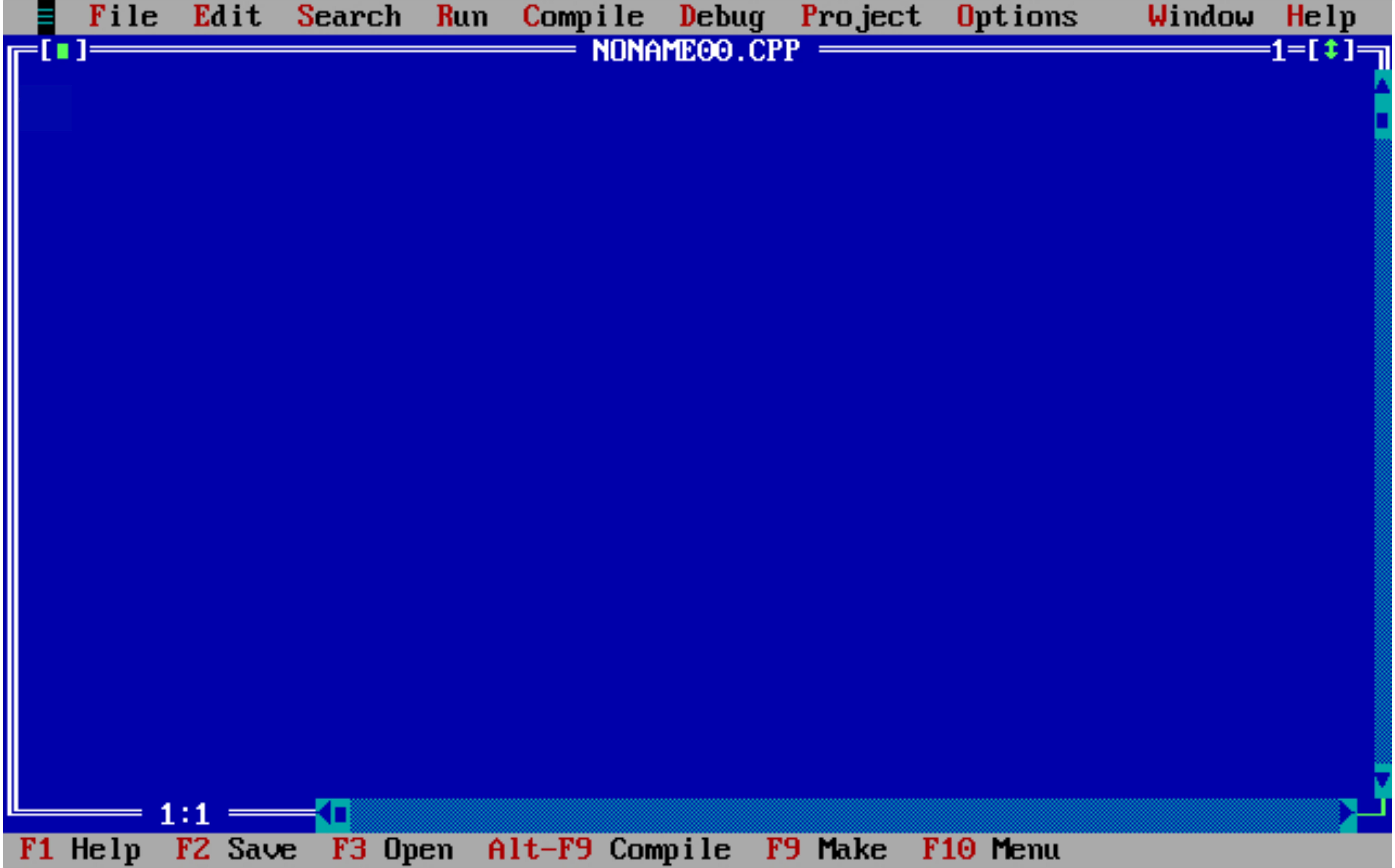
Evolving the OCaml programming language

KC Sivaramakrishnan
kcsrk.info

IITM CSE Bytes
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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NONAME00.CPP
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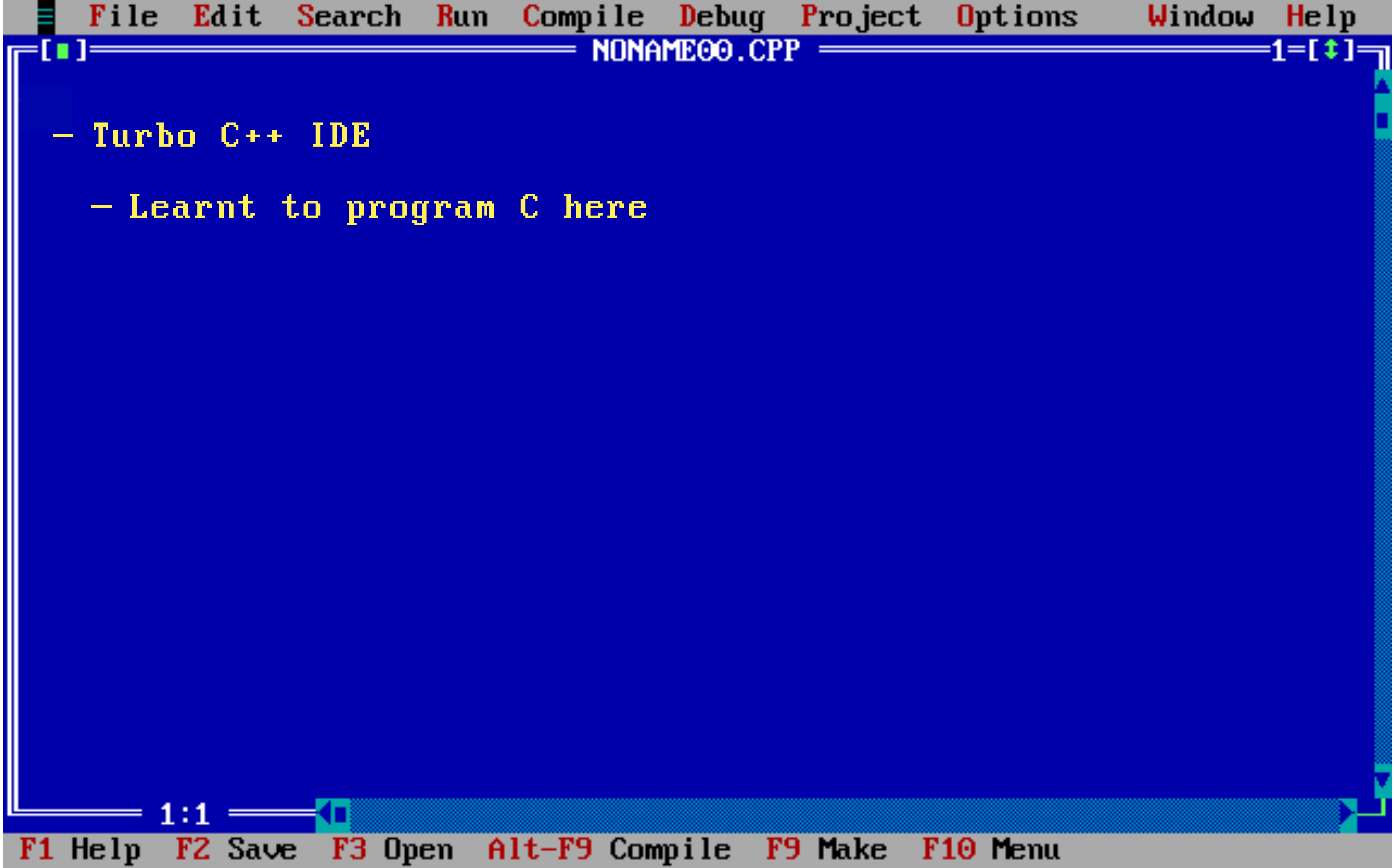

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- This talk is about the evolution of programming languages
  - Specifically, OCaml

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OCaml

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***

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- 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.

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🌐 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

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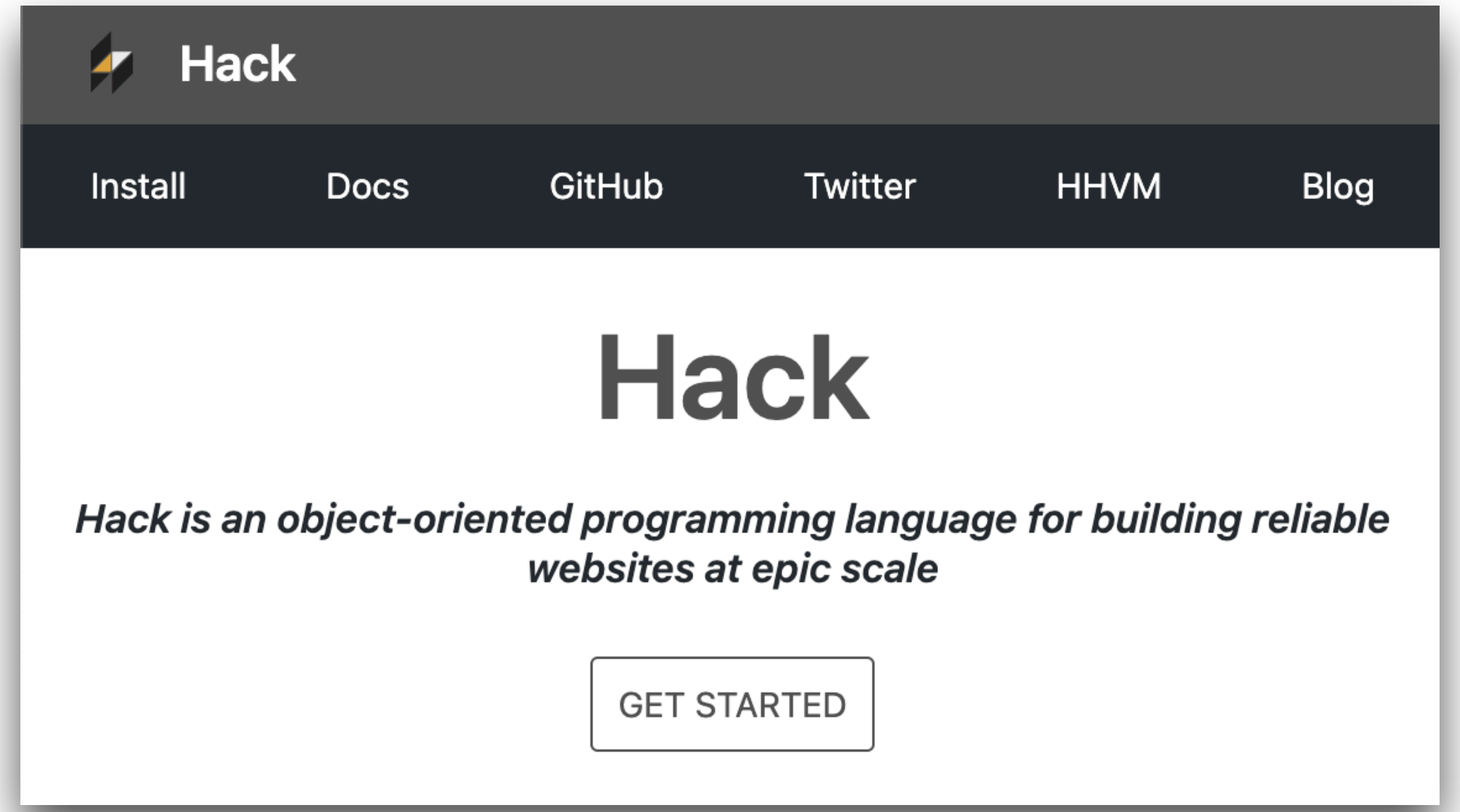

The Rust Programming Language

WA

Compilers

High dynamic range

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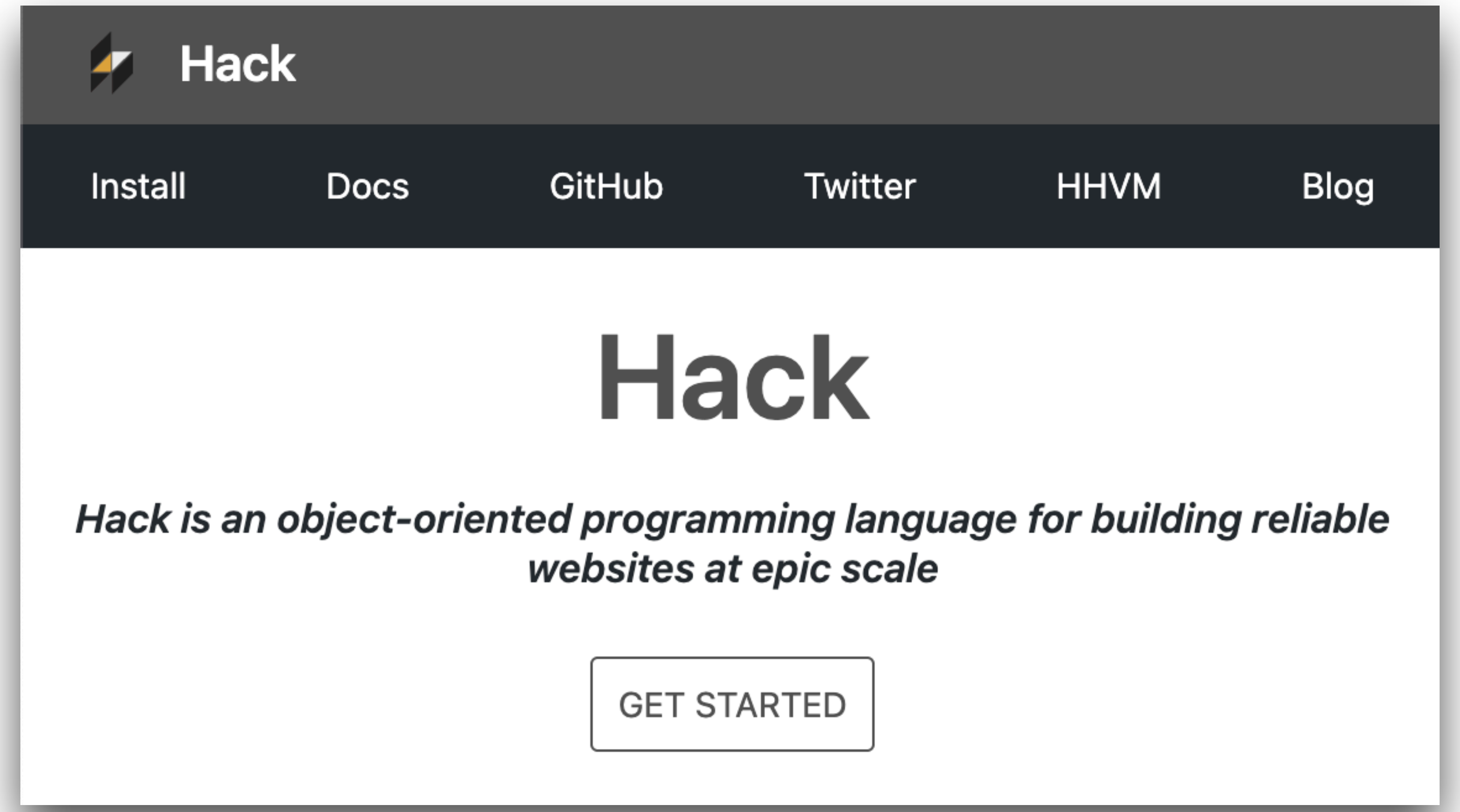

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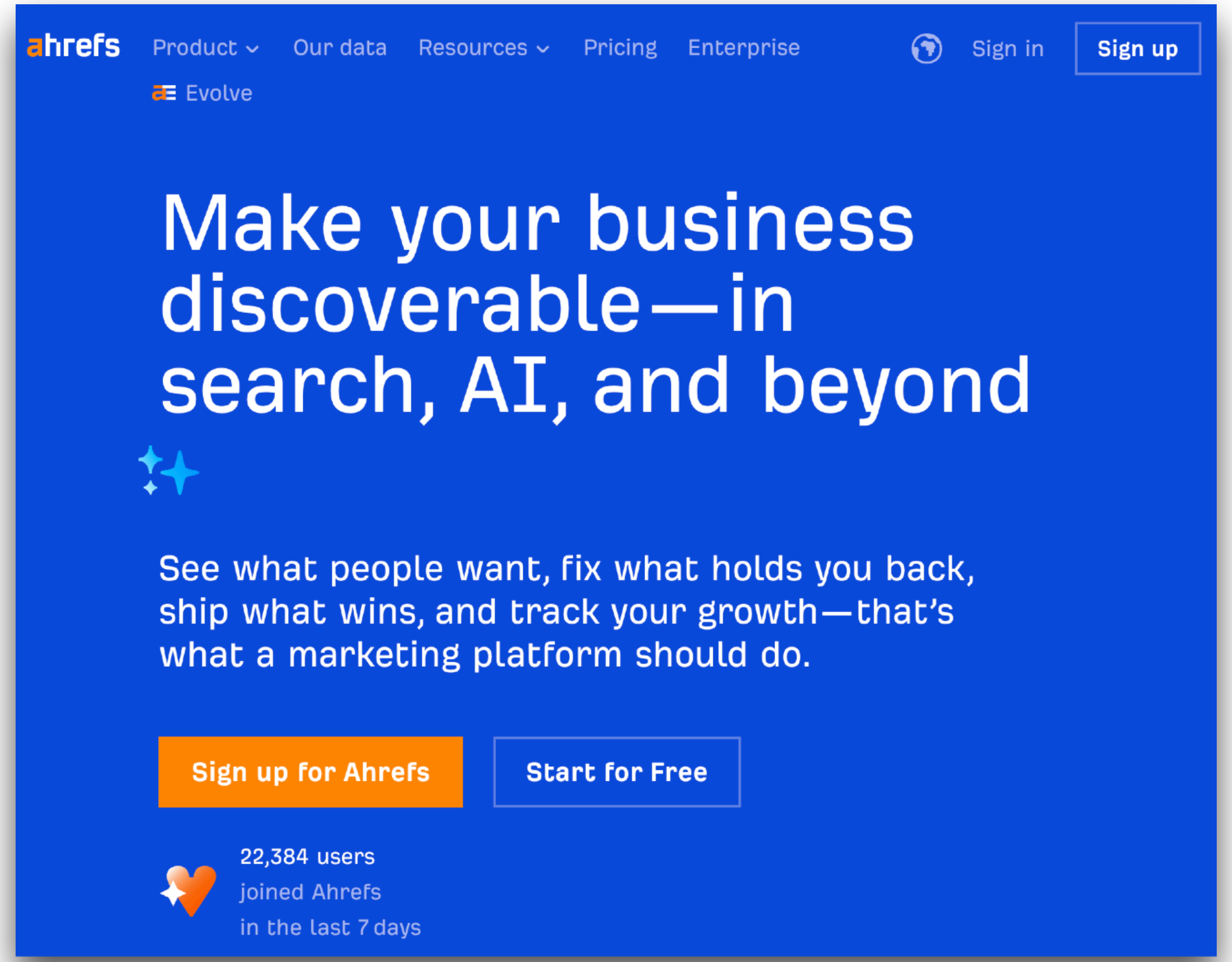

Web Frontend

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 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**.

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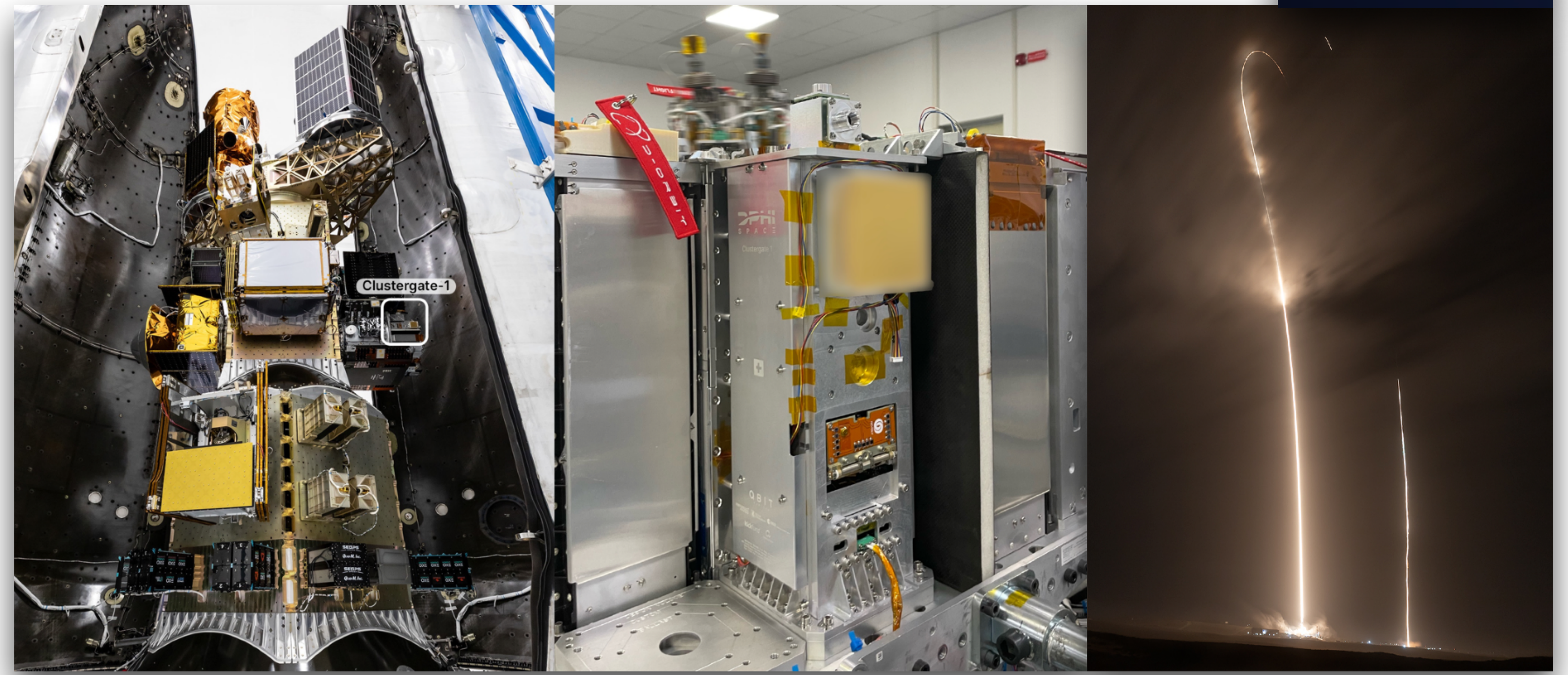
OCaml in Space 🚀

Parsimoni



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60+M lines of OCaml code!

Jane Street

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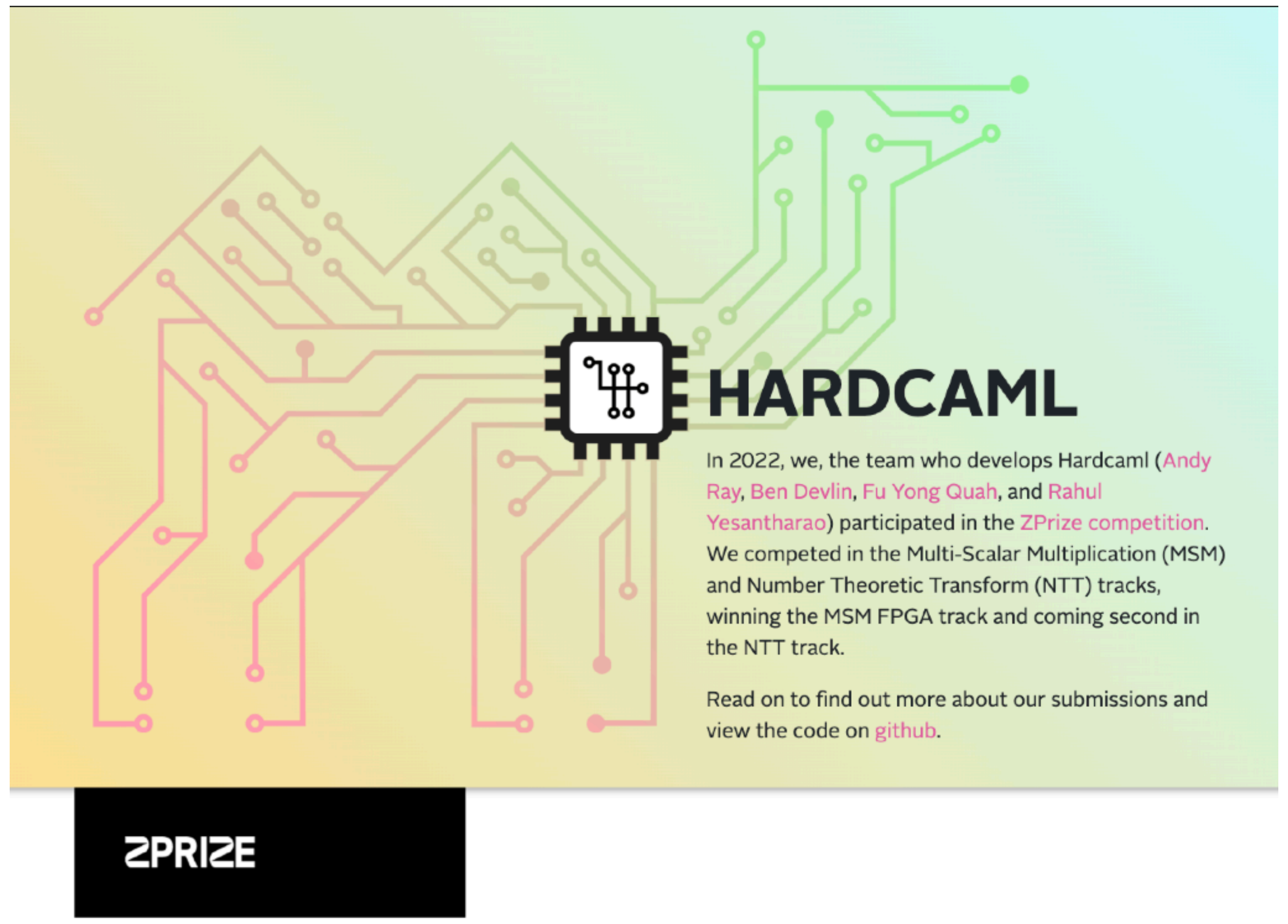

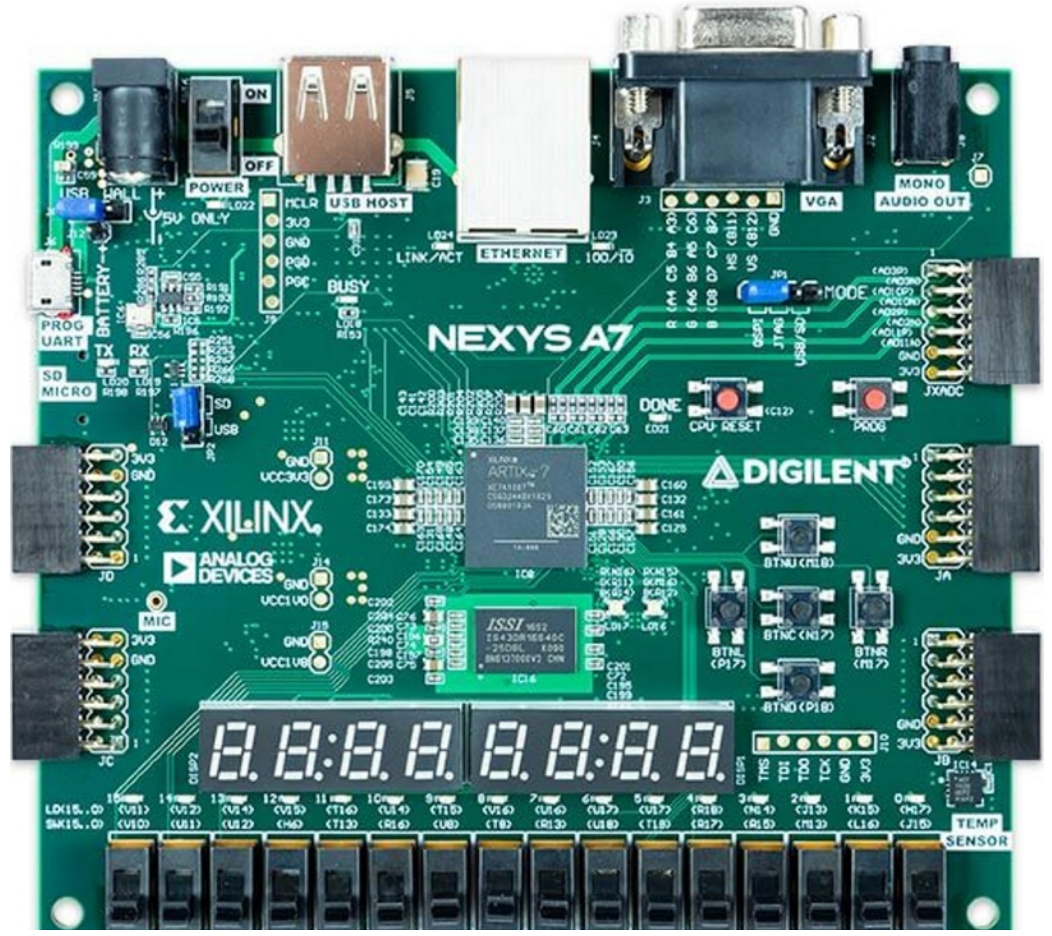

Hardware design

OCaml

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29 years old!

