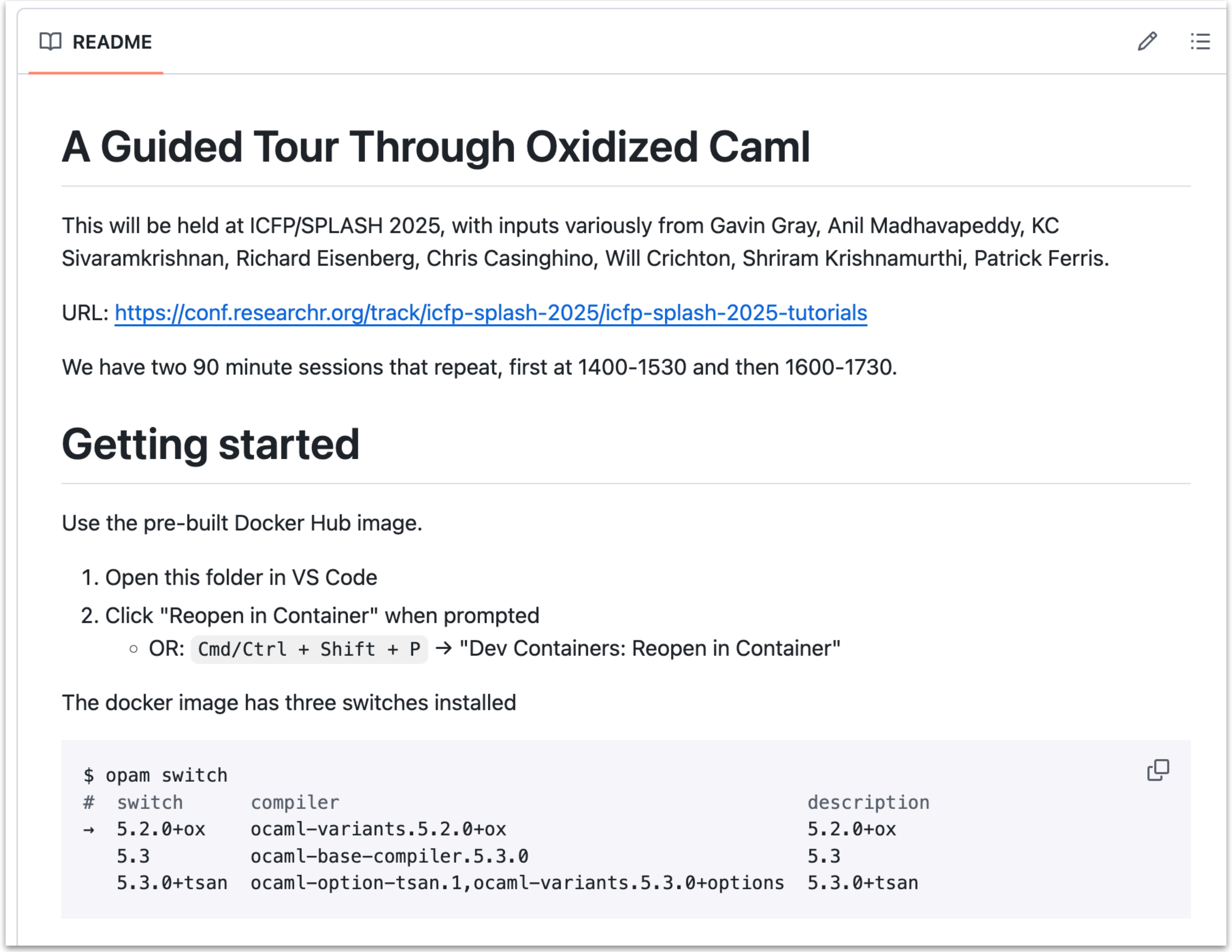


What’s next for OCaml?

- **OxCaml** — Bridging the performance and safety gap between OCaml and Rust
  - *Data-race-free parallelism* through *modes*
  - Better control over object layout, allocations and GC
- Draws lessons from Multicore OCaml execution
  - Several award-winning papers at POPL, ICFP, OOPSLA
  - CI for the external universe — https://oxcaml.check.ci.dev/
- But different in other ways…
  - In production at Jane Street
  - Valuable user-feedback-oriented design

https://oxcaml.org

OxCaml tutorial



README

A Guided Tour Through Oxidized Caml

This will be held at ICFP/SPLASH 2025, with inputs variously from Gavin Gray, Anil Madhavapeddy, KC Sivaramkrishnan, Richard Eisenberg, Chris Casinghino, Will Crichton, Shriram Krishnamurthi, Patrick Ferris.

