Melocoton

A Program Logic for Verified Interoperability Between OCaml and C

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Journées SCALP

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Inria

MAX PLANCK INSTITUTE
FOR SOFTWARE SYSTEMS

AARHUS
UNIVERSITY
DEPARTMENT OF COMPUTER SCIENCE

Multi-Language Programs Are Everywhere

NumPy

Python

C

Fortran

Firefox

C++

Rust

JavaScript

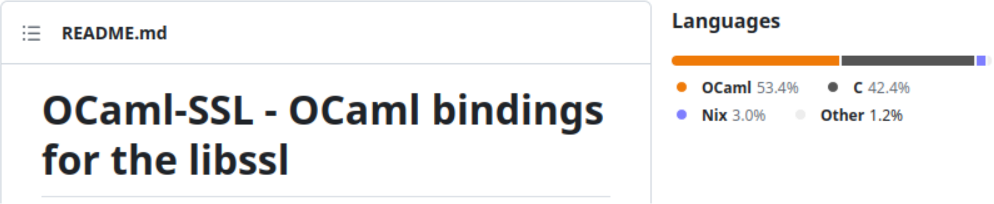
OpenSSL
Cryptography and SSL/TLS Toolkit

C

Bindings for:

- Rust
- Python
- OCaml
- Go
- ...

Multi-Language Programs Are Everywhere



README.md

OCaml-SSL - OCaml bindings for the libssl

Languages

● OCaml 53.4% ● C 42.4%
● Nix 3.0% ● Other 1.2%

a mixture of C and OCaml code
connected using the OCaml Foreign Function Interface (FFI)

- Go
- ...

Multi-Language Code is Unsafe

OCaml FFI code is **unsafe** and must follow **subtle FFI rules**

Buggy FFI code can produce segfaults, corrupt memory, break type safety and data abstraction guarantees of OCaml

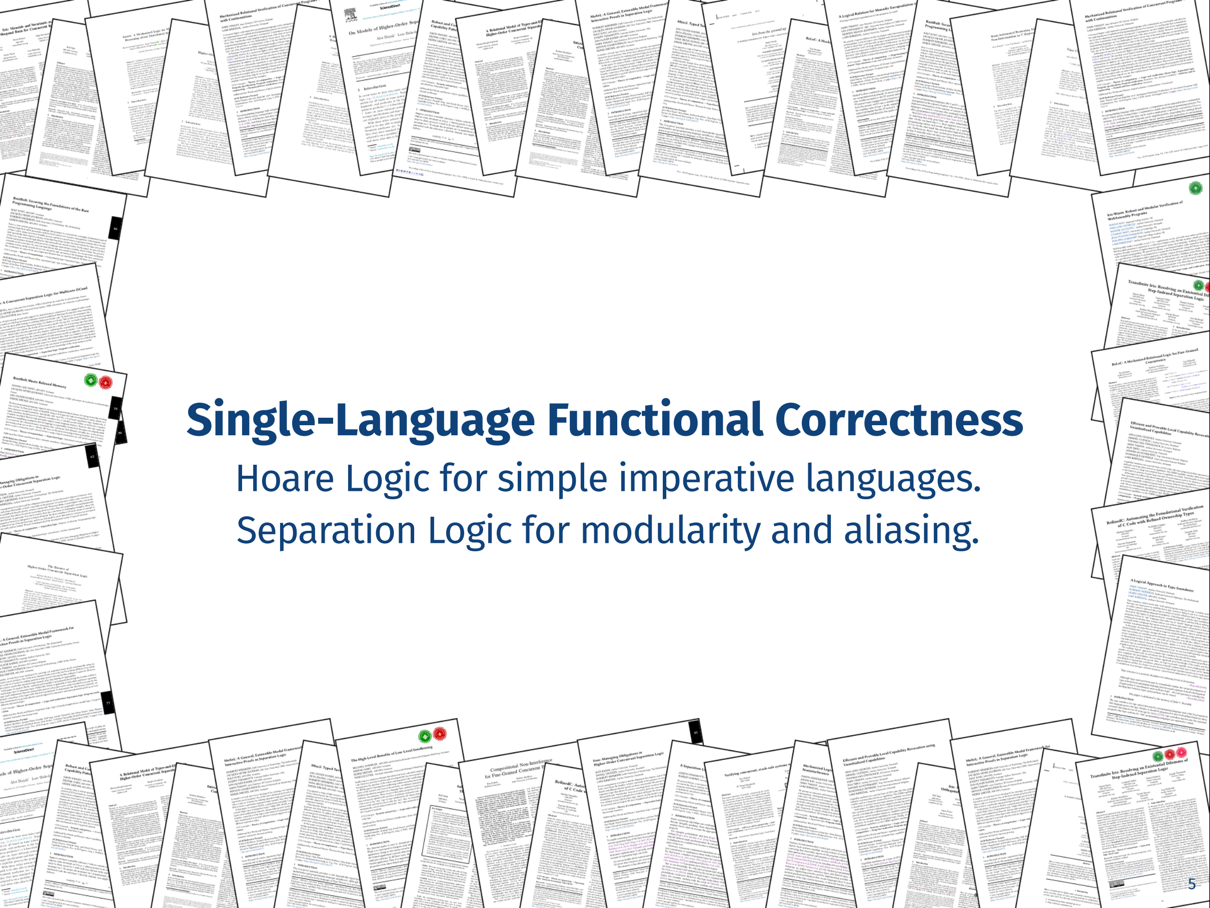
The Goal: Verifying Multi-Language Code

How do we

verify functional correctness

of code written in

different languages?

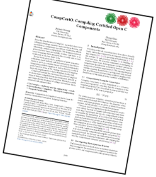


Single-Language Functional Correctness

Hoare Logic for simple imperative languages.

Separation Logic for modularity and aliasing.

Multi-Language Functional Correctness


CompCertO: Compiling Certified Open C Components

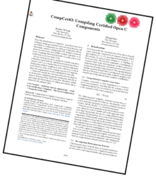

Verifying an Open Compiler Using Multi-language Semantics


Semantic Soundness for Language Interoperability


DimSum: A Decentralized Approach to Multi-lan
Semantics and Verification


perational Semantics for Multi-Language Programs


FunTAL: Reasonably Mixing a Functional Language with Assembly


CompCertO: Compiling Certified Open C Components


Verifying an Open Compiler Using Multi-language Semantics


Semantic Soundness for Language Interoperability

Multi-Language Functional Correctness

Existing work on Semantics and Logical Relations.

How do we prove functional correctness of individual, potentially unsafe libraries?


DimSum: A Decentralized Approach to Multi-lan
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perational Semantics for Multi-Language Programs


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A Multi-Language Program in OCaml and C

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C business logic

```
void hash_ptr(int * x) {
    // Implemented in OpenSSL
    // tedious to port to OCaml
}
```

A Multi-Language Program in OCaml and C

OCaml business logic

C business logic

```
let main () =
  let r = ref 42 in
  hash_ref r; (*written in C*)
  print_int !r
```

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C glue code

```
value caml_hash_ref(value r) {
    int x = Int_val(Field(r, 0));
    hash_ptr(&x);
    Store_field(r, 0, Val_int(x));
    return Val_unit;
}
```

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external hash_ref: int ref -> unit
  = "caml_hash_ref"
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A multi-language program logic for FFI

Goal: a **program logic** to prove correctness of FFI glue code

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OCaml glue code

$\{r \mapsto_{\text{ML}} n\}$

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external hash_ref: int ref -> unit
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$\{r \mapsto_{\text{ML}} m\}$

C glue code

$\{\gamma \mapsto_{\text{blk}[0|\text{mut}]} [n]\}$

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$\{\gamma \mapsto_{\text{blk}[0|\text{mut}]} [m]\}$

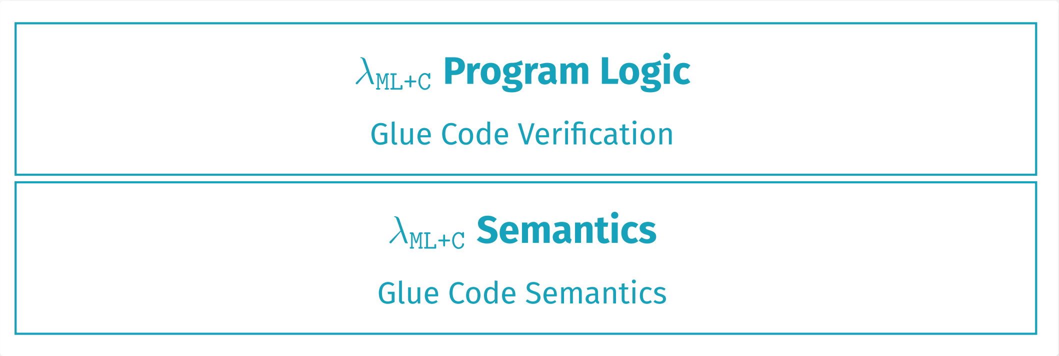
Design choice: Language-Local Reasoning

Reuse existing program logics for OCaml and C.

