Saturn: a library of verified concurrent data structures for OCaml 5

Clément Allain (INRIA Paris)
Vesa Karvonen (Tarides)
Carine Morel (Tarides)

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Why Saturn?

Github: ocaml-multicore/saturn

- A collection of concurrent-safe data structures for OCaml 5:
  - ◇ well-tested
  - ◇ benchmarked
  - ◇ optimized
  - ◇ verified

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- Writing concurrent code is hard

Buggy queue with size

```
module Queue = Saturn.Queue
type 'a t = {size : int Atomic.t; queue : 'a Queue.t}

let create () =
    {size = Atomic.make 0; queue = Queue.create ()}

let push t msg =
  Atomic.incr t.size;
  Queue.push t.queue msg

let pop_opt t =
  match Queue.pop_opt t.queue with
  | Some elt ->  Atomic.decr t.size; Some elt
  | None -> Atomic.set t.size 0; None

let size t = Atomic.get t.size
```

Buggy queue with size

```
let test () =
 let queue = create () in
 let d1 = Domain.spawn (fun () -> push queue 1) in
 let d2 = Domain.spawn (fun () -> pop_opt queue |>
     ignore) in
 Domain.join d1;
 Domain.join d2;
 pop_opt queue |> ignore;
 size queue
```

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In 10 to 20% of the tries, the test returns a size of -1.

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  - ◇ bugs that can be hard to reproduce and understand

Concurrent stack: Treiber stack

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

let create () = Atomic.make []

let rec push q a =
  let old = Atomic.get q in
  if Atomic.compare_and_set q old (a :: old) then ()
  else push q a

let rec pop_opt q =
  let old = Atomic.get q in
  match old with
  | [] -> None
  | x :: xs ->
    if Atomic.compare_and_set q old xs then Some x
    else pop_opt q
```

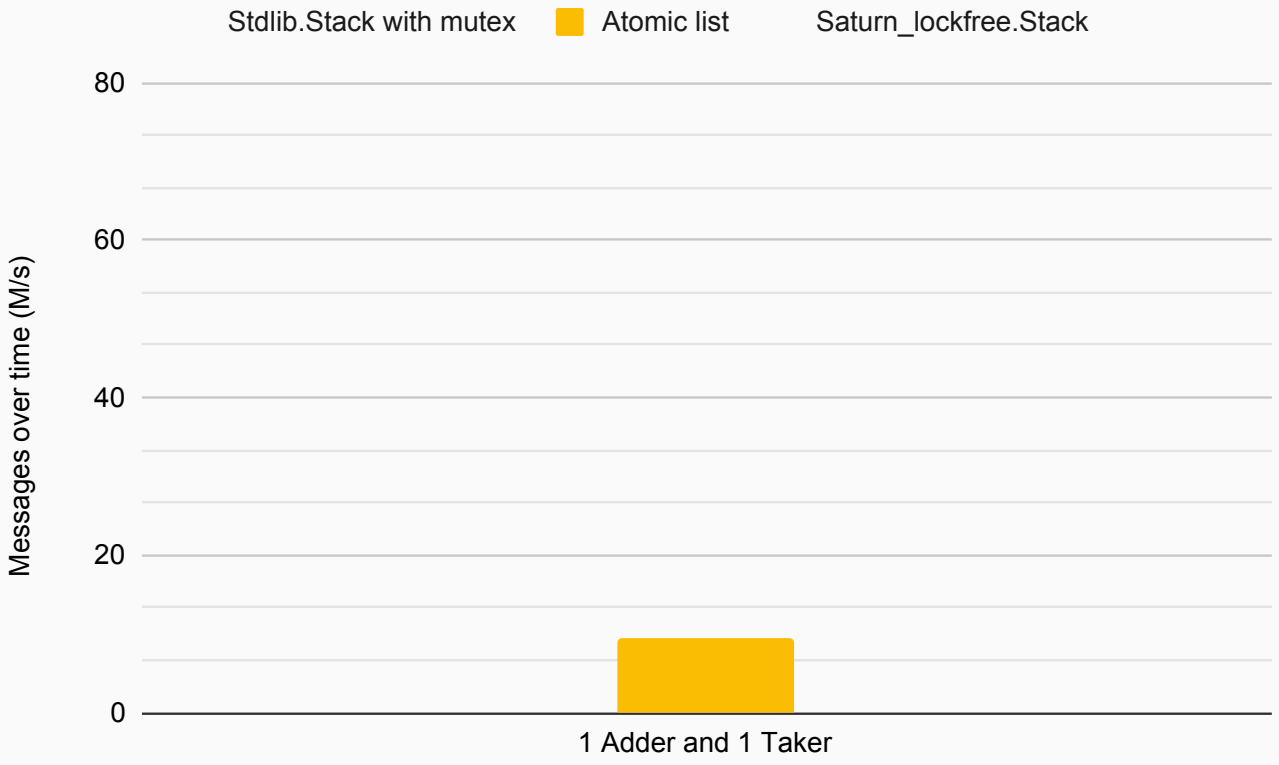
Concurrent stack: Treiber stack

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

let cr

let re
  let
  if A
  else

let re
  let
  matc
  | []
  | x
    if Atomic.compare_and_set q old xs then Some x
    else pop_opt q
```



