Modularity in programming languages, the example of OCaml

A powerful module system over a strongly typed functional language

Clément Blaudeau, Cambium team

November 28, 2022

Overview

1. Languages and language research

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1. Languages and language research

2. Typing

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2. Typing
3. Typing and modularity

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4. OCaml modules

Languages and language research

A diversity of languages

Program properties

Program properties

- Absence of error

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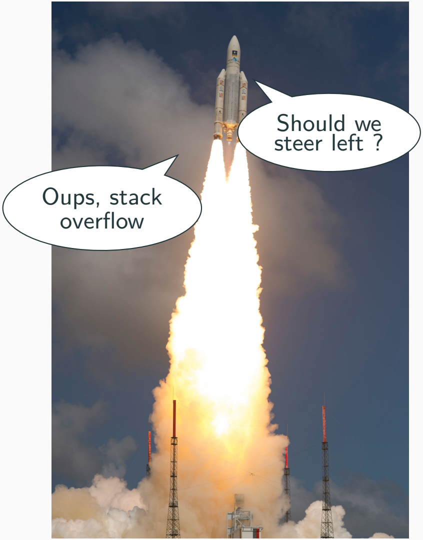
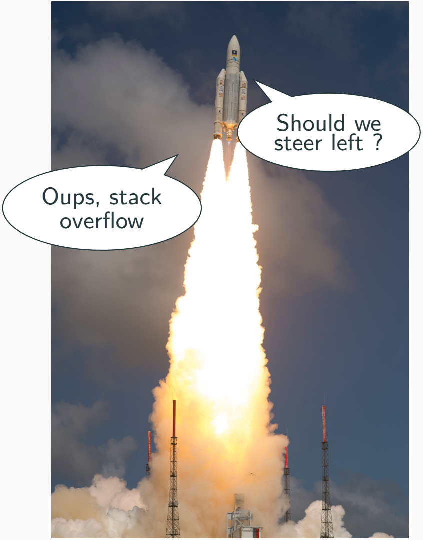


Program properties

- Absence of error
- Termination
- Time execution bounds
- Space (memory) bounds



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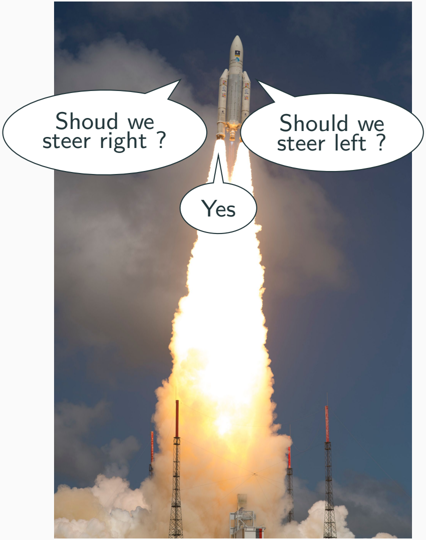

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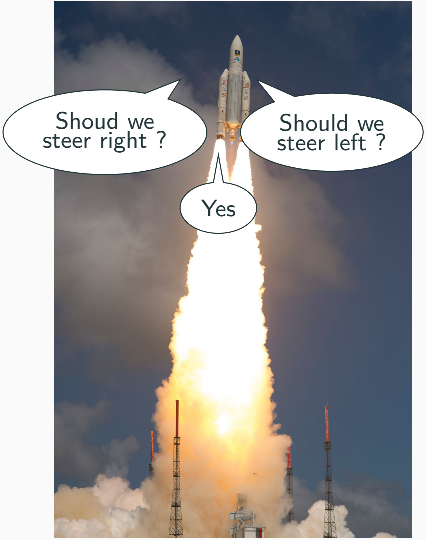

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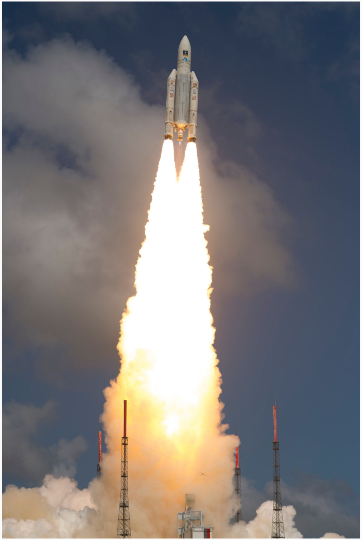

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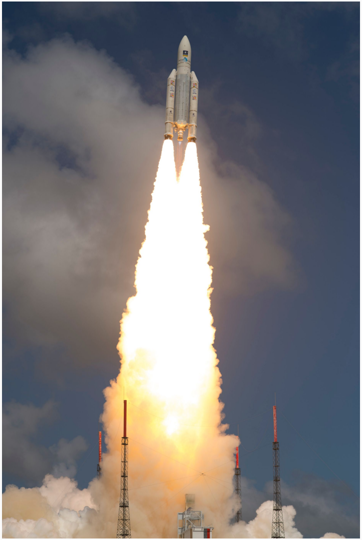

