# Correct tout seul, sûr à plusieurs

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# This talk

The story of how we got `Dynarray` in the OCaml standard library.

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The story of how we got `Dynarray` in the OCaml standard library.

... and the horrors that lie beneath ...

with Coq proofs !

# Dynarray : what ?

An array...

```
val init : int -> (int -> 'a) -> 'a t

val get : 'a t -> int -> 'a
val set : 'a t -> int -> 'a -> unit

val length : 'a t -> int
```

# Dynarray : what ?

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val init : int -> (int -> 'a) -> 'a t

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val length : 'a t -> int
```

that is also a stack (Daniel Bünzli) :

```
val create : unit -> 'a t
val add_last : 'a t -> 'a -> unit
val pop_last_opt : 'a t -> 'a option
```

# Dynarray : why ?

- You want build an array by accumulating elements,
  but you don't know the size in advance.
  (Note : `Array.of_list` may also work very well.)
- You want a stack or bag, but also indices and random access.

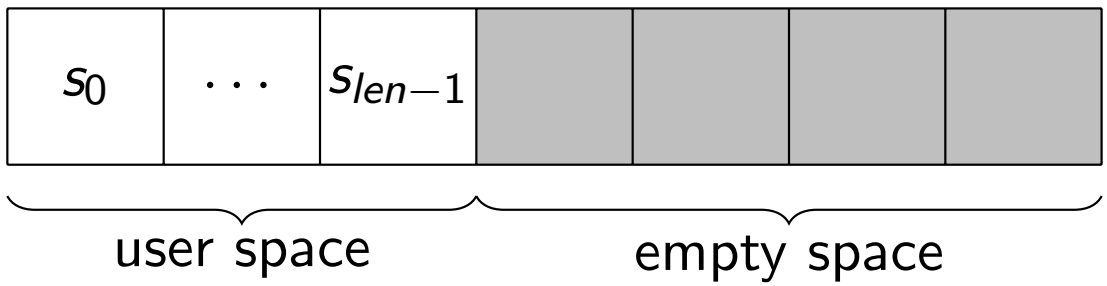
Classic examples :

- Priority queues stored in an array (textbook algorithm).
  Stdlib priority queues (@backtracking, January 2024)
  https://github.com/ocaml/ocaml/pull/12871
- The journal of a journalled data structure.
- The trail of a SAT/SMT solver.
- Clause sets in an automated prover.

# Dynarray : how ?

Implementation (`'a slot` is a secret for now) :

```
type 'a t = {
  mutable data : 'a slot array;
  mutable len : int;
}
```




Capacity (backing array length). Space control (Simon Cruanes) :