Outside of glue code, one can **forget** about other languages

Key Design Choice:
Preserve Language-Local Reasoning

Our Contribution: Melocoton



$\lambda_{\mathrm{ML+C}}$ **Program Logic**

Glue Code Verification

$\lambda_{\mathrm{ML+C}}$ **Semantics**

Glue Code Semantics

“The Usual Approach”: program logic on top of semantics, **but**

- **Language Interaction:** new semantics and logic for glue code

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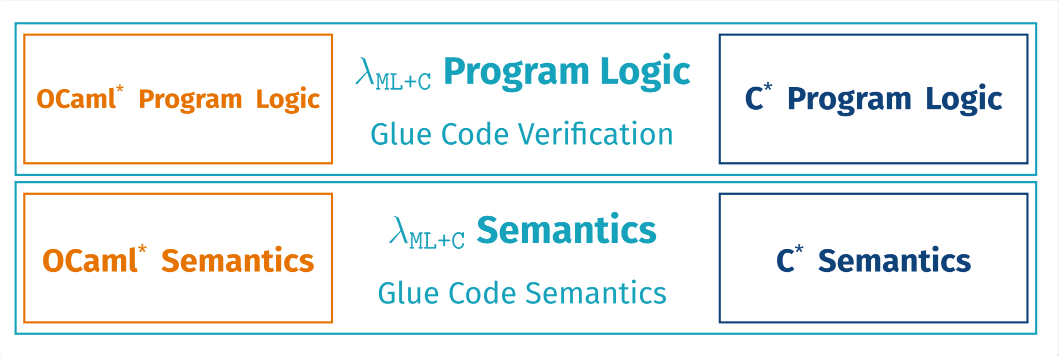

OCaml[*] Program Logic

$\lambda_{\text{ML+C}}$ **Program Logic**

Glue Code Verification

C[*] Program Logic

OCaml[*] Semantics

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“The Usual Approach”: program logic on top of semantics, **but**

- **Language Interaction:** new semantics and logic for glue code
- **Language Locality:** embed existing semantics and logics

---

[*] simplified/idealized versions of **OCaml** and **C**

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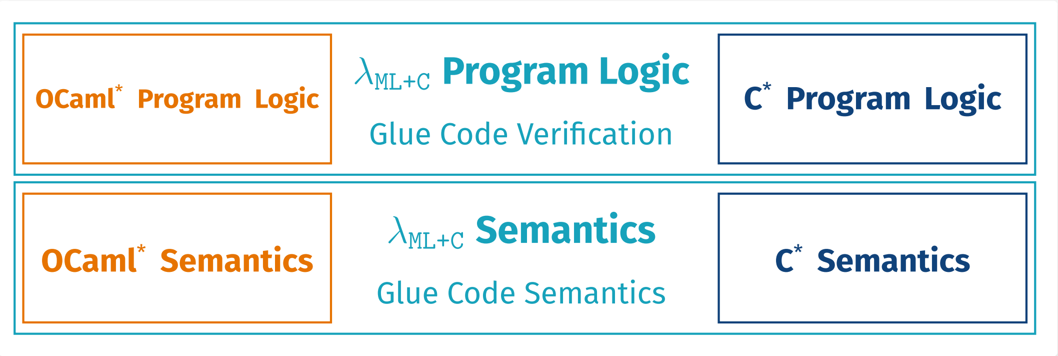
OCaml* Program Logic

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Transfinite Iris

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*simplified/idealized versions of **OCaml** and **C**

The rest of this talk

1. A Crash Course on Building Separation Logics
2. Key Idea: Bridging Separation Logics with View Reconciliation
3. Application: Verifying `hash_ref`

Melocoton is based on **Separation Logic**
…but what is Separation Logic?

A Crash Course on (Building) Separation Logics

Hoare Logic

A logic for *compositional* program verification

Establishes “Hoare triples”: $\vdash \{P\}\ C\ \{Q\}$

Compositional proof rules:

$$\textsc{Seq}\ \frac{\{P\}\ C_1\ \{Q\} \qquad \{Q\}\ C_2\ \{R\}}{\{P\}\ C_1; C_2\ \{R\}} \qquad \ldots$$

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Code we are verifying

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Precondition

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Postcondition

Compositional proof rules:

Seq

$$\frac{\{P\}\ C_1\ \{Q\} \qquad \{Q\}\ C_2\ \{R\}}{\{P\}\ C_1; C_2\ \{R\}} \qquad \ldots$$

Separation Logic

- Extension of Hoare Logic for reasoning about pointer-manipulating programs (C, OCaml, $\ldots$)

- Assertions P, Q denote **ownership** of state (=memory)
  $\rightarrow$ "$x \mapsto v$" $=$ We own x (and it points to v)

- $P * Q$ means P and Q own **disjoint** state
  $\rightarrow$ e.g. if we can assert $x \mapsto v * y \mapsto w$,
  it means that $x \neq y$, i.e. **they do not alias**

Separation Logic for OCaml: Example Rules

"$r \mapsto v$" = We own the OCaml reference r (and it points to v)

CreateRef

$$\frac{}{\{\mathrm{True}\}\ \textsf{ref}\ v\ \{\lambda r.\ r \mapsto v\}}$$

ReadRef

$$\frac{}{\{r \mapsto v\}\ !r\ \{\lambda v'.\ v' = v \land r \mapsto v\}}$$

WriteRef

$$\frac{}{\{r \mapsto v\}\ r := w\ \{r \mapsto w\}}$$

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program creating a new reference

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No precondition

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$$\frac{\textsc{CreateRef}}{\{\mathrm{True}\}\ \mathsf{ref}\ v\ \{\lambda r.\ r \mapsto v\}}$$

Ownership over the new reference

$$\frac{\textsc{ReadRef}}{\{r \mapsto v\}\ !r\ \{\lambda v'.\ v' = v \land r \mapsto v\}}$$

$$\frac{\textsc{WriteRef}}{\{r \mapsto v\}\ r := w\ \{r \mapsto w\}}$$

Separation Logic: The Frame Rule

Hoare Logic is compositional wrt. different parts of a program.

Separation Logic is also compositional wrt. **disjoint parts of memory**. SL specifications are "**small footprint**".

The following holds:

$$\frac{\overline{\{\mathrm{True}\}\ \mathsf{ref}\ v\ \{\lambda r.\ r \mapsto v\}}}{\{x \mapsto w\}\ \mathsf{ref}\ v\ \{\lambda r.\ x \mapsto w * r \mapsto v\}}$$

Separation Logic: The Frame Rule

Hoare Logic is compositional wrt. different parts of a program.

Separation Logic is also compositional wrt. **disjoint parts of memory**. SL specifications are “**small footprint**”.

More generally, the **frame rule** holds:

$$\textsc{Frame}\ \frac{\{P\}\, e\, \{Q\}}{\{P * R\}\, e\, \{Q * R\}}$$

Fifty Shades of Separation Logics

These core principles are **very versatile**.

Melocoton: a new SL for the OCaml FFI, embedding existing SLs for OCaml and C

Other SLs successfully built for **many programming languages:**

Multicore OCaml Rust C11+Weak Memory

WASM Distributed systems …

A Separation Logic For Your Language: Checklist

- A **Base Logic** of assertions:
    - generic connectives: $\exists/\forall x. P(x), P \vee Q, P \wedge Q, P \Rightarrow Q, P * Q, P \mathrel{-\!\!*} Q, \ldots$
    - language-specific assertions: $x \mapsto v$

- Triples $\vdash \{P\}\ e\ \{Q\}$ + FRAME + **proof rules** for language constructs

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a bunch of definitions

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- An **Adequacy Theorem:** $\vdash \{\mathrm{True}\}\ e\ \{\mathrm{True}\} \Rightarrow e \text{ is safe.}$

“safe”: according to the language **semantics**

Models of Separation Logic

Prove Adequacy by defining a **model** of:

base assertions: $[\![P]\!]$ validity of triples: $\vDash \{P\}\, e\, \{Q\}$

such that:

$\vdash \{P\}\, e\, \{Q\} \implies \vDash \{P\}\, e\, \{Q\}$ (the hard part)

$\vDash \{\text{True}\}\, e\, \{\text{True}\} \implies e \text{ is safe}$ (trivial by def. of $\vDash$)