Program properties

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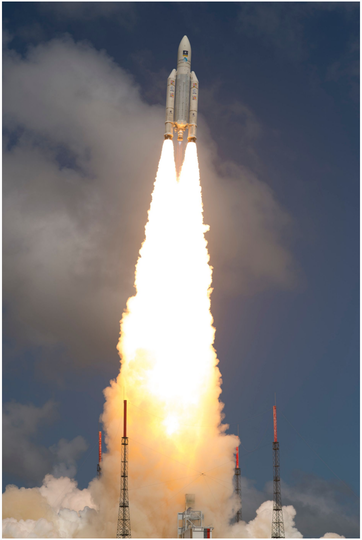

Program properties vs Language guarantees

Hard

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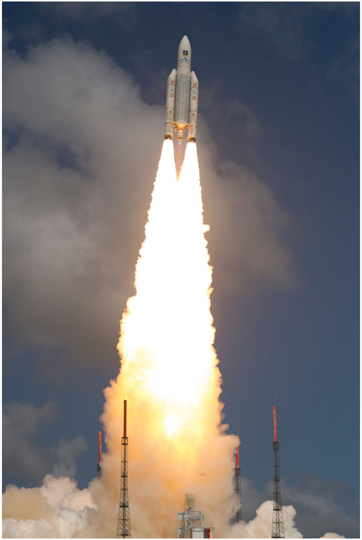

What is a language ?

What you ***say***

What is a language ?

*What you **say***

*What you **mean***

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Syntax

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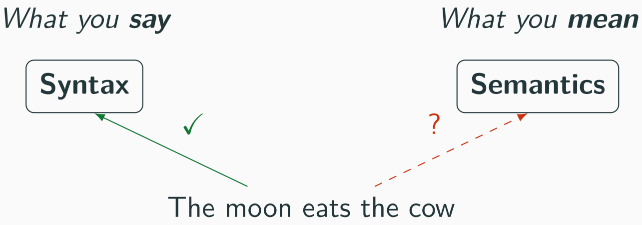

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Typing

A descriptive language overlay

$$x = \frac{1}{2}at^2 + v_0 t + x_0$$

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Typing expressivity

```
MAIN0001* PROGRAM TO SOLVE THE QUADRATIC EQUATION
MAIN0002        READ 10,A,B,C $
MAIN0003        DISC = B*B-4*A*C $
MAIN0004        IF (DISC) NEGA,ZERO,POSI $
MAIN0005   NEGA R = 0.0 - 0.5 * B/A $
MAIN0006        AI = 0.5 * SQRTF(0.0-DISC)/A $
MAIN0007        PRINT 11,R,AI $
MAIN0008        GO TO FINISH $
MAIN0009   ZERO R = 0.0 - 0.5 * B/A $
MAIN0010        PRINT 21,R $
MAIN0011        GO TO FINISH $
MAIN0012   POSI SD = SQRTF(DISC) $
MAIN0013        R1 = 0.5*(SD-B)/A $
MAIN0014        R2 = 0.5*(0.0-(B+SD))/A $
MAIN0015        PRINT 31,R2,R1 $
MAIN0016 FINISH STOP $
MAIN0017     10 FORMAT( 3F12.5 ) $
MAIN0018     11 FORMAT( 19H TWO COMPLEX ROOTS:, F12.5,14H PLUS OR MINUS,
MAIN0019        F12.5, 2H I ) $
MAIN0020     21 FORMAT( 15H ONE REAL ROOT:, F12.5 ) $
MAIN0021     31 FORMAT( 16H TWO REAL ROOTS:, F12.5, 5H AND , F12.5 ) $
MAIN0022        END $
```

Typing expressivity

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Typing expressivity

$\boxed{\text{Fruits}} \longrightarrow$

Typing expressivity

$\boxed{\text{Fruits}} \longrightarrow$  $\boxed{\text{Juice}}$

Typing expressivity

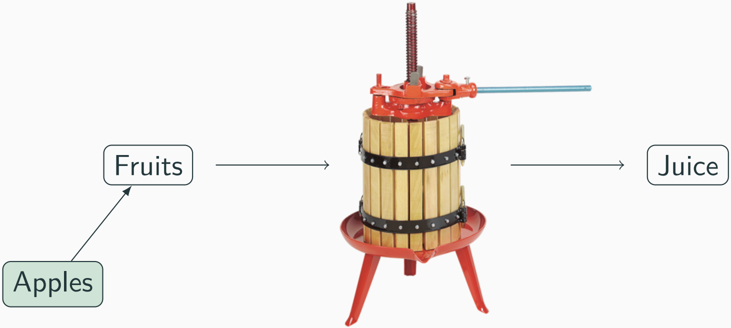
Fruits $\longrightarrow$  $\longrightarrow$ Juice