Concurrent stack: Treiber stack

```
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let cre

let rec
  let c
  if At
  else

let rec
  let c
  match
  | []
  | x :
    if Atomic.compare_and_set q old xs then Some x
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```

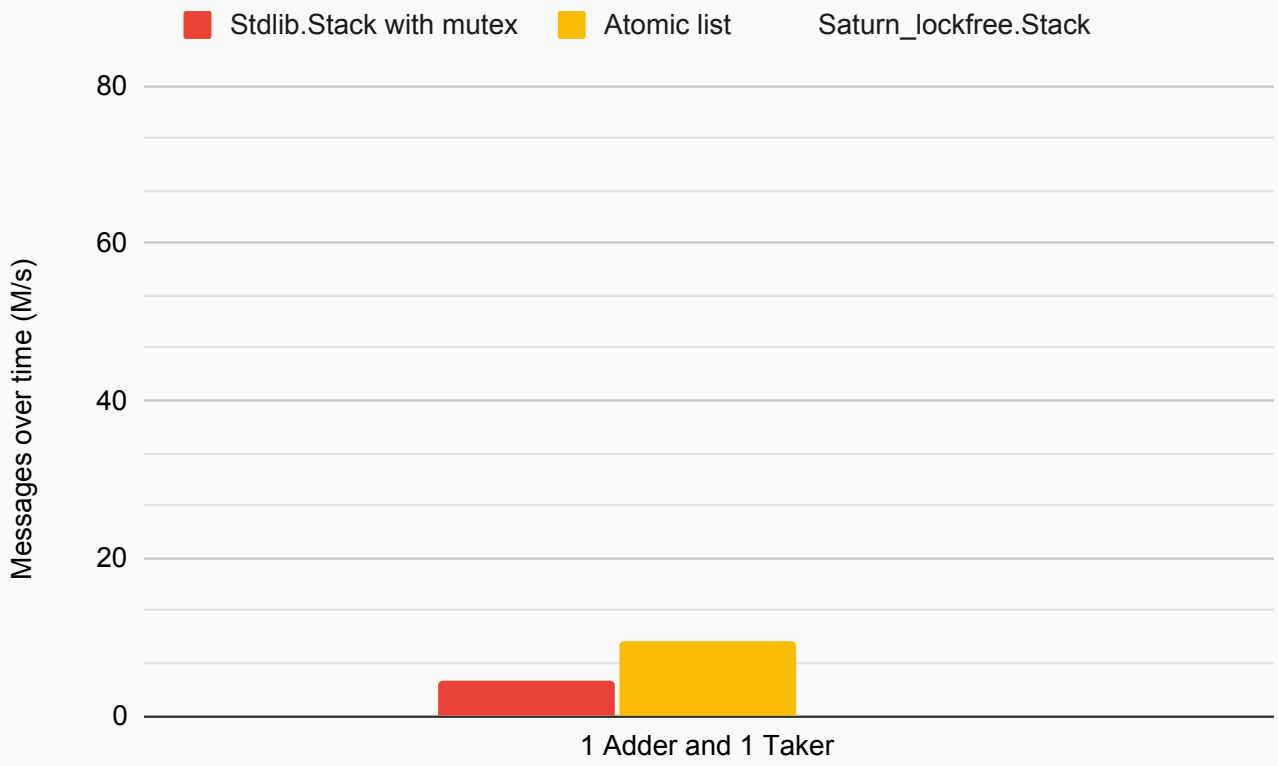

Concurrent stack: Treiber stack

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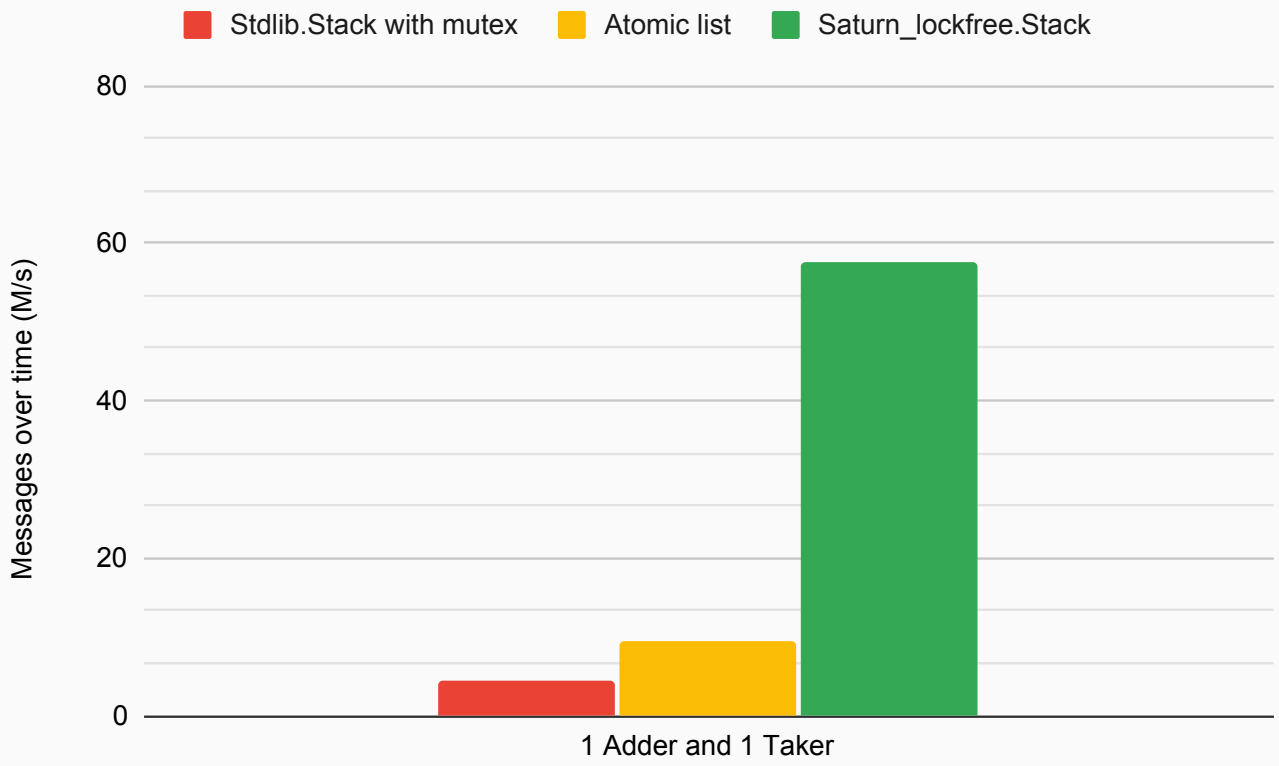

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What is in Saturn?

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- A collection of concurrent-safe data structures for OCaml 5
  - ◇ Queues
    - ○ multi-producer, multi-consumer
      (based on Michael-Scott queue algorithm)
