Iris: Monoids and Invariants as an Orthogonal basis for Concurrent Reasoning

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joint work with
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LRG

RGSep

CAP

HOCAP

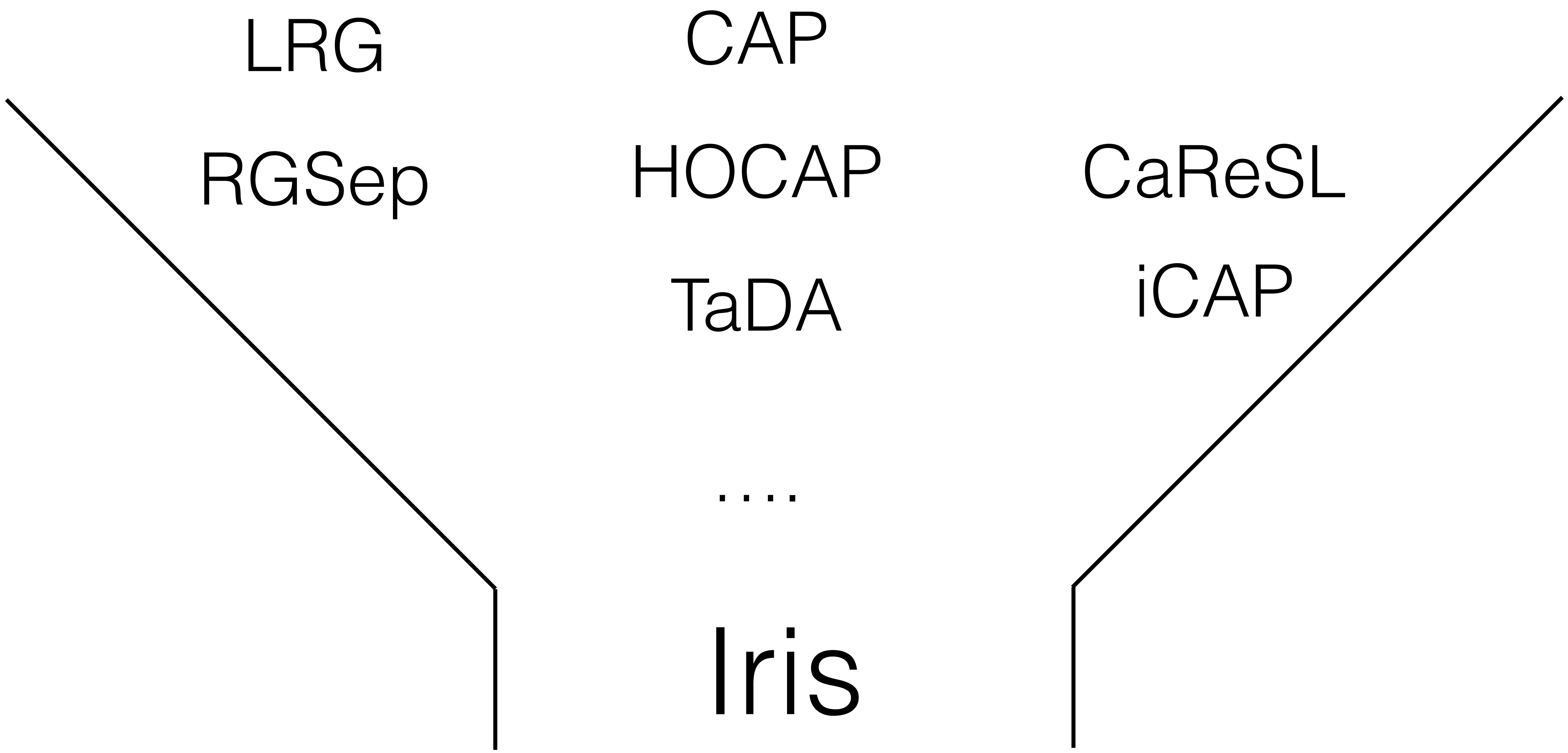
TaDA

CaReSL

iCAP

….