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$$\vDash \{P\}\, e\, \{Q\} \triangleq \forall \sigma.\, [\![P]\!](\sigma) \Rightarrow$$
$$e \text{ safe} \wedge \forall v \sigma'.\, (e, \sigma) \leadsto^{*} (v, \sigma') \Rightarrow [\![Q(v)]\!](\sigma')$$

similar to Hoare logic

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operational semantics

similar to Hoare logic

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operational semantics

predicate on memories

similar to Hoare logic

Models of Separation Logics: Base Logic

The **interesting part**: interpretation of base assertions $[\![P]\!]$

In general: $[\![P]\!] : R \to \mathsf{Prop}$
with R **any** *Partial Commutative Monoid* equipped with $\uplus$

$$
\begin{array}{rcl}
[\![\mathrm{True}]\!](r) & \triangleq & \mathrm{True} \\
[\![P * Q]\!](r) & \triangleq & \exists r_1, r_2.\, r = r_1 \uplus r_2 \wedge [\![P]\!](r_1) \wedge [\![Q]\!](r_2)
\end{array}
$$

For OCaml, pick $R = Loc \xrightarrow{\text{fin}} Val$:

$$
[\![\ell \mapsto v]\!](\sigma) \triangleq \ell \in \mathrm{dom}(\sigma) \wedge \sigma(\ell) = v
$$

Models of Separation Logics: Base Logic

The **interesting part**: interpretation of base assertions $[\![P]\!]$

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wi

You are free to pick **any PCM** R that:

- is customized for your language semantics
- includes extra resources (“ghost state”) not directly tied to program execution

For OCaml, pick $R = Loc \overset{\text{fin}}{\rightharpoonup} Val$:

$$[\![\ell \mapsto v]\!](\sigma) \triangleq \ell \in \mathrm{dom}(\sigma) \land \sigma(\ell) = v$$

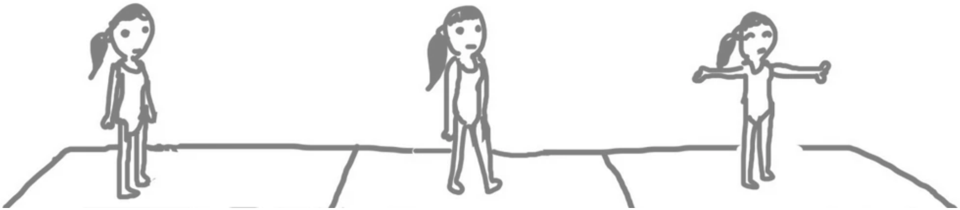
Iris: a Framework for Building Separation Logics

Iris provides SL building blocks as **reusable**, **language agnostic** Coq libraries:

- **expressive base logic** parameterized by an arbitrary PCM
- modular **pre-built PCMs**
- predefined **triples** and their **adequacy theorem**

Most steps of the Checklist become `Require Import iris`!

mono-language separation logic gymnastics



Bridging Separation Logics with View Reconciliation

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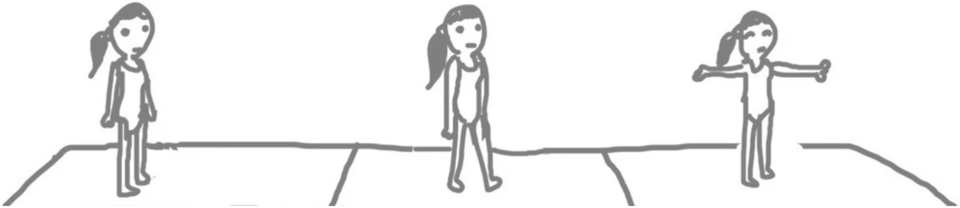
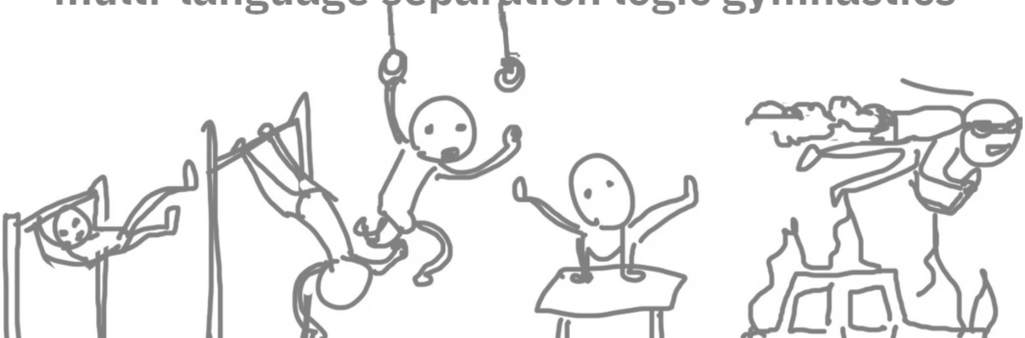


Bridging Separation Logics with View Reconciliation

multi-language separation logic gymnastics



Melocoton brings the Checklist to a multi-language setting

OCaml SL

$\{P\}\, e_{\text{ML}}\, \{Q\}$

$r \mapsto_{\text{ML}} v$

+

FFI SL

$\{P\}\, e_{\text{FFI}}\, \{Q\}$

$\gamma \mapsto_{\text{blk}[0|\mathsf{mut}]} blk$

+

C SL

$\{P\}\, e_{\text{C}}\, \{Q\}$

$a \mapsto_{\text{C}} w$

OCaml semantics

$(e_{\text{ML}}, \sigma) \rightsquigarrow (e_{\text{ML}}, \sigma)$

FFI semantics

$(e_{\text{FFI}}, \rho) \rightsquigarrow (e_{\text{FFI}}, \rho)$

C semantics

$(e_{\text{C}}, m) \rightsquigarrow (e_{\text{C}}, m)$

Problem: how do we connect the different languages/logics?

Language Interaction: Different Views of the Same Data

OCaml glue code

C glue code

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How is **OCaml** data accessed from **C** glue code?

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How is **OCaml** data accessed from **C** glue code?

High-level **OCaml** values are accessed..
..through a low-level **block** representation.

Language Interaction: Semantics

High-level **OCaml** value $\sim_{\mathtt{ML}}$ Low-level **block** representation

Language Interaction: Semantics

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integers $\sim_{\mathtt{ML}}$ integers

booleans $\sim_{\mathtt{ML}}$ integers (0 or 1)

true $\sim_{\mathtt{ML}}$ 1

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$\ell \sim_{\mathtt{ML}} \gamma$

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$\lambda_{\mathtt{ML+C}}$ Semantics

$\sigma : \mathit{Heap}_{\mathtt{ML}}$

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$\lambda_{\mathtt{ML+C}}$ **Semantics**

$$\begin{tikzcd}
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switch at the language barrier

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pairs $\sim_{\mathtt{ML}}$ blocks (of size 2)

lists $\sim_{\mathtt{ML}}$ block-based linked lists

`true` $\sim_{\mathtt{ML}}$ 1

$\ell \sim_{\mathtt{ML}} \gamma$

$\lambda_{\mathtt{ML+C}}$ **Semantics**

$$\begin{tikzcd} \sigma : \mathit{Heap}_{\mathtt{ML}} \arrow[r, bend left] & \zeta : \mathit{BlockHeap} \arrow[l, bend left] \end{tikzcd}$$

switch at the language barrier

Language Interaction: Program Logic, Take 1

$\lambda_{\mathtt{ML+C}}$ **Semantics**

$$\begin{tikzcd} \sigma : Heap_{\mathtt{ML}} \arrow[r, shift left] & \zeta : BlockHeap \arrow[l, shift left] \end{tikzcd}$$

Language Interaction: Program Logic, Take 1

$\lambda_{\texttt{ML+C}}$ **Program Logic**

$\lambda_{\texttt{ML+C}}$ **Semantics**

$$\begin{tikzcd}
\sigma : \mathit{Heap}_{\texttt{ML}} \arrow[r, bend left] & \zeta : \mathit{BlockHeap} \arrow[l, bend left]
\end{tikzcd}$$

Language Interaction: Program Logic, Take 1

$\lambda_{\texttt{ML+C}}$ **Program Logic**

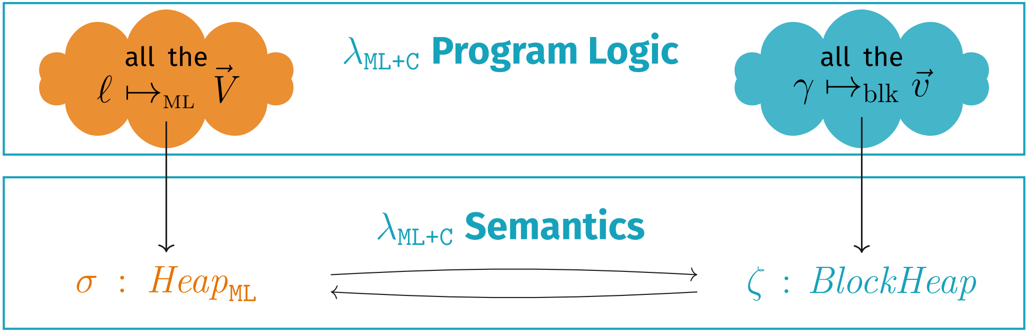
$\ell \mapsto_{\texttt{ML}} \vec{V}$

$\gamma \mapsto_{\text{blk}} \vec{v}$

$\lambda_{\texttt{ML+C}}$ **Semantics**

$$\begin{tikzcd} \sigma : \mathit{Heap}_{\texttt{ML}} \arrow[r, bend left] & \zeta : \mathit{BlockHeap} \arrow[l, bend left] \end{tikzcd}$$

