Zoo: A framework for the verification of concurrent OCaml 5 programs using separation logic

Clément Allain

Gabriel Scherer

Introduction

Zoo overview

Verification contributions

Physical equality

Future work

OCaml 5 (2022)

Parallelism: multi-core runtime, domains, atomic references

Concurrency: algebraic effects

$\Downarrow$

Nascent ecosystem of parallel & concurrent software

`Domainslib`, `Saturn`, `Eio` ...

$\Downarrow$

Software verification!

OCaml verification ecosystem

Language	Concurrency	Iris	≈ OCaml	Translation	Automation
Cameleer	☹	☹	☺	☺	☺
`coq_of_ocaml`	☹	☹	☺	☺	☹
CFML	☹	☹	☺	☺	☹
Osiris	☹	☺	☺	☺	☹
HeapLang	☺	☺	☹	☹	😐
Zoo	☺	☺	☺	☺	😐

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Zoo

OCaml

DUNE

ocaml2zoo $\longrightarrow$

Iris

Zoo

ROCQ

Zoo in practice

```
project
├── dune-project
└── lib
    ├── domainslib
    │   ├── dune
    │   ├── scheduler.ml
    │   └── scheduler.mli
    └── saturn
        ├── dune
        ├── stack.ml
        └── stack.mli
```

$\longrightarrow$

```
theories
├── domainslib
│   ├── scheduler__code.v
│   └── scheduler__types.v
└── saturn
    ├── stack__code.v
    └── stack__types.v
```

```
$ ocaml2zoo project theories
```

Zoo in practice

```
let rec push t v =
  let old = Atomic.get t in
  let new_ = v :: old in
  if not (Atomic.compare_and_set t old new_) then (
    Domain.cpu_relax () ;
    push t v
  )
```

```
Definition stack_push : val :=
  rec: "stack_push" "t" "v" =>
    let: "old" := !"t" in
    let: "new" := ‘Cons( "v", "old" ) in
    if: ~ CAS "t" "old" "new" then (
      domain_cpu_relax () ;;
      "stack_push" "t" "v"
    ).
```

Zoo in practice

```
Lemma stack_push_spec t ι v :
  <<<
    stack_inv t ι
  | ∀∀ vs, stack_model t vs
  >>>
    stack_push t v @ ↑ι
  <<<
    stack_model t (v :: vs)
  | RET (); True
  >>>.
Proof. ... Qed.
```