A uniform framework for describing interference



Iris

Higher-order separation logic + **Impredicative Invariants** + **Monoids**

- Supports encoding of existing reasoning principles
  - Monoids for **expressing** protocols on shared state
  - Invariants for **enforcing** protocols on shared state

Iris

Higher-order separation logic	+	Impredicative Invariants	+	Monoids

- Invariants and monoids are **orthogonal**
    - Treating them as such, leads to a simpler logic, and a **model** simple enough to **formalize in Coq**

Iris

Higher-order separation logic + **Impredicative Invariants** + **Monoids**

- Supports a notion of **logical atomicity**
  - extends reasoning principles usually reserved for atomic code to code that **appears** to be atomic
  - we can **define** logical atomicity in Iris

Iris

Higher-order separation logic + **Impredicative** + **Monoids**

Normally we have to reason about possible interference between every statement

R* | c1 | R* | c2 | R*

- Supports a notion of **logical atomicity**
  - extends reasoning principles usually reserved for atomic code to code that **appears** to be atomic
  - we can **define** logical atomicity in Iris

Iris

Higher-order separation logic + **Impredicative** + **Monoids**

No need to reason about interference **inside** logically atomic operations

R* c1 c2 R*

- Supports a notion of **logical atomicity**
  - extends reasoning principles usually reserved for atomic code to code that **appears** to be atomic
  - we can **define** logical atomicity in Iris

Part 1
Iris

Invariants

- An invariant is a property that holds of some piece of shared state at **all** times

$$\frac{\{\triangleright R * P\}\ e\ \{\triangleright R * Q\}_{\mathcal{E}} \qquad e \text{ atomic}}{\left\{\boxed{R}^{\iota} * P\right\}\ e\ \left\{Q\right\}_{\mathcal{E} \uplus \{\iota\}}}$$

The set of invariants that we may open

Invariants

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There exists a shared invariant that owns *R*

The set of invariants that we may open

Invariants

- An invariant is a property that holds of some piece of shared state at **all** times

We open the invariant and take ownership of R

$$\frac{\{\triangleright R * P\}\ e\ \{\triangleright R * Q\}_{\mathcal{E}} \qquad e\ \text{atomic}}{\left\{\boxed{R}^{\iota} * P\right\}\ e\ \left\{Q\right\}_{\mathcal{E} \uplus \{\iota\}}}$$

There exists a shared invariant that owns *R*

The set of invariants that we may open

Invariants

- An invariant is a property that holds of some piece of shared state at **all** times

We open the invariant and take ownership of R

To close the invariant, we must relinquish ownership of R

$$\frac{\{\triangleright R * P\}\ e\ \{\triangleright R * Q\}_{\mathcal{E}} \qquad e \text{ atomic}}{\left\{\boxed{R}^{\iota} * P\right\}\ e\ \left\{Q\right\}_{\mathcal{E} \uplus \{\iota\}}}$$

There exists a shared invariant that owns *R*

The set of invariants that we may open

Invariants

Higher-order separation logic + **Impredicative Invariants** + **Monoids**

- Introduces a circularity in the model
- Modelled using standard metric-based techniques (ModuRes library in Coq)

Monoids

- Iris is parameterised by a notion of ghost resources
- Ghost resources consists of
  - **Information** about the current ghost state
  - **Rights** to update ghost state
- We use monoids to model ghost resources

Monoids

- Ghost resource $\boxed{m}$ asserts ownership of m fragment

- Ghost resources can be split arbitrarily

$$\boxed{m_1 \cdot m_2} \Leftrightarrow \boxed{m_1} * \boxed{m_2}$$

- and support frame-preserving updates

$$\frac{\forall a_f.\ (a \cdot a_f)\downarrow \Rightarrow (b \cdot a_f)\downarrow}{\boxed{a} \Rrightarrow \boxed{b}}$$

Part 2
Recovering existing reasoning principles

Deriving small-footprint specifications

- **Example**: recovering small-footprint specifications from large-footprint specifications

- Same idea as in Superficially Substructural Types (ICFP12) and Fictional Separation Logic (ESOP12)

A λ-calculus with channels

- We instantiate Iris with a λ-calculus with channels

$$e ::= \ldots \mid \textbf{newch} \mid \textbf{send}(e, e) \mid \textbf{tryrecv}(e) \mid \textbf{fork}(e)$$