    - ○ single-producer, single-consumer
    - ○ single-producer, multi-consumer
    - ○ bounded, blocking (opened PRs)

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- A collection of concurrent-safe data structures for OCaml 5
  - ◇ Queues
  - ◇ Work-stealing deque
  - ◇ Stacks
  - ◇ Hashtable (almost in a PR)
  - ◇ Skiplist: a sorted linked list with $o(\log(n))$ operations
  - ◇ Bag

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- Need something else ?

  $\rightarrow$ Open an issue on ocaml-multicore/saturn

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- Most available data structures are lock-free

  → Two libraries: Saturn and Saturn_lockfree

Testing in Saturn

What should (and can) be tested ?

- Correctness
- Linearizability
- Progress (i.e. lock freedom)

How ?

- Lin / STM (ocaml-multicore/multicoretests):
  - ◇ Correctness
  - ◇ Linearizability
- Dscheck (ocaml-multicore/dscheck):
  - ◇ Correctness
  - ◇ Lock-freedom

About optimizations

Numerous micro-optimizations:

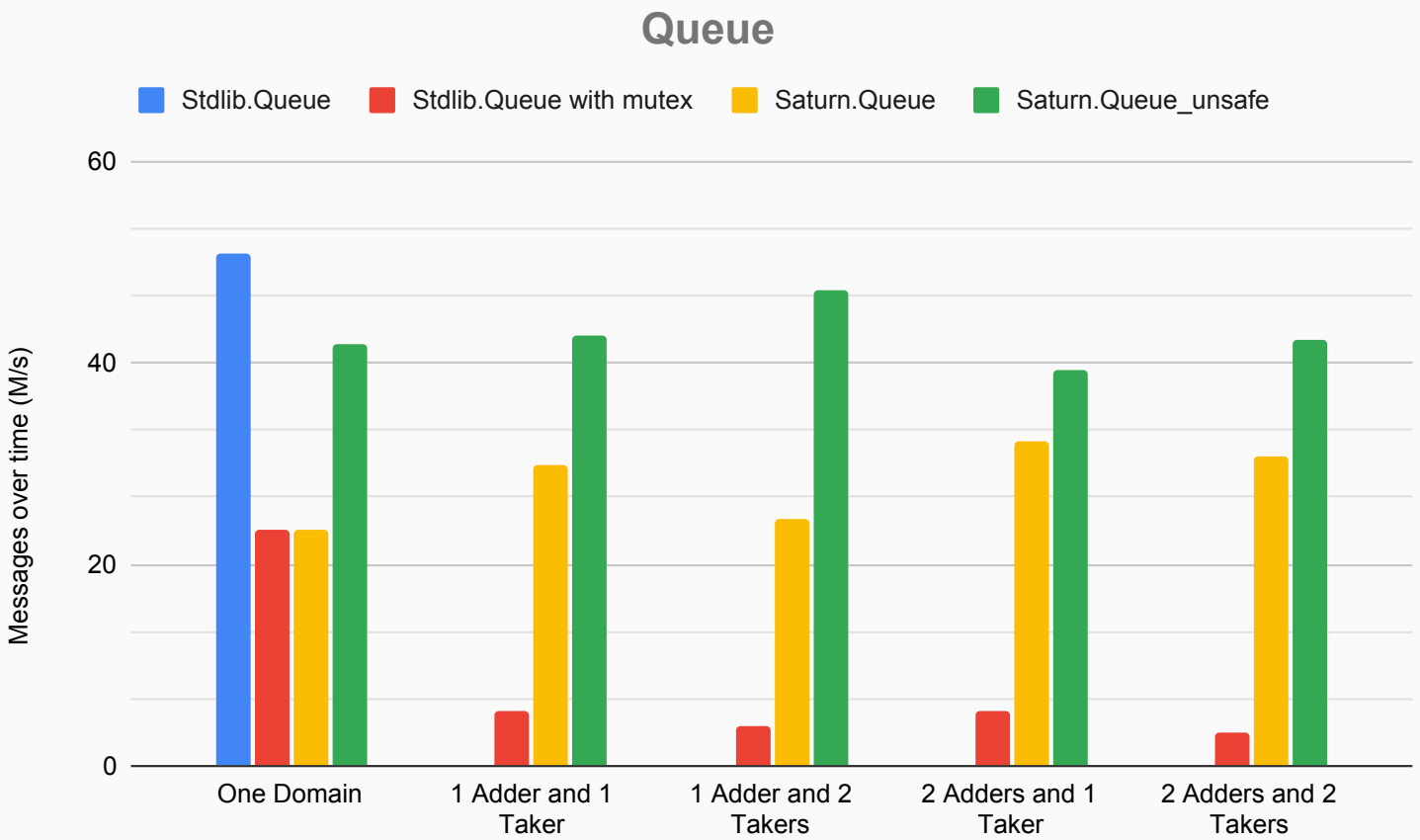
- ◇ Improving algorithms,
- ◇ Preventing false sharing,
- ◇ Removing indirections etc..
- ◇ Experimental: some optimizations use **Obj.magic** (e.g. Saturn.Queue_unsafe)

About optimizations

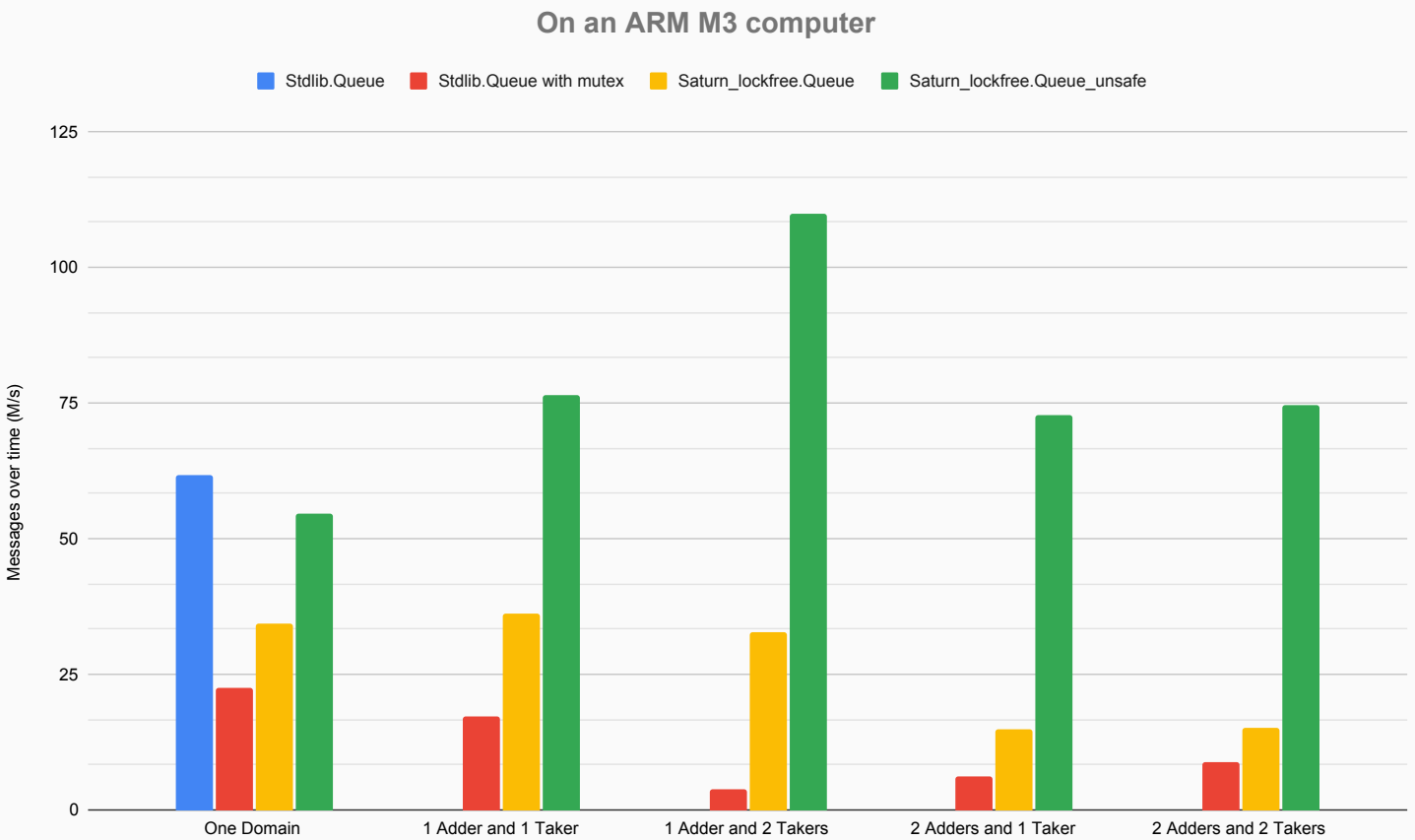
Numerous micro-optimizations:

- ◇ Improving algorithms,
- ◇ Preventing false sharing,
- ◇ Removing indirections etc..
- ◇ Experimental: some optimizations use **Obj.magic** (e.g. Saturn.Queue_unsafe)
  - → a source of inspiration for langage features for efficient concurrent code (e.g. opened PR on atomic record fields)

Benchmarks


Queue
Stdlib.Queue
Stdlib.Queue with mutex
Saturn.Queue
Saturn.Queue_unsafe
Messages over time (M/s)
60
40
20
0
One Domain
1 Adder and 1 Taker
1 Adder and 2 Takers
2 Adders and 1 Taker
2 Adders and 2 Takers

Benchmarks


On an ARM M3 computer
Stdlib.Queue
Stdlib.Queue with mutex
Saturn_lockfree.Queue
Saturn_lockfree.Queue_unsafe
Messages over time (M/s)
125
100
75
50
25
0
One Domain
1 Adder and 1 Taker
1 Adder and 2 Takers
2 Adders and 1 Taker
2 Adders and 2 Takers

Formal verification

Testing a concurrent algorithm is hard due to the number of potential interleavings.

Formal verification is here to help us!

From OCaml to Coq