```
val capacity : 'a t -> int
val ensure_capacity : 'a t -> int -> unit
val fit_capacity : 'a t -> unit
```

# Story time (1)

Once upon a time, a brave, *brave* contributor

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wanted to improve the OCaml standard library
by adding a `Dynarray` module from his containers library.
Many had tried before him...

- ...
- https://discuss.ocaml.org/t/adding-dynamic-arrays-vectors-to-stdlib/4697/38
- https://github.com/ocaml/ocaml/pull/9122

# Story time

He held a secret meeting with two gate keepers of the stdlib

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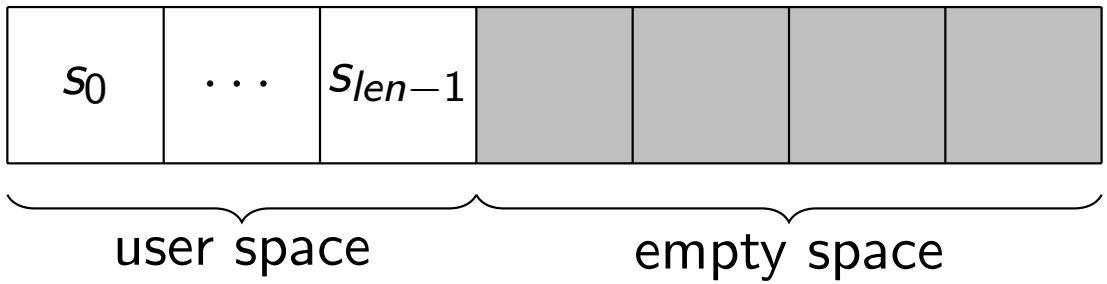
**Florian Angeletti**
Octachron

They brainstormed an API, and a PR was born.

"add 'Dynarray' to the stdlib" (@c-cube, September 2022)
https://github.com/ocaml/ocaml/pull/11563

# Horror 1 : empty value




What value should we store in the empty space ?

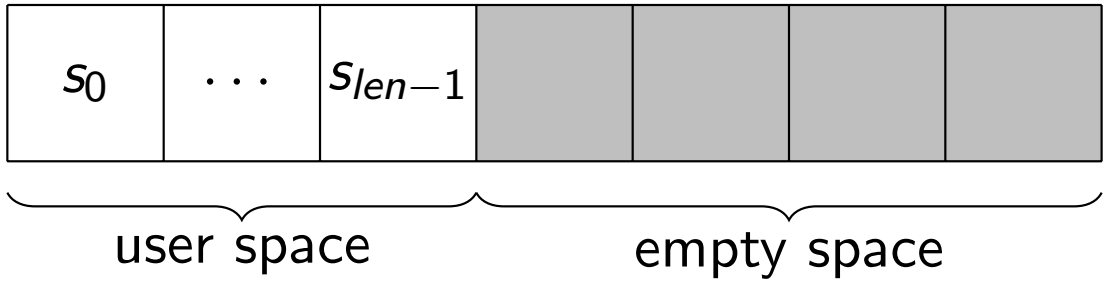
A user-provided default value : inconvenient API.

The last user-provided value : space leak.

`Obj.magic ()` : ew.

`None` : ew. `('a option array)`

# Horror 2 : concurrency




```
let[@inline] get v i =
  if i < 0 || i >= v.len then
    invalid_arg "CCVector.get";
  Array.unsafe_get v.data i
```

What if another domain races on `v.len` ?

`unsafe_get` : segfault (out of backing array)

`Obj.magic ()` : segfault (out of user space)

# Story, continued

After endless nights fighting the zombie hordes of `Obj.magic ()`, the PR went into an eternal sleep.

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the PR went into an eternal sleep.

Until :
"Dynarrays, boxed" (@gasche, January 2023)
https://github.com/ocaml/ocaml/pull/11882

```
type 'a slot =
| Empty
| Elem of { mutable v : 'a }
```

Reassuring benchmarks.
Problem solved ?

# Horror 3 : iterator invalidation

```
val iter : ('a -> unit) -> 'a t -> unit
```

What happens if elements are added or removed during `iter` ?

1. something reasonable (but slower) ?
2. weak memory model ?
3. invalid, maybe an error ?
4. invalid, always an error ?

# Story, end

Many more months of feedback, changes, decisions.

Clément Allain reviewed the code for correctness.

Merged in OCaml 5.2 ! (to be released soon)

# Take away

```
let[@inline] get v i =
  if i < 0 || i >= v.len then
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```

Public announcements :

> Library code must remain memory-safe for *all* uses,
> *including* incorrect concurrent code.