- with the following per-thread reduction semantics

$$C[c \mapsto M]; \textbf{send}(c, v) \to C[c \mapsto M \uplus \{v\}]; ()$$
$$C[c \mapsto \emptyset]; \textbf{tryrecv}(c) \to C[c \mapsto \emptyset]; \textbf{none}$$
$$C[c \mapsto M \uplus \{v\}]; \textbf{tryrecv}(c) \to C[c \mapsto M]; \textbf{some}(v)$$

Large-footprint specs

- Reduction relation lifts directly to large-footprint specs
- The reduction

$$C[c \mapsto M]; \textbf{send}(c, v) \to C[c \mapsto M \uplus \{v\}]; ()$$

yields the following axiom

$$\{\lfloor C[c \mapsto M] \rfloor\}\ \textbf{send}(c, v)\ \{r.\ r = () \wedge \lfloor C[c \mapsto M \uplus \{v\}] \rfloor\}$$

Asserts exclusive ownership of entire physical state

Small-footprint specs

- Large-footprint spec requires global reasoning

$$\{\lfloor C[c \mapsto M] \rfloor\}\ \textbf{send}(c, v)\ \{r.\ r = () \wedge \lfloor C[c \mapsto M \uplus \{v\}] \rfloor\}$$

- **Goal:** Derive small-footprint specification that only mentions channels affected by each operation

Small-footprint specs

- **Idea**
    - Introduce appropriate channel ghost resources
    - Introduce an invariant that owns the physical state (so that it can be shared) and ties ghost resources to physical state
- Extends to a general construction

Channel-local monoid

- **Goal:** ghost channels resources that support exclusive ownership of individual channels

- Use partial channel "heaps"

$$|\textsc{Net}| = Chan \overset{\text{fin}}{\rightharpoonup} MsgBag$$
$$f \cdot g = f \cup g, \qquad \text{if } \mathrm{dom}(f) \cap \mathrm{dom}(g) = \emptyset$$

- $\boxed{[c \mapsto M]}$ asserts exclusive ownership of ghost channel c and that contains messages M

Authoritative monoid

- **Goal:** a monoid with
  - An authoritative element $m\bullet$ that asserts that the current ghost state is exactly m
  - A partial element $m\circ$ that asserts ownership of an m fragment of the authoritative state
- s.t. all fragments combine to the authoritative state

Deriving a channel-local specification

$$\{c \prec M\}$$

$$\textbf{send}(c, m)$$

$$\{c \prec M \uplus \{m\}\}$$

Deriving a channel-local specification

Channel resource asserts ownership of corresponding fragment:

$$c \prec M \triangleq \boxed{[c \mapsto M]}^{\circ}$$

$$\{c \prec M\}$$

$$\textbf{send}(c, m)$$

$$\{c \prec M \uplus \{m\}\}$$

Deriving a channel-local specification

Invariant: the physical state is authoritative ghost state

$$\exists C.\ \boxed{C\bullet} * \lfloor C \rfloor$$

Channel resource asserts ownership of corresponding fragment:

$$c \prec M \triangleq \boxed{[c \mapsto M]\circ}$$

$\{c \prec M\}$

send(c, m)

$\{c \prec M \uplus \{m\}\}$

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$$\{c \prec M\}$$

$$\{\boxed{[c \mapsto M]^{\circ}} * \boxed{C^{\bullet}} * \lfloor C \rfloor\}$$

$$\textbf{send}(c, m)$$

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$$\{c \prec M\}$$

$$\{\boxed{[c \mapsto M]\circ} * \boxed{C\bullet} * \lfloor C \rfloor\}$$

$\color{blue}{\textbf{send}(c, m)}$

$$\{ \qquad\qquad\qquad\qquad * \lfloor C[c \mapsto C(c) \uplus \{m\}] \rfloor\}$$

$$\{c \prec M \uplus \{m\}\}$$

Deriving a channel-local specification

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$$\{c \prec M\}$$

$$\{\boxed{[c \mapsto M]^{\circ}} * \boxed{C^{\bullet}} * \lfloor C \rfloor\}$$

$\textbf{send}(c, m)$

$$\{\boxed{[c \mapsto M]^{\circ}} * \boxed{C^{\bullet}} * \lfloor \overbrace{C[c \mapsto C(c) \uplus \{m\}]}^{C'} \rfloor\}$$

$$\{c \prec M \uplus \{m\}\}$$

Deriving a channel-local specification

Invariant: the physical state is authoritative ghost state

$$\exists C.\ \boxed{C\bullet} * \lfloor C \rfloor$$

Channel resource asserts ownership of corresponding fragment:

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$$\{c \prec M\}$$

$$\{\boxed{[c \mapsto M]\circ} * \boxed{C\bullet} * \lfloor C \rfloor\}$$

$\textbf{send}(c, m)$

$$\{\boxed{[c \mapsto M]\circ} * \boxed{C\bullet} * \lfloor \overbrace{C[c \mapsto C(c) \uplus \{m\}]}^{C'} \rfloor\}$$

$$\{\boxed{[c \mapsto M \uplus \{m\}]\circ} * \boxed{C'\bullet} * \lfloor C' \rfloor\}$$

$$\{c \prec M \uplus \{m\}\}$$

Deriving small-footprint specifications

- Channel monoid encodes small-footprint channel resources
- Invariant relates ghost and physical state using authoritative monoid to allow ownership of channel fragments

Recovering existing reasoning techniques

- We saw how to recover reasoning principles from Superficially Substructural Types and Fictional Separation

- One can also recover reasoning principles from CaReSL and iCAP through a encoding of STSs as monoids

Part 3
Logical atomicity

Logical atomicity

- In part 2 we used the invariant rule to access the shared physical resource

$$\frac{\{\triangleright R * P\}\ e\ \{\triangleright R * Q\}_{\mathcal{E}} \qquad e \text{ atomic}}{\left\{\boxed{R}^{\iota} * P\right\}\ e\ \left\{Q\right\}_{\mathcal{E} \uplus \{\iota\}}}$$

- This rule only applies to **atomic** expressions

- Iris allows us to extend this reasoning principle to **logically atomic** code

Logical atomicity

- In part 2 we used the invariant rule to access the shared physical resource

$$\frac{\{\triangleright R * P\}\; e\; \{\triangleright R * Q\}_{\mathcal{E}} \qquad e \text{ atomic}}{\left\{\boxed{R}^{\iota} * P\right\}\; e}$$

- This rule only applies to **ato**

We can **define** logically atomic triples

$$\langle P \rangle\; e\; \langle Q \rangle$$

- Iris allows us to extend this reasoning principle to **logically atomic** code

Logical atomicity

- **Example:** a blocking receive operation

$$\textbf{recv} \triangleq \textbf{rec}\ recv(c).\ \textbf{let}\ v = \textbf{tryrecv}(c)\ \textbf{in}$$
$$\textbf{case}\ v\ \textbf{of}\ \textbf{none} => recv(c) \mid \textbf{some}(m) => m$$

- Spins (without side effects) until a msg is received
- The linearisation point is the first successful **tryrecv**

Logical atomicity

- **Ideas**
  - Let clients reason about the state immediately before and after the linearisation point
  - Let clients open invariants **around** the linearisation point

Logical atomicity

- **Ideas**

  Parameterise our specifications with view shifts

  - Let clients reason about the state immediately before and after the linearisation point
  - Let clients open invariants **around** the linearisation point

  Let view shifts open and close invariants

Mask-changing view shifts

- Index view shifts with the set of invariants enabled before and after the view shift

$$P \;{}^{\mathcal{E}_1}\!\!\Rrightarrow^{\mathcal{E}_2}\; Q$$

- **Asserts**
    - that we can update the instrumented state from P to Q without changing the physical state
    - where the invariants in $\mathcal{E}_1$ are enabled before the view shift
    - and the invariants in $\mathcal{E}_2$ are enabled after the view shift

Mask-changing view shifts

- We can change the invariant mask around atomic expressions, provided we restore it again

$$\frac{e \text{ atomic} \qquad P \;{}^{\{\iota\}}\!\Rrightarrow^{\emptyset}\; P' \qquad \{P'\}\; e\; \{v.\, Q'\}_{\emptyset} \qquad \forall v.\, Q' \;{}^{\emptyset}\!\Rrightarrow^{\{\iota\}}\; Q}{\{P\}\; e\; \{v.\, Q\}_{\{\iota\}}}$$