Language Interaction: Program Logic, Take 1



$\lambda_{\texttt{ML+C}}$ **Program Logic**

all the $\ell \mapsto_{\text{ML}} \vec{V}$

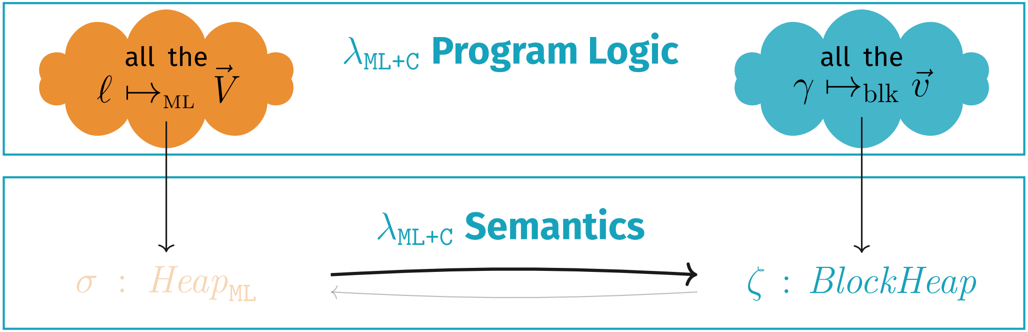
all the $\gamma \mapsto_{\text{blk}} \vec{v}$

$\lambda_{\texttt{ML+C}}$ **Semantics**

$\sigma : \mathit{Heap}_{\texttt{ML}}$

$\zeta : \mathit{BlockHeap}$

Language Interaction: Program Logic, Take 1



all the $\ell \mapsto_{\text{ML}} \vec{V}$

$\lambda_{\text{ML+C}}$ **Program Logic**

all the $\gamma \mapsto_{\text{blk}} \vec{v}$

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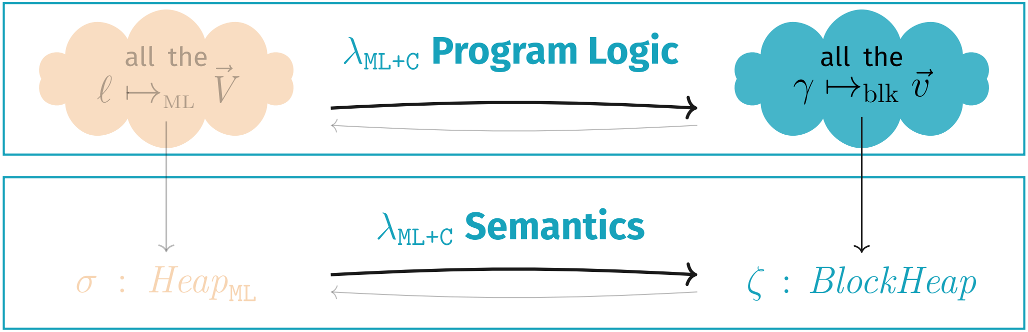
Language Interaction: Program Logic, Take 1



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$\lambda_{\text{ML+C}}$ **Program Logic**

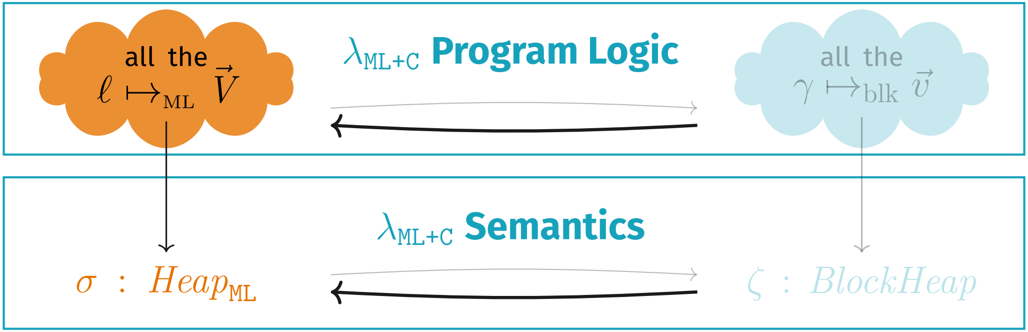
all the $\gamma \mapsto_{\text{blk}} \vec{v}$

$\sigma : \mathit{Heap}_{\text{ML}}$

$\lambda_{\text{ML+C}}$ **Semantics**

$\zeta : \mathit{BlockHeap}$

Language Interaction: Program Logic, Take 1



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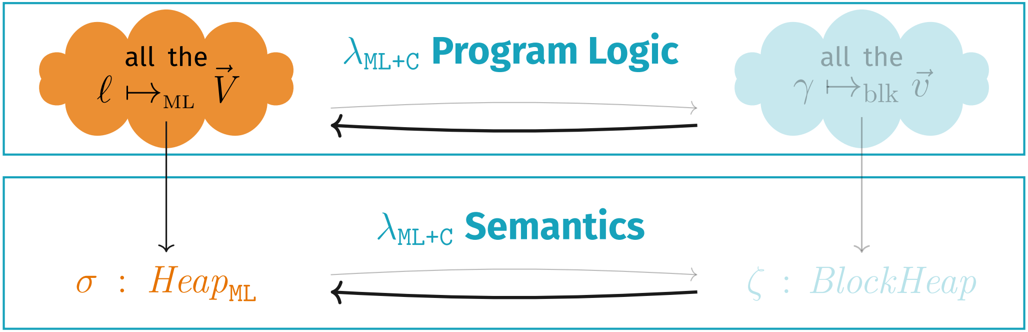
Language Interaction: Program Logic, Take 1

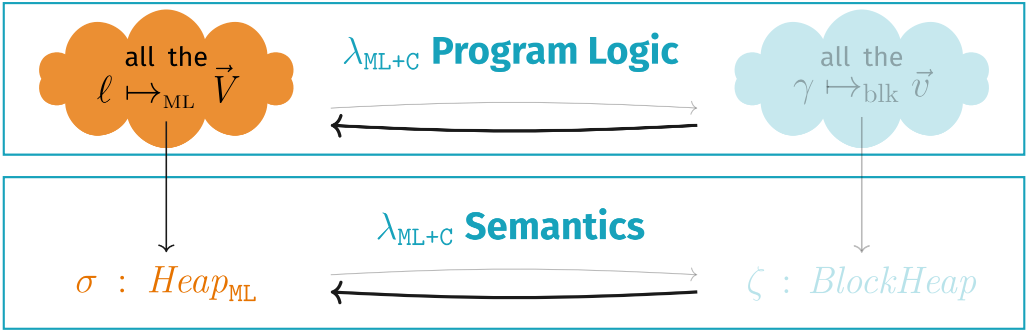


ExtCall

{ all } **C** function body { all }

{ all } call into **C** { all }

Language Interaction: Program Logic, Take 1



all the $\ell \mapsto_{\text{ML}} \vec{V}$

$\lambda_{\text{ML+C}}$ **Program Logic**

all the $\gamma \mapsto_{\text{blk}} \vec{v}$

$\lambda_{\text{ML+C}}$ **Semantics**

$\sigma : \mathit{Heap}_{\text{ML}}$

$\zeta : \mathit{BlockHeap}$

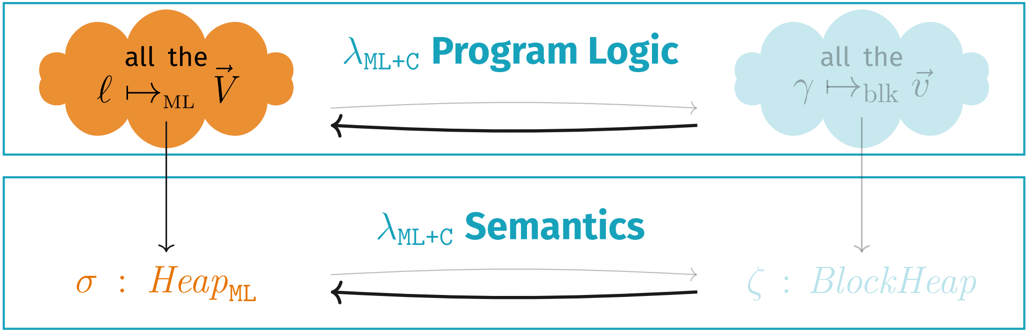
EXTCALL

$$\frac{\{\text{all}\}\ \textbf{C}\ \text{function body}\ \{\text{all}\}}{\{\text{all}\}\ \text{call into}\ \textbf{C}\ \{\text{all}\}}$$