Typing expressivity

Fruits ⟶  ⟶ Juice

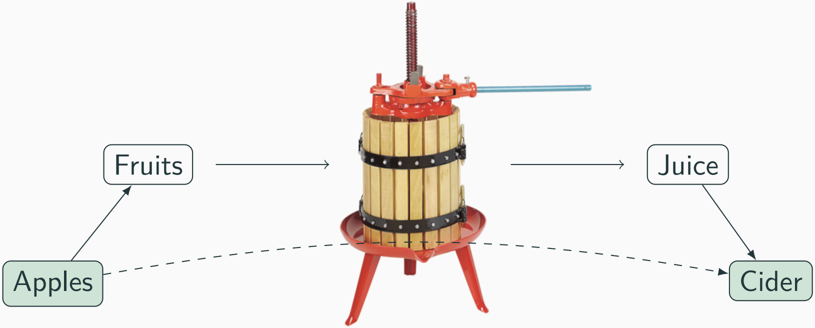
Apples ⟶ Fruits

Typing expressivity



- Subtyping : Apples $<:$ Juice

Typing expressivity



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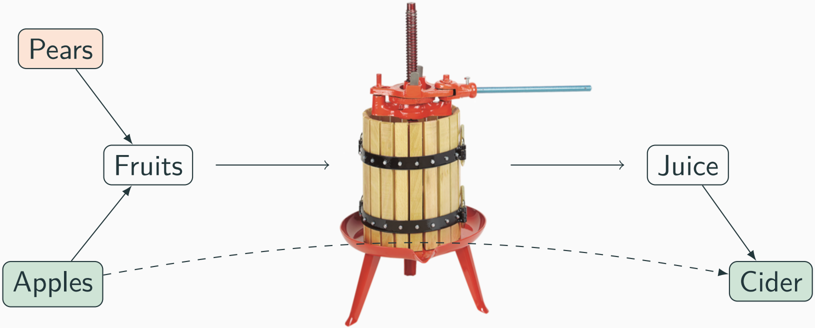

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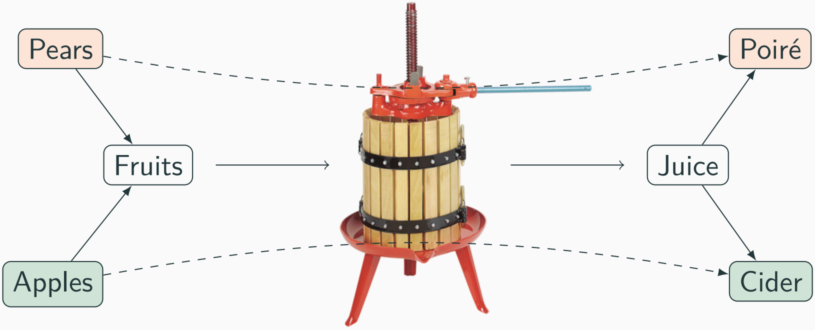

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Typing expressivity

Fruit (α) $\longrightarrow$  $\longrightarrow$ Juice

- Subtyping : Apples $<:$ Juice

Typing expressivity

$\boxed{\text{Fruit } (\alpha)} \longrightarrow$

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Typing expressivity

Fruit (α) $\longrightarrow$  $\longrightarrow$ Juice (α)

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- Polymorphism : $\forall \alpha. \mathrm{Fruit}(\alpha) \rightarrow \mathrm{Juice}(\alpha)$

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$\boxed{\{x : \mathsf{Fruit}(\alpha)\}}$ $\longrightarrow$  $\longrightarrow$

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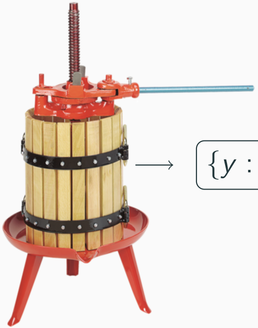
$\boxed{\{x : \text{Fruit}(\alpha)\}}$ $\longrightarrow$  $\longrightarrow$ $\boxed{\{y : \text{Juice of}\,(\alpha) \mid y < x\}}$

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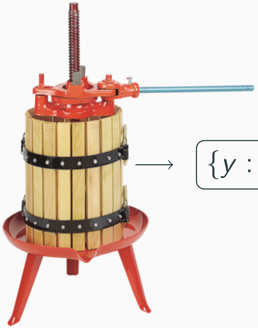