```ocaml
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
  )
```

OCaml

Coq

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

Proving linearizability

linearizability $\underset{\text{in SC}}{\simeq}$

$$\frac{\frac{\frac{\frac{\{\,\text{stack-inv}\ t\,\}}{\langle\, vs.\,\text{stack-model}\ t\ vs\,\rangle}}{\texttt{stack\_push}\ t\ v}}{\langle\,\text{stack-model}\ t\ (v :: vs)\,\rangle}}{\{\ ().\,\text{True}\,\}}$$

Theorems for free from separation logic specifications

Birkedal, Dinsdale-Young, Guéneau, Jaber, Svendsen & Tzevelekos

Writing concurrent protocols in Iris

```
Definition stack_inv t ι : iProp Σ :=
  ∃ l γ,
  ⌜t = #l⌝ ∗ meta l nroot γ ∗
  inv ι (
    ∃ vs, l ↦ lst_to_val vs ∗ stack_model₂ γ vs
  ).

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.
```


Thank you for your attention!
AMATEUR
IMAGES

Relaxed memory model (future work)

$$\frac{\{\,\text{stack-inv } t\,\}}{\langle\, v_0, \ldots, v_n, \mathcal{V}_0, \ldots, \mathcal{V}_n.\, \text{stack-model } t\ ((v_0, \mathcal{V}_0), \ldots (v_n, \mathcal{V}_n))\,\rangle}$$
$$\frac{}{\texttt{stack\_push}\ t\ v, \mathcal{V}}$$
$$\frac{\langle\, \text{stack-model } t\ ((v, \mathcal{V}), (v_0, \mathcal{V}_0), \ldots (v_n, \mathcal{V}_n))\,\rangle}{\{\ ()\ .\ \text{True}\,\}}$$

Cosmo: a concurrent separation logic for multicore OCaml, Mével, Jourdan & Pottier

Formal verification of a concurrent bounded queue in a weak memory model, Mével & Jourdan

Stack benchmarks