FRAME

$$\frac{\{P\}\, e\, \{Q\}}{\{R * P\}\, e\, \{Q * R\}}$$

Language Interaction: Program Logic, Take 1



all the $\ell \mapsto_{\text{ML}} \vec{V}$

$\lambda_{\text{ML+C}}$ **Program Logic**

all the $\gamma \mapsto_{\text{blk}} \vec{v}$

$\lambda_{\text{ML+C}}$ **Semantics**

$\sigma : \mathit{Heap}_{\text{ML}}$

$\zeta : \mathit{BlockHeap}$

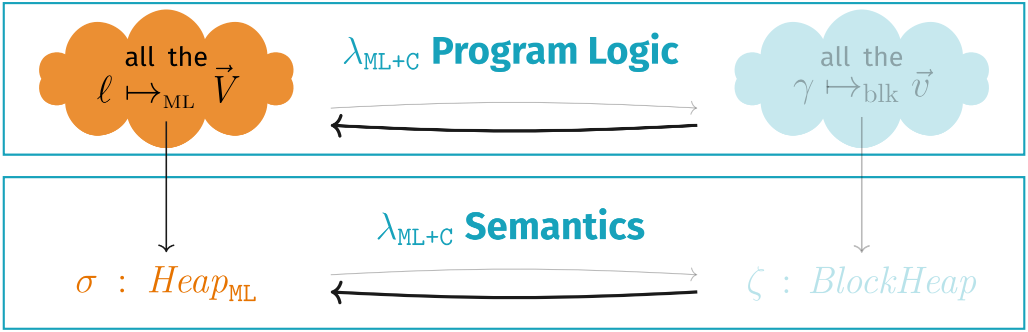
ExtCall

$$\frac{\{\text{all}\}\ \textbf{C}\ \text{function body}\ \{\text{all}\}}{\{\text{all}\}\ \text{call into}\ \textbf{C}\ \{\text{all}\}}$$

Frame

$$\frac{\{P\}\ \text{call into}\ \textbf{C}\ \{Q\}}{\{R * P\}\ \text{call into}\ \textbf{C}\ \{Q * R\}}$$

Language Interaction: Program Logic, Take 1



all the $\ell \mapsto_{\mathrm{ML}} \vec{V}$

$\lambda_{\mathrm{ML+C}}$ **Program Logic**

all the $\gamma \mapsto_{\mathrm{blk}} \vec{v}$

$\lambda_{\mathrm{ML+C}}$ **Semantics**

$\sigma : \mathit{Heap}_{\mathrm{ML}}$

$\zeta : \mathit{BlockHeap}$

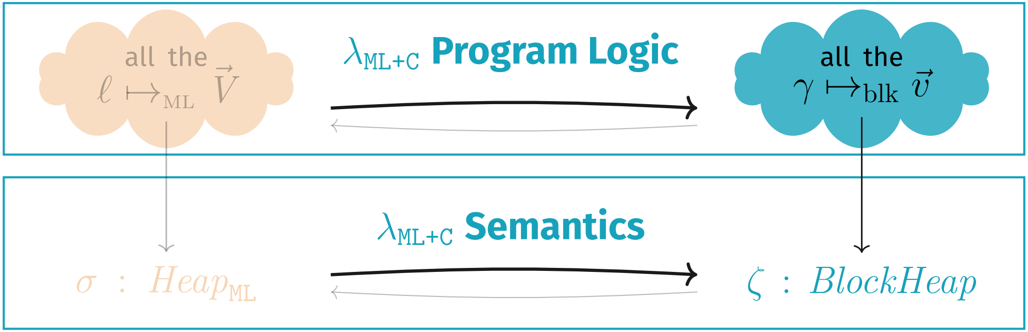
ExtCall

$$\frac{\{\text{all}\}\ \textbf{C}\ \text{function body}\ \{\text{all}\}}{\{\text{all}\}\ \text{call into}\ \textbf{C}\ \{\text{all}\}}$$

Frame

$$\frac{\{P\}\ \text{call into}\ \textbf{C}\ \{Q\}}{\{\ell \mapsto_{\mathrm{ML}} \vec{V} * P\}\ \text{call into}\ \textbf{C}\ \{Q * \ell \mapsto_{\mathrm{ML}} \vec{V}\}}$$

Language Interaction: Program Logic, Take 1



all the $\ell \mapsto_{\text{ML}} \vec{V}$

$\lambda_{\text{ML+C}}$ **Program Logic**

all the $\gamma \mapsto_{\text{blk}} \vec{v}$

$\lambda_{\text{ML+C}}$ **Semantics**

$\sigma : \mathit{Heap}_{\text{ML}}$

$\zeta : \mathit{BlockHeap}$

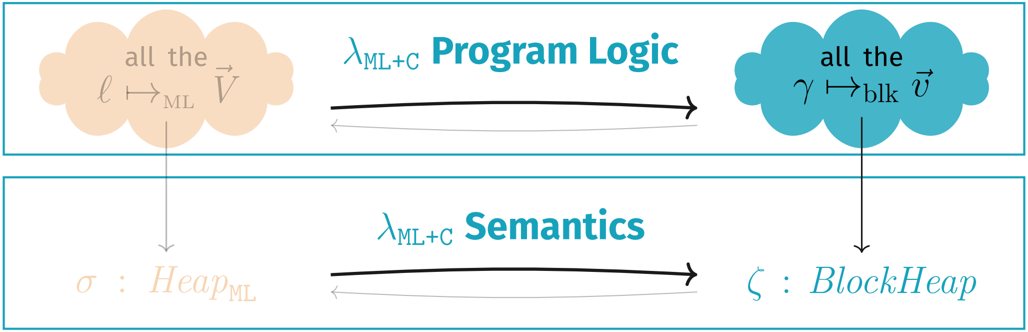
ExtCall

$$\frac{\{\text{all}\}\ \textbf{C}\text{ function body }\{\text{all}\}}{\{\text{all}\}\text{ call into }\textbf{C}\ \{\text{all}\}}$$

Frame

$$\frac{\{P\}\text{ call into }\textbf{C}\ \{Q\}}{\{\ell \mapsto_{\text{ML}} \vec{V} * P\}\text{ call into }\textbf{C}\ \{Q * \ell \mapsto_{\text{ML}} \vec{V}\}}$$

Language Interaction: Program Logic, Take 1



ExtCall

$$\frac{\{\text{all}\}\ \textbf{C}\ \text{function body}\ \{\text{all}\}}{\{\text{all}\}\ \text{call into }\textbf{C}\ \{\text{all}\}}$$

RAME

$$\frac{\{P\}\ \text{call into }\textbf{C}\ \{Q\}}{\{\ell \mapsto_{\mathrm{ML}} \vec{V} * P\}\ \text{call into }\textbf{C}\ \{Q * \ell \mapsto_{\mathrm{ML}} \vec{V}\}}$$

Language Interaction: Program Logic, Take 1

$\lambda_{\text{ML+C}}$ **Program Logic**

The $\lambda_{\text{ML+C}}$ Semantics operate **globally** on the state

↯

The $\lambda_{\text{ML+C}}$ Program Logic needs **local** reasoning rules

EXTCALL

$$\frac{\{\text{all}\}\ \textsf{C function body}\ \{\text{all}\}}{\{\text{all}\}\ \textsf{call into C}\ \{\text{all}\}}$$

RAME

$$\frac{\{P\}\ \textsf{call into C}\ \{Q\}}{\{\ell \mapsto_{\text{ML}} \vec{V} * P\}\ \textsf{call into C}\ \{Q * \ell \mapsto_{\text{ML}} \vec{V}\}}$$

Language Interaction: More Gradual Rules

OCaml points-tos *remain valid* when switching to **C**!

Language Interaction: More Gradual Rules

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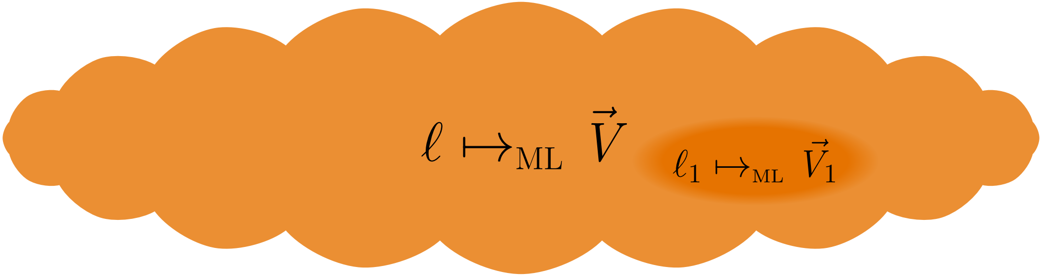
$$\ell \mapsto_{\mathrm{ML}} \vec{V}$$

Language Interaction: More Gradual Rules

OCaml points-tos *remain valid* when switching to **C**!