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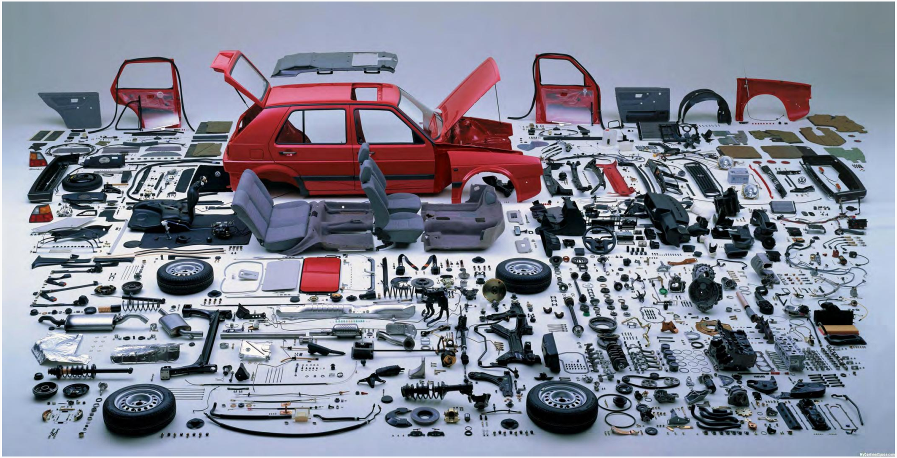
- Polymorphism : $\forall\alpha.\, \mathrm{Fruit}(\alpha) \to \mathrm{Juice}(\alpha)$
- Dependent types : $\forall\alpha.\, \{x : \mathrm{Fruit}(\alpha)\} \to \{y : \mathrm{Juice}(\alpha) \mid y < x\}$

Typing and modularity

Why modules in complex systems ?



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Re-usability

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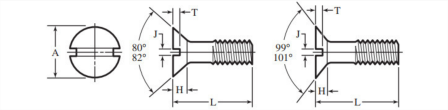

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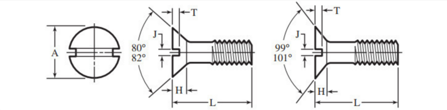

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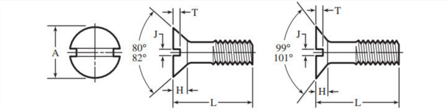

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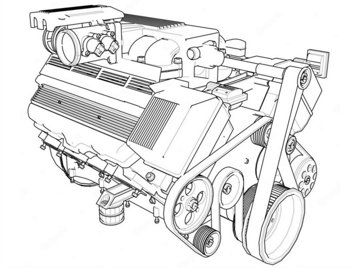

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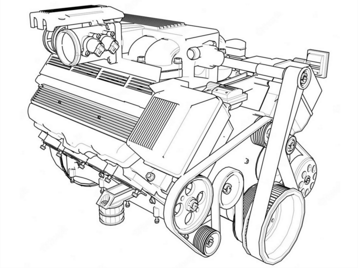

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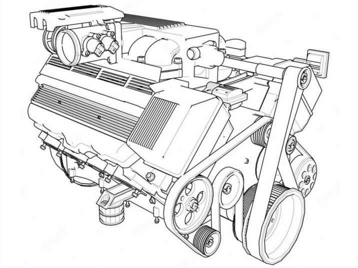

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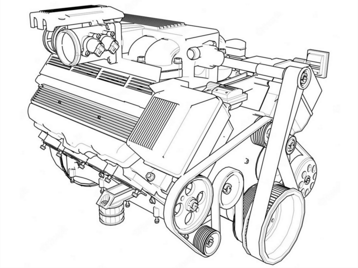

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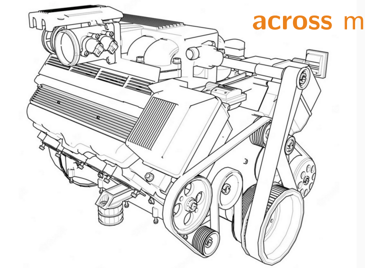

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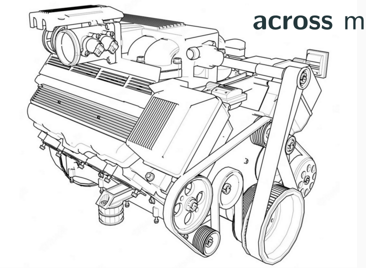

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Common building blocks

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- Abstraction

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Modularity in PL

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Object oriented programming

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Type-classes / Traits

- A method-focused approach

OCaml modules

The module language in OCaml

Generic interface

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Generic interface

```ocaml
module type ComplexNumbers = sig








end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t







end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t





end
```

The module language in OCaml

Generic interface

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  val add : t -> t -> t




end
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The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float



end
```

The module language in OCaml

Generic interface

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  val modulus : t -> float
  val real_part : t -> float


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module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a developer

```










```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a developer

```
module ComplexCartesian = struct
end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a developer

```
module ComplexCartesian = struct
  type t = {re:float; im:float}







end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a developer

```
module ComplexCartesian = struct
  type t = {re:float; im:float}
  let make x y = {re=x; im=y}
end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a developer

```
module ComplexCartesian = struct
  type t = {re:float; im:float}
  let make x y = {re=x; im=y}
  let add c1 c2 = ...





end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a developer

```
module ComplexCartesian = struct
  type t = {re:float; im:float}
  let make x y = {re=x; im=y}
  let add c1 c2 = ...
  let modulus ({re:x; im:y}) =
    sqrt (x*.x +. y*.y)



end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a developer

```
module ComplexCartesian = struct
  type t = {re:float; im:float}
  let make x y = {re=x; im=y}
  let add c1 c2 = ...
  let modulus ({re:x; im:y}) =
    sqrt (x*.x +. y*.y)
  let real_part ({re:x; im:_}) = x
end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a developer