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

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Type system, type inference

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How to thrive not just survive after ~30 years?

Simplicity and *stability*

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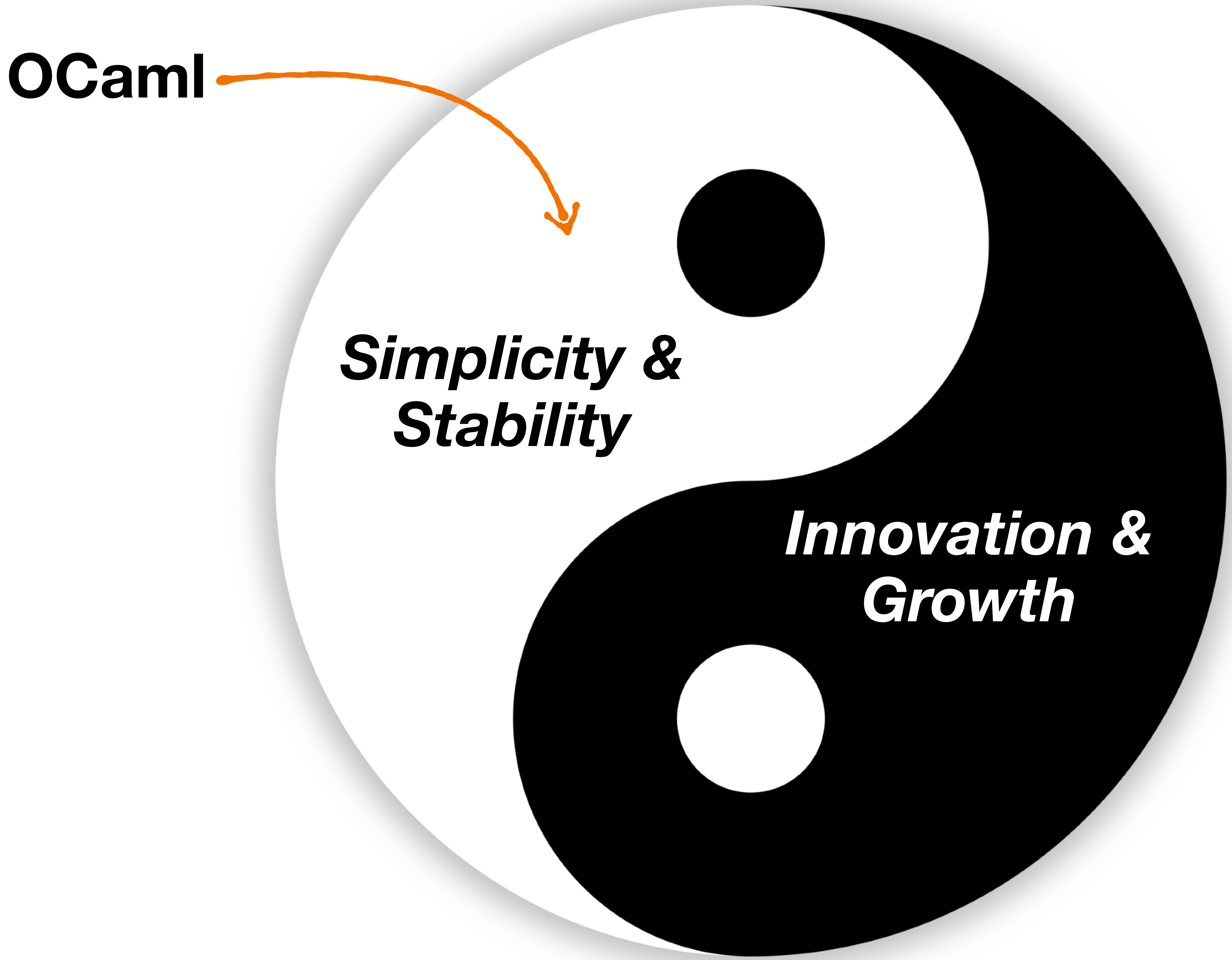
- If you take OCaml from 20 years ago, the code will likely ***continue to work!***
- No recent releases for some popular packages
  - They are ***good enough***, and continue to be so.
  - Nothing to be done to keep it working!


Simplicity &
Stability
Innovation &
Growth


OCaml
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OCaml Maintainers

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Alain Frisch	Jacques-Henri Jourdan	Florian Angeletti
Armaël Guéneau	KC Sivaramakrishnan	Olivier Nicole
Anil Madhavapeddy	Frédéric Bour	Sadiq Jaffer
Pierre Chambart	Leo White	Sébastien Hinderer
Damien Doligez	Vincent Laviron	Stephen Dolan
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- Custodians of the compiler
  - ***Not the ones deciding how the language should evolve!***

Who decides how OCaml evolves?

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- Evolution
  - **User-driven:** OCaml, Python
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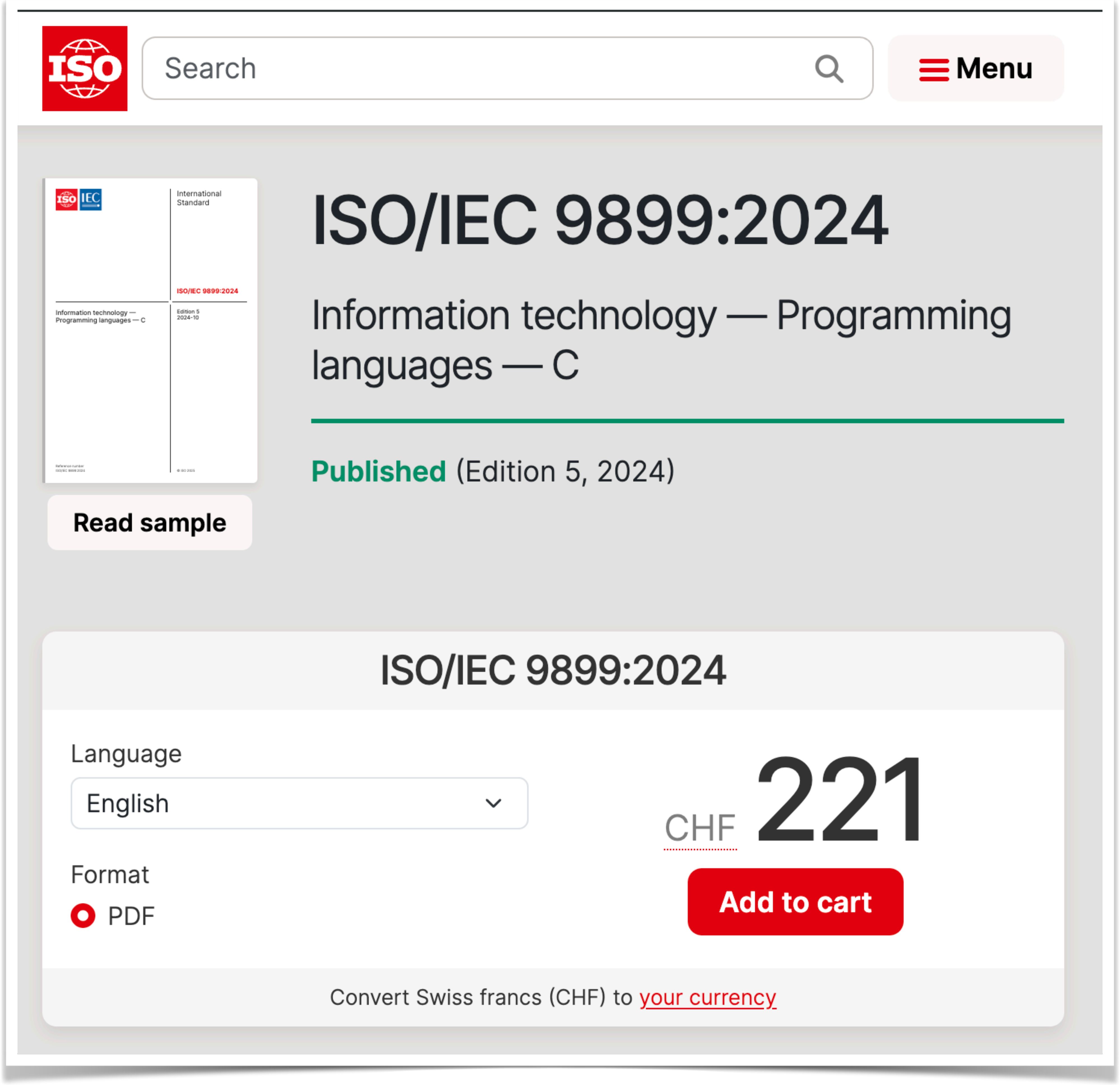

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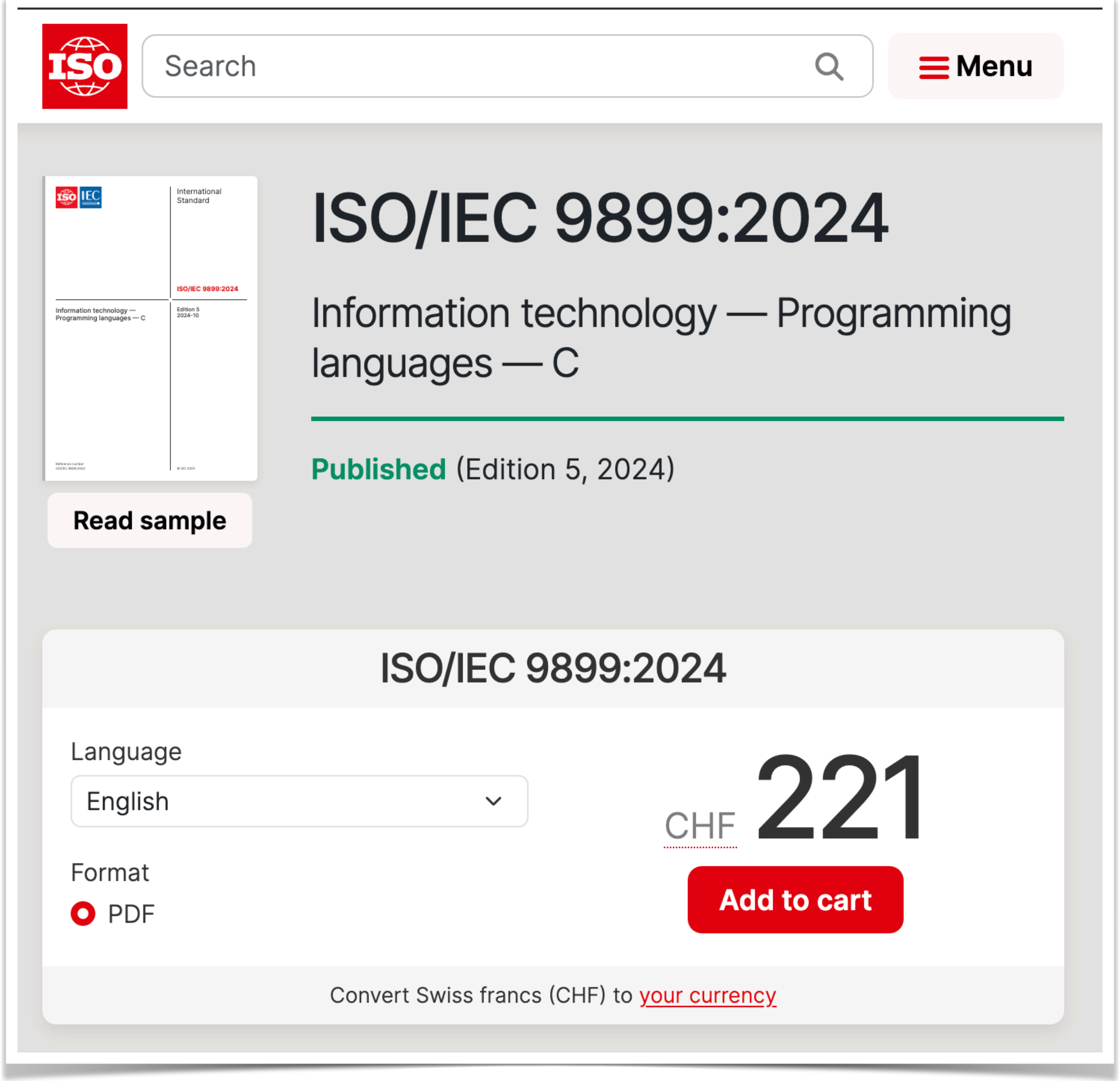
- *The bar is lower to change the language*



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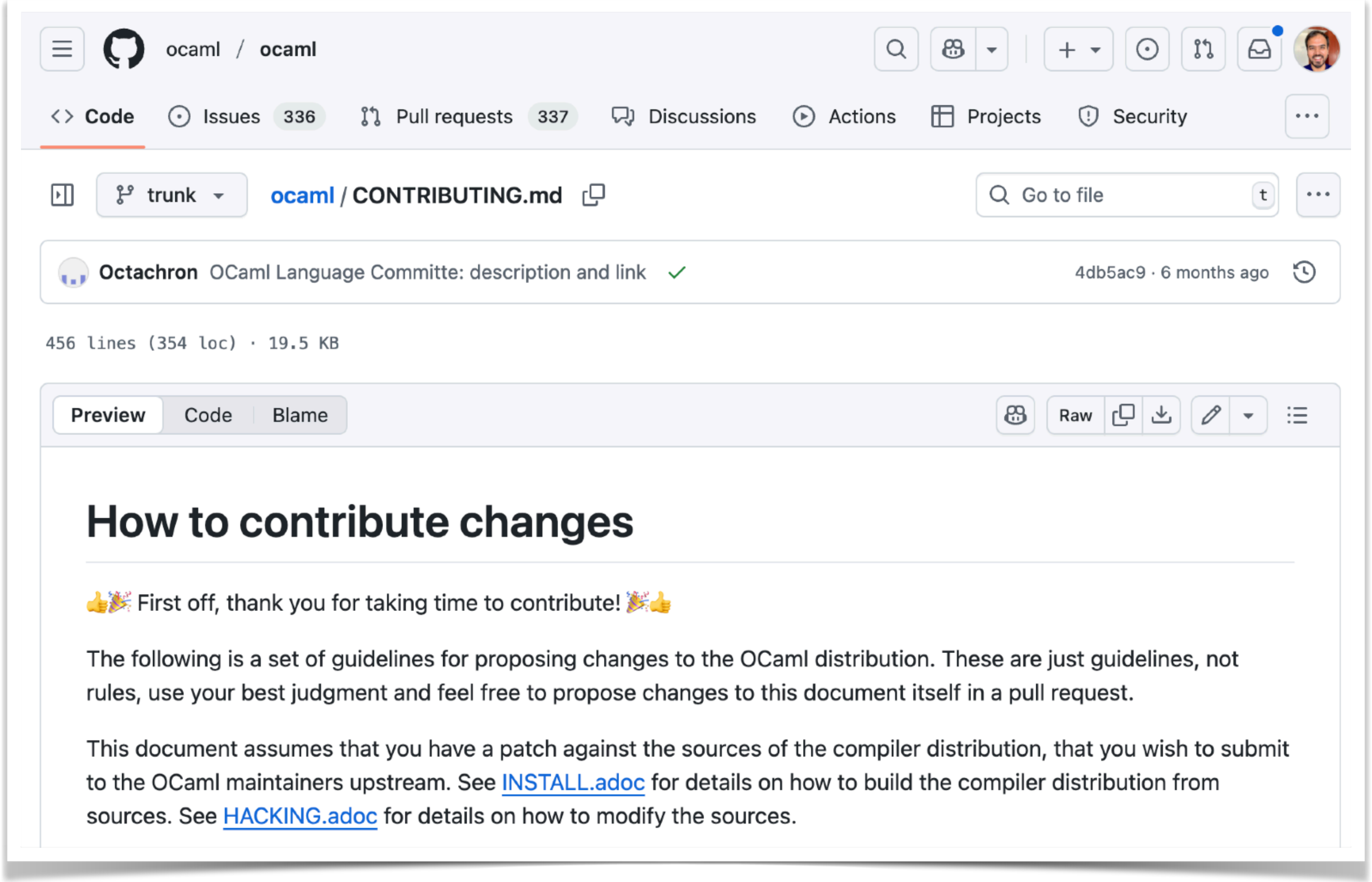

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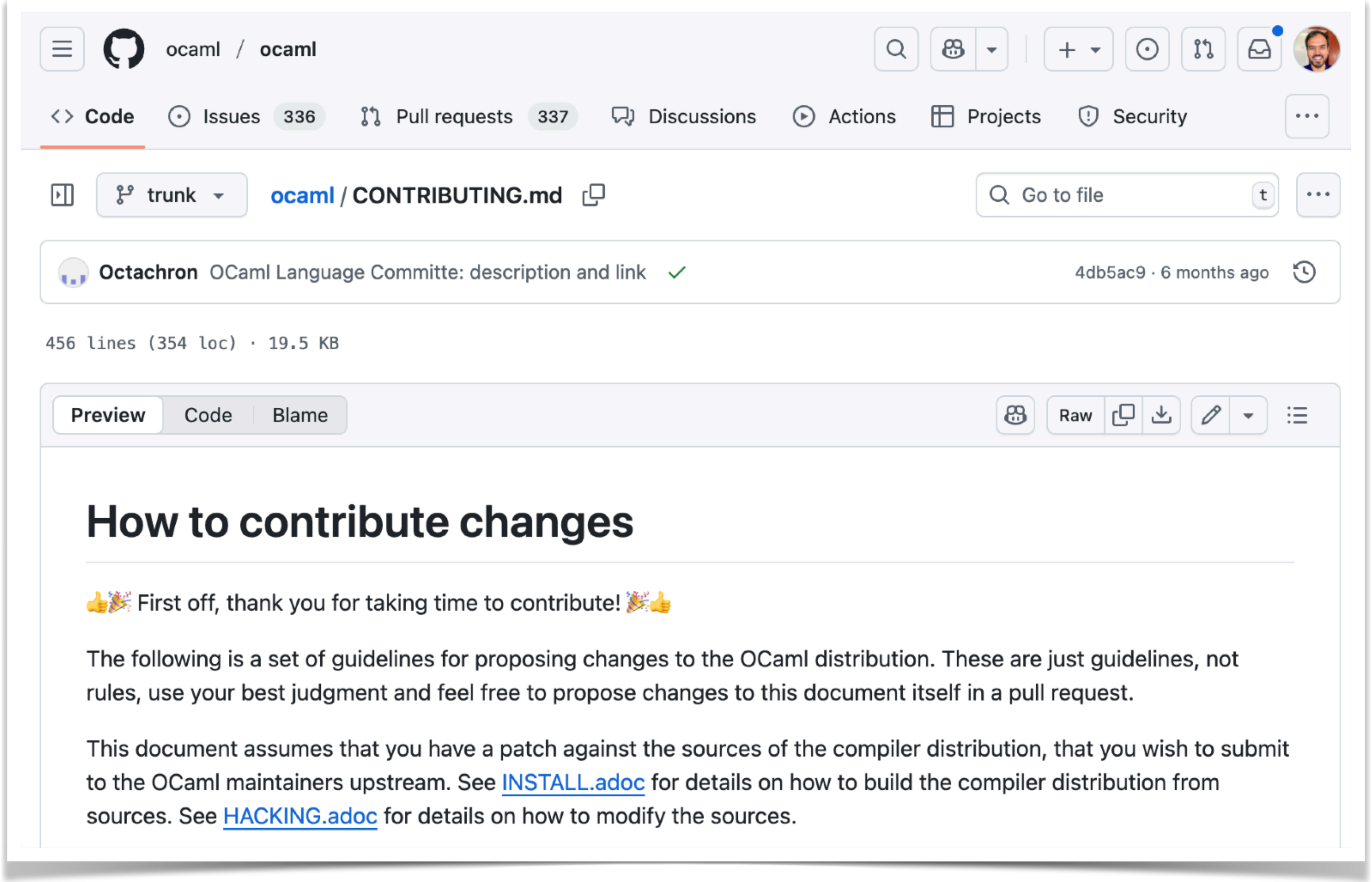

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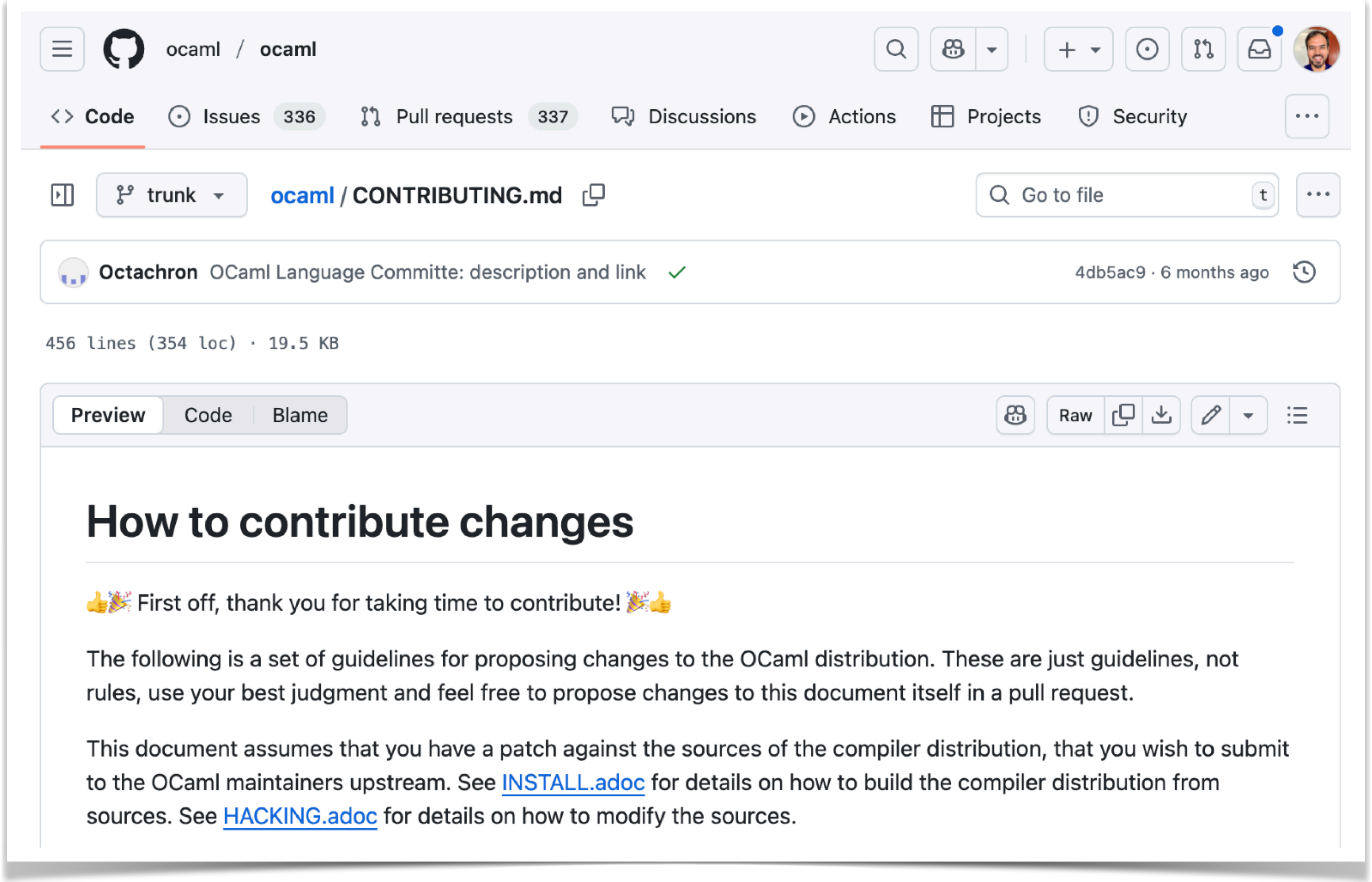

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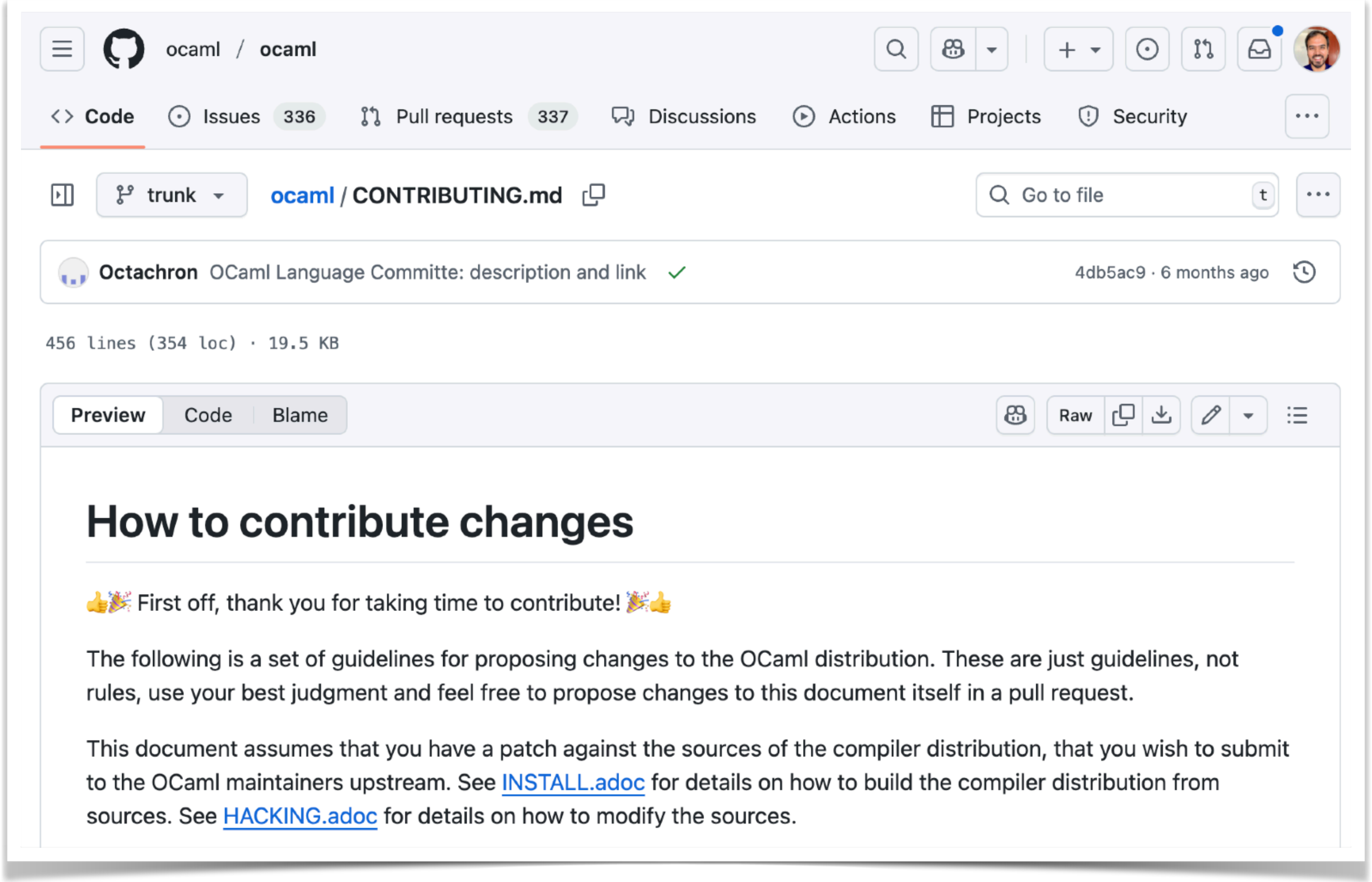
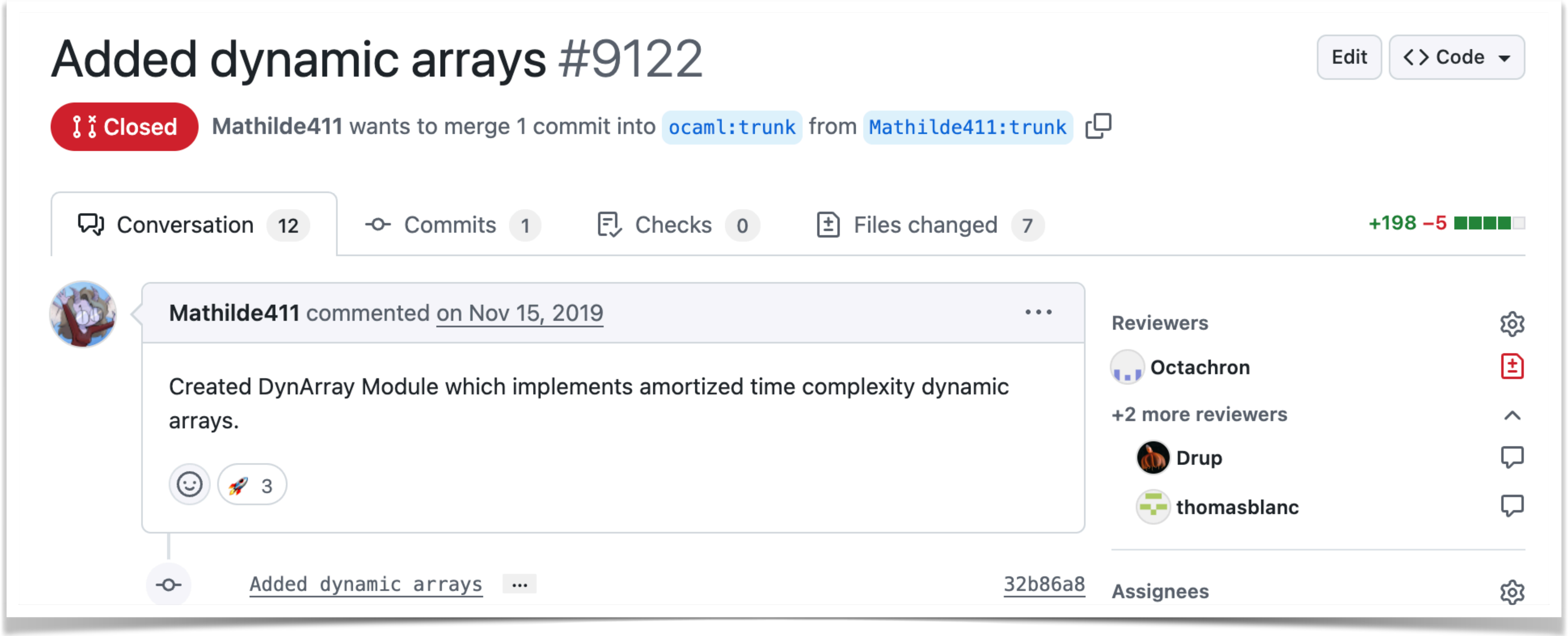
  - **Large features** → Bespoke based on the features
    - May need publishing papers, extensive performance evaluation, formalised/mechanised soundness results, etc.
- ***Often, presumably small feature requests take a life of their own!***