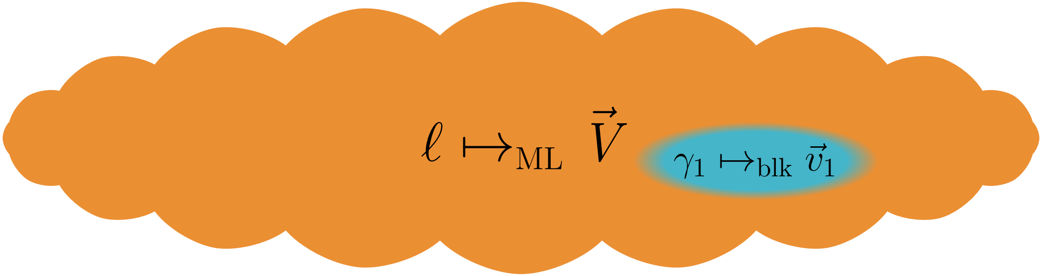


$\ell \mapsto_{\mathrm{ML}} \vec{V}$

$\ell_1 \mapsto_{\mathrm{ML}} \vec{V}_1$

Language Interaction: More Gradual Rules

OCaml points-tos *remain valid* when switching to **C**!

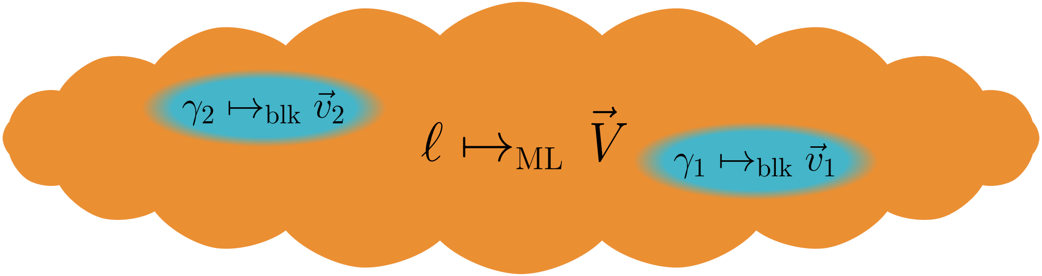


$\ell \mapsto_{\mathrm{ML}} \vec{V}$

$\gamma_1 \mapsto_{\mathrm{blk}} \vec{v}_1$

Language Interaction: More Gradual Rules

OCaml points-tos *remain valid* when switching to **C**!



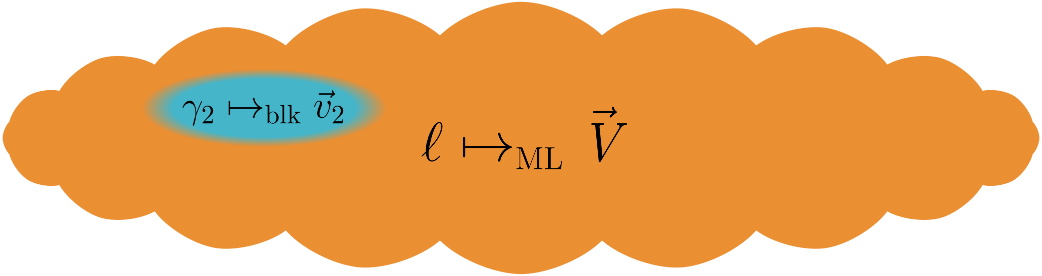
$\gamma_2 \mapsto_{\mathrm{blk}} \vec{v}_2$

$\ell \mapsto_{\mathrm{ML}} \vec{V}$

$\gamma_1 \mapsto_{\mathrm{blk}} \vec{v}_1$

Language Interaction: More Gradual Rules

OCaml points-tos *remain valid* when switching to **C**!



$\gamma_2 \mapsto_{\mathrm{blk}} \vec{v}_2$

$\ell \mapsto_{\mathrm{ML}} \vec{V}$

Language Interaction: More Gradual Rules

OCaml points-tos *remain valid* when switching to **C**!

$$\ell \mapsto_{\mathrm{ML}} \vec{V}$$

Language Interaction: More Gradual Rules

OCaml points-tos *remain valid* when switching to **C**!

$$\ell \mapsto_{\mathrm{ML}} \vec{V}$$

View Reconciliation Rules for Converting On-Demand:

$$\ell \mapsto_{\mathrm{ML}} \vec{V} \Rrightarrow\!\!\ast\; \exists \gamma \vec{v}.\, \gamma \mapsto_{\mathrm{blk}} \vec{v} * \ell \sim_{\mathtt{ML}} \gamma * \vec{V} \sim_{\mathtt{ML}} \vec{v}$$

$$\vec{V} \sim_{\mathtt{ML}} \vec{v} * \gamma \mapsto_{\mathrm{blk}} \vec{v} \Rrightarrow\!\!\ast\; \exists \ell\ .\, \ell \mapsto_{\mathtt{ML}} \vec{V} * \ell \sim_{\mathtt{ML}} \gamma$$

Language Interaction: View Reconciliation

View Reconciliation Rules

$$\ell \mapsto_{\mathtt{ML}} \vec{V} \equiv\!\!\!\ast \exists \gamma \vec{v}.\ \gamma \mapsto_{\mathrm{blk}} \vec{v} \ast \ell \sim_{\mathtt{ML}} \gamma \ast \vec{V} \sim_{\mathtt{ML}} \vec{v}$$

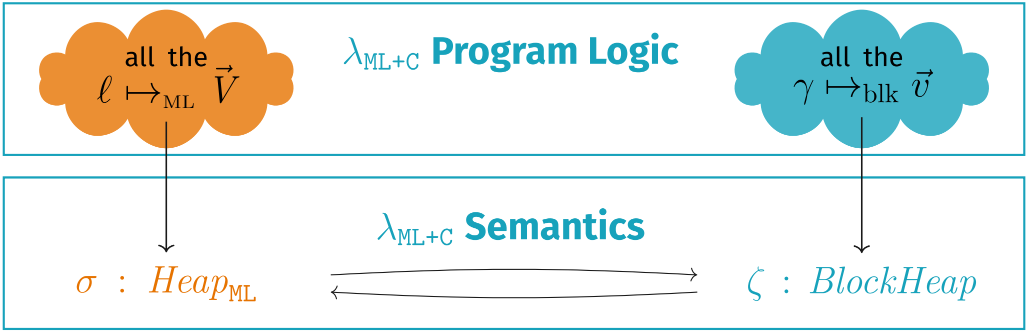
$$\vec{V} \sim_{\mathtt{ML}} \vec{v} \ast \gamma \mapsto_{\mathrm{blk}} \vec{v} \equiv\!\!\!\ast \exists \ell.\ \ell \mapsto_{\mathtt{ML}} \vec{V} \ast \ell \sim_{\mathtt{ML}} \gamma$$

Language Interaction: View Reconciliation

View Reconciliation Rules

$$\ell \mapsto_{\mathtt{ML}} \vec{V} \equiv\!\!\ast\ \exists \gamma \vec{v}.\ \gamma \mapsto_{\mathrm{blk}} \vec{v} * \ell \sim_{\mathtt{ML}} \gamma * \vec{V} \sim_{\mathtt{ML}} \vec{v}$$

$$\vec{V} \sim_{\mathtt{ML}} \vec{v} * \gamma \mapsto_{\mathrm{blk}} \vec{v} \equiv\!\!\ast\ \exists \ell.\ \ell \mapsto_{\mathtt{ML}} \vec{V} * \ell \sim_{\mathtt{ML}} \gamma$$



all the $\ell \mapsto_{\mathtt{ML}} \vec{V}$

$\lambda_{\mathtt{ML+C}}$ **Program Logic**

all the $\gamma \mapsto_{\mathrm{blk}} \vec{v}$

$\lambda_{\mathtt{ML+C}}$ **Semantics**

$\sigma : \mathit{Heap}_{\mathtt{ML}}$

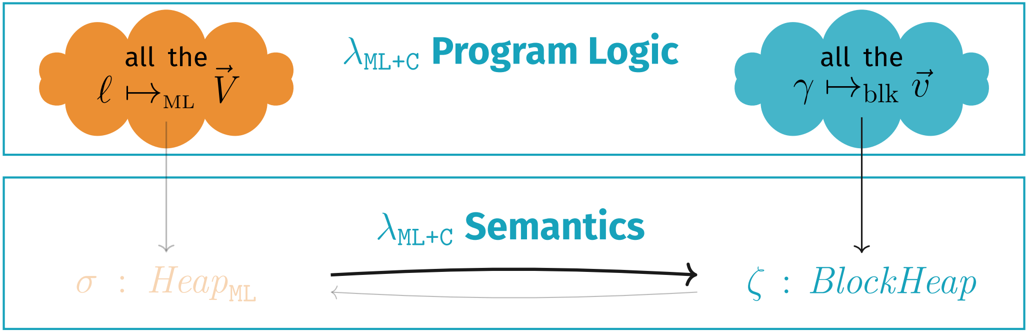
$\zeta : \mathit{BlockHeap}$

Language Interaction: View Reconciliation

View Reconciliation Rules

$$\ell \mapsto_{\mathtt{ML}} \vec{V} \;\Rrightarrow\!\!\ast\; \exists \gamma \vec{v}.\, \gamma \mapsto_{\mathrm{blk}} \vec{v} * \ell \sim_{\mathtt{ML}} \gamma * \vec{V} \sim_{\mathtt{ML}} \vec{v}$$

$$\vec{V} \sim_{\mathtt{ML}} \vec{v} * \gamma \mapsto_{\mathrm{blk}} \vec{v} \;\Rrightarrow\!\!\ast\; \exists \ell .\, \ell \mapsto_{\mathtt{ML}} \vec{V} * \ell \sim_{\mathtt{ML}} \gamma$$



all the $\ell \mapsto_{\mathtt{ML}} \vec{V}$

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Language Interaction: View Reconciliation