URL: https://conf.researchr.org/track/icfp-splash-2025/icfp-splash-2025-tutorials

We have two 90 minute sessions that repeat, first at 1400-1530 and then 1600-1730.

Getting started

Use the pre-built Docker Hub image.

1. Open this folder in VS Code
2. Click "Reopen in Container" when prompted
   - OR: `Cmd/Ctrl + Shift + P` → "Dev Containers: Reopen in Container"

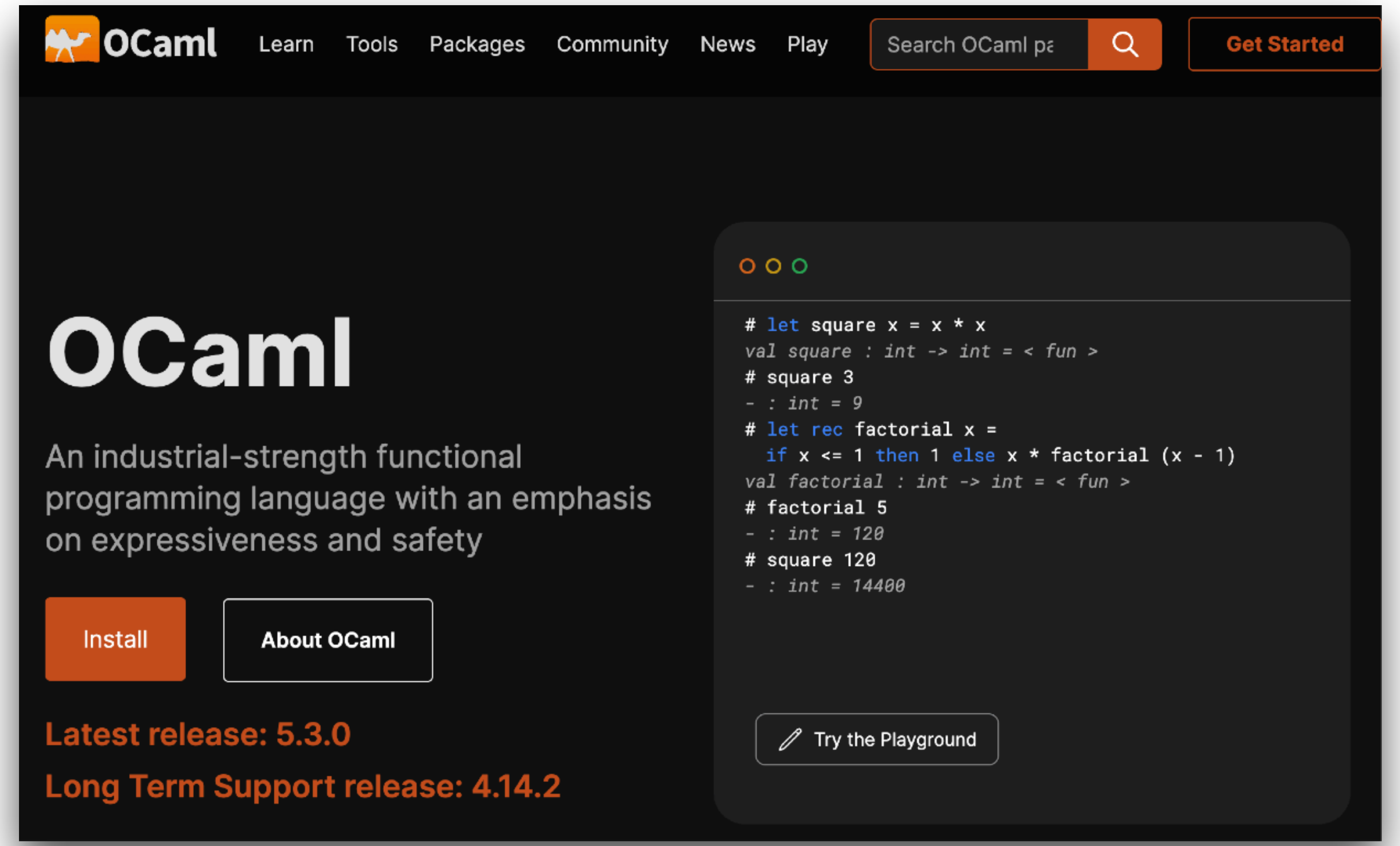
The docker image has three switches installed