A small(?) change — Dynamic Arrays



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Implementation rather naive, room for improvements

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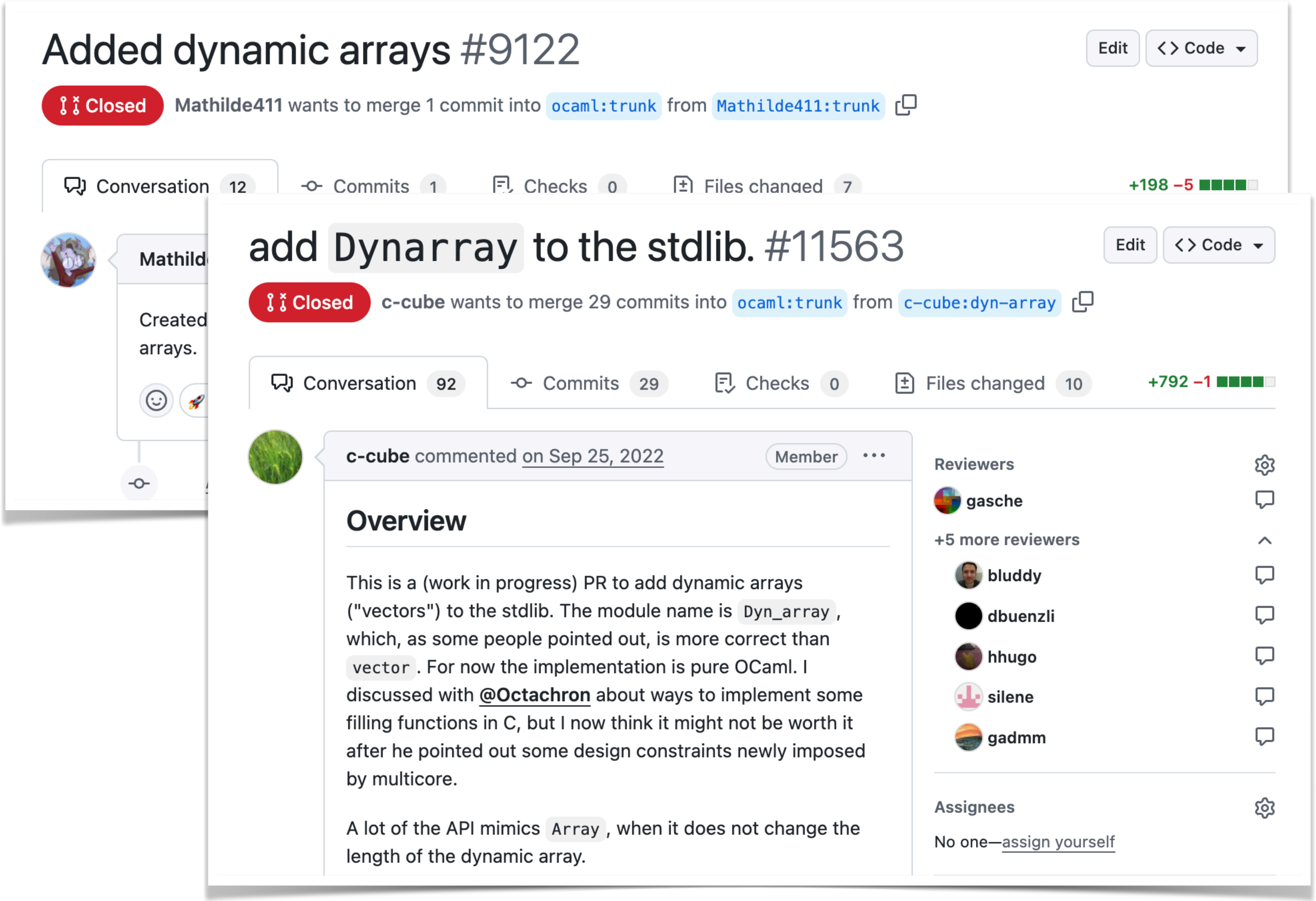

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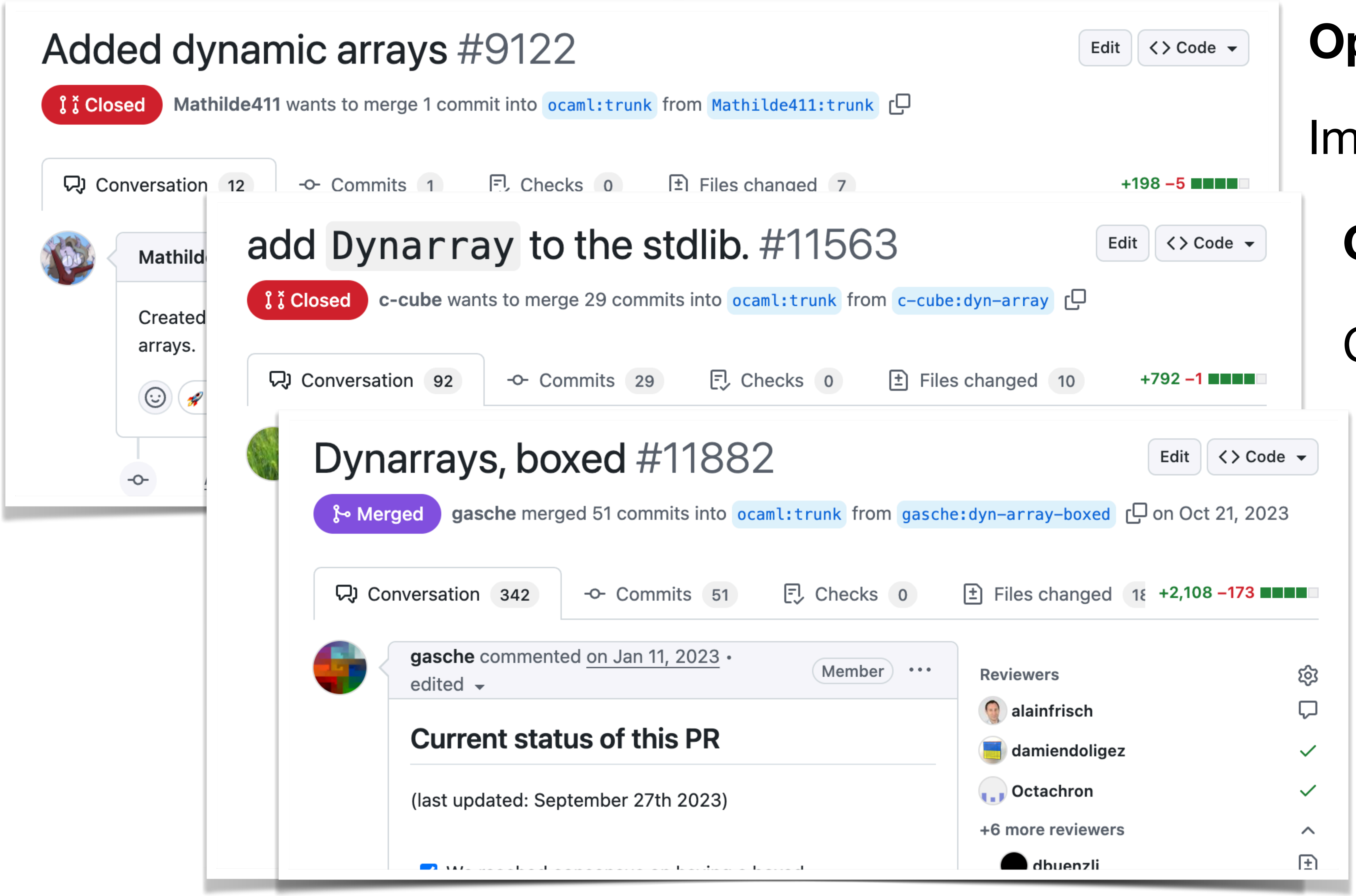

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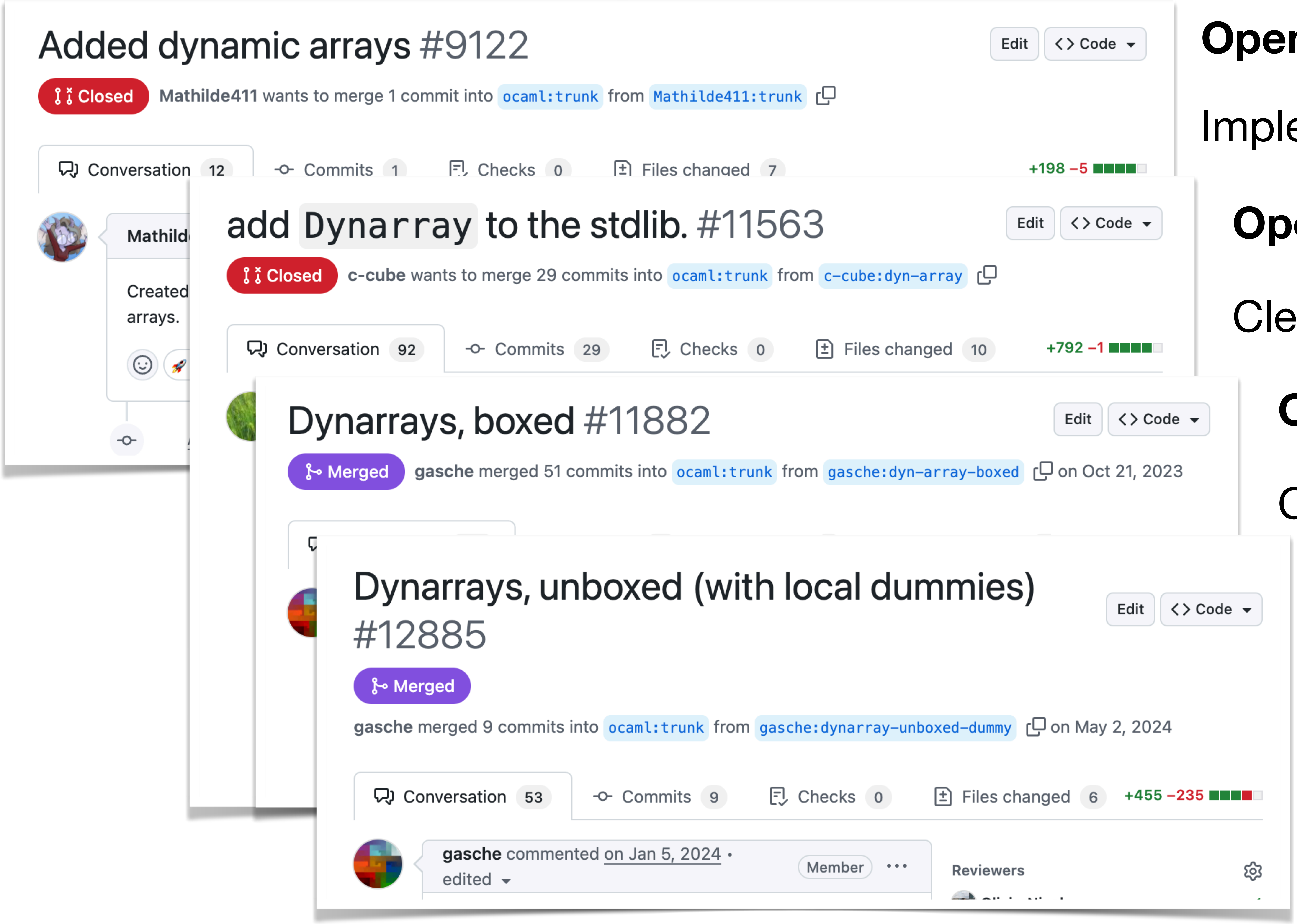

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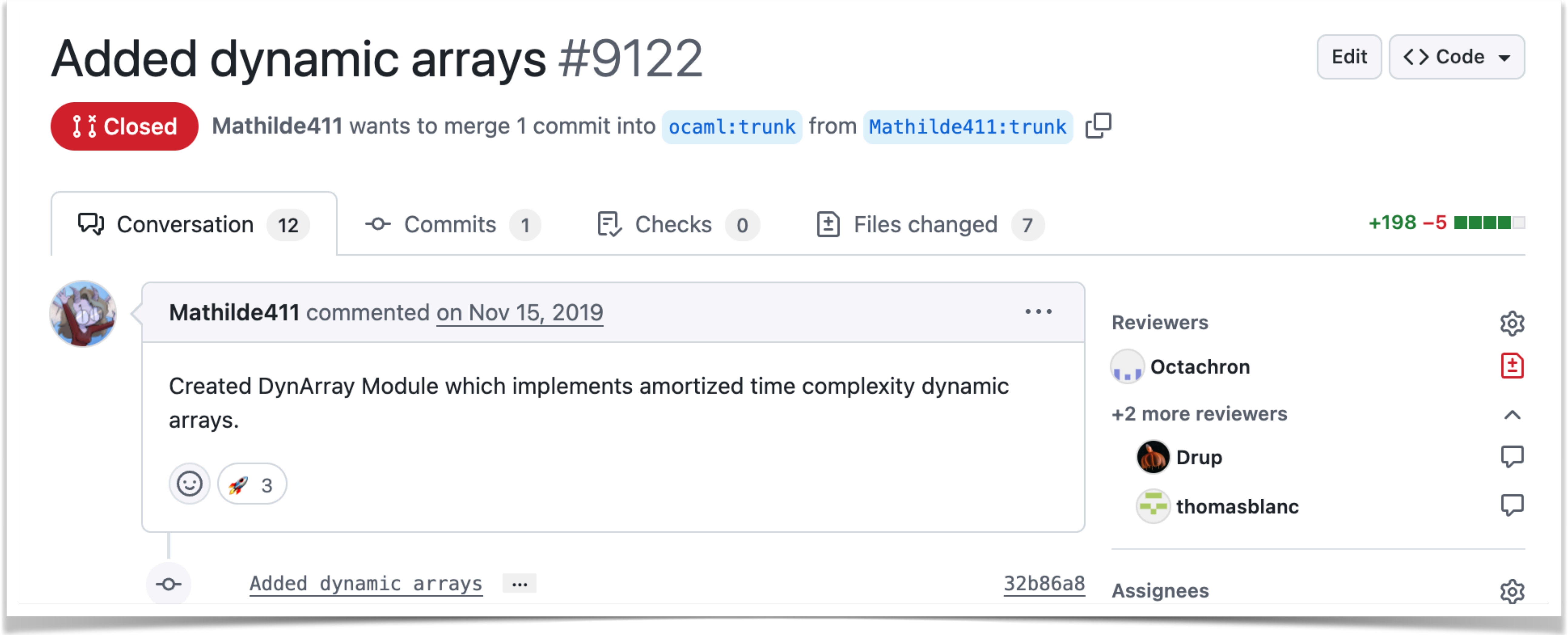
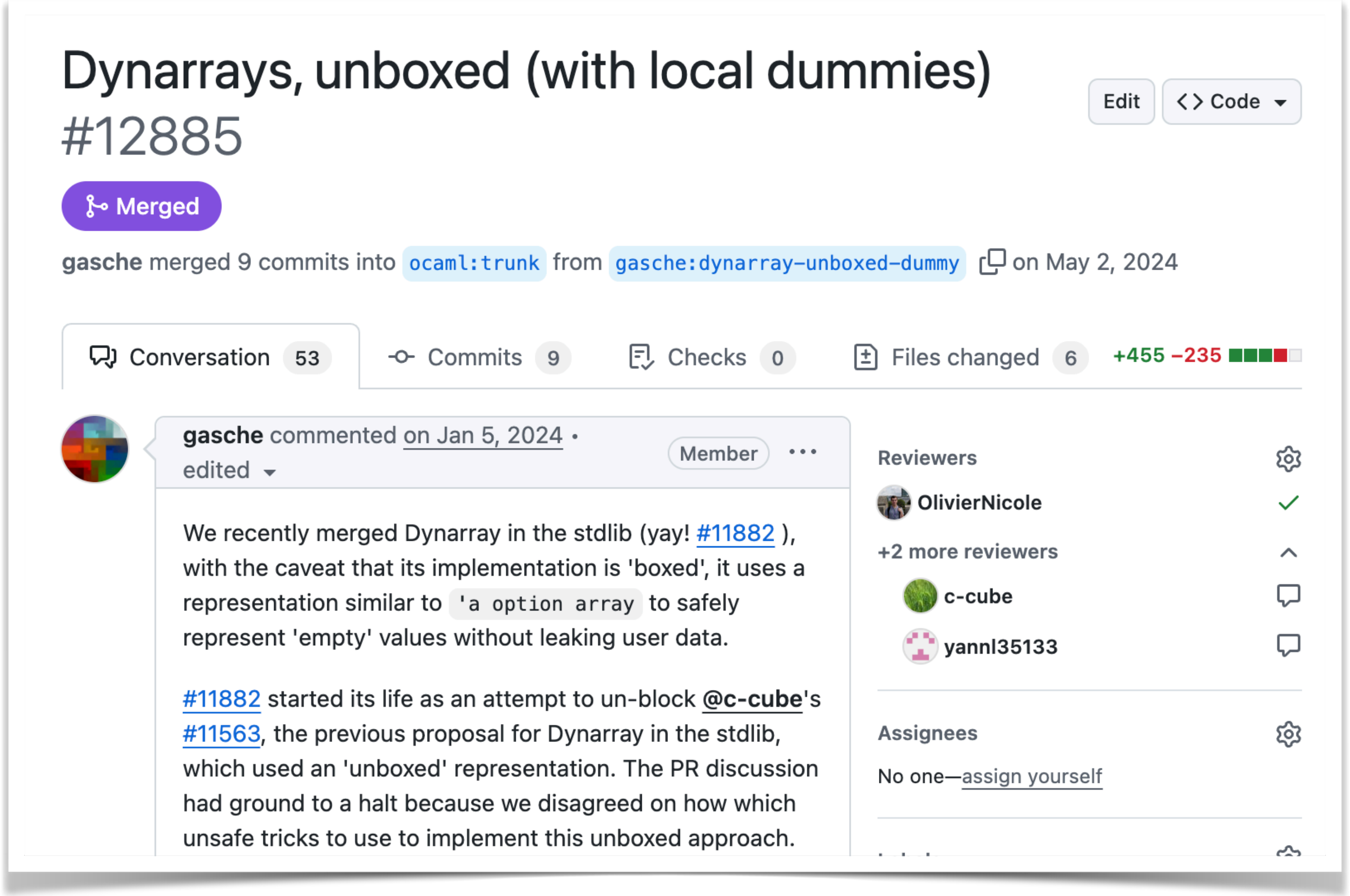
Clean API ***and*** simple implementation

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

Clean API and ***optimised*** implementation

Dynamic Arrays





- **Summary**
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  - Initially — 198 loc, finally — ~2500 loc
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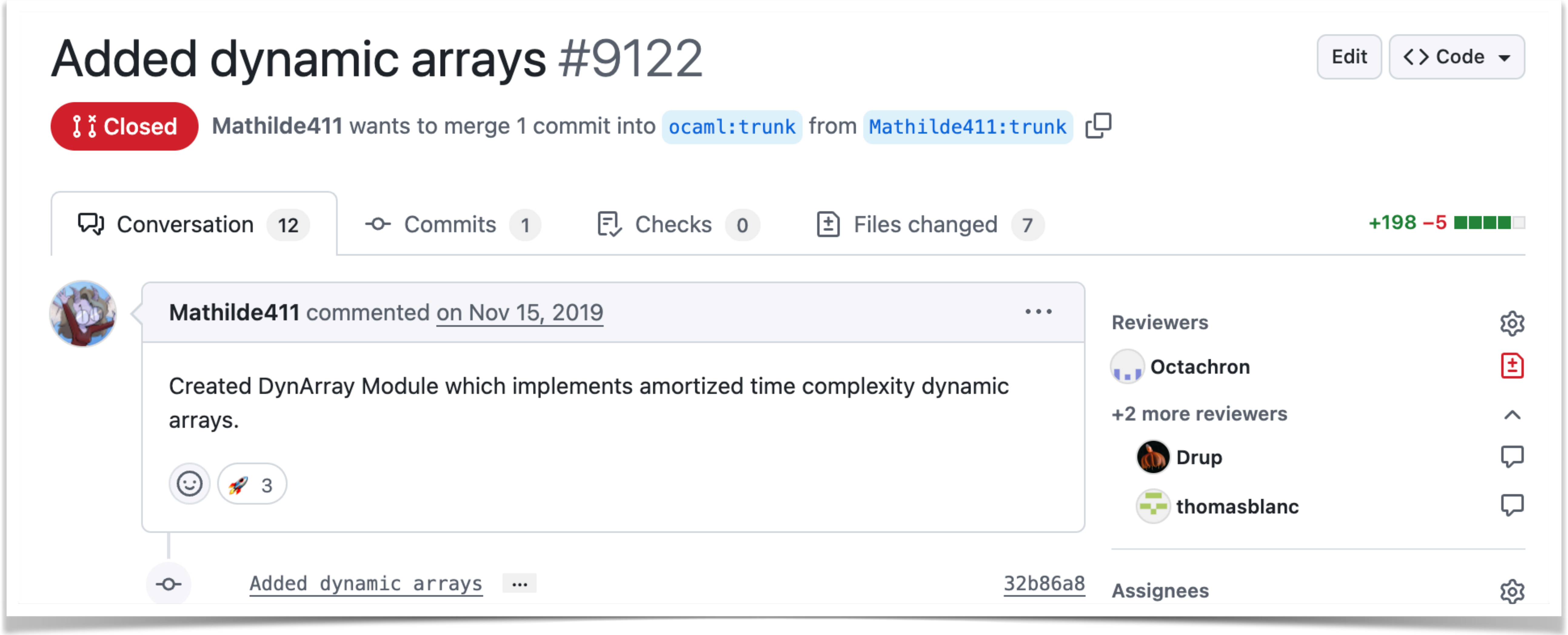
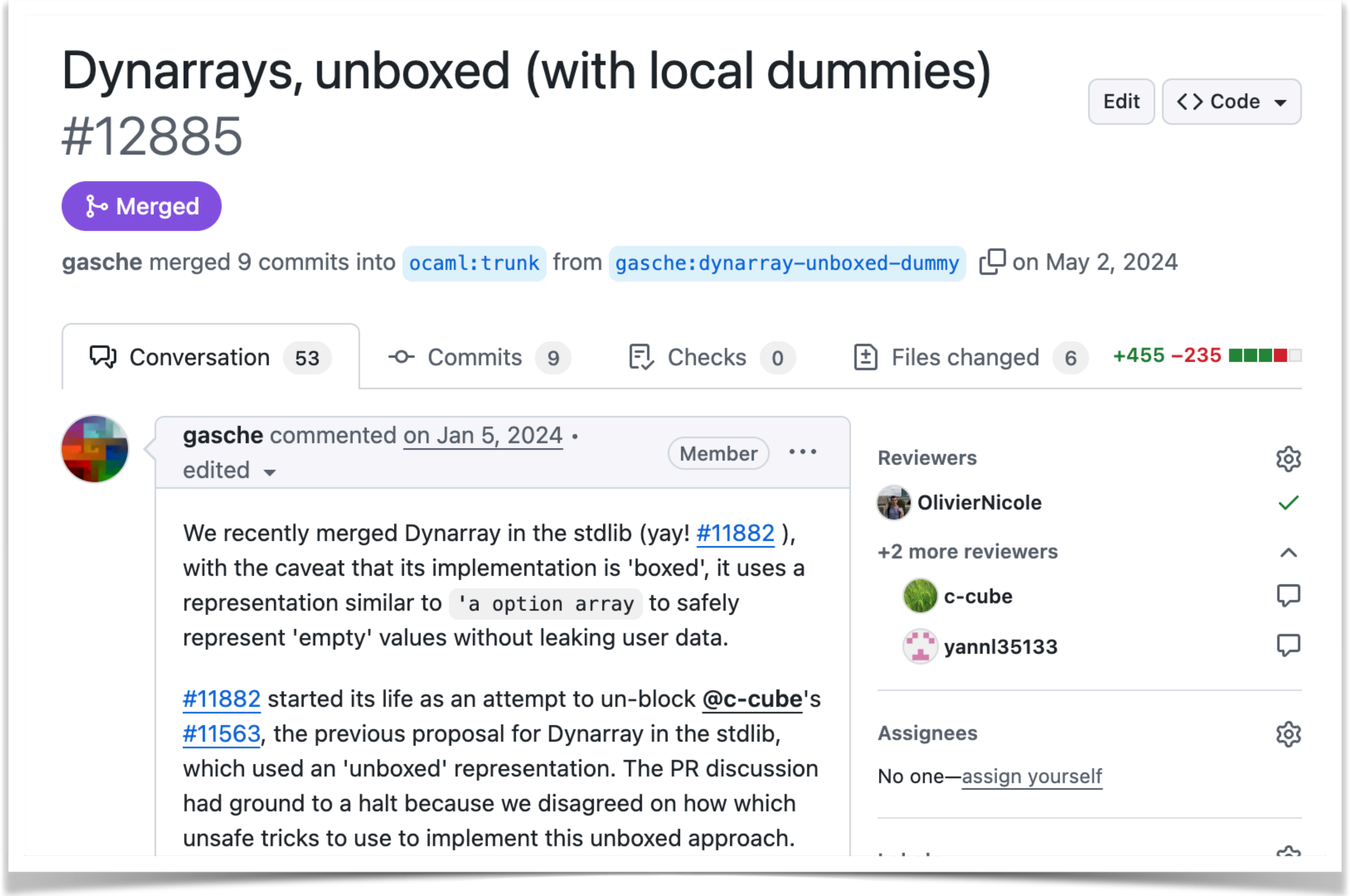
Dynamic Arrays





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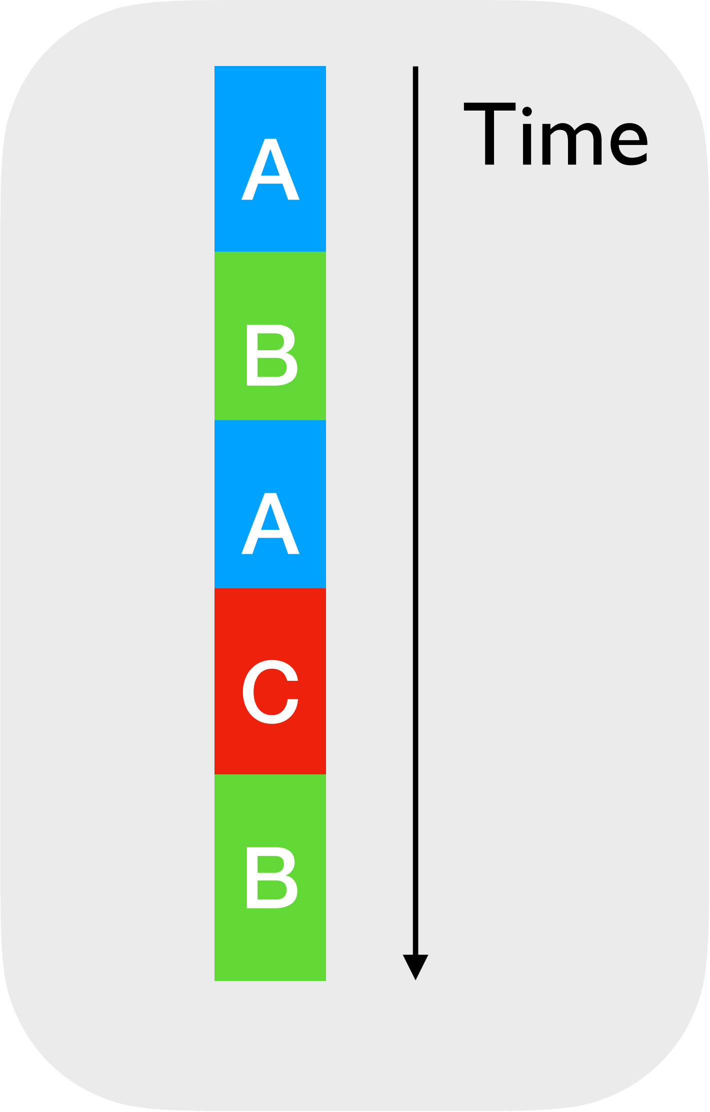
  - Initially — 198 loc, finally — ~2500 loc
  - 500+ comments in the various PRs
- **Worth it?**
  - ***Yes!*** Should work for the next couple of decades.
  - Harder to undo changes after the release.