`stack_push` is *linearizable*

Zoo in practice

```
Lemma stack_push_spec t ι v :
  <<<
    stack_inv t ι
  | ∀∀ vs, stack_model t vs
  >>>
    stack_push t v @ ↑ι
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    stack_model t (v :: vs)
  | RET (); True
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Proof. ... Qed.
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stack_push is *linearizable*

Zoo features

- Algebraic data types
- Records
- Mutually recursive functions
- Physical equality
- Structural equality

- Prophecy variables
- Diaframe (basic automation)

- Atomic references
- Atomic record fields
- Atomic arrays
- Generative constructors

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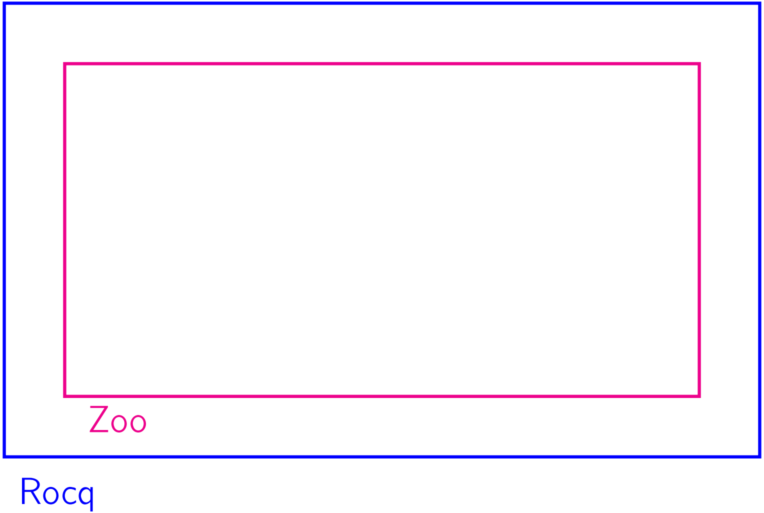
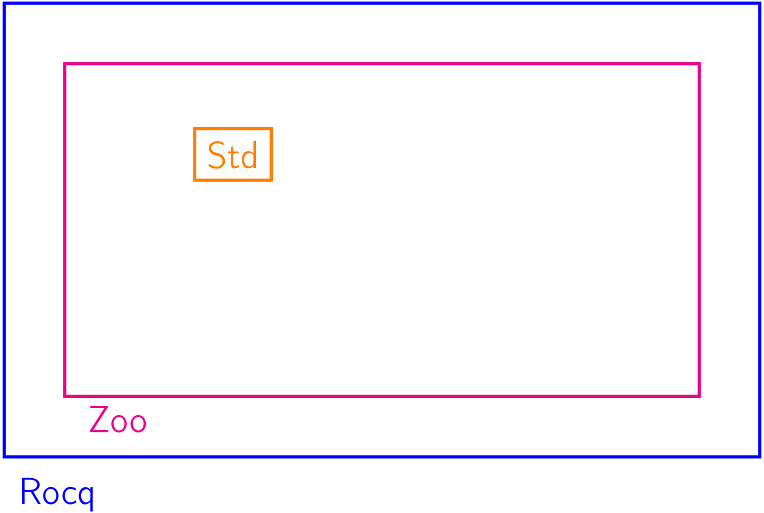


Verification contributions

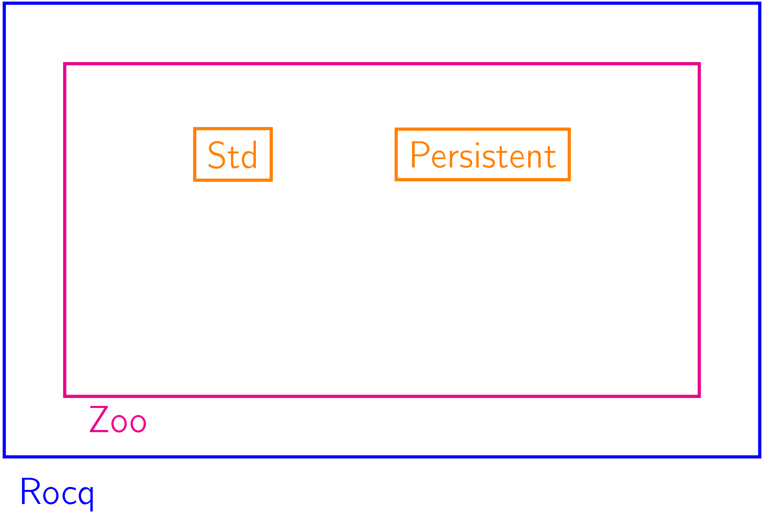


Standard data structures

- `Array`
- `Dynarray`
- `List`
- `Stack`
- `Queue`
- `Inf_array`
- `Deque`
- `Domain`
- `Mutex`
- `Semaphore`
- `Condition`
- `Ivar`
- `Mvar`

Rocq

Verification contributions



Verification contributions

Basile Clément

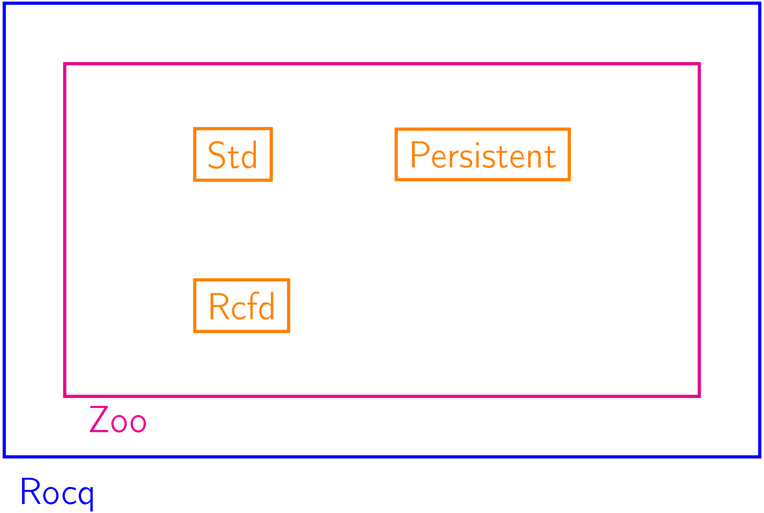
Gabriel Scherer

Persistent data structures

- Persistent array
- Persistent store
- Persistent union-find

Rocq

Verification contributions



Verification contrib

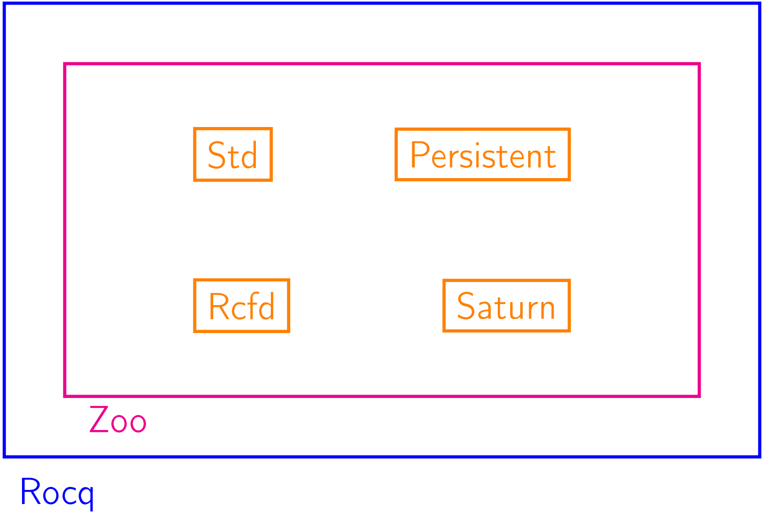
Thomas Leonard

Parallelism-safe file descriptor

- Generative constructors
- Intricate concurrent protocol
- Two ownership regimes

Rocq

Verification contributions



Vesa Karvonen

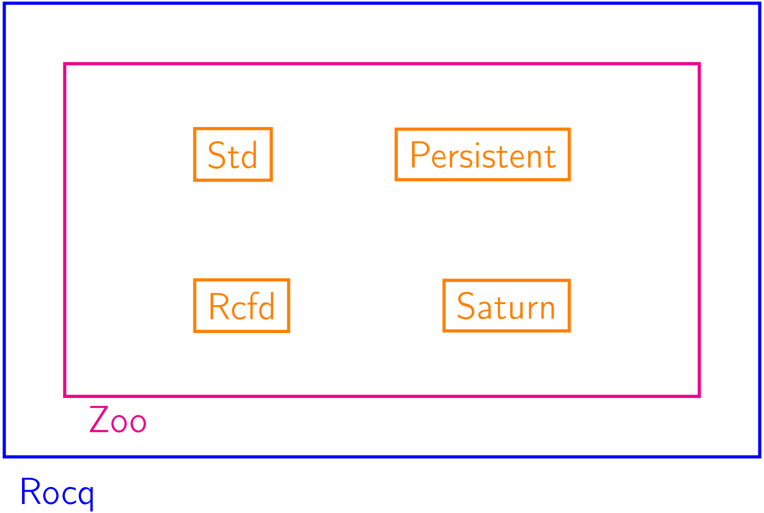
Carine Morel

Standard lock-free data structures

- Stacks
- List-based queues
- Array-based queues
- Stack-based queues

Roc

Verification contributions



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Physical equality in *fine-grained* concurrent programs