```
module ComplexCartesian = struct
  type t = {re:float; im:float}
  let make x y = {re=x; im=y}
  let add c1 c2 = ...
  let modulus ({re:x; im:y}) =
    sqrt (x*.x +. y*.y)
  let real_part ({re:x; im:_}) = x
  let imag_part ({re:_; im:y}) = y

end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a developer

```
module ComplexCartesian = struct
  type t = {re:float; im:float}
  let make x y = {re=x; im=y}
  let add c1 c2 = ...
  let modulus ({re:x; im:y}) =
    sqrt (x*.x +. y*.y)
  let real_part ({re:x; im:_}) = x
  let imag_part ({re:_; im:y}) = y
  ...
end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a developer

```
module ComplexCartesian = struct
  type t = {re:float; im:float}
  let make x y = {re=x; im=y}
  let add c1 c2 = ...
  let modulus ({re:x; im:y}) =
    sqrt (x*.x +. y*.y)
  let real_part ({re:x; im:_}) = x
  let imag_part ({re:_; im:y}) = y
  ...
end
```

The module language in OCaml

Generic interface

```ocaml
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a developer

```ocaml
module ComplexCartesian = (struct
  type t = {re:float; im:float}
  let make x y = {re=x; im=y}
  let add c1 c2 = ...
  let modulus ({re:x; im:y}) =
    sqrt (x*.x +. y*.y)
  let real_part ({re:x; im:_}) = x
  let imag_part ({re:_; im:y}) = y
  ...
end : ComplexNumbers)
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As another developer

```
module ComplexPolar = struct








end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As another developer

```
module ComplexPolar = struct
  type t = float * float








end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As another developer

```
module ComplexPolar = struct
  type t = float * float
  let make x y = ...







end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As another developer

```
module ComplexPolar = struct
  type t = float * float
  let make x y = ...
  let add c1 c2 = ...





end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As another developer

```
module ComplexPolar = struct
  type t = float * float
  let make x y = ...
  let add c1 c2 = ...
  let modulus (m,a) = a




end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As another developer

```
module ComplexPolar = struct
  type t = float * float
  let make x y = ...
  let add c1 c2 = ...
  let modulus (m,a) = a
  let real_part (m,a) =
     m *. (cos a)


end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As another developer

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module ComplexPolar = struct
  type t = float * float
  let make x y = ...
  let add c1 c2 = ...
  let modulus (m,a) = a
  let real_part (m,a) =
     m *. (cos a)
  let imag_part (m,a) = ...

end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
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```

As another developer

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module ComplexPolar = struct
  type t = float * float
  let make x y = ...
  let add c1 c2 = ...
  let modulus (m,a) = a
  let real_part (m,a) =
     m *. (cos a)
  let imag_part (m,a) = ...
  ...
end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As another developer

```
module ComplexPolar = struct
  type t = float * float
  let make x y = ...
  let add c1 c2 = ...
  let modulus (m,a) = a
  let real_part (m,a) =
     m *. (cos a)
  let imag_part (m,a) = ...
  ...
end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As another developer

```
module ComplexPolar = (struct
  type t = float * float
  let make x y = ...
  let add c1 c2 = ...
  let modulus (m,a) = a
  let real_part (m,a) =
     m *. (cos a)
  let imag_part (m,a) = ...
  ...
end : ComplexNumbers)
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a user

```
module ComplexPolynomials =
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a user

```
module ComplexPolynomials = functor
  (C: ComplexNumbers) -> struct





end


```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a user

```
module ComplexPolynomials = functor
  (C: ComplexNumbers) -> struct
    type t = C.t list




end


```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a user

```
module ComplexPolynomials = functor
  (C: ComplexNumbers) -> struct
    type t = C.t list
    let add p1 p2 = ...



end


```

The module language in OCaml

Generic interface

```ocaml
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a user

```ocaml
module ComplexPolynomials = functor
  (C: ComplexNumbers) -> struct
    type t = C.t list
    let add p1 p2 = ...
    let degree p = ...


end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a user

```
module ComplexPolynomials = functor
  (C: ComplexNumbers) -> struct
    type t = C.t list
    let add p1 p2 = ...
    let degree p = ...
    let roots p = ...

end
```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a user

```
module ComplexPolynomials = functor
  (C: ComplexNumbers) -> struct
    type t = C.t list
    let add p1 p2 = ...
    let degree p = ...
    let roots p = ...
    ...
end
```

The module language in OCaml

Generic interface

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module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a user

```
module ComplexPolynomials = functor
  (C: ComplexNumbers) -> struct
    type t = C.t list
    let add p1 p2 = ...
    let degree p = ...
    let roots p = ...
    ...
end
module M =