View Reconciliation Rules

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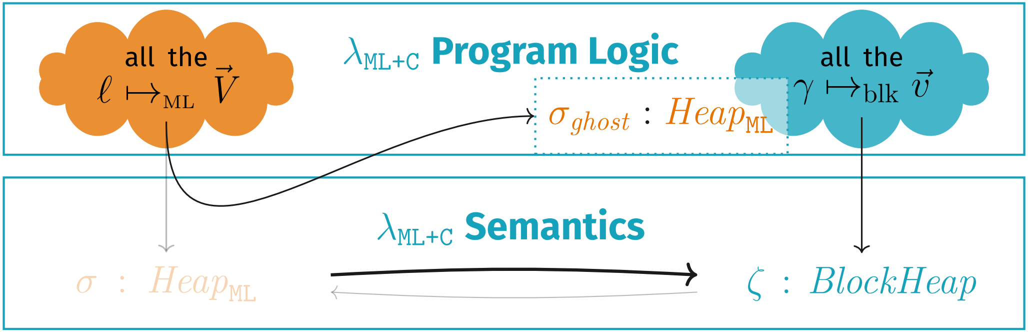

all the $\ell \mapsto_{\mathtt{ML}} \vec{V}$

$\lambda_{\mathtt{ML+C}}$ **Program Logic**

all the $\gamma \mapsto_{\mathrm{blk}} \vec{v}$

$\sigma_{ghost} : Heap_{\mathtt{ML}}$

$\lambda_{\mathtt{ML+C}}$ **Semantics**

$\sigma : Heap_{\mathtt{ML}}$

$\zeta : BlockHeap$

Language Interaction: View Reconciliation

View Reconciliation Rules

$$\ell \mapsto_{\mathtt{ML}} \vec{V} \;\Rrightarrow\!\!\ast\; \exists \gamma \vec{v}.\; \gamma \mapsto_{\mathrm{blk}} \vec{v} * \ell \sim_{\mathtt{ML}} \gamma * \vec{V} \sim_{\mathtt{ML}} \vec{v}$$

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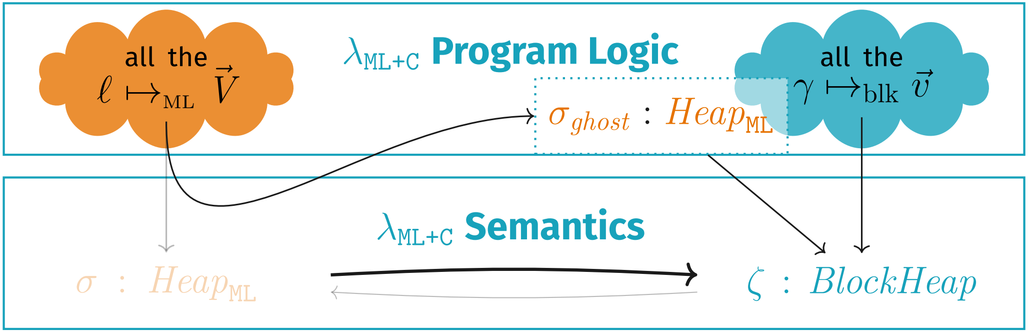

Language Interaction: View Reconciliation

View Reconciliation Rules

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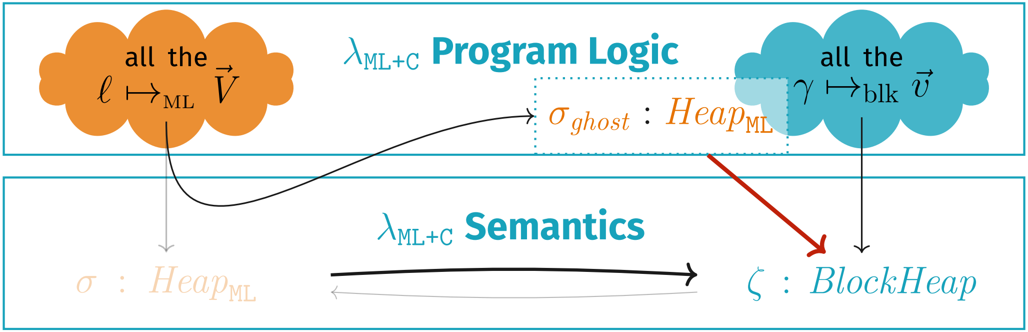

all the $\ell \mapsto_{\mathtt{ML}} \vec{V}$

$\lambda_{\mathtt{ML+C}}$ **Program Logic**

all the $\gamma \mapsto_{\mathrm{blk}} \vec{v}$

$\sigma_{ghost} : Heap_{\mathtt{ML}}$

$\lambda_{\mathtt{ML+C}}$ **Semantics**

$\sigma : Heap_{\mathtt{ML}}$

$\zeta : BlockHeap$

Application: Verifying `hash_ref` with Melocoton

Verifying `hash_ref` with Melocoton

OCaml glue code

```
external hash_ref: int ref -> unit
  = "caml_hash_ref"
```

C glue code

```
value caml_hash_ref(value v) {
  int x = Int_val(Field(v, 0));
  hash_ptr(&x);
  Store_field(v, 0, Val_int(x));
  return Val_unit;
}
```

Verifying `hash_ref` with Melocoton

OCaml glue code

```
external hash_ref: int ref -> unit
  = "caml_hash_ref"
```

$$\{r \mapsto_{\mathrm{ML}} n\}$$

$$\texttt{hash\_ref}(r)$$

$$\{\exists m.\, r \mapsto_{\mathrm{ML}} m\}$$

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  hash_ptr(&x);
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  return Val_unit;
}
```

ExtCall

$$\frac{\{P * x \sim_{\mathrm{ML}} v\}\; \texttt{f}(v)\; \{\lambda v'.\, \exists y.\, y \sim_{\mathrm{ML}} v' * Q(y)\}}{\{P\}\; \texttt{external "f"}(x)\; \{\lambda y.\, Q(y)\}}$$

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$$\texttt{hash\_ref}(r)$$

$$\{\exists m.\, r \mapsto_{\mathrm{ML}} m\}$$

C glue code

```
value caml_hash_ref(value v) {
```

$$\{r \mapsto_{\mathrm{ML}} n * r \sim_{\mathrm{ML}} v\}$$

```
  int x = Int_val(Field(v, 0));
  hash_ptr(&x);
  Store_field(v, 0, Val_int(x));
  return Val_unit;
```

$$\{\exists m.\, r \mapsto_{\mathrm{ML}} m * \exists y.\, y \sim_{\mathrm{ML}} \texttt{Val\_unit}\}$$

```
}
```

$$\textsc{ExtCall}\quad \frac{\{P * x \sim_{\mathrm{ML}} v\}\ \texttt{f}(v)\ \{\lambda v'.\, \exists y.\, y \sim_{\mathrm{ML}} v' * Q(y)\}}{\{P\}\ \texttt{external "f"}(x)\ \{\lambda y.\, Q(y)\}}$$

Verifying `hash_ref` with Melocoton

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$$\texttt{hash\_ref}(r)$$

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C glue code

```
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```

$$\{r \mapsto_{\mathrm{ML}} n * r \sim_{\mathrm{ML}} v\}$$

```
  int x = Int_val(Field(v, 0));
  hash_ptr(&x);
  Store_field(v, 0, Val_int(x));
  return Val_unit;
```

$$\{\exists m.\, r \mapsto_{\mathrm{ML}} m * () \sim_{\mathrm{ML}} \texttt{Val\_unit}\}$$

```
}
```