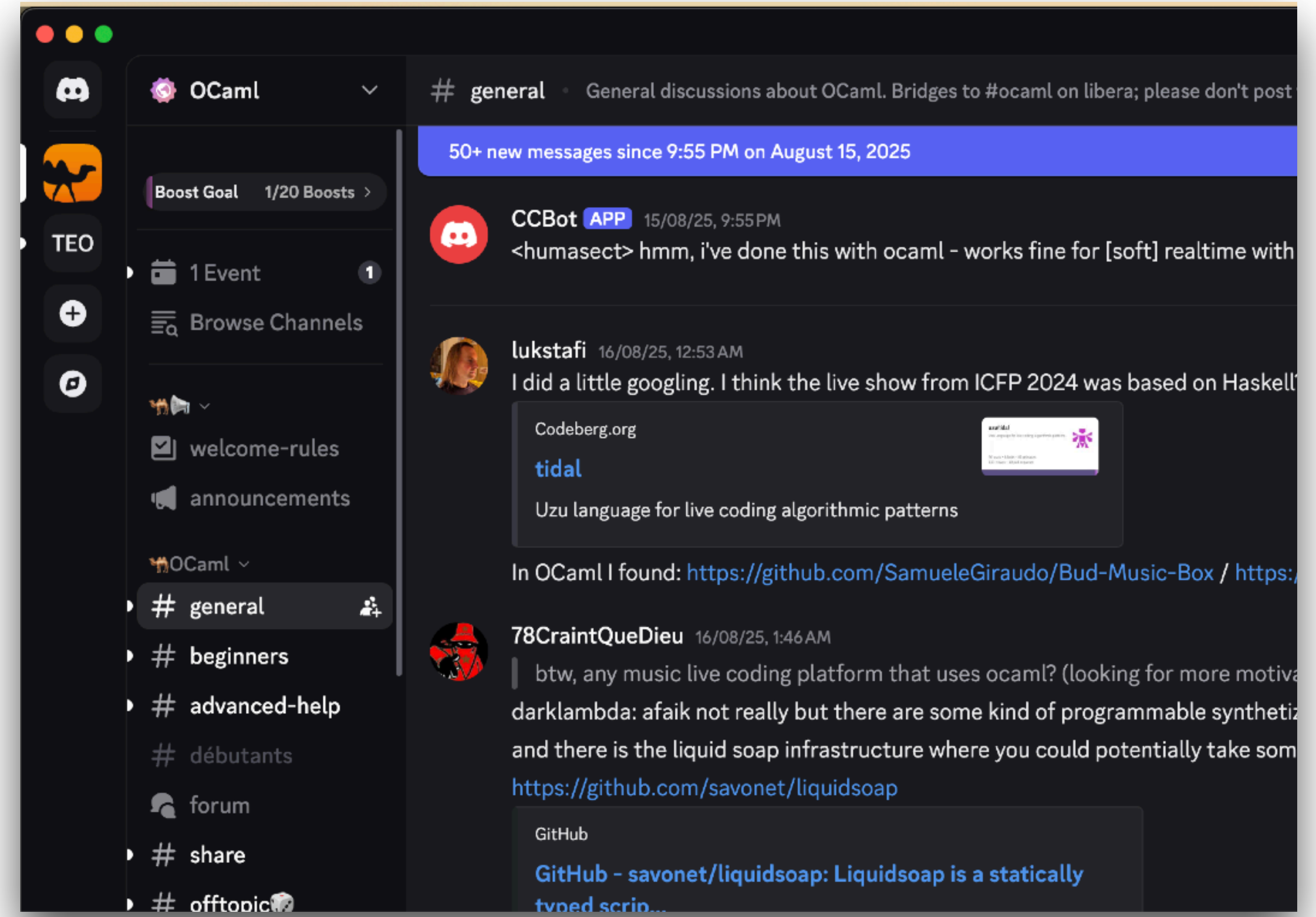
```
$ opam switch
#  switch      compiler                                          description
→  5.2.0+ox    ocaml-variants.5.2.0+ox                           5.2.0+ox
   5.3         ocaml-base-compiler.5.3.0                         5.3
   5.3.0+tsan  ocaml-option-tsan.1,ocaml-variants.5.3.0+options  5.3.0+tsan
```

https://github.com/oxcaml/tutorial-icfp25

Get Involved!