A large change — Multicore OCaml

- Native support for concurrency and parallelism to OCaml

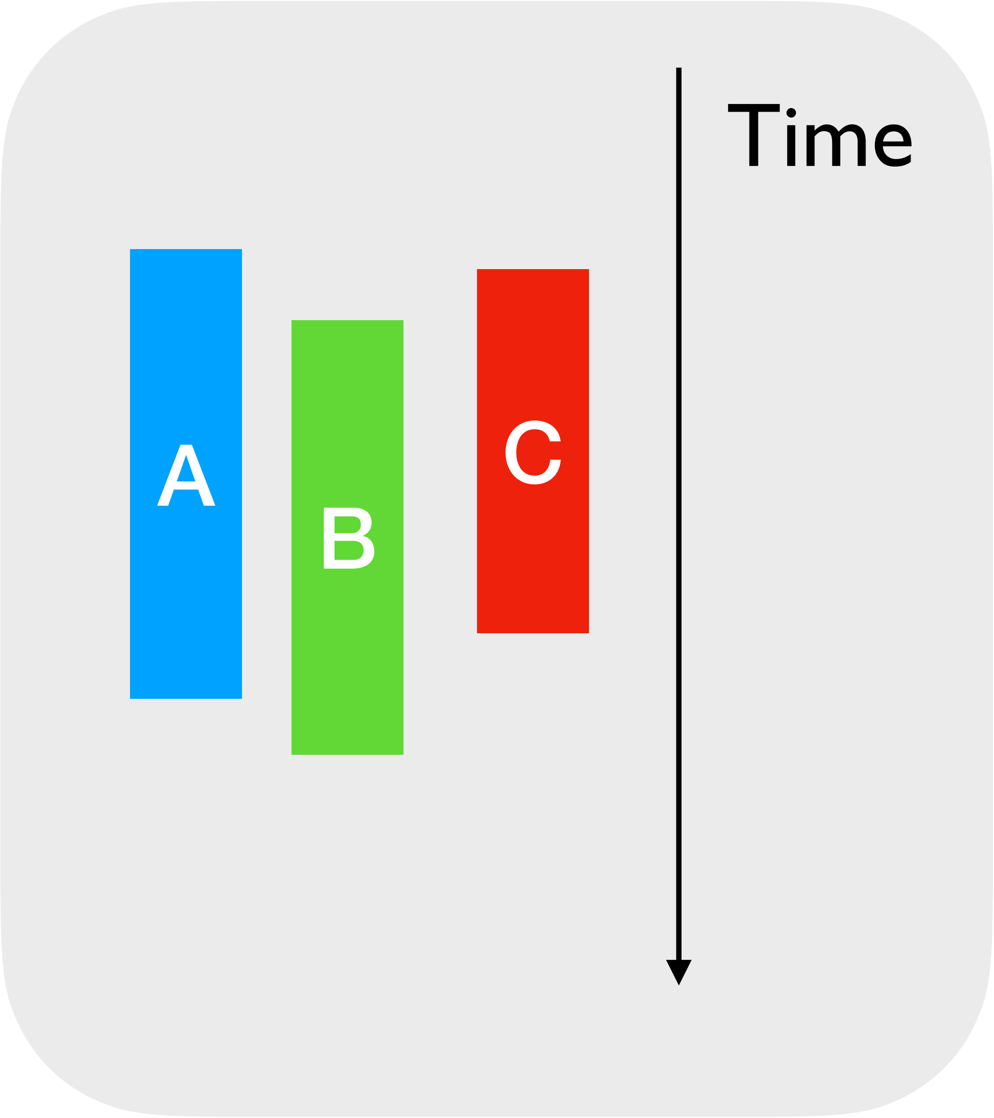
Concurrency



Interleaved execution

Effect Handlers

Parallelism



Simultaneous execution

Domains

Challenges

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- Maintain feature and performance backwards compatibility!
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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

Starting out

Upstream OCaml

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Stephen Dolan   Leo White   Anil Madhavapeddy

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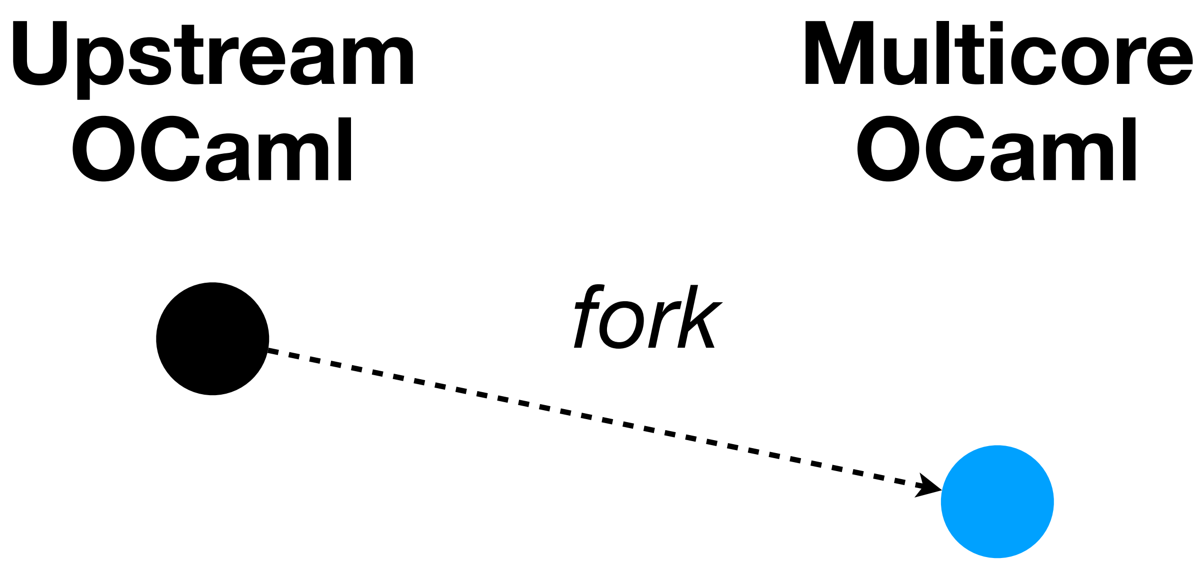
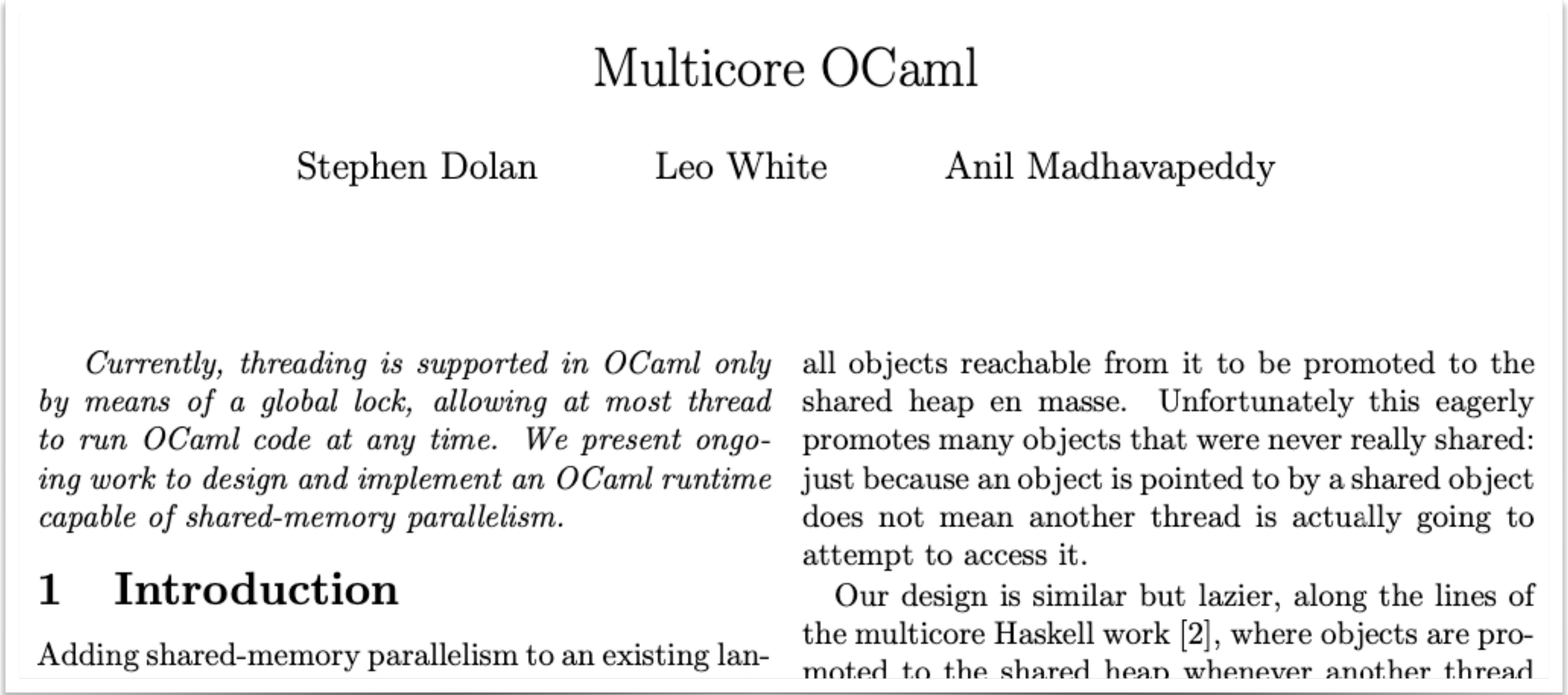
all objects reachable from it to be promoted to the shared heap en masse. Unfortunately this eagerly promotes many objects that were never really shared: just because an object is pointed to by a shared object does not mean another thread is actually going to attempt to access it.

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*

Starting out





Multicore OCaml

Stephen Dolan   Leo White   Anil Madhavapeddy

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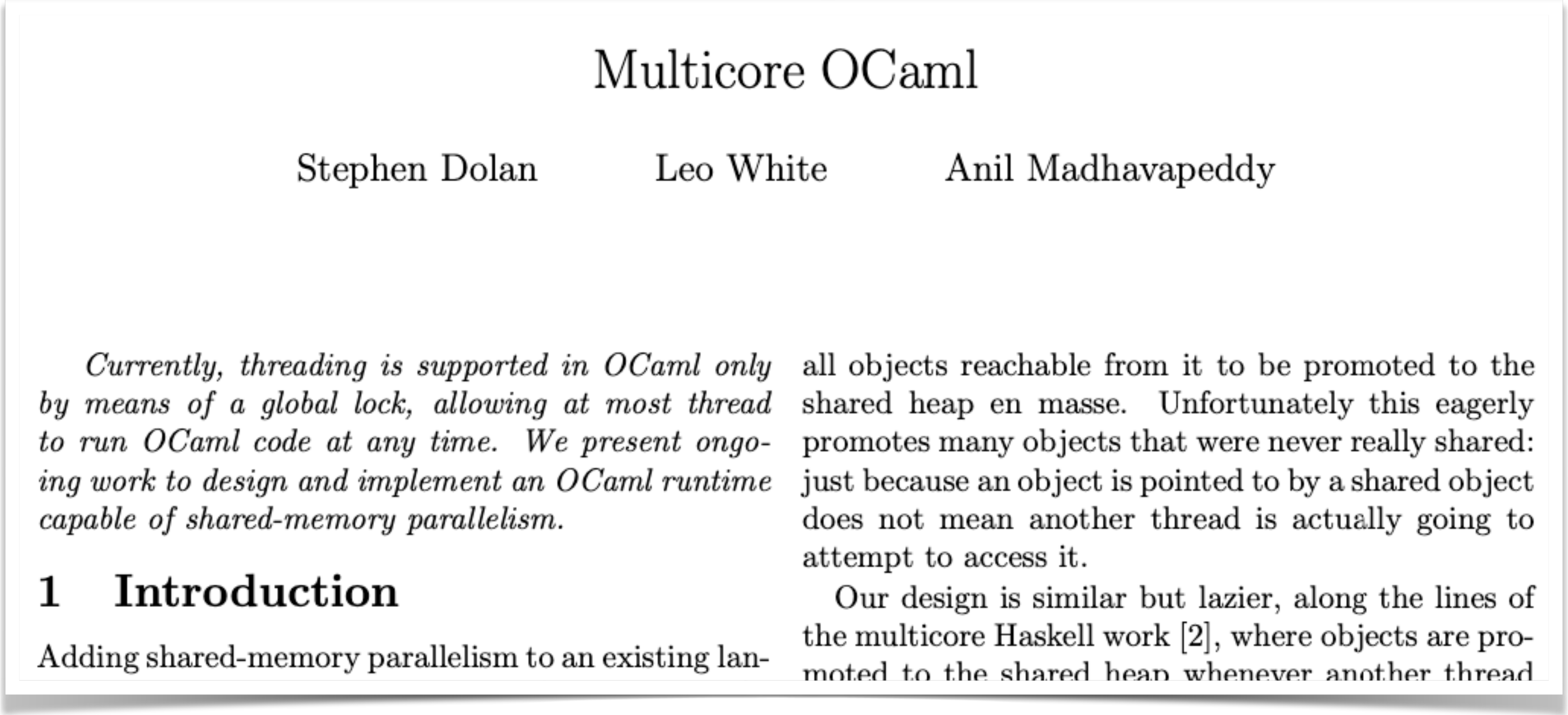

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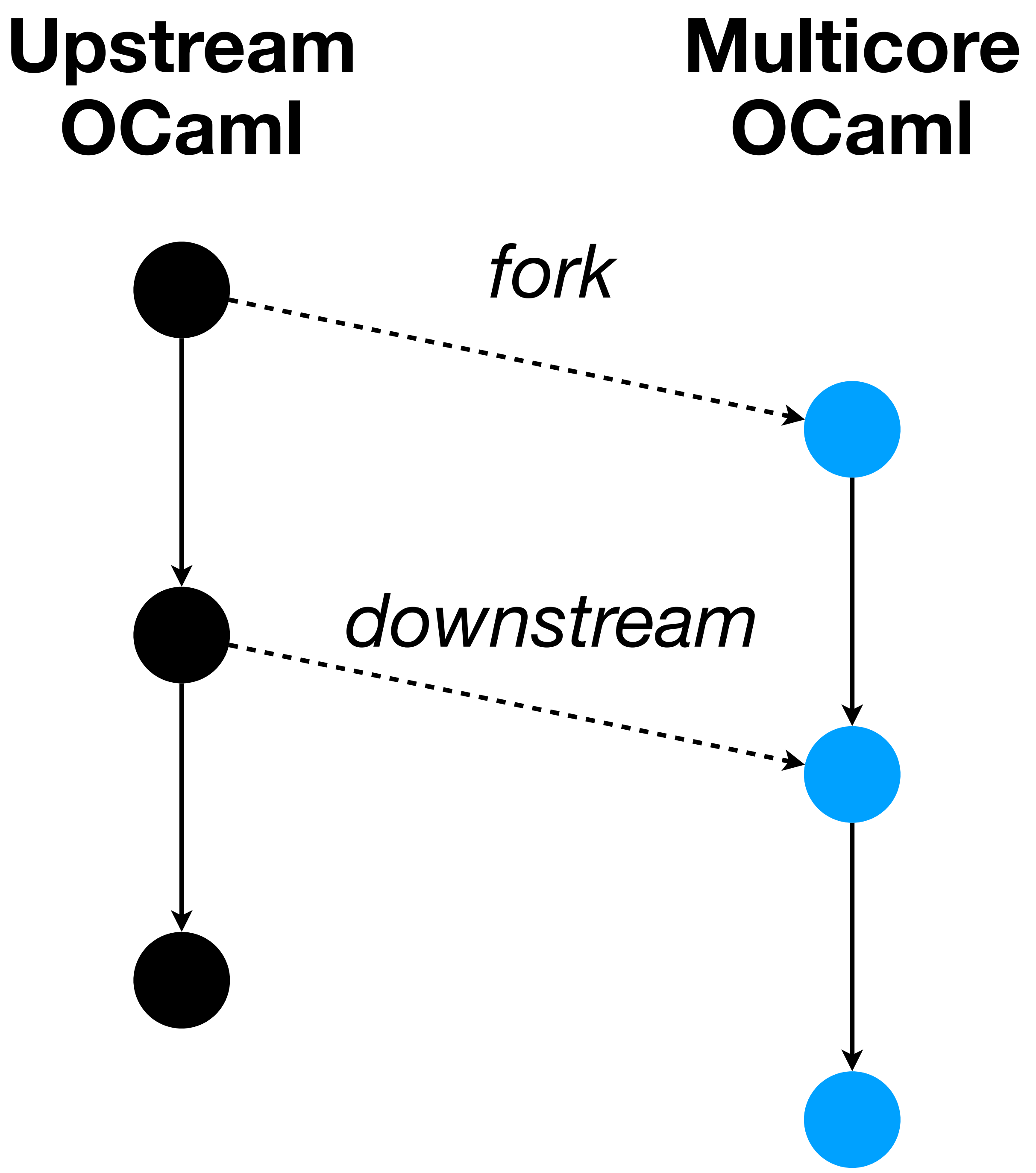

OCaml Workshop 2014

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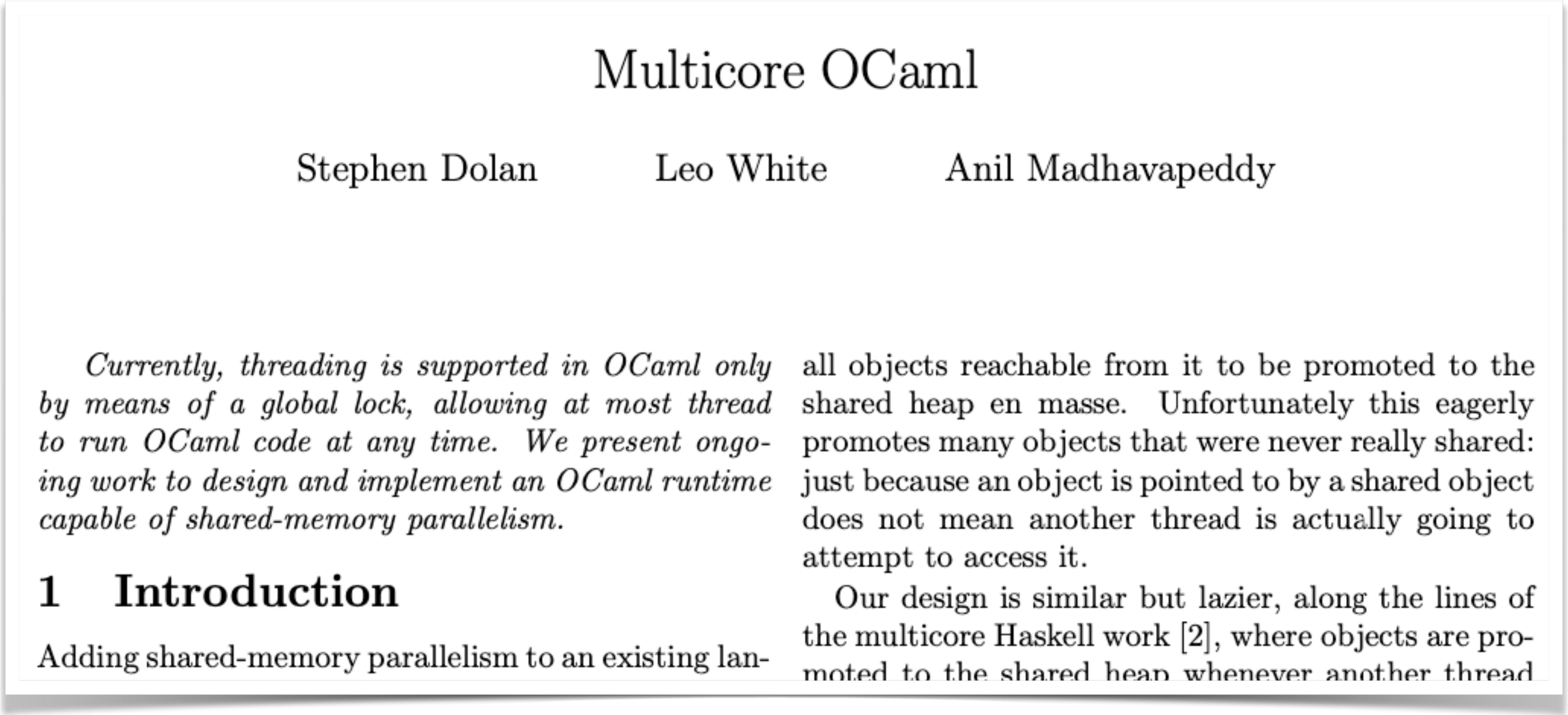

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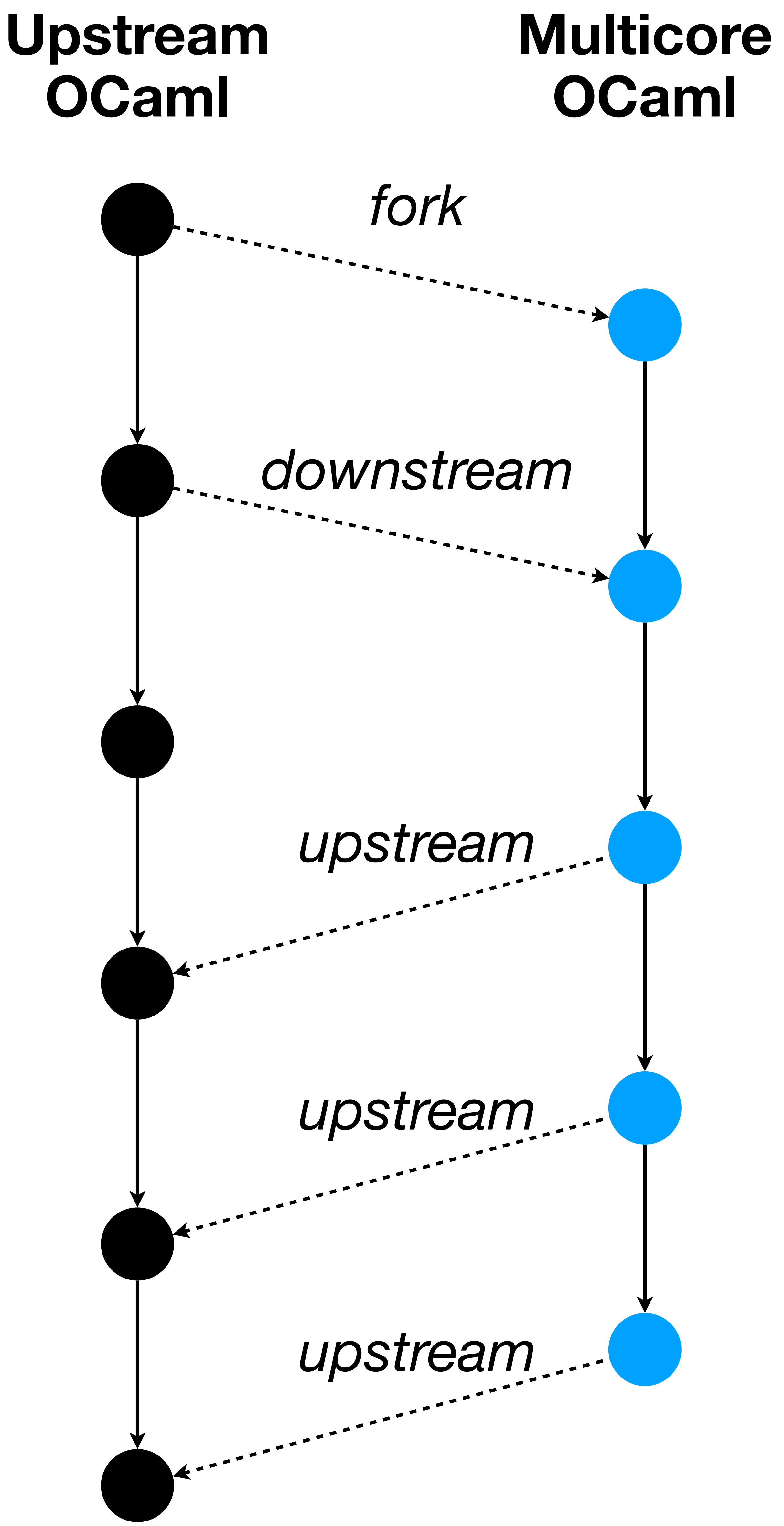
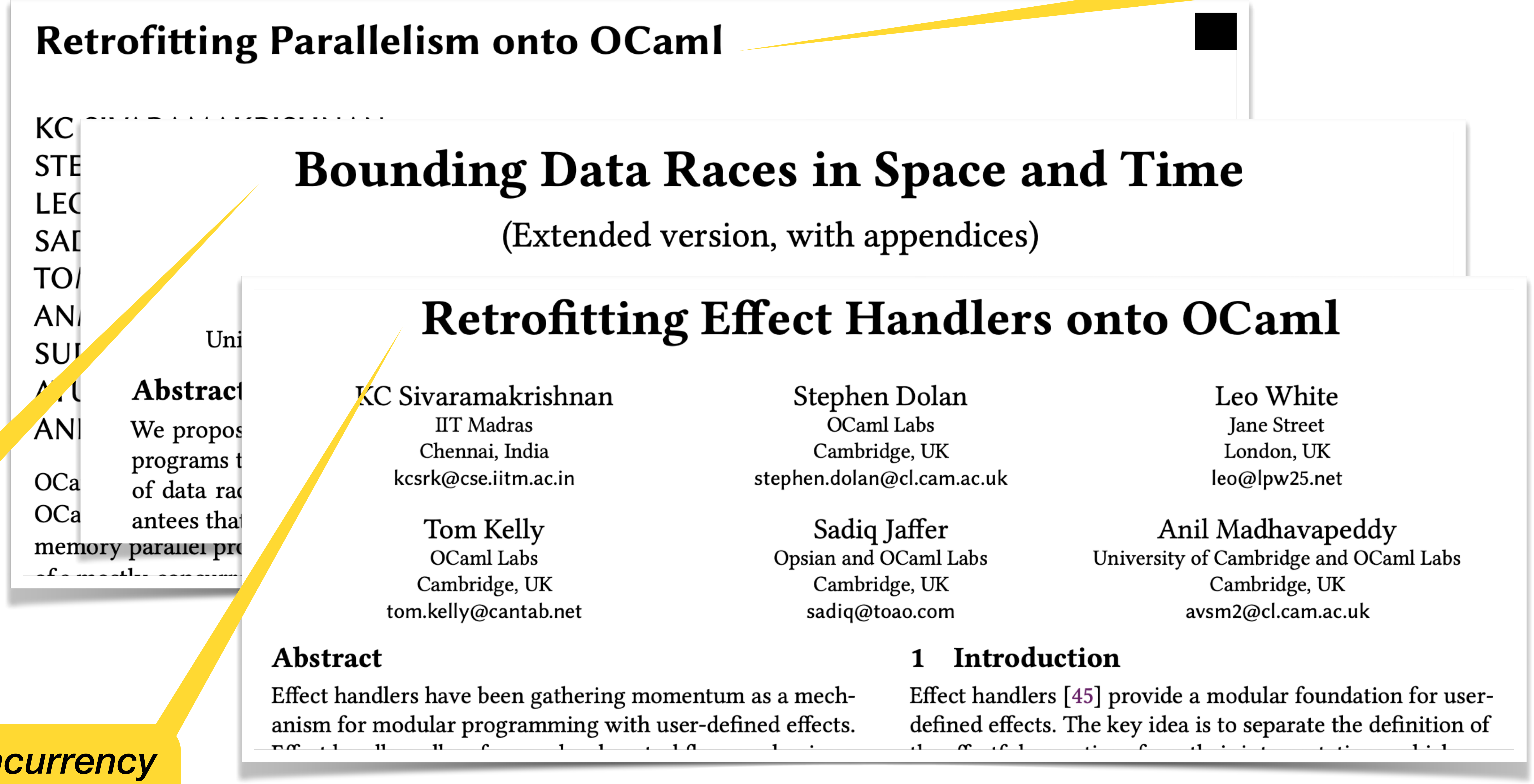


Building confidence — Papers

Multicore GC and runtime system


Retrofitting Parallelism onto OCaml

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memory parallel pro

Bounding Data Races in Space and Time

(Extended version, with appendices)

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Abstract

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Retrofitting Effect Handlers onto OCaml