# Take away

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let[@inline] get v i =
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```

Public announcements :

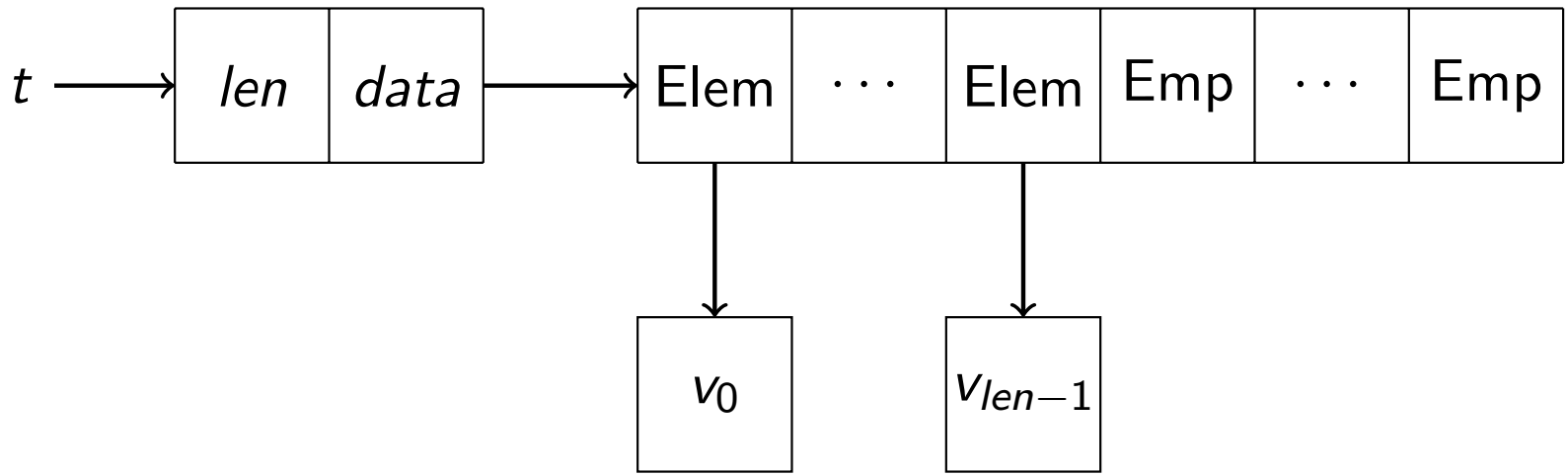
Library code must remain memory-safe for *all* uses,
*including* incorrect concurrent code.

Consequence :
Some unsafe code that was *perfectly fine* with OCaml 4
is now *unsound* with OCaml 5

Time to review all your unsafe_{get,set} calls.

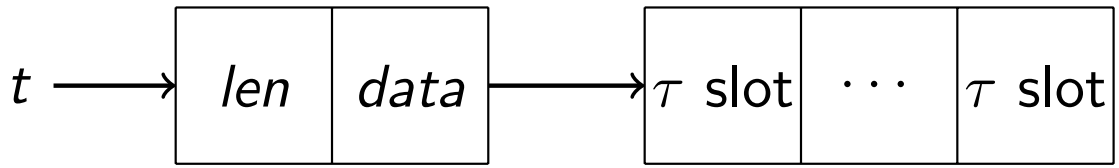
How do we *reason* about this ?

# Strong invariant for functional correctness



# Weak invariant for memory safety

$t : \tau$ t




$$0 \leq len$$

---

$slot : \tau$ slot

$$slot = \text{Emp} \quad \Big| \quad slot \longrightarrow \boxed{\tau}$$

# A method [1] to reason about sequential/concurrent algorithms using unsafe features in OCaml 5

| **Functional correctness** | **Memory safety** |
| --- | --- |
| Each function respects its specification. | Each function inhabits its semantic type. |
| Strong invariant | Weak invariant |

1. Thanks to Armaël Guéneau for stating clearly the dichotomy.

# Reviewing `Dynarray`

`Dynarray` review
$+$ Separation logic (Iris)
$+$ Coq

$=$ OCamlBelt
$=$ semantic typing implying memory safety

$\approx$ RustBelt

# Formalization in the Iris separation logic (mechanized in Coq)

```
val create : unit -> 'a t
val make : int -> 'a -> 'a t
val init : int -> (int -> 'a) -> 'a t
val length : 'a t -> int
val get : 'a t -> int -> 'a
val set : 'a t -> int -> 'a -> unit
val add_last : 'a t -> 'a -> unit
val pop_last : 'a t -> 'a
val ensure_capacity : 'a t -> int -> unit
val ensure_extra_capacity : 'a t -> int -> unit
val fit_capacity : 'a t -> unit
val reset : 'a t -> unit
```