ExtCall

$$\frac{\{P * x \sim_{\mathrm{ML}} v\}\ \texttt{f}(v)\ \{\lambda v'.\, \exists y.\, y \sim_{\mathrm{ML}} v' * Q(y)\}}{\{P\}\ \texttt{external "f"}(x)\ \{\lambda y.\, Q(y)\}}$$

Verifying `hash_ref` with Melocoton

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$$\texttt{hash\_ref}(r)$$

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C glue code

```
value caml_hash_ref(value v) {
```

$$\{r \mapsto_{\mathrm{ML}} n * r \sim_{\mathrm{ML}} v\}$$

$$\{v \mapsto_{\mathrm{blk}} [n] * r \sim_{\mathrm{ML}} v\}$$

```
  int x = Int_val(Field(v, 0));
  hash_ptr(&x);
  Store_field(v, 0, Val_int(x));
  return Val_unit;
```

$$\{\exists m.\ r \mapsto_{\mathrm{ML}} m * () \sim_{\mathrm{ML}} \texttt{Val\_unit}\}$$

```
}
```

VIEW RECONCILIATION (1)

$$\ell \mapsto_{\mathrm{ML}} \vec{V} \equiv\!\!\!\ast\ \exists \gamma \vec{v}.\ \gamma \mapsto_{\mathrm{blk}} \vec{v} * \ell \sim_{\mathrm{ML}} \gamma * \vec{V} \sim_{\mathrm{ML}} \vec{v}$$

Verifying `hash_ref` with Melocoton

OCaml glue code

```
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$$\{r \mapsto_{\mathrm{ML}} n\}$$

$$\texttt{hash\_ref}(r)$$

$$\{\exists m.\, r \mapsto_{\mathrm{ML}} m\}$$

C glue code

```
value caml_hash_ref(value v) {
```

$$\{r \mapsto_{\mathrm{ML}} n * r \sim_{\mathrm{ML}} v\}$$

$$\{v \mapsto_{\mathrm{blk}} [n] * r \sim_{\mathrm{ML}} v\}$$

```
  int x = Int_val(Field(v, 0));
  hash_ptr(&x);
  Store_field(v, 0, Val_int(x));
  return Val_unit;
```

$$\{\exists m.\, v \mapsto_{\mathrm{blk}} [m] * r \sim_{\mathrm{ML}} v\}$$

$$\{\exists m.\, r \mapsto_{\mathrm{ML}} m * () \sim_{\mathrm{ML}} \texttt{Val\_unit}\}$$

```
}
```

VIEW RECONCILIATION (2)

$$\vec{V} \sim_{\mathrm{ML}} \vec{v} * \gamma \mapsto_{\mathrm{blk}} \vec{v} \Rrightarrow\!\!\ast\ \exists \ell\ .\, \ell \mapsto_{\mathrm{ML}} \vec{V} * \ell \sim_{\mathrm{ML}} \gamma$$

Verifying `hash_ref` with Melocoton

OCaml glue code

```
external hash_ref: int ref -> unit
  = "caml_hash_ref"
```

$$\{r \mapsto_{\mathtt{ML}} n\}$$

$$\texttt{hash\_ref}(r)$$

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C glue code

```
value caml_hash_ref(value v) {
```

$$\{r \mapsto_{\mathtt{ML}} n * r \sim_{\mathtt{ML}} v\}$$

$$\{v \mapsto_{\mathrm{blk}} [n] * r \sim_{\mathtt{ML}} v\}$$

```
  int x = Int_val(Field(v, 0));
  hash_ptr(&x);
  Store_field(v, 0, Val_int(x));
  return Val_unit;
```

$$\{\exists m.\, v \mapsto_{\mathrm{blk}} [m] * r \sim_{\mathtt{ML}} v\}$$

$$\{\exists m.\, r \mapsto_{\mathtt{ML}} m * () \sim_{\mathtt{ML}} \texttt{Val\_unit}\}$$

```
}
```

`Field` SPECIFICATION

$$\{\gamma \mapsto_{\mathrm{blk}} [\ldots v_i \ldots]\}\ \texttt{Field}(\gamma, i)\ \{\lambda v'.\, v' = v_i \wedge \gamma \mapsto_{\mathrm{blk}} [\ldots v_i \ldots]\}$$

Verifying `hash_ref` with Melocoton

OCaml glue code

```
external hash_ref: int ref -> unit
  = "caml_hash_ref"
```

$$\{r \mapsto_{\mathrm{ML}} n\}$$

$$\texttt{hash\_ref}(r)$$

$$\{\exists m.\, r \mapsto_{\mathrm{ML}} m\}$$

C glue code

```
value caml_hash_ref(value v) {
```

$$\{r \mapsto_{\mathrm{ML}} n * r \sim_{\mathrm{ML}} v\}$$

$$\{v \mapsto_{\mathrm{blk}} [n] * r \sim_{\mathrm{ML}} v\}$$

```
  int x = Int_val(Field(v, 0));
  hash_ptr(&x);
  Store_field(v, 0, Val_int(x));
  return Val_unit;
```

$$\{\exists m.\, v \mapsto_{\mathrm{blk}} [m] * r \sim_{\mathrm{ML}} v\}$$

$$\{\exists m.\, r \mapsto_{\mathrm{ML}} m * () \sim_{\mathrm{ML}} \texttt{Val\_unit}\}$$

```
}
```

`Store_field` SPECIFICATION

$$\{\gamma \mapsto_{\mathrm{blk}} [\ldots v_i \ldots]\}\ \texttt{Store\_field}(\gamma, i, v')\ \{\gamma \mapsto_{\mathrm{blk}} [\ldots v' \ldots]\}$$

But wait, there is more!

- Language-local reasoning for **external calls**.
- Additional **OCaml FFI features**: garbage collection, registering roots, custom blocks, callbacks, etc.
- **Case studies** utilising all of these features.
- **Semantic model of OCaml types** (a logical relation) to verify type safety and encapsulation of FFI code.

Transfinite

Iris

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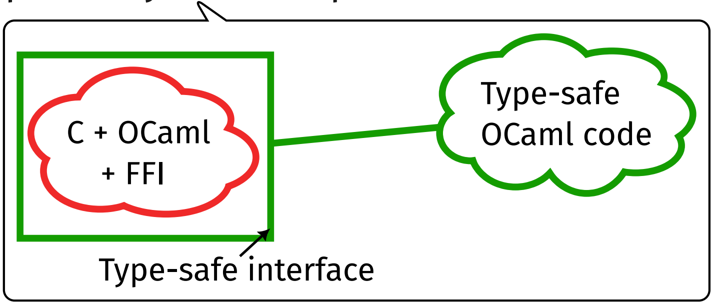


Future work

Extend Melocoton to model all of the OCaml FFI

exceptions, multithreading, “zero-copy” operations on byte arrays, ...

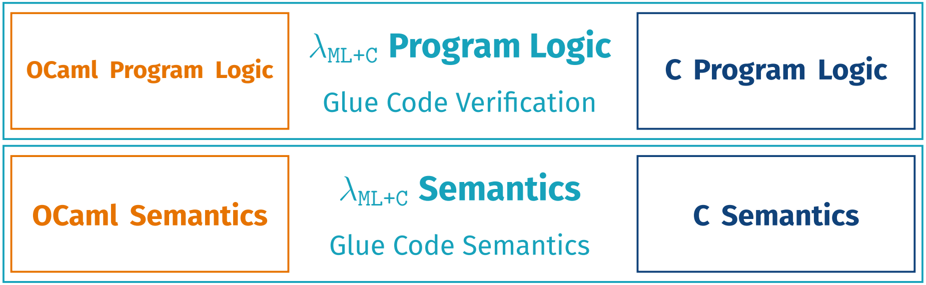
Build code-analysis tools based on Melocoton

Allow OCaml programmers to check correctness of their FFI glue code

Ideally, both verification and bug finding tools

Melocoton

Language Locality: Embed Existing Languages



OCaml Program Logic

$\lambda_{\mathrm{ML+C}}$ **Program Logic**

Glue Code Verification

C Program Logic

OCaml Semantics

$\lambda_{\mathrm{ML+C}}$ **Semantics**

Glue Code Semantics

C Semantics

Language Interaction: View Reconciliation Rules

$$\ell \mapsto_{\mathrm{ML}} \vec{V} \Rrightarrow\!\!\ast\; \exists \gamma \vec{v}.\, \gamma \mapsto_{\mathrm{blk}} \vec{v} * \ell \sim_{\mathrm{ML}} \gamma * \vec{V} \sim_{\mathrm{ML}} \vec{v}$$

$$\vec{V} \sim_{\mathrm{ML}} \vec{v} * \gamma \mapsto_{\mathrm{blk}} \vec{v} \Rrightarrow\!\!\ast\; \exists \ell .\, \ell \mapsto_{\mathrm{ML}} \vec{V} * \ell \sim_{\mathrm{ML}} \gamma$$

https://melocoton-project.github.io