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

Abstract

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

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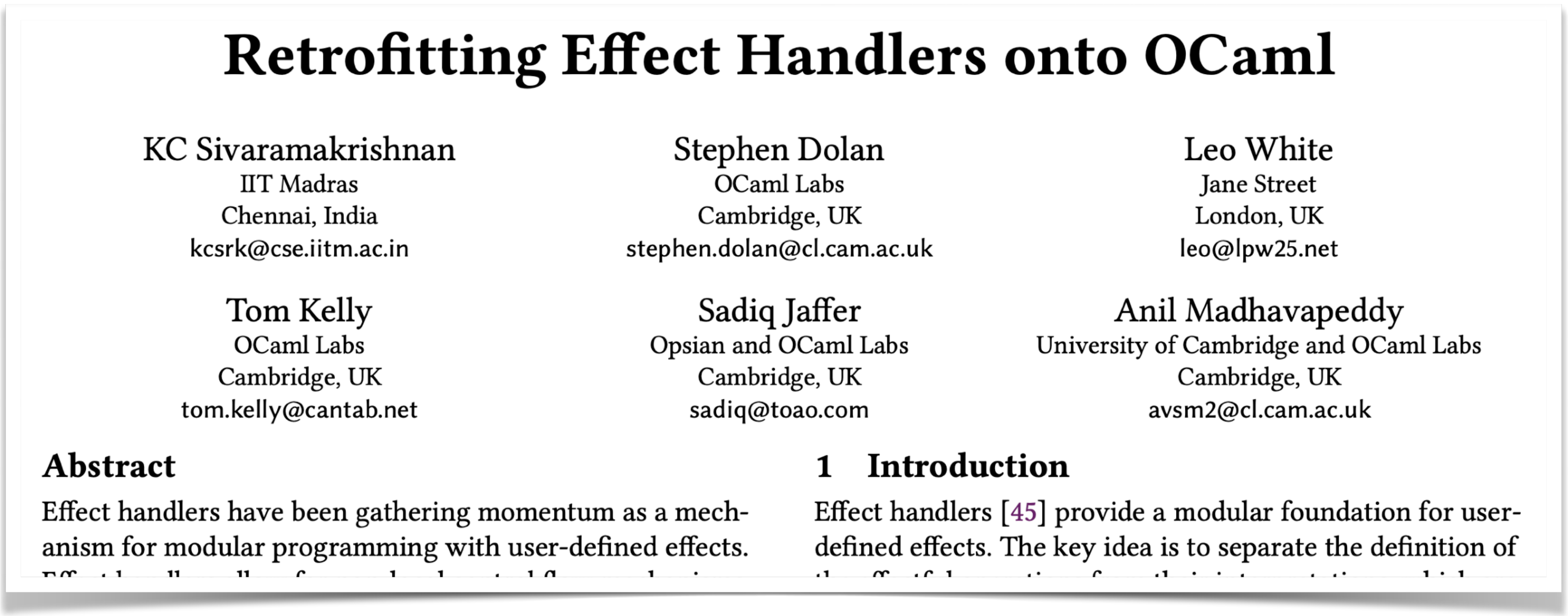
Effect handlers [45] provide a modular foundation for user-defined effects. The key idea is to separate the definition of

Relaxed Memory Model

Concurrency story

Peer-reviewed ideas build confidence

Diving deeper — Concurrency



Retrofitting Effect Handlers onto OCaml

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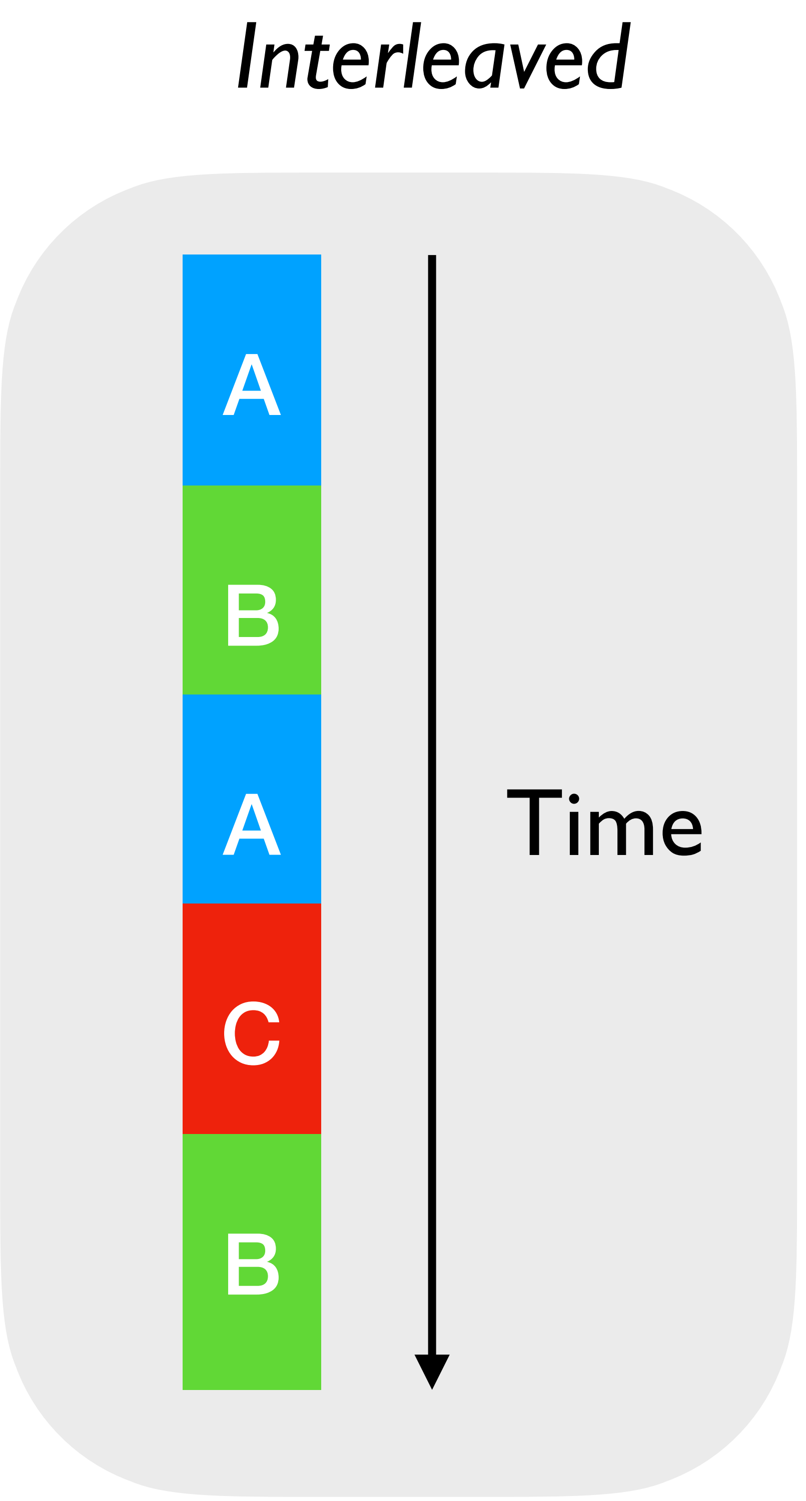

Concurrent Programming

- Computations may be *suspended* and *resumed* later

Concurrent Programming

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- 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, …
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  - ✦ **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*

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*

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- *Modular* and *composable* basis of non-local control-flow mechanisms
  - Exceptions, generators, lightweight threads, promises, asynchronous IO, coroutines as *libraries*

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  - ✦ Structured programming with *delimited continuations*

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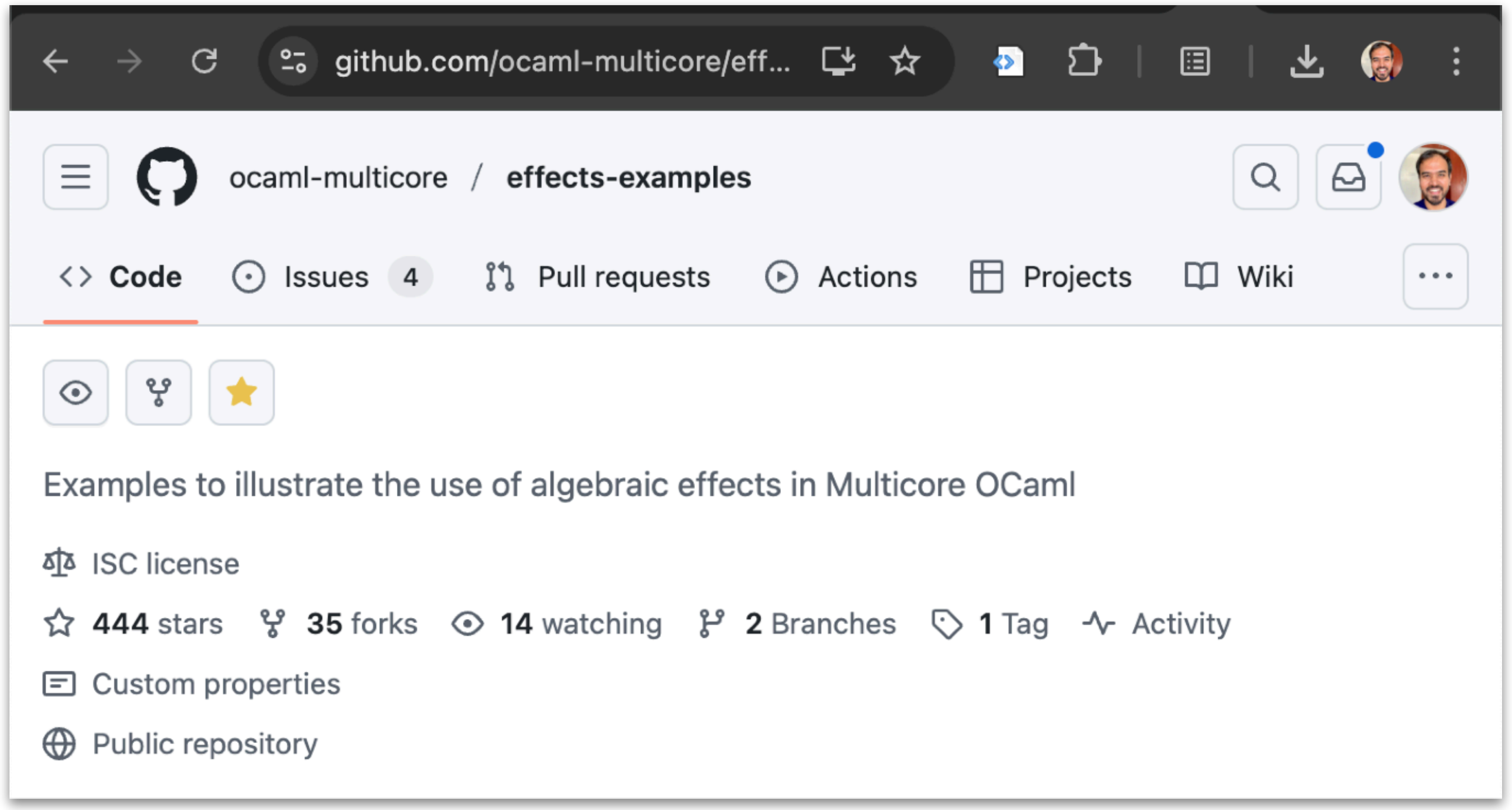

- Direct-style asynchronous I/O
- Generators
- Resumable parsers
- Probabilistic Programming
- Reactive UIs
- ....

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 ";
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Effect handlers

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effect declaration

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resume suspended computation

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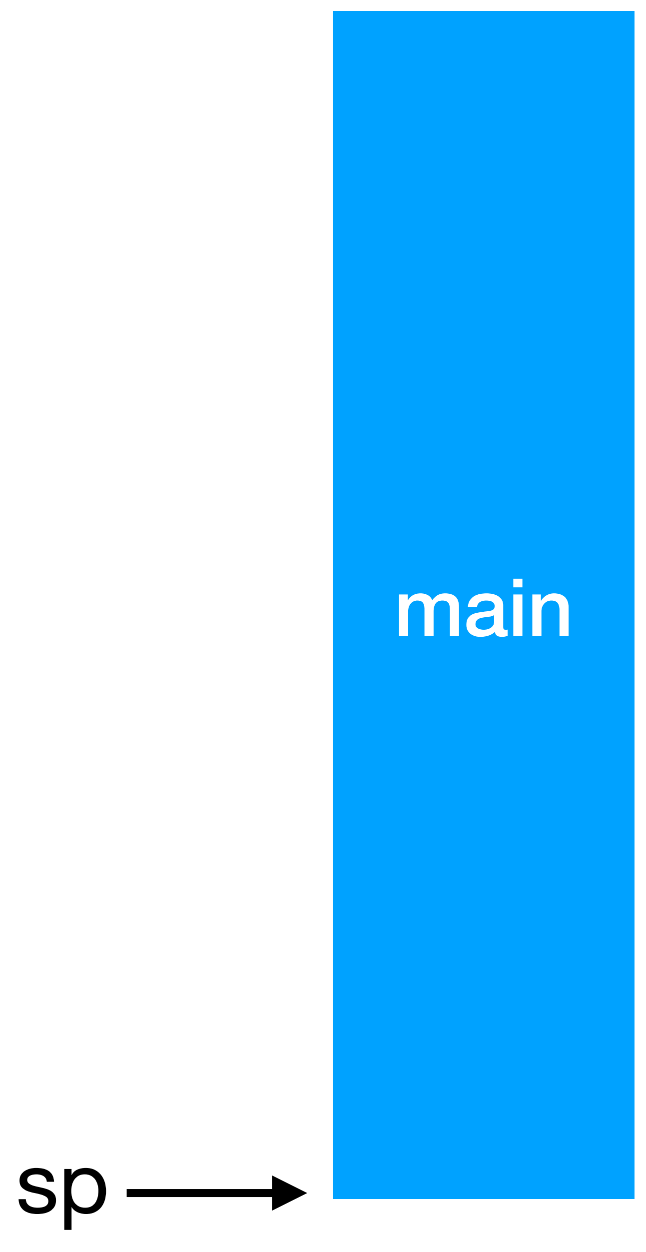
pc



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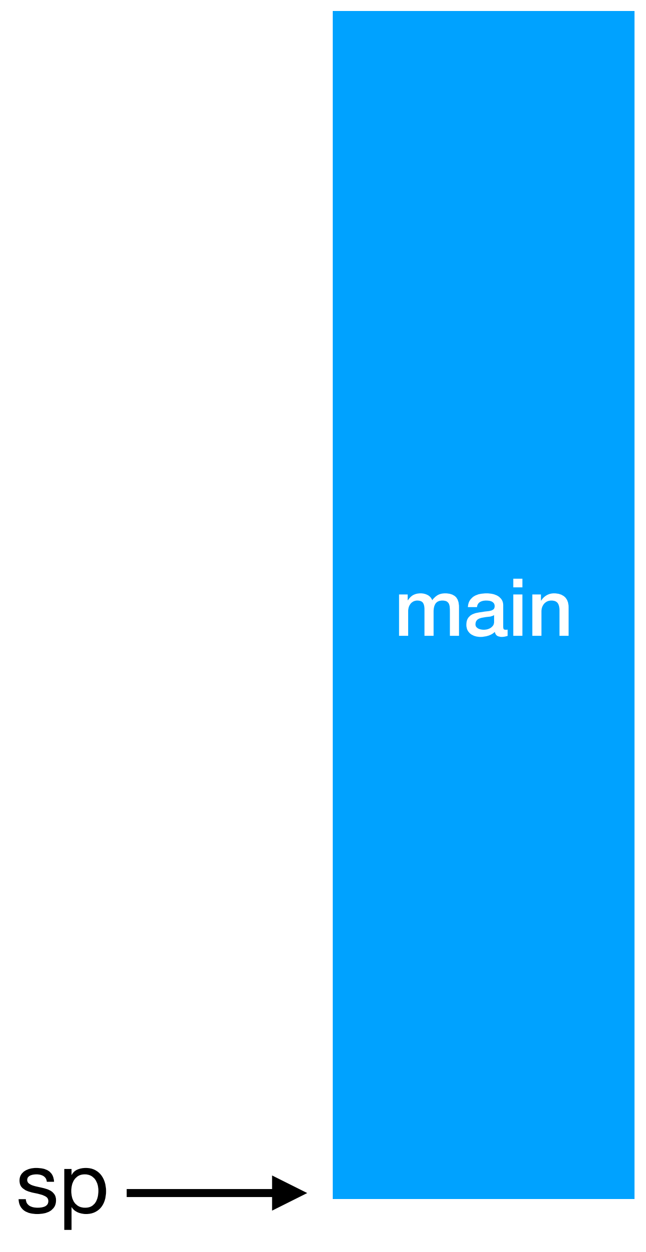

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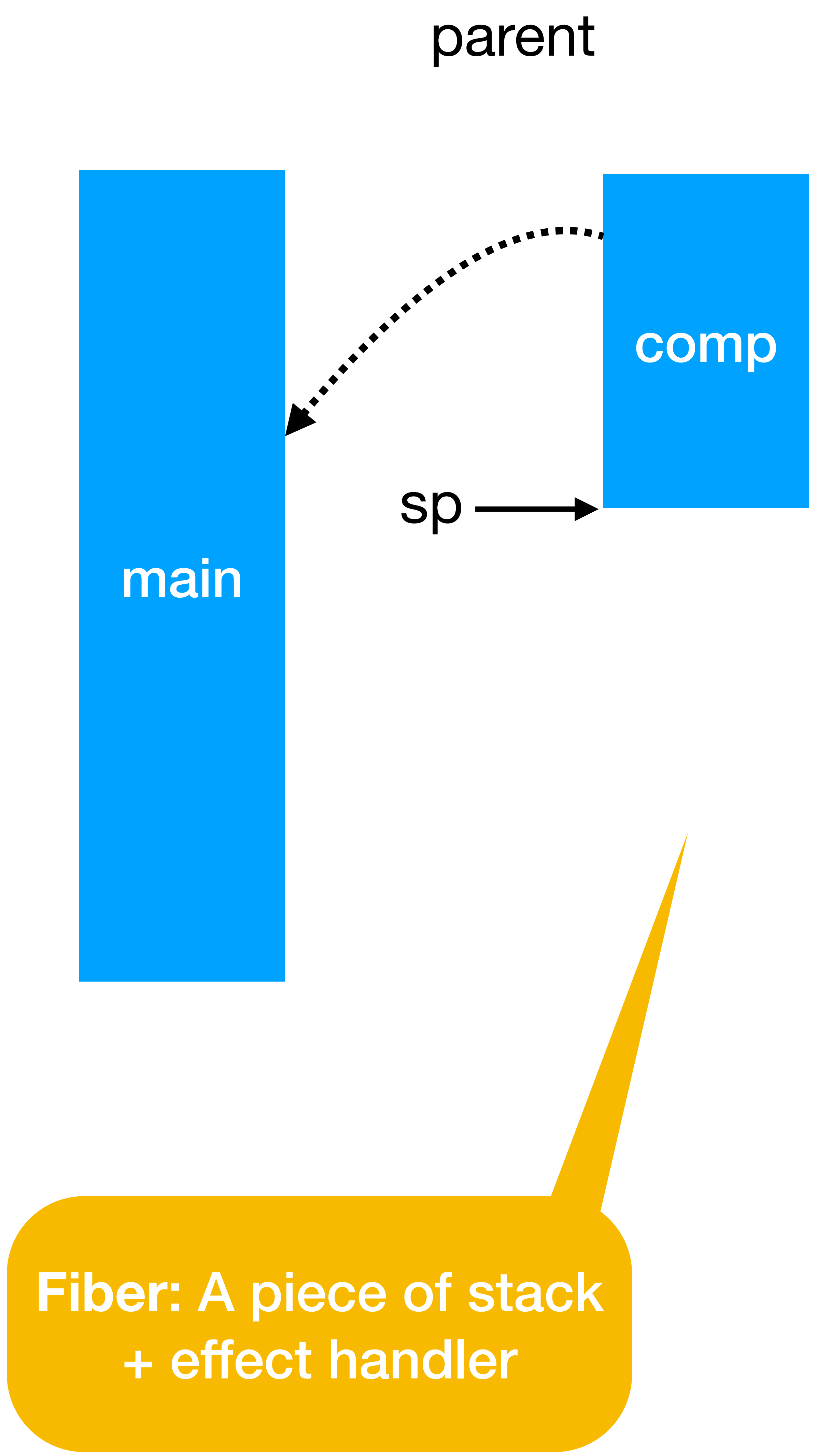

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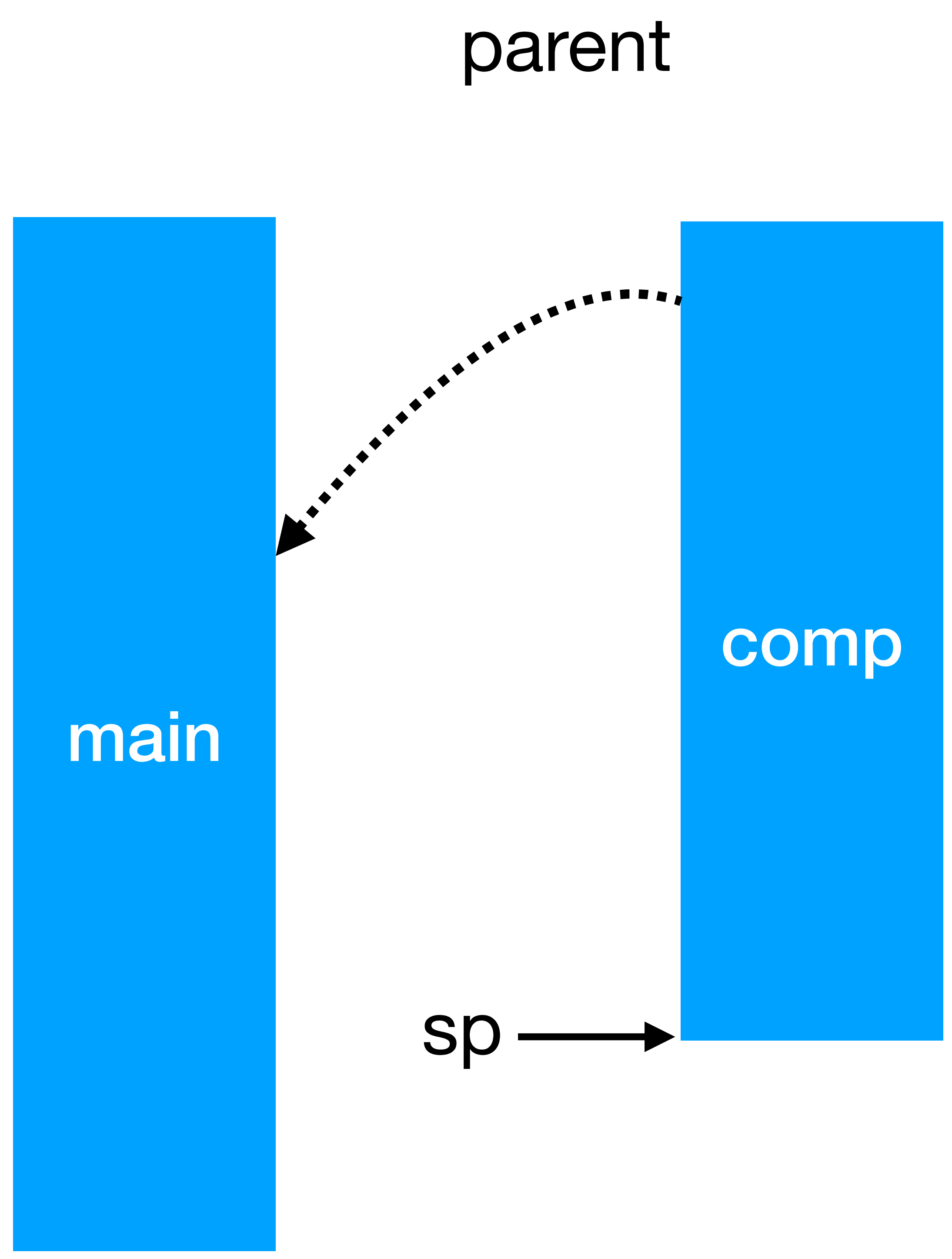

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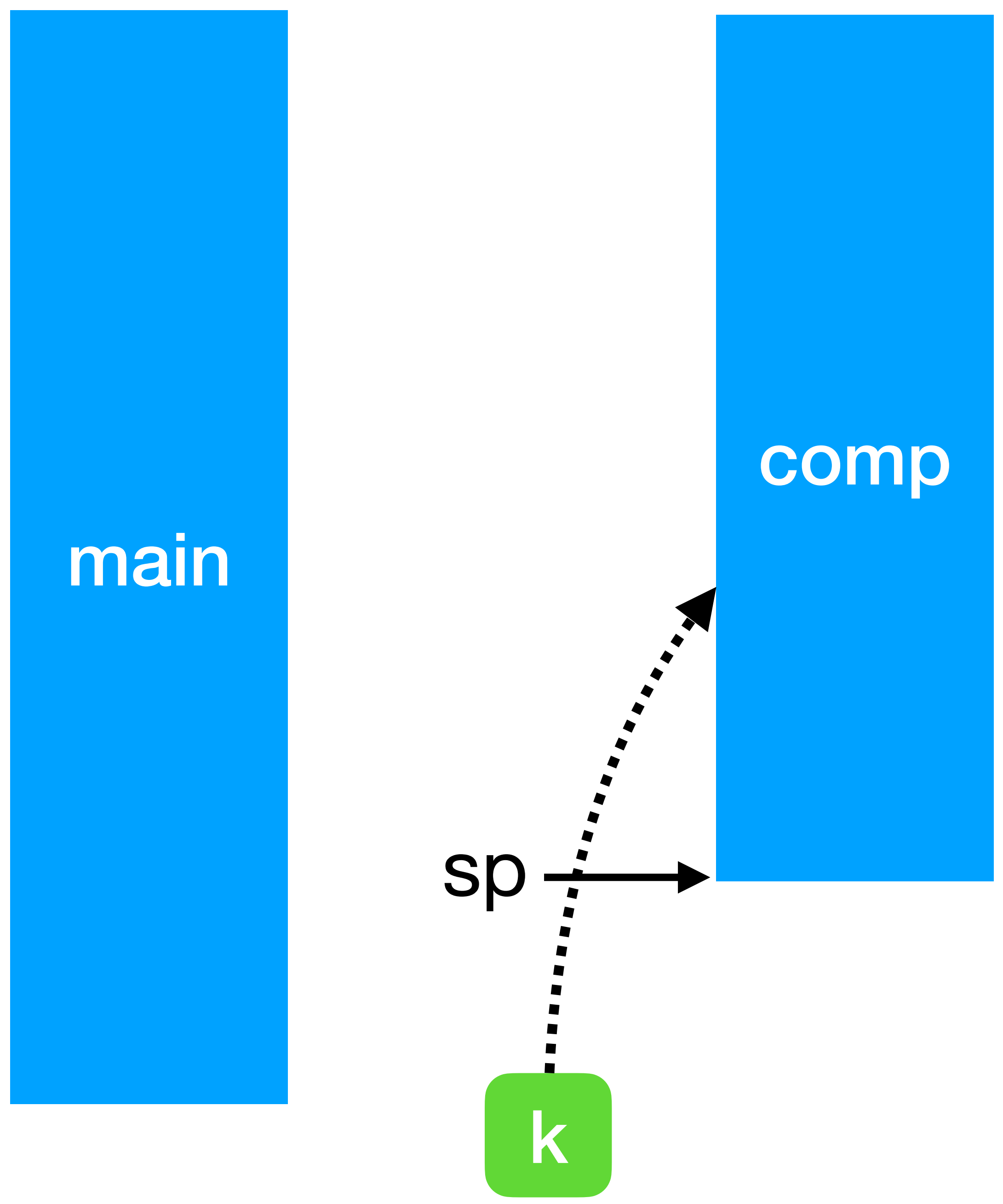