```

The module language in OCaml

Generic interface

```
module type ComplexNumbers = sig
  type t
  val make : float -> float -> t
  val add : t -> t -> t
  val modulus : t -> float
  val real_part : t -> float
  val imag_part : t -> float
  ...
end
```

As a user

```
module ComplexPolynomials = functor
  (C: ComplexNumbers) -> struct
    type t = C.t list
    let add p1 p2 = ...
    let degree p = ...
    let roots p = ...
    ...
end
module M =
  ComplexPolynomials(ComplexPolar)
```

The ML[1] approach

[1] Not machine-learning

The ML[1] approach

An interface language (description)

[1] Not machine-learning

The ML[1] approach

An interface language (description)

- User-defined *signatures*

[1] Not machine-learning

The ML[1] approach

An interface language (description)

- User-defined *signatures* `sig ... end`

[1]Not machine-learning

The ML[1] approach

An interface language (description)

- User-defined *signatures* `sig ... end`
- Abstract types

[1]Not machine-learning

The ML[1] approach

An interface language (description)

- User-defined *signatures* `sig ... end`
- Abstract types `type t`

[1]Not machine-learning

The ML[1] approach

An interface language (description)

- User-defined *signatures* `sig ... end`
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[1]Not machine-learning

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An interface language (description)

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A module language (construction)

[1] Not machine-learning

The ML[1] approach

An interface language (description)

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A module language (construction)

- Separate the module and core languages

[1] Not machine-learning

The ML[1] approach

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[1] Not machine-learning

The ML[1] approach

An interface language (description)

- User-defined *signatures* `sig ... end`
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- Developer-side abstraction : sealing

[1] Not machine-learning

The ML[1] approach

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- User-defined *signatures* `sig ... end`
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A module language (construction)

- Separate the module and core languages `struct ... end`
- Developer-side abstraction : sealing `(M : S)`

[1] Not machine-learning

The ML[1] approach

An interface language (description)

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A module language (construction)

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- Developer-side abstraction : sealing `(M : S)`
- Client-side abstraction : functors

[1] Not machine-learning

The ML[1] approach

An interface language (description)

- User-defined *signatures* `sig ... end`
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- Separate the module and core languages `struct ... end`
- Developer-side abstraction : sealing `(M : S)`
- Client-side abstraction : functors `functor (X:S) -> M`

[1]Not machine-learning

The ML[1] approach

An interface language (description)

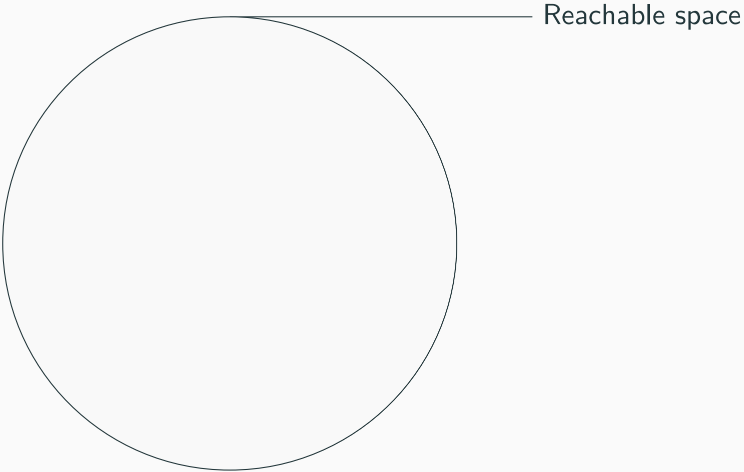
- User-defined *signatures* `sig ... end`
- Abstract types `type t`

A module language (construction)

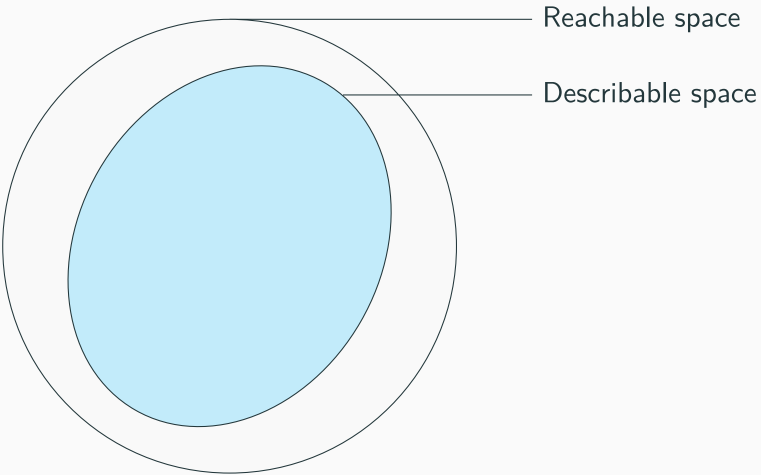
- Separate the module and core languages `struct ... end`
- Developer-side abstraction : sealing `(M : S)`
- Client-side abstraction : functors `functor (X:S) -> M`
- A real module calculus (functions, calls, projections, ...)