- We can open and close invariants using view shifts

$$\boxed{P}^{\iota} \;{}^{\{\iota\}}\!\Rrightarrow^{\emptyset}\; \triangleright P \qquad\qquad \boxed{P}^{\iota} * \triangleright P \;{}^{\emptyset}\!\Rrightarrow^{\{\iota\}}\; \top$$

Logical atomicity

- **Idea:** Let clients open and close invariants around linearisation point and update instrumented state

$$
\begin{aligned}
\langle P \rangle\ e\ \langle Q \rangle_{\mathcal{E}} \approx \forall R_p, R_q, \mathcal{E}_R.\ & \mathcal{E} \cap \mathcal{E}_R = \emptyset\ \wedge \\
& (R_p \Lleftarrow\!\!\Rrightarrow^{-\mathcal{E}_R} P) \wedge (Q \Rrightarrow_{-\mathcal{E}_R} R_q) \\
& \Rightarrow\ \{R_p\}\ e\ \{R_q\}
\end{aligned}
$$

- This allows us to open invariants around logically atomic code

$$
\frac{\langle \triangleright R * P \rangle\ e\ \langle \triangleright R * Q \rangle_{\mathcal{E}}}{\left\langle \boxed{R}^{\iota} * P \right\rangle\ e\ \left\langle Q \right\rangle_{\mathcal{E} \uplus \{\iota\}}}
$$

Logical atomicity

- **Idea:** Let clients open and close invariants around linearisation point and update instrumented state

$$\langle P \rangle \; e \; \langle Q \rangle_{\mathcal{E}} \approx \forall R_p, R_q, \mathcal{E}_R.\; \mathcal{E} \cap \mathcal{E}_R = \emptyset \;\wedge$$
$$(R_p \Lleftarrow\!\!\Rrightarrow^{-\mathcal{E}_R} P) \wedge (Q \Rrightarrow_{-\mathcal{E}_R} R_q)$$
$$\Rightarrow \; \{R_p\} \; e \; \{R_q\}$$

- This allows us to open invariants around logically atomic code

$$\frac{\langle \triangleright R * P \rangle \; e \; \langle \triangleright R * Q \rangle_{\mathcal{E}}}{\left\langle \boxed{R}^{\iota} * P \right\rangle \; e \; \left\langle Q \right\rangle_{\mathcal{E} \uplus \{\iota\}}}$$

From the client's point of view it looks like we have access to the invariant R for the duration of e.

Logical atomicity

- **Idea:** Let clients open and c
linearisation point and update instru

$$\langle P\rangle\ e\ \langle Q\rangle_{\mathcal{E}} \approx \forall R_p, R_q, \mathcal{E}_R.\ \mathcal{E}\cap\mathcal{E}_R=\emptyset \wedge$$
$$(R_p \Lleftarrow\!\!\Rrightarrow^{-\mathcal{E}_R} P) \wedge (Q \Rrightarrow_{-\mathcal{E}_R} R_q)$$
$$\Rightarrow\ \{R_p\}\ e\ \{R_q\}$$

From the module's point of view we only access the invariant in the linearisation point.

- This allows us to open invariants around logically atomic code

$$\frac{\langle \triangleright R * P\rangle\ e\ \langle \triangleright R * Q\rangle_{\mathcal{E}}}{\left\langle \boxed{R}^{\iota} * P\right\rangle\ e\ \left\langle Q\right\rangle_{\mathcal{E}\uplus\{\iota\}}}$$

From the client's point of view it looks like we have access to the invariant R for the duration of e.

Case study

logically atomic

- elimination stack
- mutable references as channels
- message passing blocking receive

physically atomic

- small-footprint specifications
- λ-calculus with asynchronous message passing

Logical atomicity

- Logical atomicity is not built into Iris, but Iris is sufficiently expressive that we can **define** it in Iris.

Conclusions

- Iris is
  - simpler than previous logics
  - can encode reasoning principles from previous logics
  - and can do some fancy new stuff (logical atomicity)
- **Monoids and invariants are all you need**