```
type 'a t =
  'a list Atomic.t

let create () =
  Atomic.make []

let rec push t v =
  let old = Atomic.get t in
  let new = v :: old in
  if Atomic.compare_and_set t old new then
    ()
  else
    push t v
```

Physical equality in *fine-grained* concurrent programs

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Physical comparison (==)

Physical equality in *fine-grained* concurrent programs

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Physical comparison (==)

OCaml: under-specified

Physical equality in *fine-grained* concurrent programs

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```

Physical comparison (==)

OCaml: under-specified

HeapLang: too restrictive
incompatible w/ OCaml

When physical equality returns `true`

```
let rec push t v =
  let old = Atomic.get t in
  let new = v :: old in

  if Atomic.compare_and_set t old new then


    ()
  else
    push t v
```

When physical equality returns `true`

```
let rec push t v =
  let old = Atomic.get t in
  let new = v :: old in
  ⟨ vs. stack-model t vs ∗ . . . ⟩
  if Atomic.compare_and_set t old new then


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When physical equality returns `true`

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let rec push t v =
  let old = Atomic.get t in
  let new = v :: old in
```
$\langle\ vs.\ \mathsf{stack\text{-}model}\ t\ vs * \ldots\ \rangle$
```
  if Atomic.compare_and_set t old new then
```
$\langle\ \mathsf{stack\text{-}model}\ t\ (v :: old) * vs \overset{\mathsf{phys}}{\approx} old\ \rangle$
```
    ()
  else
    push t v
```

When physical equality returns `true`

```
let rec push t v =
  let old = Atomic.get t in
  let new = v :: old in
  ⟨ vs. stack-model t vs ∗ . . . ⟩
  if Atomic.compare_and_set t old new then
    ⟨ stack-model t (v :: old) ∗ vs ≈phys old ⟩
    ⟨ stack-model t (v :: vs) ⟩
    ()
  else
    push t v
```

$$\langle\ vs.\ \mathsf{stack\text{-}model}\ t\ vs * \ldots\ \rangle$$

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$$\langle\ \mathsf{stack\text{-}model}\ t\ (v :: vs)\ \rangle$$

When physical equality returns true