ocaml.org





OCaml Discord

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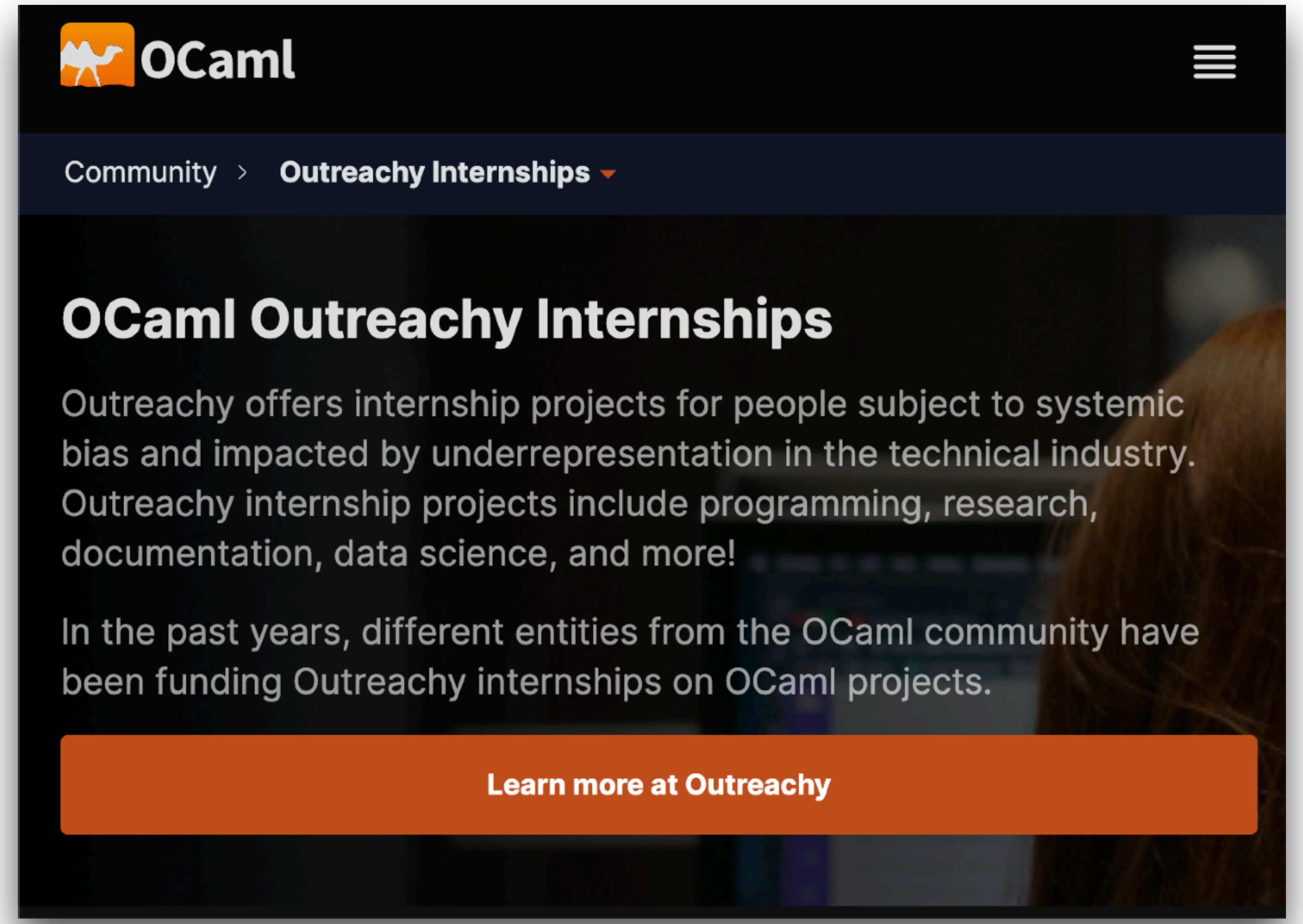