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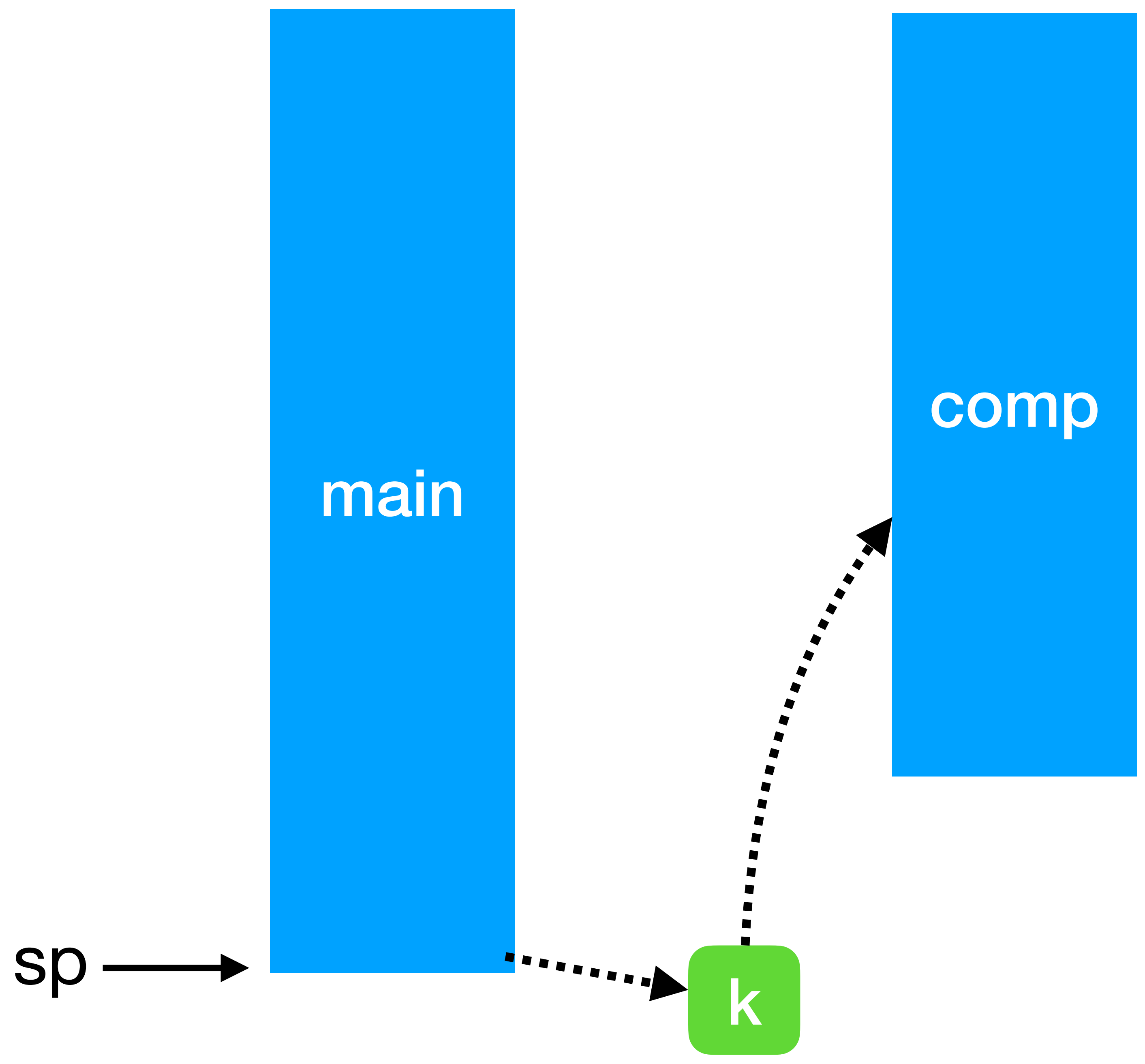

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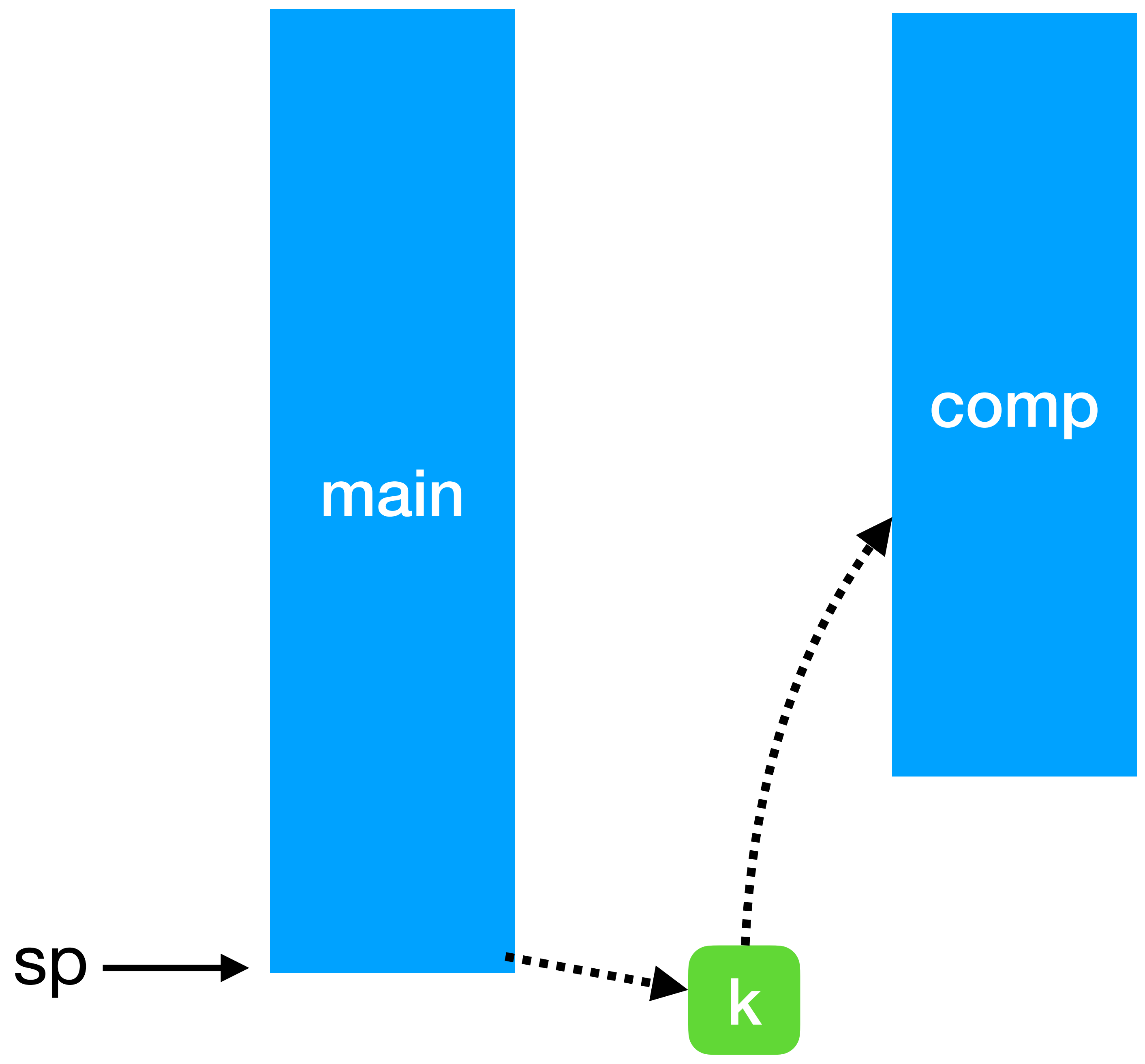

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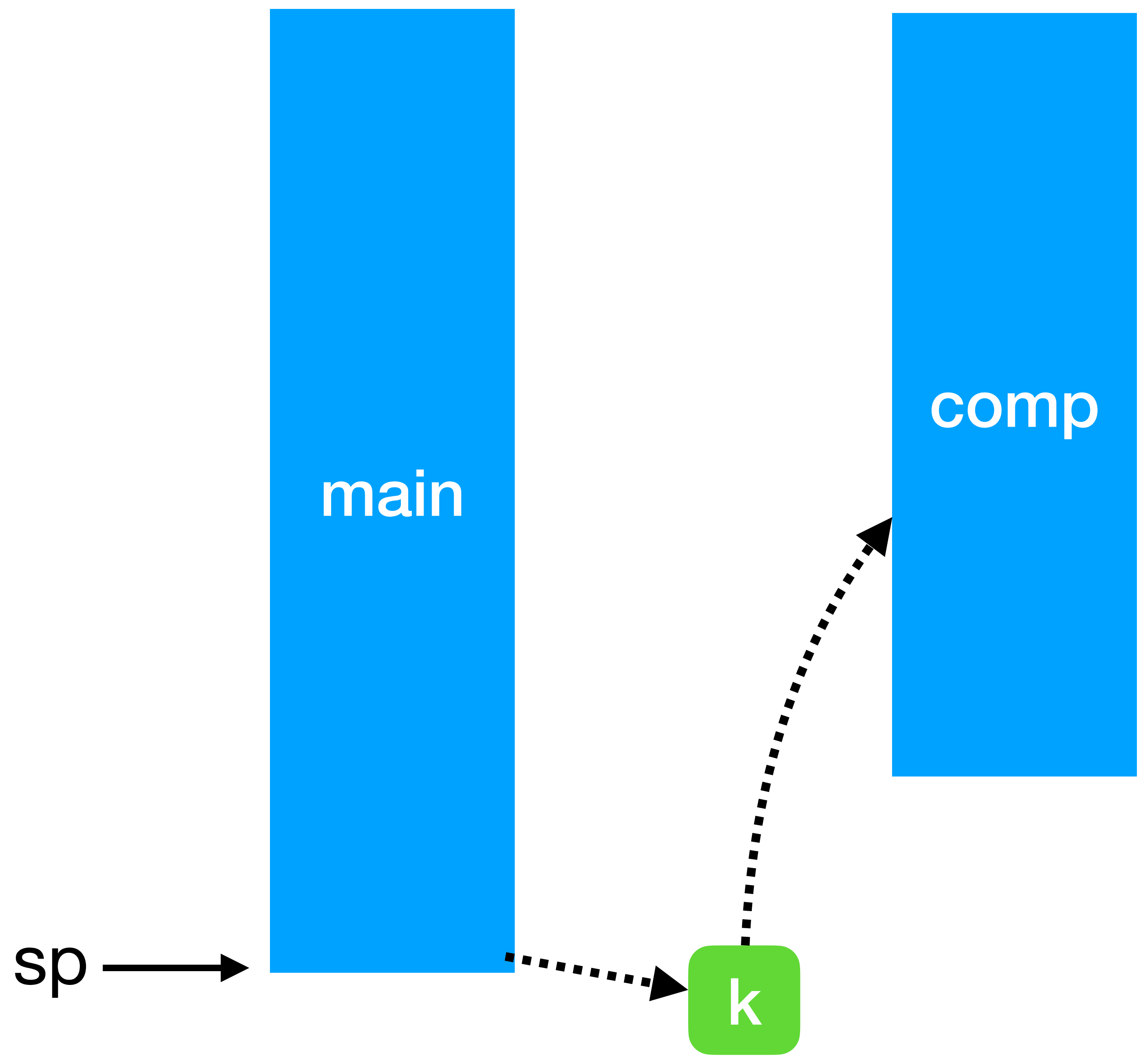

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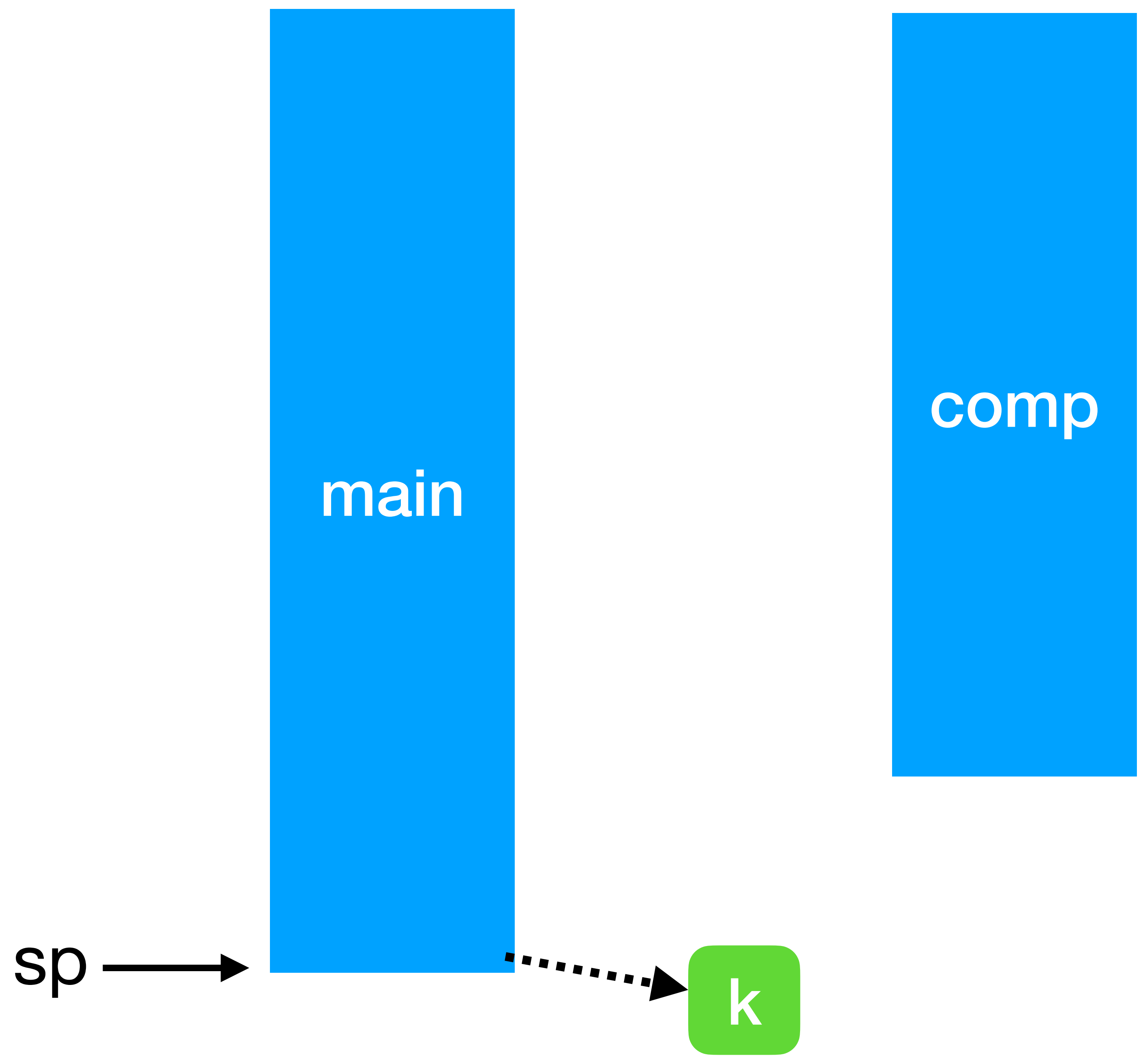

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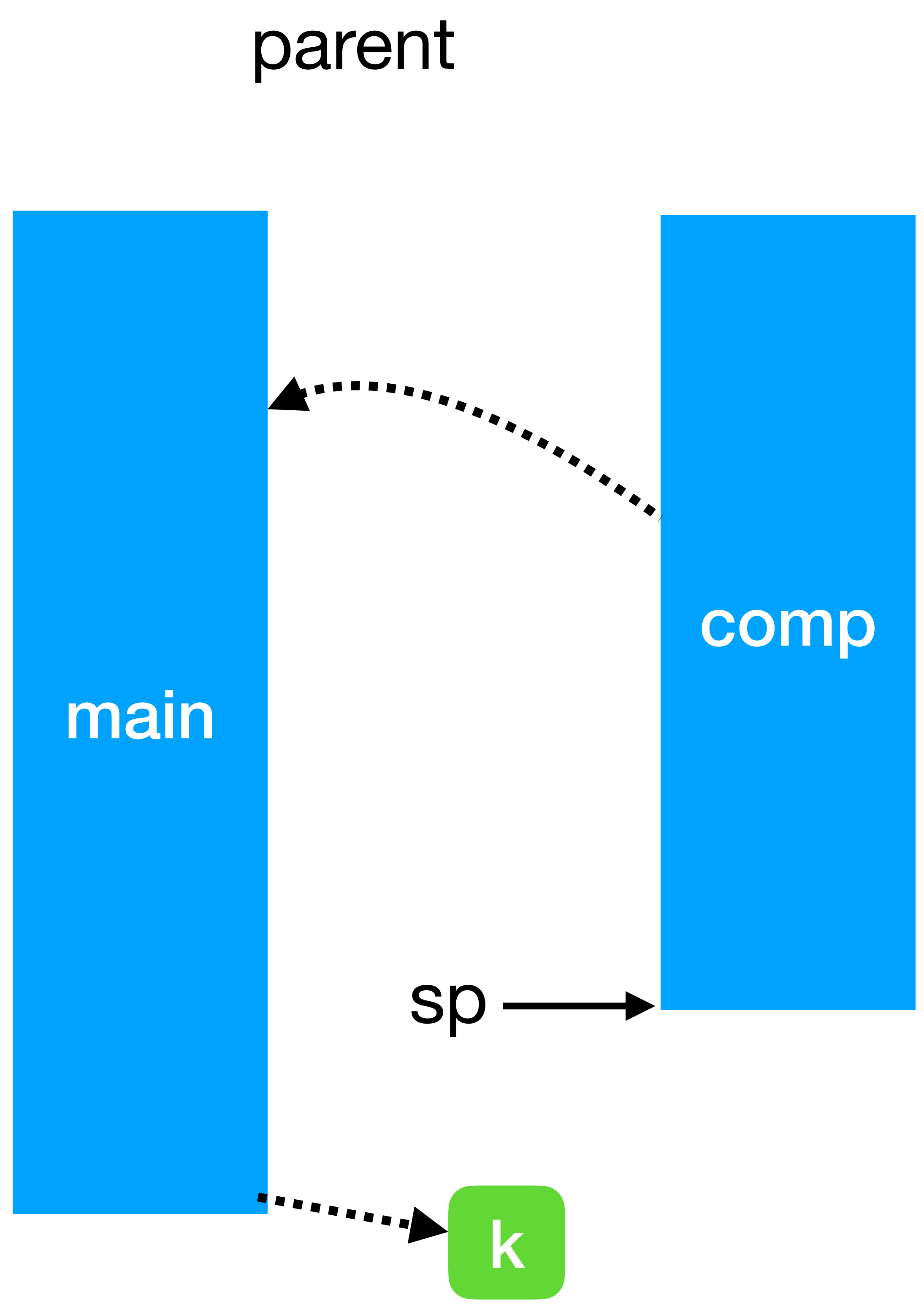

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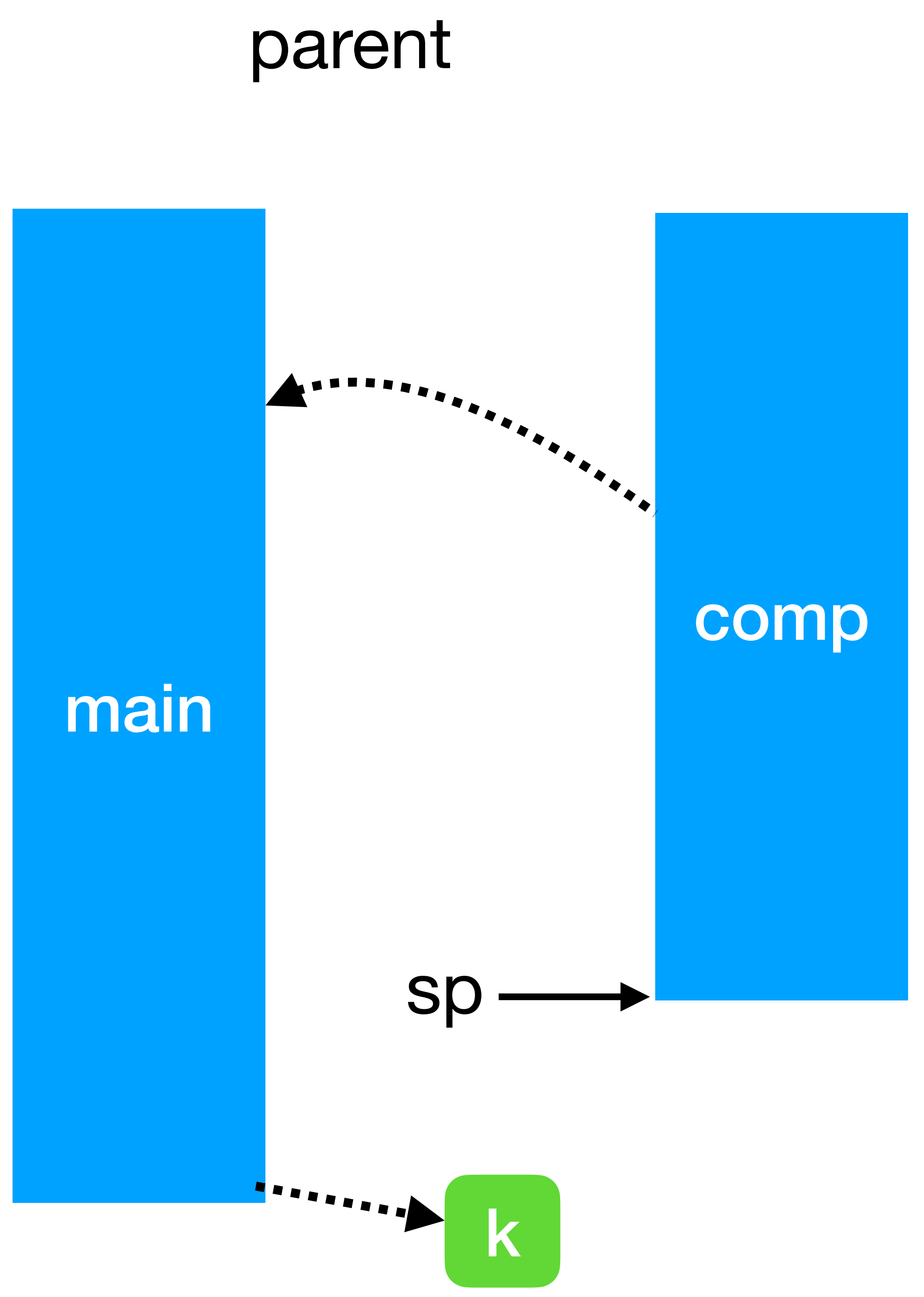

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Lightweight threading

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

Effect Handler

Lightweight threading

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  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
```

Lightweight threading

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;;
run main
```

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

Lightweight threading

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let main () =
  fork (fun _ ->
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    yield ();
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;;
run main
```

User-code need not be aware of effects

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

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run main
```

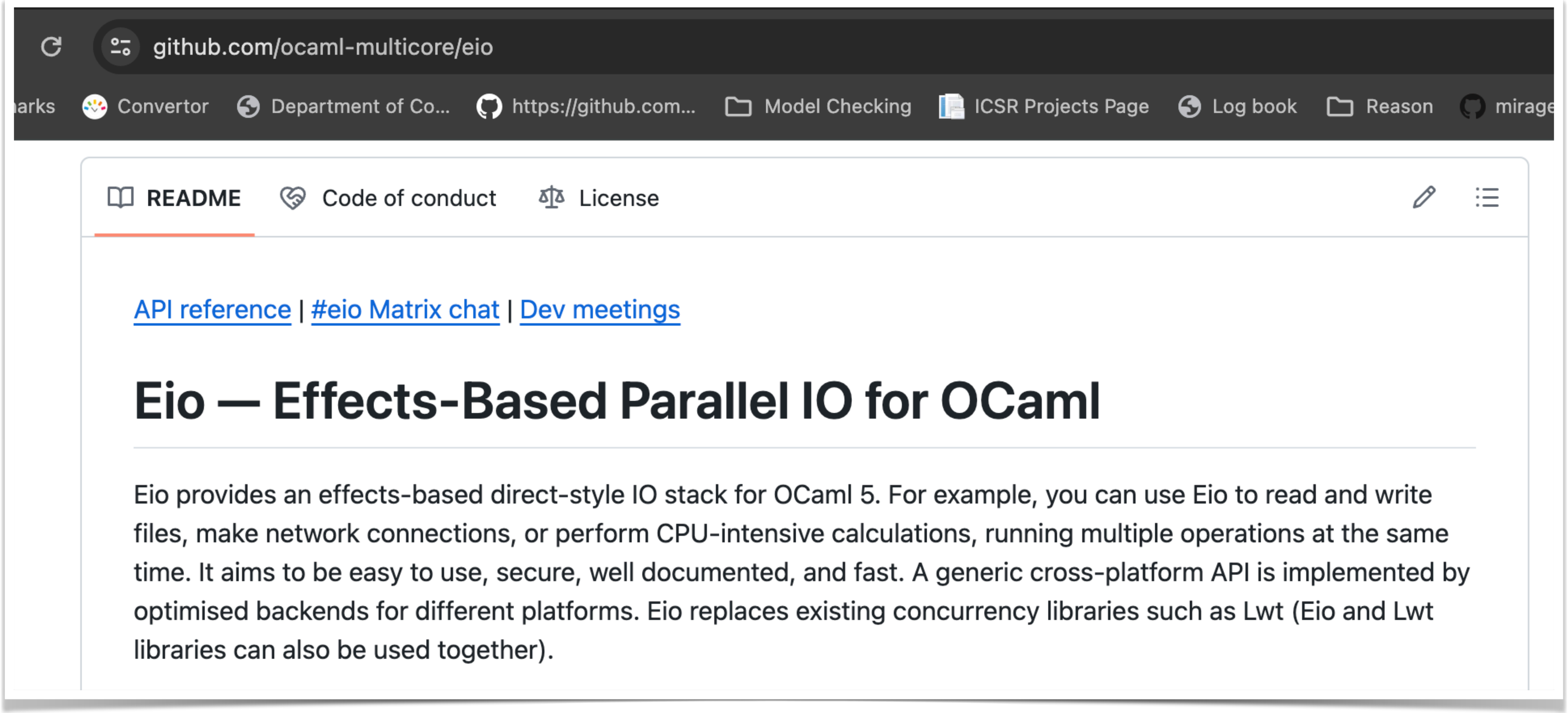
Ability to specialise scheduler unlike GHC Haskell / Go

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

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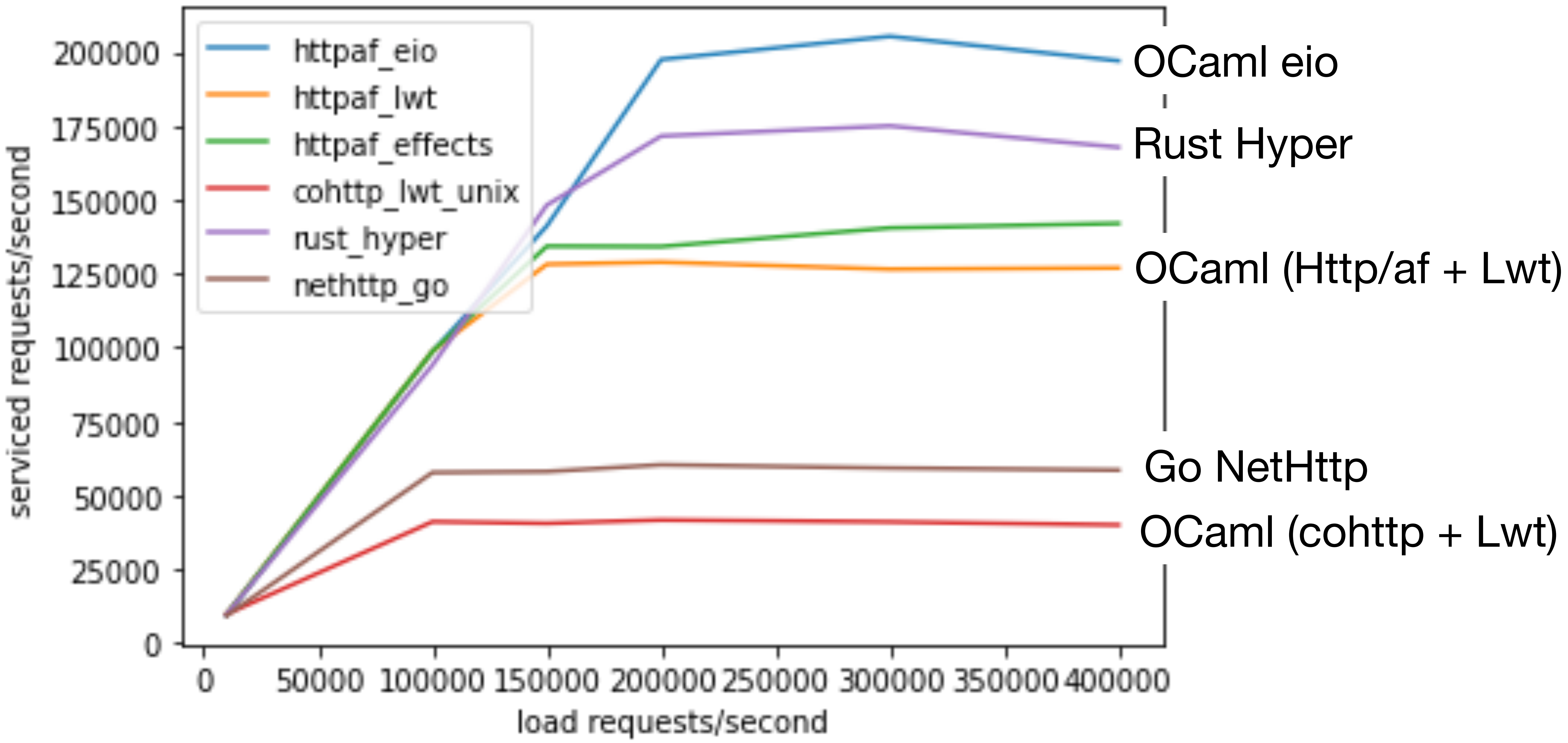

100 open connections, 60 seconds w/ io_uring

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

Unexpected uses

- Hardware simulations for HardCaml

Jane Street Blog

Algebraic effects were originally added to OCaml for general-purpose concurrent execution of programs for OCaml 5, which supports thread-level parallelism. The fact that they can be repurposed for Hardcaml simulations speaks to how well-thought-out and general a language feature this is.