```
let rec push t v =
  l
  l
  ⟨
  i
  e
  push t v
```

Sharing of immutable blocks

```
let test1 = 1 :: [] == 1 :: []   (* maybe true *)
let test2 = 1 :: [] == 1 :: []   (* maybe false *)
```

$$v_1 \overset{\text{rocq}}{=} v_2 \quad \not\Longrightarrow \quad v_1 \overset{\text{phys}}{\approx} v_2$$

let
l
l
⟨
i

e

Value representation conflicts

```
type any = Any : 'a -> any
let test1 = Any false == Any 0   (* maybe true *)
let test2 = Any None  == Any 0   (* maybe true *)
let test3 = Any []    == Any 0   (* maybe true *)
```

$$v_1 \overset{\text{phys}}{\approx} v_2 \quad \not\Longrightarrow \quad v_1 \overset{\text{rocq}}{=} v_2$$

When physical equality returns `true`

```
let rec push t v =
  let old = Atomic.get t in
  let new = v :: old in
```

$\langle\ vs.\ \text{stack-model}\ t\ vs * \ldots\ \rangle$

```
  if Atomic.compare_and_set t old new then
```

$\langle\ \text{stack-model}\ t\ (v :: old) * vs \overset{\text{phys}}{\approx} old\ \rangle$

$\cancel{\langle\ \text{stack-model}\ t\ (v :: vs)\ \rangle}$

```
    ()
  else
    push t v
```

When physical equality returns false

```
type state = Open of Unix.file_descr | Closing of (unit -> unit)
type t = { mutable state: state [@atomic]; ... }

let make fd = { state= Open fd; ... }
let close t = match t.state with
  | Closing _ -> false
  | Open fd as old ->
    let close () = Unix.close fd in
    let new = Closing close in

    if Atomic.Loc.compare_and_set [%atomic.loc t.state] old new
    then ... else



      false
```

When physical equality returns false

```
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When physical equality returns `false`

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```

$\langle\ \mathit{state}.\ t.\mathsf{state} \mapsto \mathit{state} * \ldots\ \rangle$

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```
      if Atomic.Loc.compare_and_set [%atomic.loc t.state] old new
      then ... else
```

$\langle\ \mathit{t}.\mathsf{state} \mapsto \mathit{state} * \mathit{state} \overset{\text{phys}}{\not\approx} \mathit{old} * \ldots\ \rangle$

```
        false
```

When physical equality returns false

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```

$\langle\ t.\mathsf{state} \mapsto \mathit{state} * \mathit{state} \overset{\mathsf{phys}}{\not\approx} \mathit{old} * \ldots\ \rangle$

$\langle\ t.\mathsf{state} \mapsto \mathsf{Closing}\ \_ * \ldots\ \rangle$

```
        false
```

Unsharing of immutable blocks

```
let x = Some 0
let test = x == x   (* maybe false *)
```

$$v_1 \overset{\text{phys}}{\not\approx} v_2 \quad \not\Longrightarrow \quad v_1 \overset{\text{rocq}}{\neq} v_2$$

Clément Allain
Impossible! Unique identity.

Armaël Guéneau
This would be *unsharing*.

Vincent Laviron
It's possible!

When physical equality returns `false`

```
type state = Open of Unix.file_descr | Closing of (unit -> unit)
type t = { mutable state: state [@atomic]; ... }

let make fd = { state= Open fd; ... }

let close t = match t.state with
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$\langle\ \mathit{state}.\ t.\mathsf{state} \mapsto \mathit{state} * \ldots\ \rangle$

```
      if Atomic.Loc.compare_and_set [%atomic.loc t.state] old new
      then ... else
```

$\langle\ t.\mathsf{state} \mapsto \mathit{state} * \mathit{state} \overset{\text{phys}}{\not\approx} \mathit{old} * \ldots\ \rangle$

$\cancel{\langle\ t.\mathsf{state} \mapsto \mathsf{Closing}\ \_ * \ldots\ \rangle}$

```
        false
```

Generative constructors

```
type 'a glist =
  | Nil
  | Cons of 'a * 'a glist [@generative]

type state =
  | Open of Unix.file_descr [@generative] [@zoo.reveal]
  | Closing of (unit -> unit)
```

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Future work

- **Language features**
  - Exceptions
  - Algebraic effects
  - Modules & functors
- **Coupling with semi-automated verification**
- **Relaxed memory**

Thank you for your attention!