[1] Not machine-learning

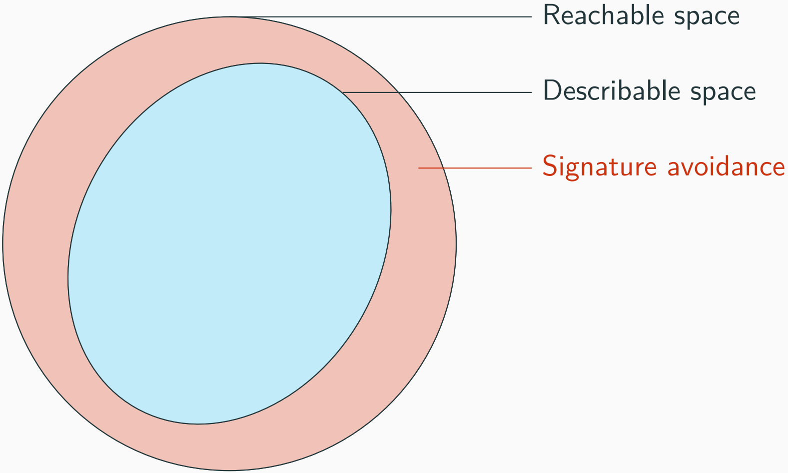
Reachable and *describable* spaces mismatch



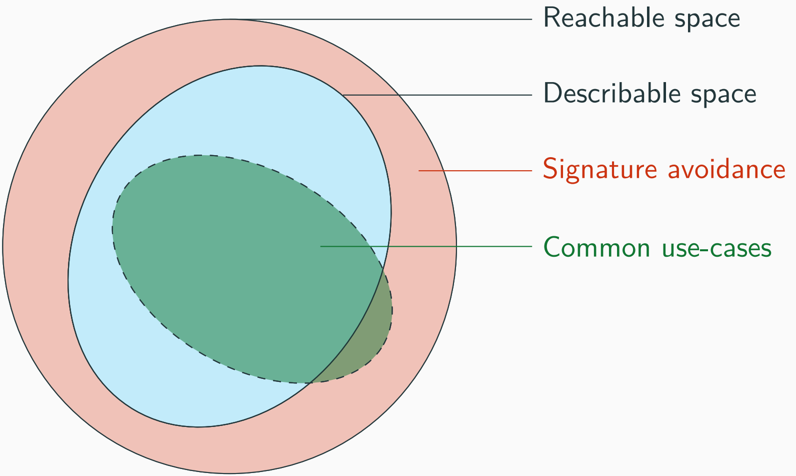
Reachable and *describable* spaces mismatch



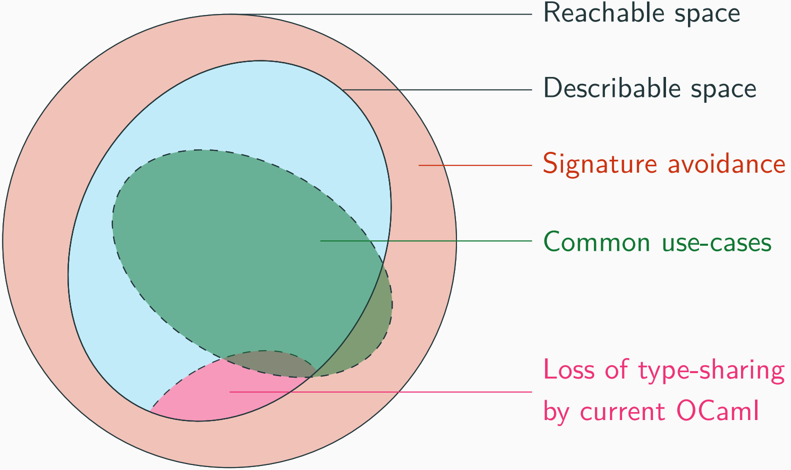
Reachable and *describable* spaces mismatch



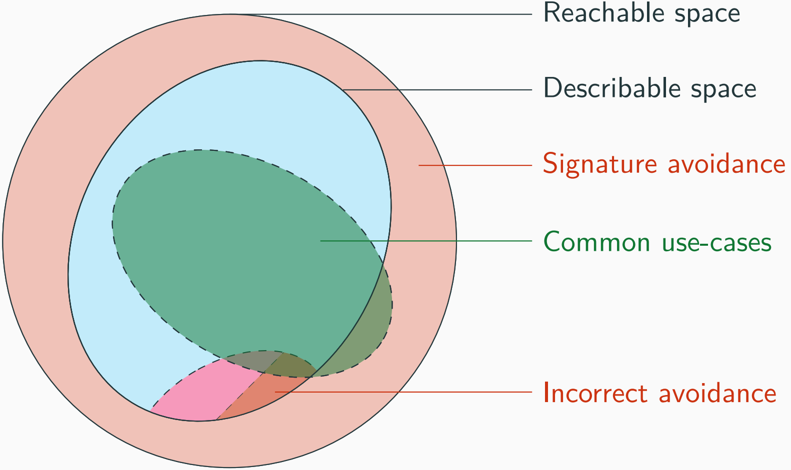
Reachable and *describable* spaces mismatch