I am writing this post as someone who is *not* a type-theory expert. The fact that I can use algebraic effects without fully understanding the underlying mechanics is one nice feature of their design.

https://blog.janestreet.com/fun-with-algebraic-effects-hardcaml/

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

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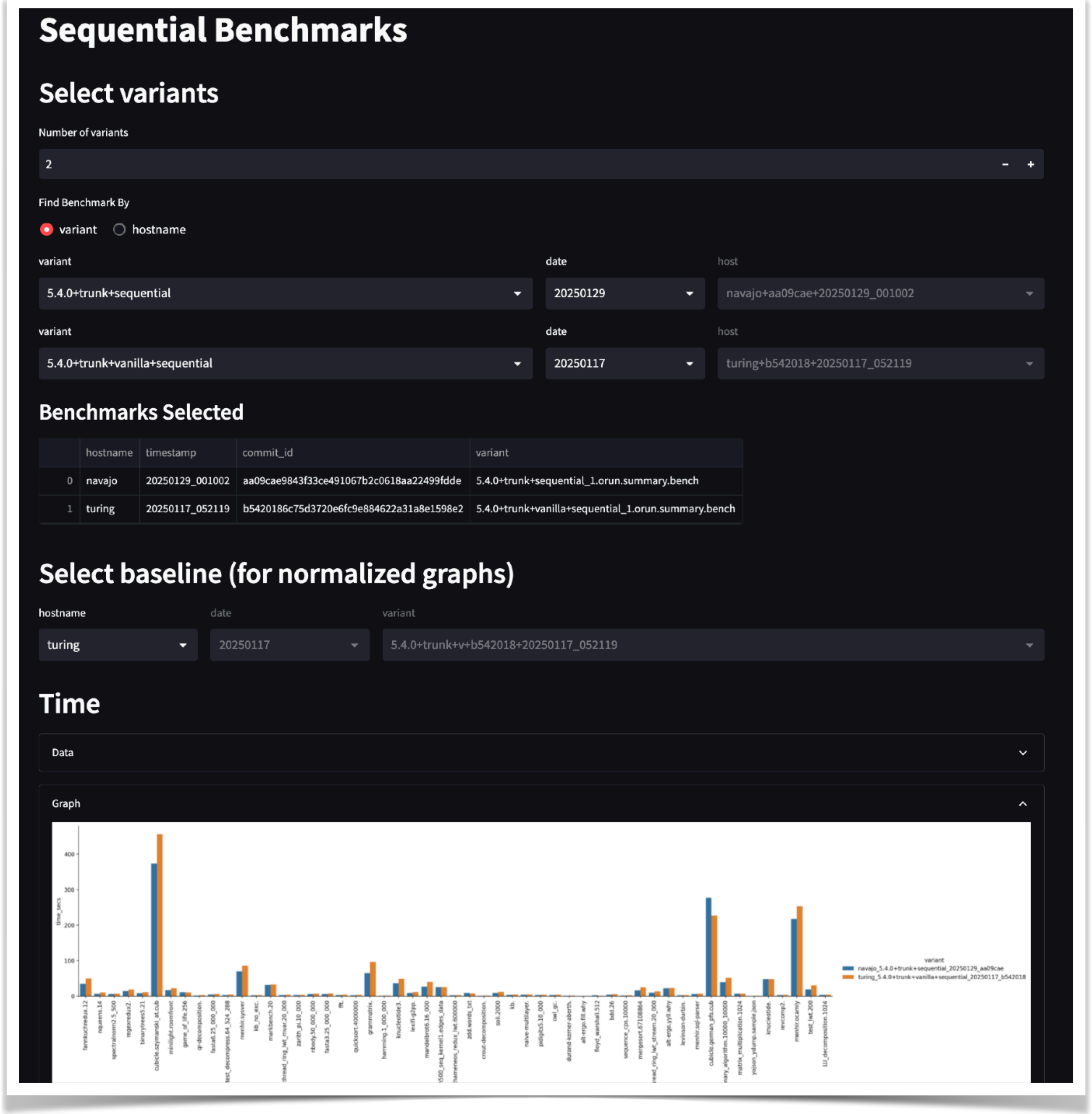
- Table of contents
- Introduction

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

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  - Build the OPAM universe of packages against ***upstream*** and ***multicore*** compilers

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	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
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amqp-client-async.2.2.2	☑	☒	0
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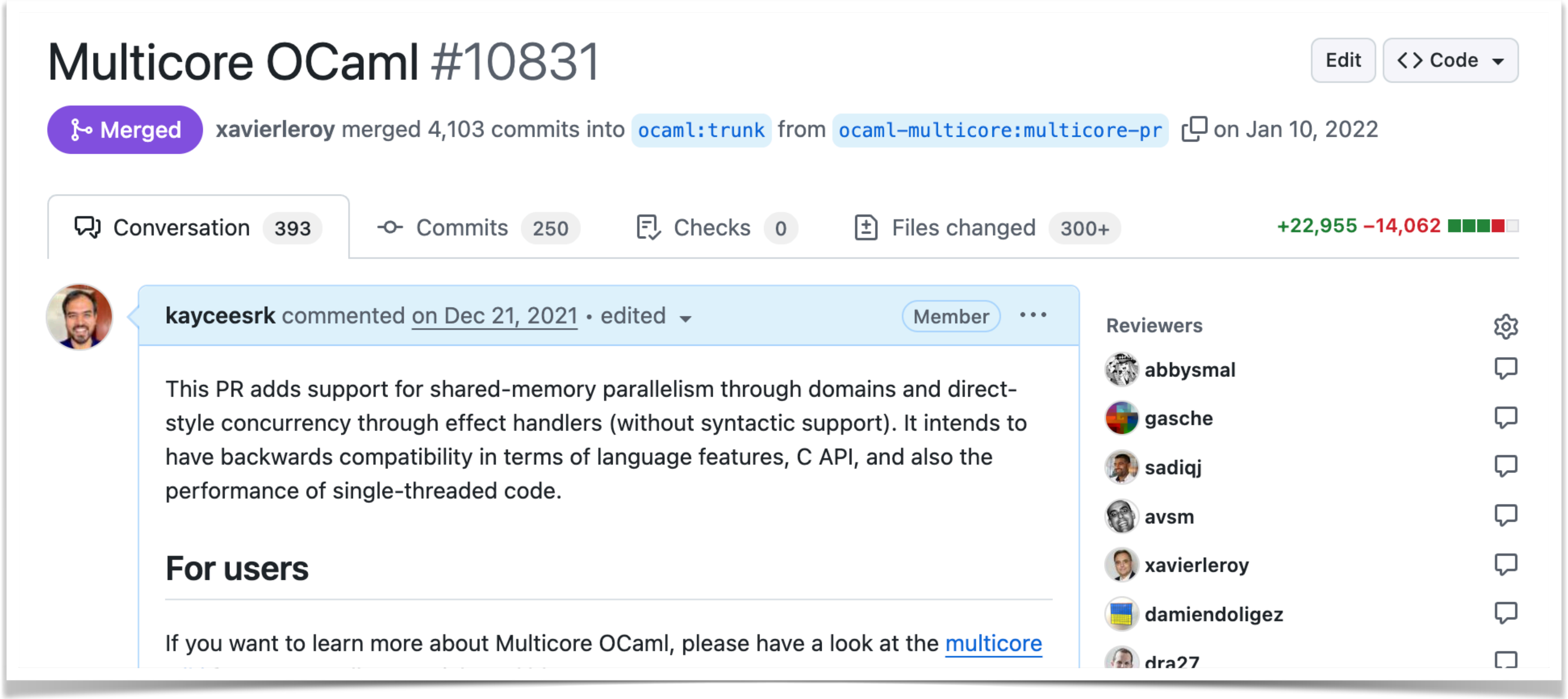
You can contribute to the compiler development without hacking on the compiler

Release and Long Tail

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



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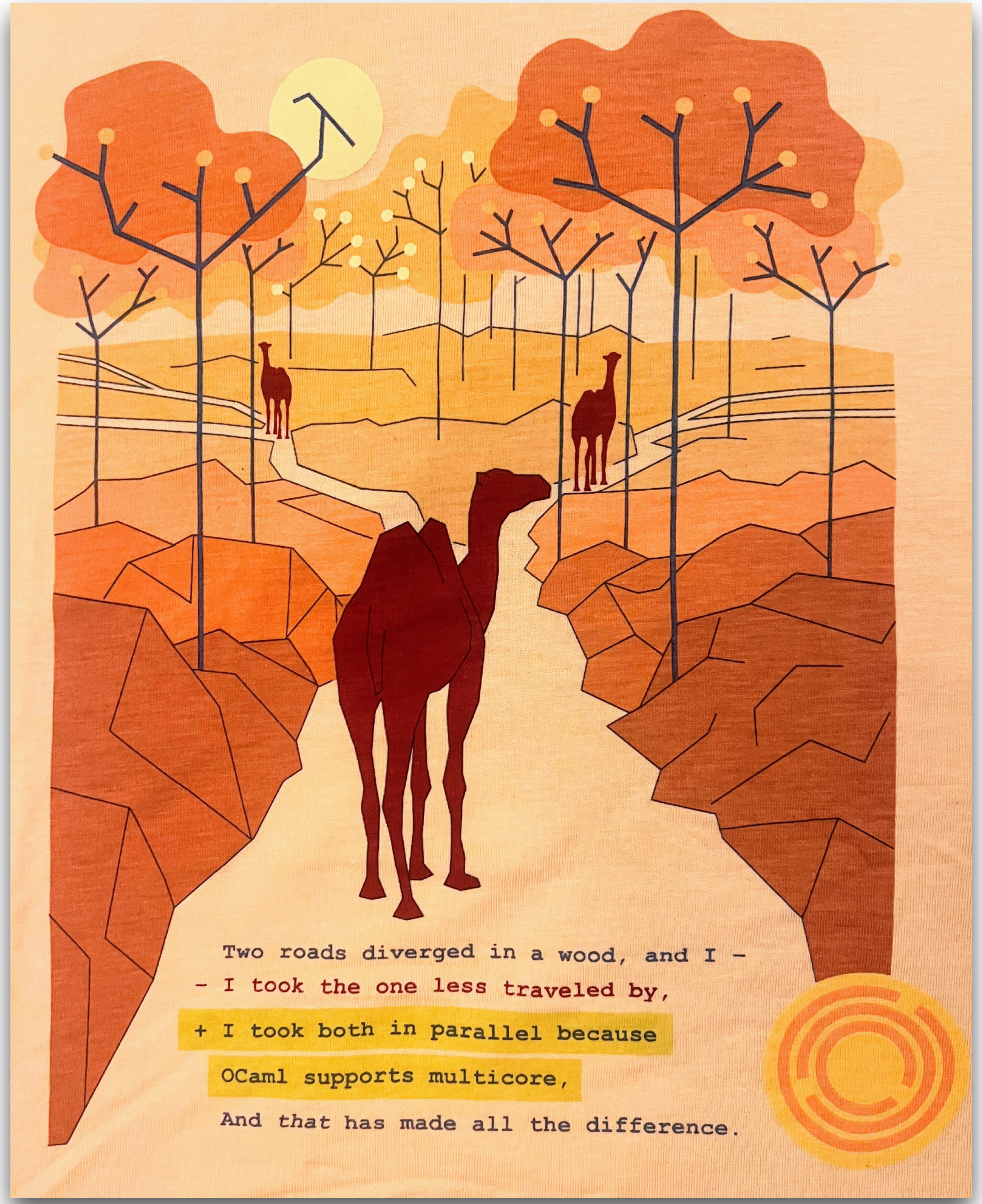

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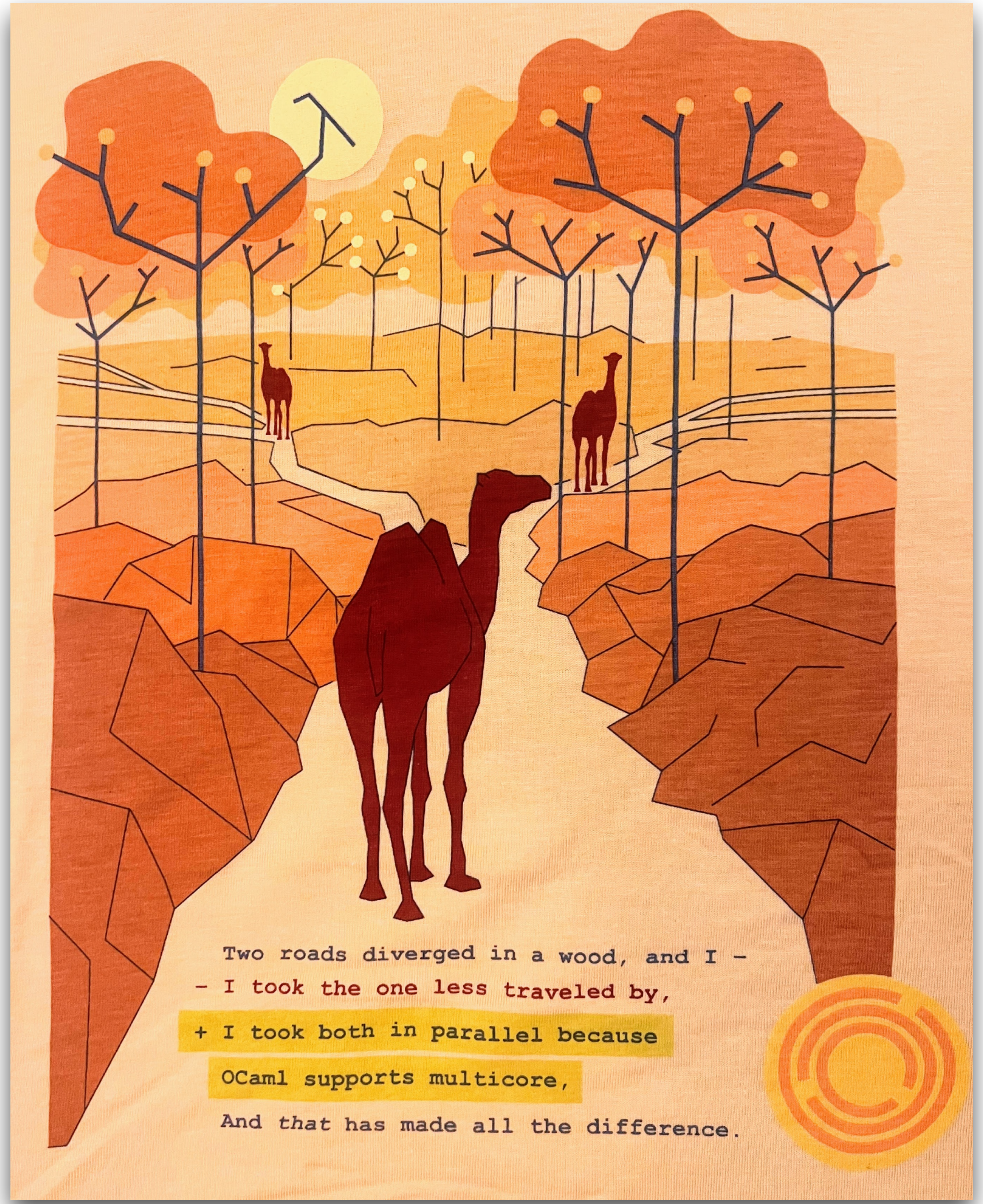
  - *….A few months of iteration to fix design issues and bugs….*
- **Released —** Dec 16 2022, as OCaml 5.0
- **Long tail** of adding missing features, bug fixes and performance improvements
  - 5.1 — Sep 2023
  - 5.2 — May 2024
  - 5.3 — Jan 2025
  - 5.4 — Sep 2025



What’s next for OCaml?

- **OxCaml** — Bridging the performance and safety gap between OCaml and Rust
  - ***Data-race-free parallelism*** through ***modes***
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https://oxcaml.org

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- But different in other ways…
  - In production at Jane Street
  - Valuable user-feedback-oriented design

https://oxcaml.org

CS6868 Concurrent Programming

CS6868 Spring 2026 Schedule Assignments Resources GitHub

Photo © Madras Inherited

CS6868: Concurrent Programming

Course Overview

This course explores the fundamentals of concurrent and parallel programming with a focus on shared-memory multiprocessor systems. You'll learn to design and implement correct, efficient concurrent programs while understanding the theoretical foundations and practical challenges of concurrency and parallelism.

Key Topics:

- Principles of concurrent programming
- Mutual exclusion and synchronization
- Concurrent data structures
- Lock-free and wait-free algorithms
- Memory models and consistency
- Parallel programming patterns
- Effect handlers
- Nested parallelism, Asynchronous I/O
- Practical implementations using OCaml 5's multicore features
- Safe parallel programming with OxCaml

The course uses **OCaml 5** with native support for parallelism via domains and concurrency via effect handlers, providing hands-on experience with modern concurrent programming techniques.

https://kcsrk.info/cs6868_s26/

FP Launchpad

Build research and educational capacity for crafting ***efficient, reliable and trustworthy software with mathematical guardrails***.

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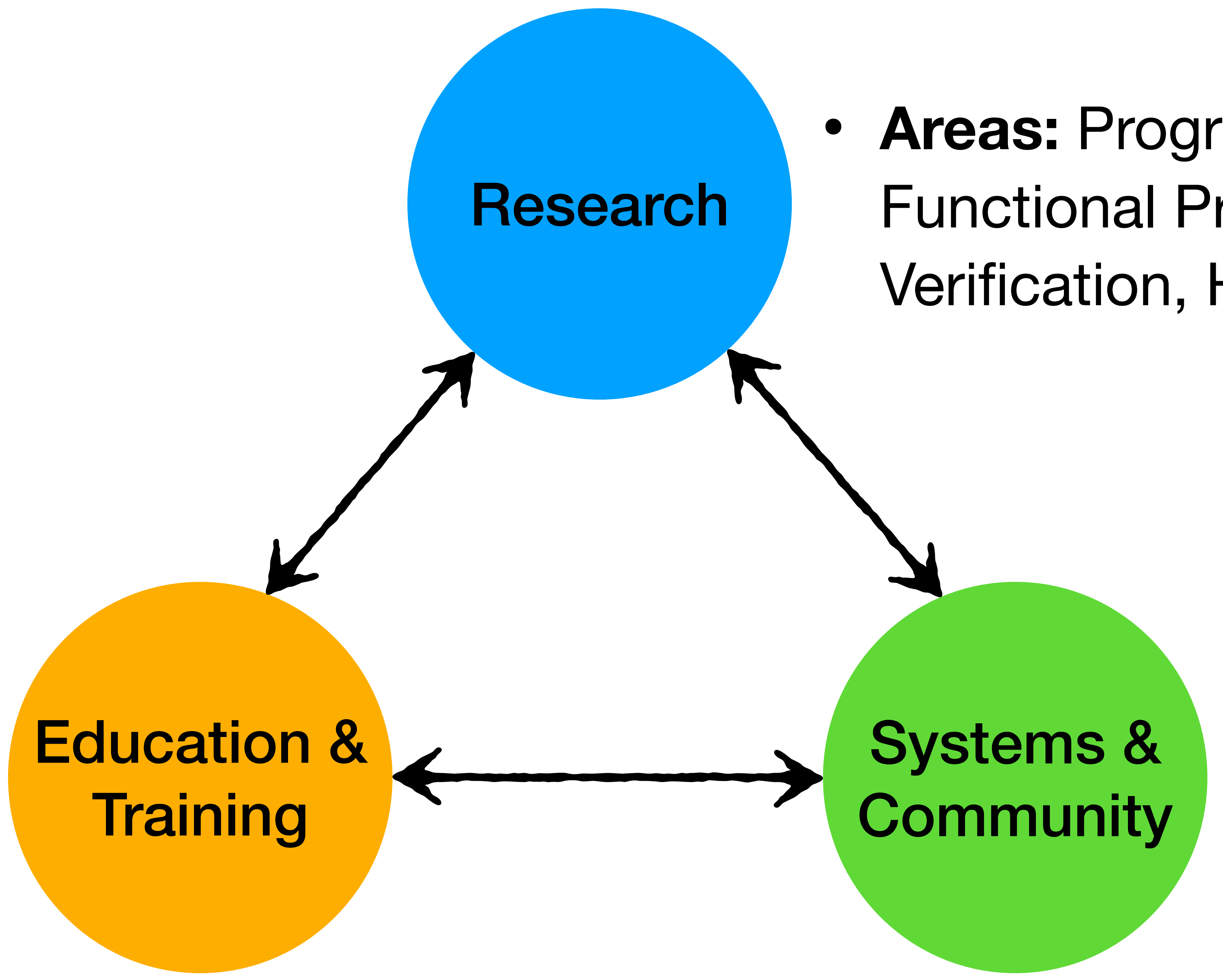

- **Areas:** Programming Languages, Functional Programming, Program Verification, Hardware Design, FM x AI

- Post-bacc Fellowships
- Summer and winter schools, Dagstuhl-style research seminars
- Compiler Hacking events

- Industrial-strength & open-source
- **Examples:** verifiable voting, DPI for environmental planning, robust foundational SW stack

Get Involved!

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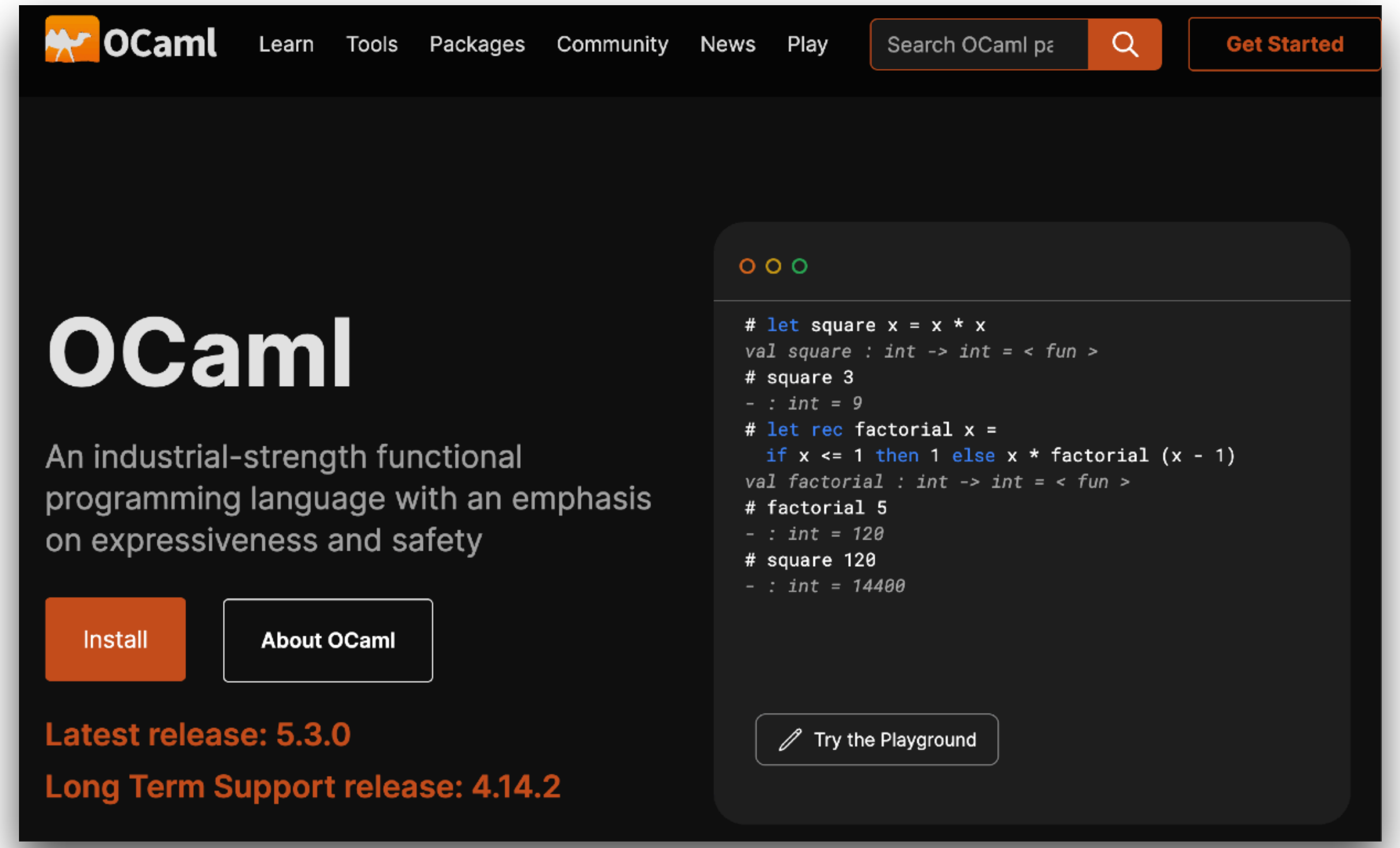
ocaml.org



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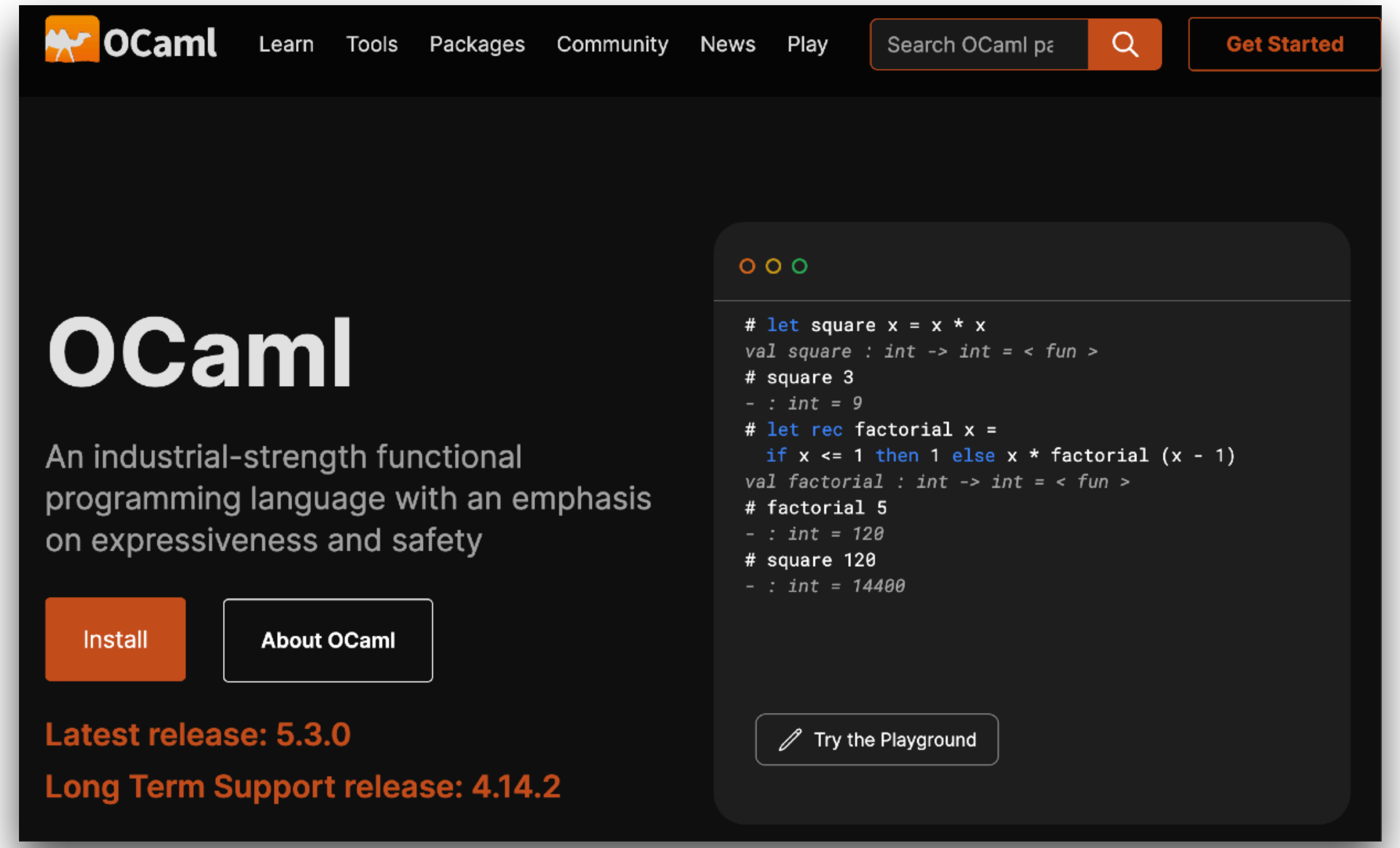