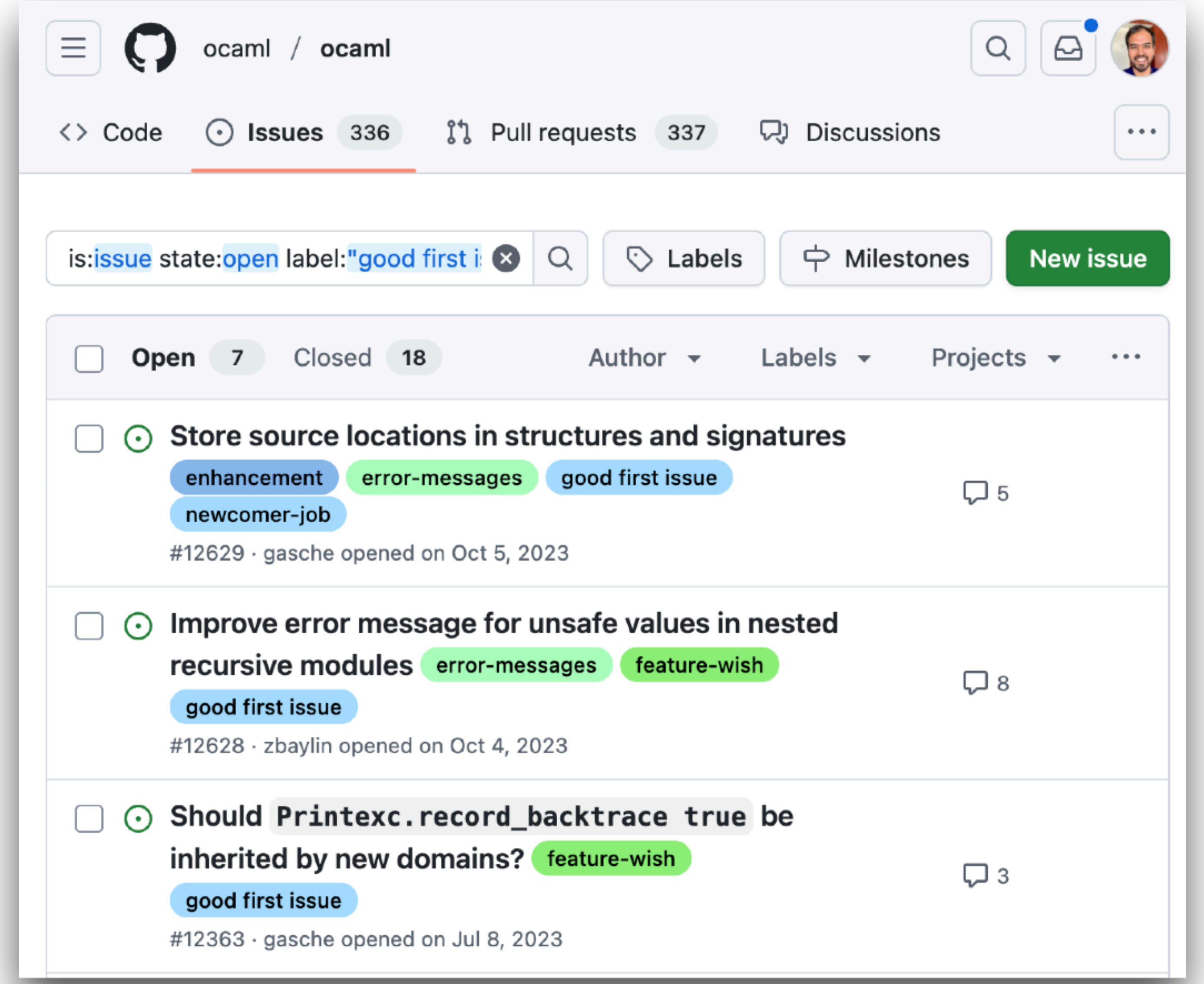

github.com/ocaml