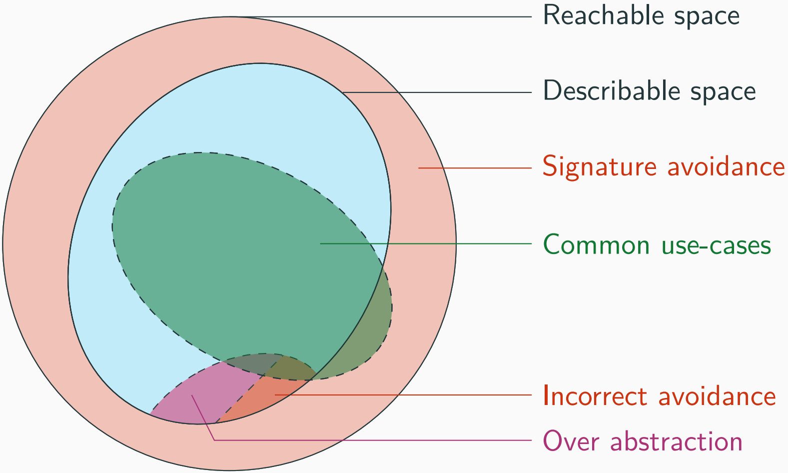
Reachable and *describable* spaces mismatch



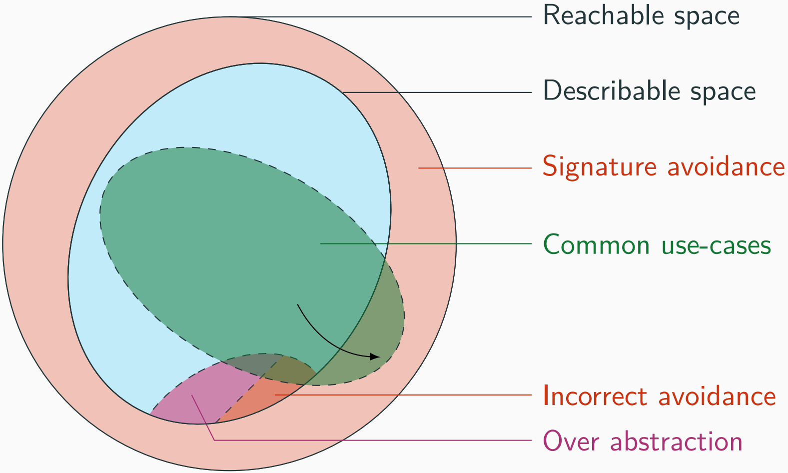
Reachable and *describable* spaces mismatch



Reachable and *describable* spaces mismatch



Reachable and *describable* spaces mismatch



A approach by *elaboration*

OCaml

A approach by *elaboration*

$\boxed{\textsc{OCaml}}$

Hard to formalize

A approach by *elaboration*

OCaml → Hard to formalize

OCaml → Ad-hoc techniques

A approach by *elaboration*

OCaml

- Hard to formalize
- Ad-hoc techniques
- Signature avoidance

A approach by *elaboration*

OCaml

- Hard to formalize
- Ad-hoc techniques
- Signature avoidance

A approach by *elaboration*

OCaml

F^{ω}

A approach by *elaboration*

Clear formalization

OCaml

F^{ω}

A approach by *elaboration*

OCaml

Clear formalization

Standard techniques $\leftarrow$ F^ω

A approach by *elaboration*

OCaml

Clear formalization

Standard techniques

Expressivity

F^ω

A approach by *elaboration*

OCaml

Clear formalization

Standard techniques

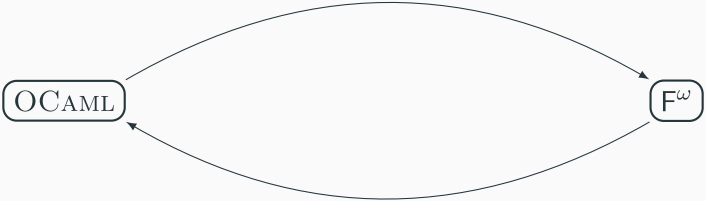
Expressivity

F^{ω}

A approach by *elaboration*

$$\begin{tikzcd} \boxed{\textsc{OCaml}} \arrow[rrrr, bend left] & & & & \boxed{\mathsf{F}^{\omega}} \end{tikzcd}$$

A approach by *elaboration*



Conclusion

- Programming languages are continuously evolving

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- Type systems help write safer and better code

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- We work to understand it, fix it and improve it

Conclusion

- Programming languages are continuously evolving
- Type systems help write safer and better code
- Modularity is crucial when building complex systems
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- We work to understand it, fix it and improve it

Questions ?