# Strong invariant for functional correctness... in Iris

```
Definition dynarray_model t vs : iProp Σ :=
  ∃ l data slots extra,
  ⌜t = #l⌝ ∗
  l.[len] ↦ #(length vs) ∗
  l.[data] ↦ data ∗
  array_model data (slots ++ replicate extra &&None) ∗
  [∗ list] slot; v ∈ slots; vs, slot_model slot v.
```

---

```
Lemma dynarray_pop_last_spec t vs v :
  {{{ dynarray_model t (vs ++ [v]) }}}
    dynarray_pop_last t
  {{{ RET v; dynarray_model t vs }}}.
```

# Weak invariant for memory safety... in Iris

```
Definition dynarray_type τ `{iType _ τ} t : iProp Σ :=
  ∃ l,
  ⌜t = #l⌝ ∗
  inv nroot (
    ∃ len cap data,
    ⌜0 <= len⌝ ∗
    l.[len] ↦ #len ∗
    l.[data] ↦ data ∗
    array_type (slot_type τ) cap data
  ).
```

---

```
Lemma dynarray_pop_last_type τ t :
  {{{ dynarray_type τ t }}}
    dynarray_pop_last t
  {{{ v, RET v; τ v }}}.
```

# HeapLang (standard Iris language)

```
Definition dynarray_pop_last : val :=
  λ: "t",
    let: "len" := dynarray_len "t" in
    let: "arr" := dynarray_data "t" in
    assume ("len" <= array_length "arr") ;;
    assume (#0 < "len") ;;
    let: "last" := "len" - #1 in
    match: array_unsafe_get "arr" "last" with
    | None =>
        diverge #()
    | Some "ref" =>
        array_unsafe_set "arr" "last" &None ;;
        dynarray_set_size "t" "last" ;;
        !"ref"
    end.
```

# What the mechanized Iris proofs look like :

```
Proof.
  iIntros "%Φ #Htype HΦ".
  wp_rec.
  wp_apply (dynarray_len_type with "Htype") as "%sz _".
  wp_smart_apply (dynarray_data_type with "Htype") as "%cap %data #Hdata_type".
  wp_smart_apply (array_size_type with "Hdata_type") as "_".
  wp_smart_apply assume_spec' as "%Hcap".
  wp_smart_apply assume_spec' as "%Hsz".
  wp_smart_apply (array_unsafe_get_type with "Hdata_type") as "%slot #Hslot".
  { lia. }
  wp_apply (opt_type_match with "Hslot"). iSplit.
  - wp_apply diverge_spec.
  - iIntros "%r #Hr /=".
    wp_smart_apply (array_unsafe_set_type with "[Hdata_type]") as "_".
    { lia. }
    { iSteps. }
    wp_smart_apply (dynarray_set_size_type with "Htype") as "_".
    { lia. }
    wp_smart_apply (reference_get_type with "Hr").
    iSteps.
Qed.
```

# End

Thanks !

Questions ?

# Bonus slide : pop_last in OCaml

```
let pop_last a =
  let {data = arr; len = length} = a in
  check_valid_length length arr;
  (* We know [length <= capacity a]. *)
  if length = 0 then raise Not_found;
  let last = length - 1 in
  (* We know [length > 0] so [last >= 0]. *)
  match Array.unsafe_get arr last with
  | Empty ->
      Error.missing_element ~i:last ~length
  | Elem s ->
      Array.unsafe_set arr last Empty;
      a.length <- last;
      s.v
```