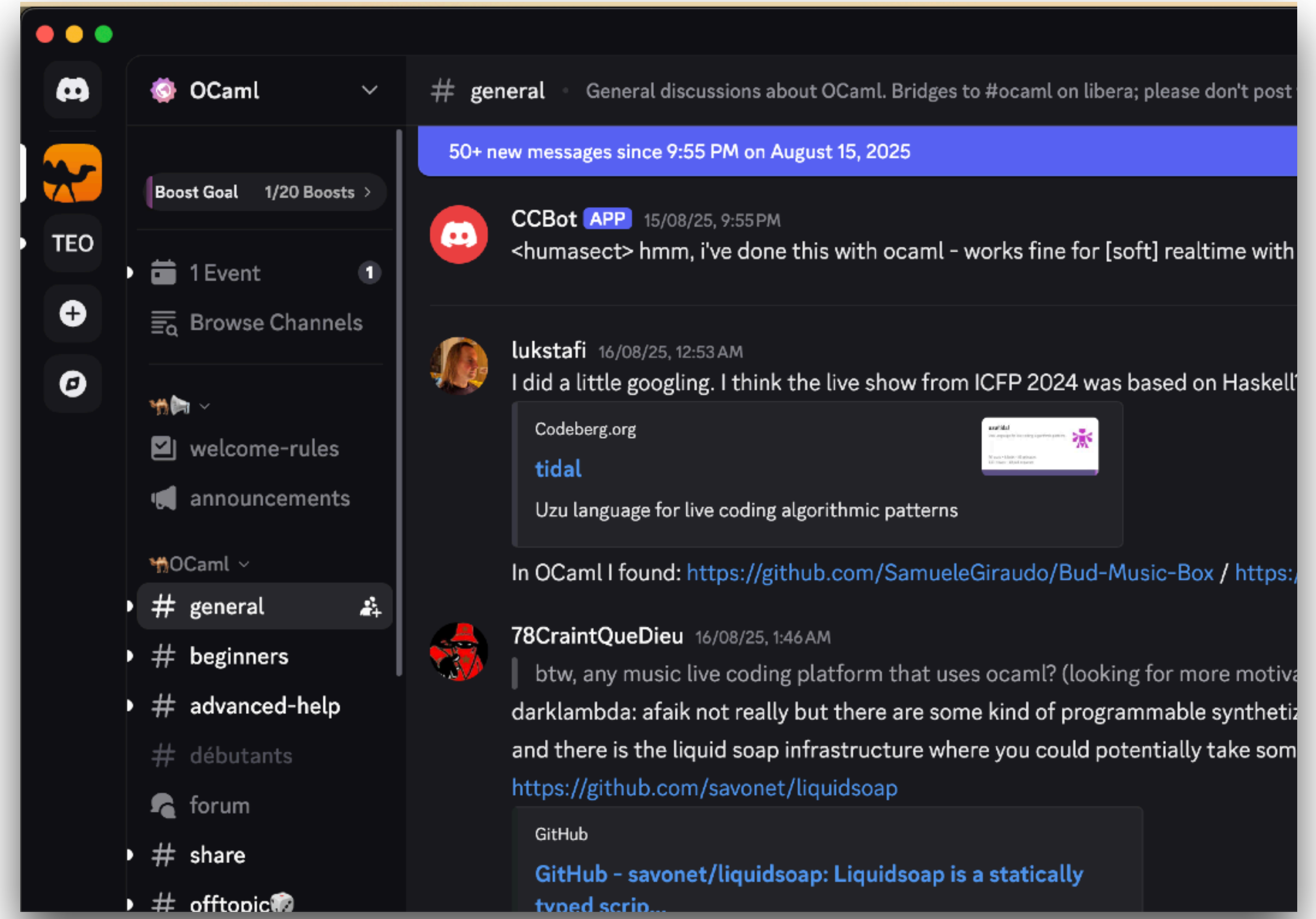

OCaml Discord

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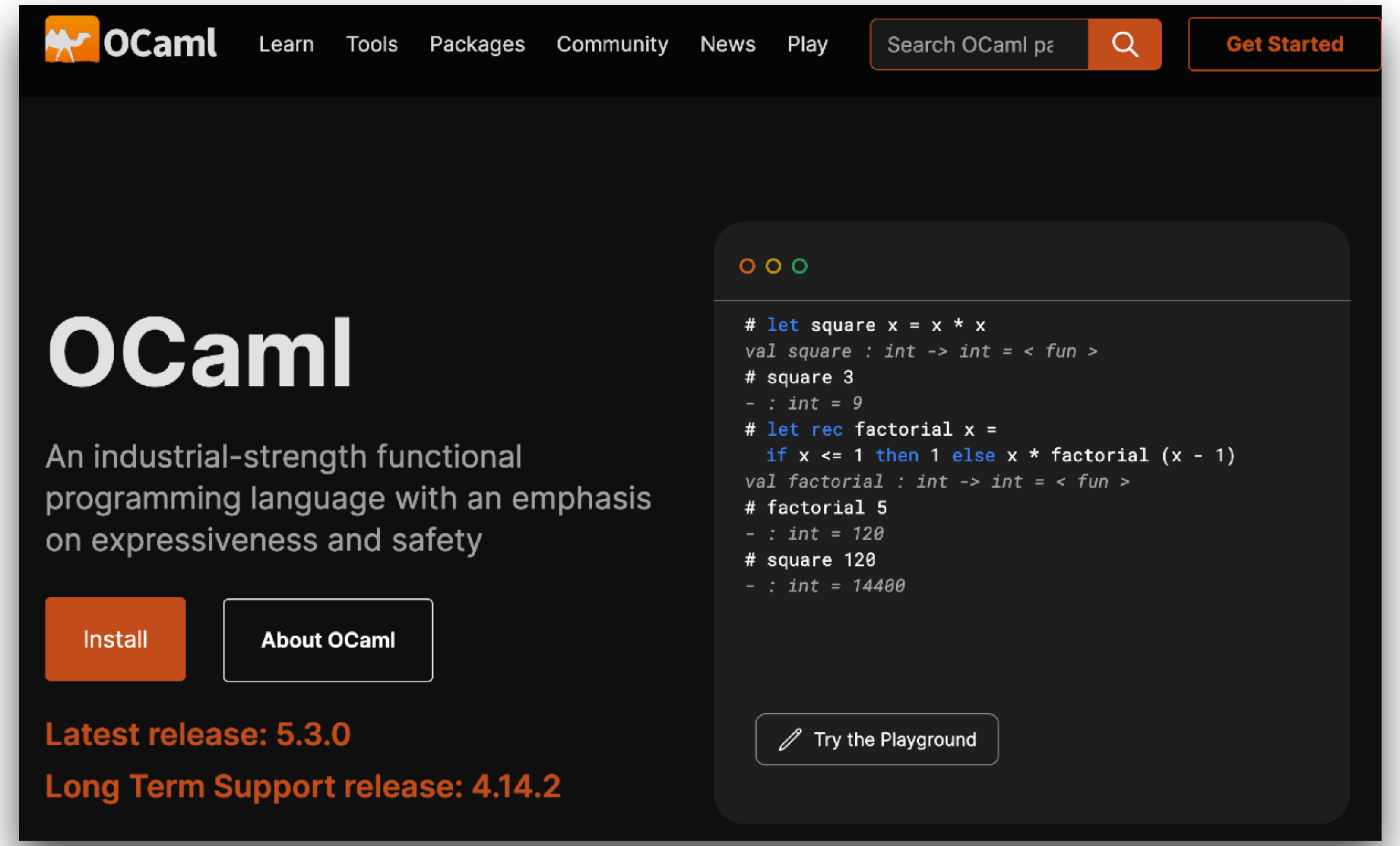

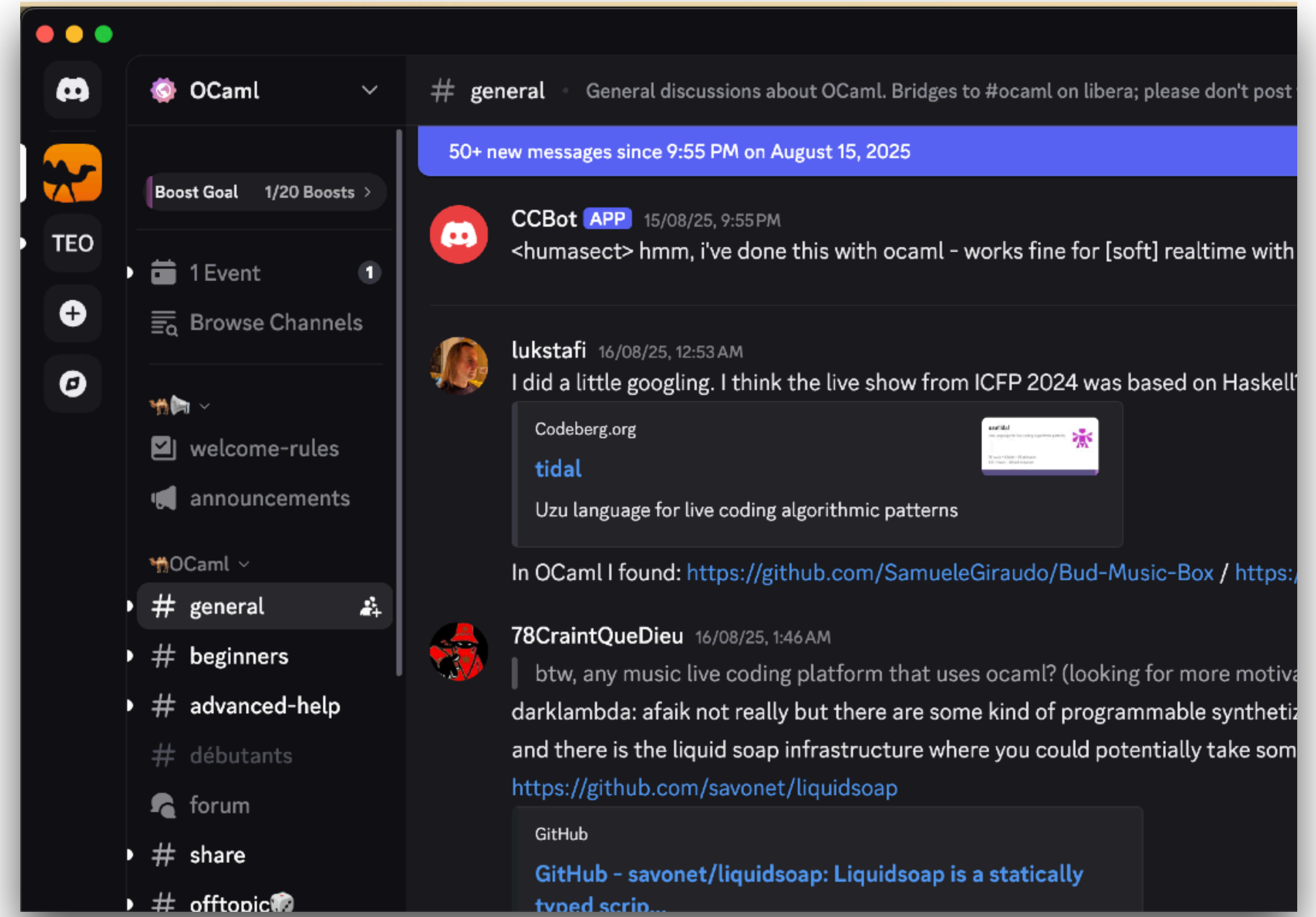

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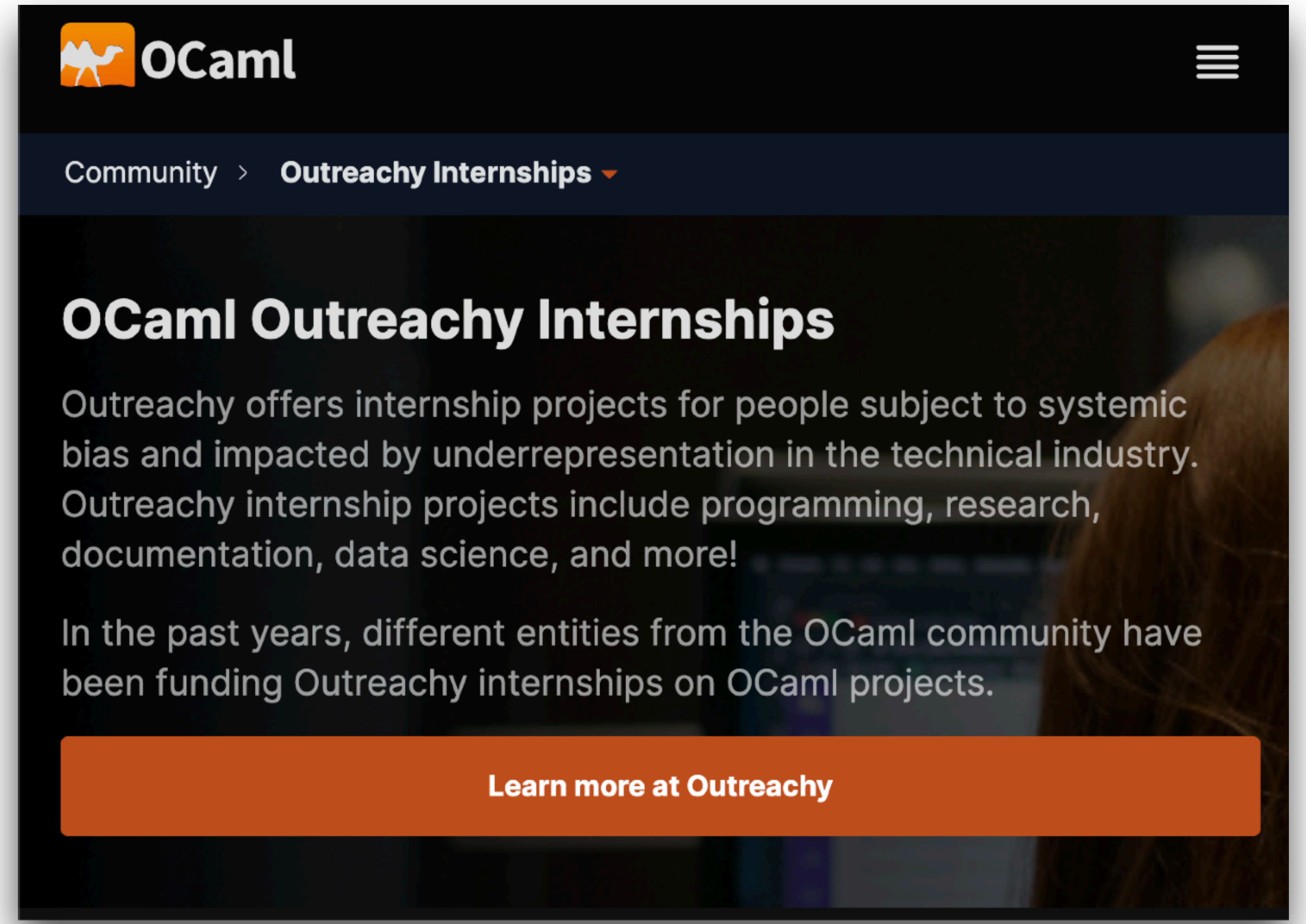

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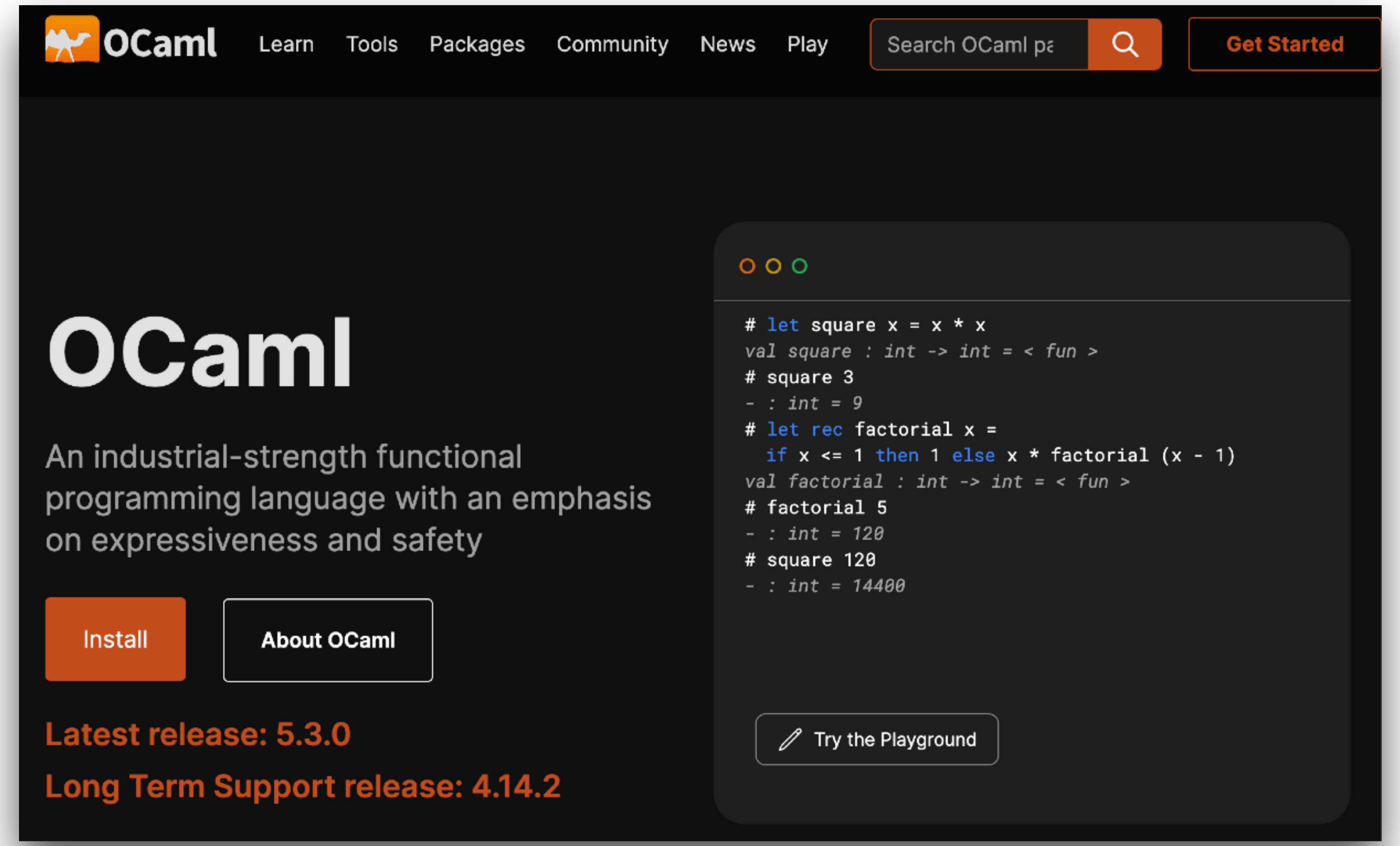

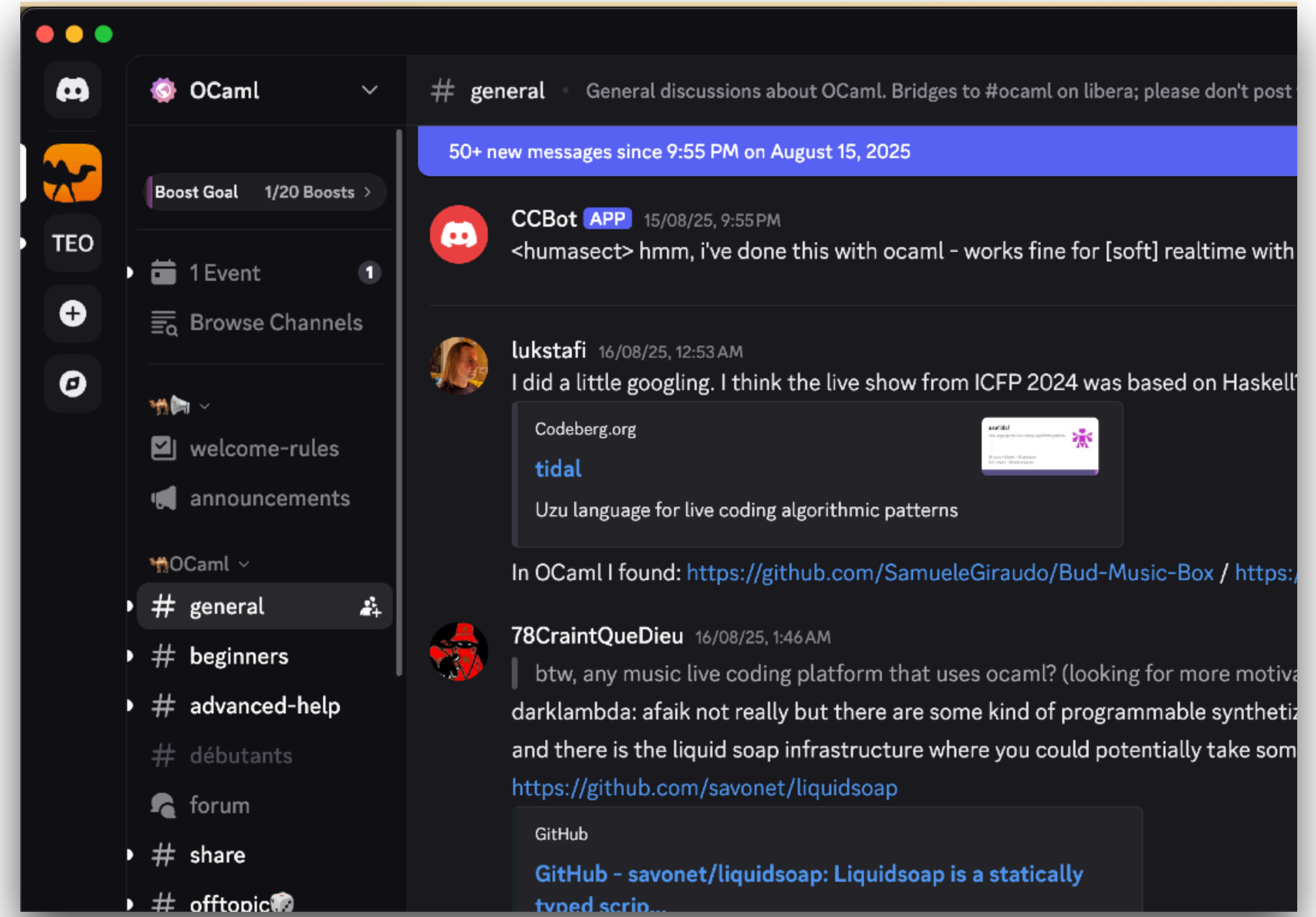

OCaml
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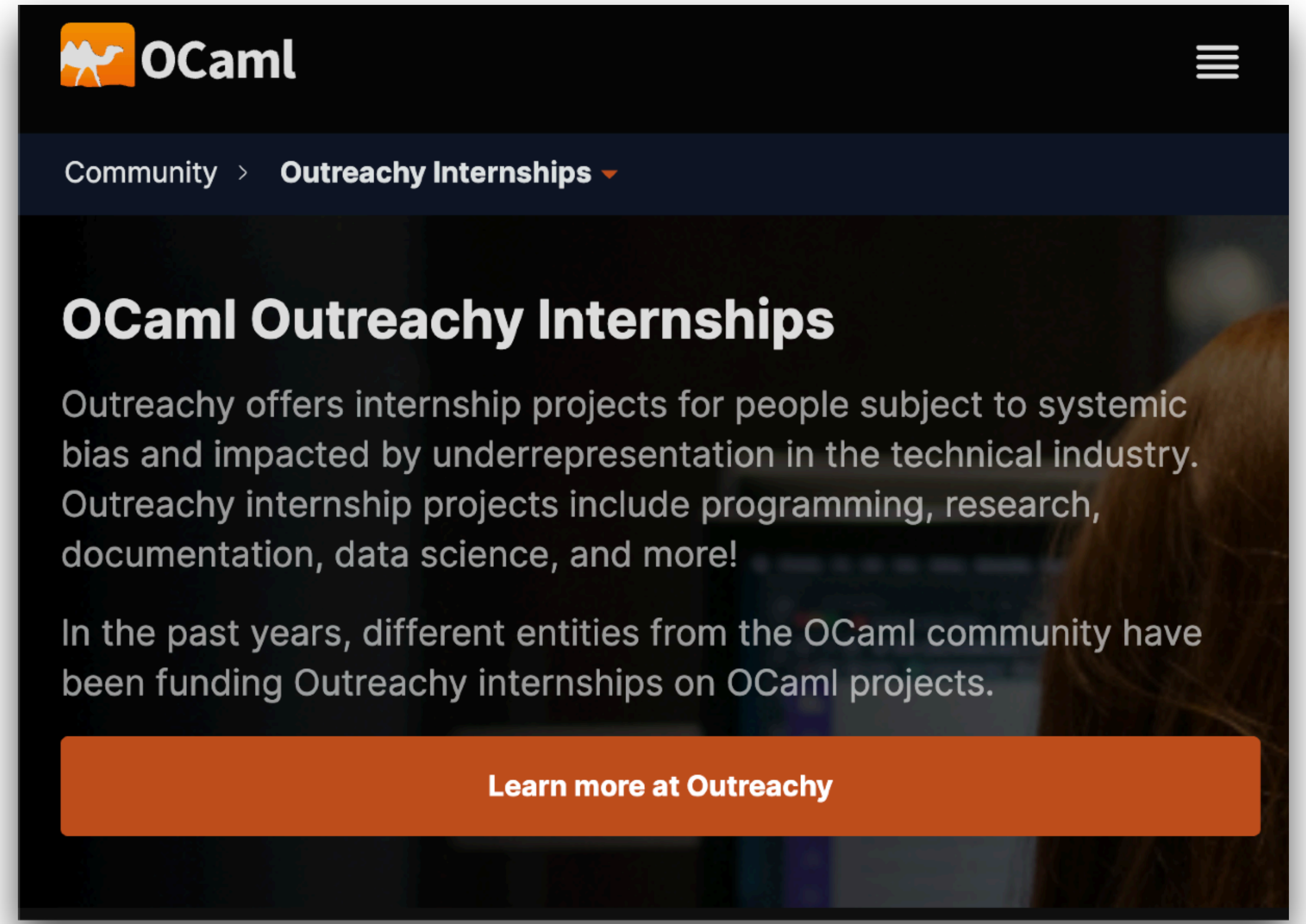

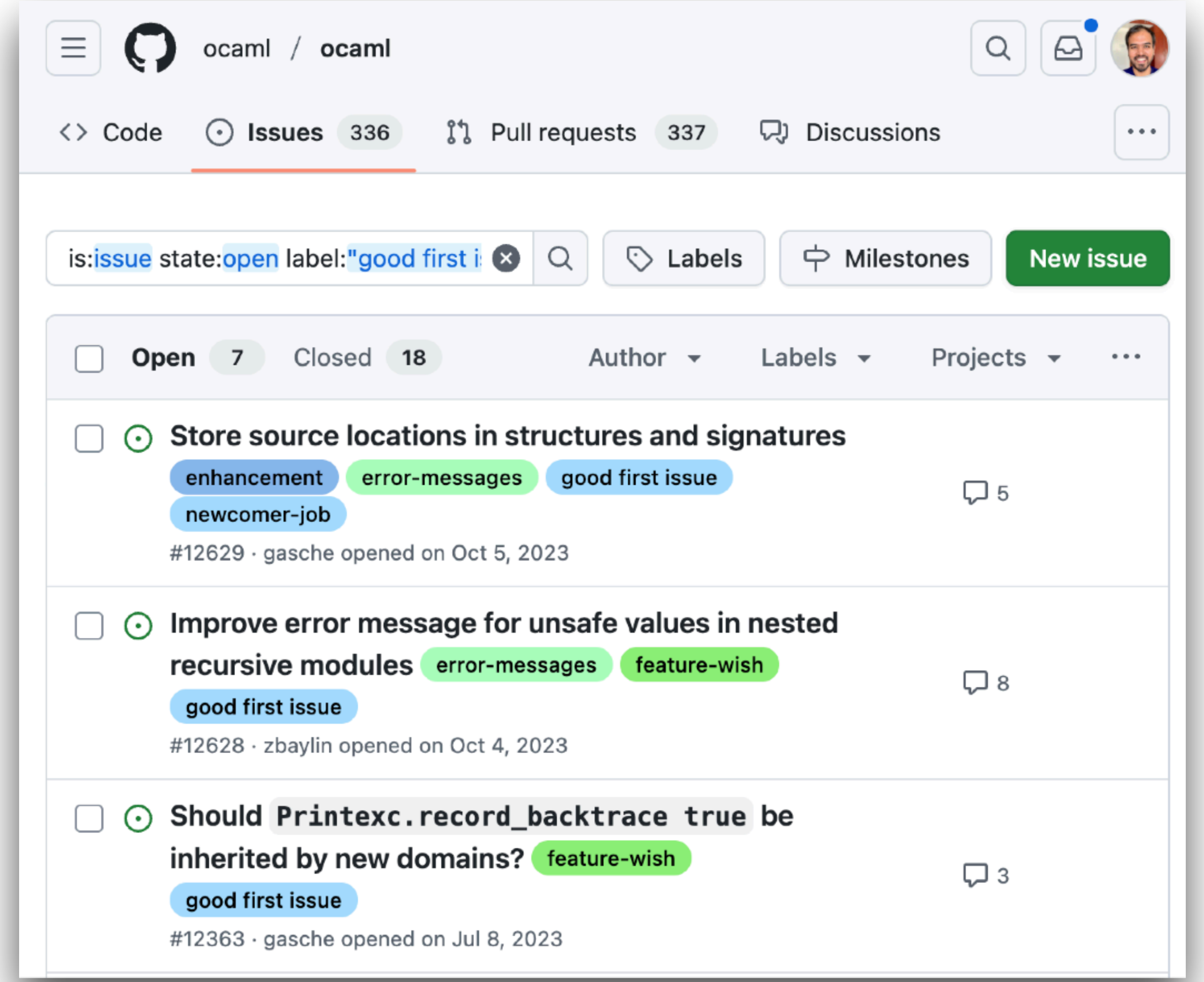

github.com/ocaml