Verifying Functional Correctness of Message-Passing Programs with Separation Logic

Separation Logic meets Session Types

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Why: Formal Verification of Message Passing

Rigid validation needed

- Critical infrastructure based on concurrency
- Concurrency notoriously hard

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Message passing is a good (and necessary) abstraction

- **Good:** Used in shared memory (Go)
- **Necessary:** Inherent to distributed systems (TCP)

What: Message Passing Concurrency in Shared Memory

Shared-memory message passing concurrency:

- Structured approach to concurrent programming
- Threads act as services or clients
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Bi-directional asynchronous session channels:

`new_chan`()	Create channel and return two endpoints c1 and c2
c.**send**(v)	Send value v over endpoint c
c.**recv**()	Receive and return next inbound value on endpoint c

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\begin{array}{l}
\texttt{let}\,(c_1, c_2) = \texttt{new\_chan}\,()\;\texttt{in} \\
\left(\begin{array}{l}
c_1.\texttt{send}(40); \\
\texttt{let}\,y = c_1.\texttt{recv}()\;\texttt{in} \\
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\end{array}
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How: Separation Logic Meets Session Types

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Goal: Prove crash-freedom (safety) in presence of asserts (functional correctness)

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! is send, **?** is receive

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Roadmap of This Talk

Separation Logic

- Safety and functional correctness
- Modular verification
- Verification of example program

Actris

- Reasoning methodology for message passing
- Demonstration of select Actris features

Beyond this talk

- Sample Actris features
- The Actris line of work

Separation Logic

[O'Hearn, Reynolds, Yang 2001]

Language Under Consideration

HeapLang: Untyped OCaml-like language

$$\begin{aligned} v, w \in \mathsf{Val} &::= z \mid \mathtt{true} \mid \mathtt{false} \mid () \mid \ell & (z \in \mathbb{Z}, \ell \in \mathsf{Loc}) \\ e \in \mathsf{Expr} &::= v \mid x \mid e_1\ e_2 \mid \\ &\quad\ \mathtt{ref}\, e \mid {!\,e} \mid e_1 \leftarrow e_2 \mid \\ &\quad\ (e_1 \parallel e_2) \mid \mathtt{assert}(e) \ldots \end{aligned}$$

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Example program:

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&\mathbf{assert}(!\,\ell_1 + !\,\ell_2 = 4)
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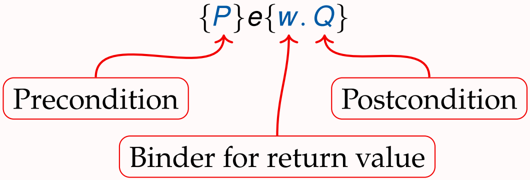
\mathtt{assert}(!\, \ell_1 + !\, \ell_2 = 4)
\end{array}
$$

Goal: Program does not crash

Hoare Triples

Hoare triples for partial functional correctness:



$$\{P\}e\{w.\,Q\}$$

Precondition

Binder for return value

Postcondition

If the initial state satisfies P, then:

- **Safety:** e does not crash
- **Postcondition validity:** if e terminates with value v, then the final state satisfies $Q[v/w]$

Separation Logic

Separation logic propositions assert ownership of resources

The points-to connective $\ell \mapsto v$

- Provides the knowledge that location ℓ has value v, and
- Provides exclusive ownership of ℓ

Separating conjunction $P * Q$ captures that the state consists of disjoint parts satisfying P and Q.

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Separating conjunction $P * Q$ captures that the state consists of disjoint parts satisfying P and Q.

Enables modular reasoning, through disjointness:

$$\frac{\{P\}\, e\, \{w.\, Q\}}{\{P * R\}\, e\, \{w.\, Q * R\}}\ \textsc{Ht-frame}$$

Hoare Triples for Seperation Logic

Hoare triples for references:

HT-ALLOC
$\{\mathsf{True}\}\ \mathtt{\textbf{ref}}\, v\ \{\ell.\, \ell \mapsto v\}$

HT-LOAD
$\{\ell \mapsto v\}\ !\,\ell\ \{w.\, w = v * \ell \mapsto v\}$

HT-STORE
$\{\ell \mapsto v\}\ \ell \leftarrow w\ \{\ell \mapsto w\}$

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Ht-alloc
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Ht-load
$\{\ell \mapsto v\}\ !\,\ell\ \{w.\, w = v * \ell \mapsto v\}$

Ht-store
$\{\ell \mapsto v\}\ \ell \leftarrow w\ \{\ell \mapsto w\}$

Hoare triples for structural expressions:

Ht-let
$$\frac{\{P\}\ e_1\ \{w_1.\, Q\} \qquad \forall w_1.\, \{Q\}\ e_2[w_1/x]\ \{w_2.\, R\}}{\{P\}\ \mathbf{let}\, x = e_1\ \mathbf{in}\, e_2\ \{w_2.\, R\}}$$

Ht-assert
$$\frac{\{P\}\ e\ \{w.\, w = \mathbf{true} * Q\}}{\{P\}\ \mathbf{assert}(e)\ \{Q\}}$$

Ht-seq
$$\frac{\{P\}\ e_1\ \{w_1.\, Q\} \qquad \forall w_1.\, \{Q\}\ e_2\ \{w_2.R\}}{\{P\}\ e_1 ; e_2\ \{w_2.\, R\}}$$

Ht-par
$$\frac{\{P_1\}\ e_1\ \{Q_1\} \qquad \{P_2\}\ e_2\ \{Q_2\}}{\{P_1 * P_2\}\ (e_1 \parallel e_2)\ \{Q_1 * Q_2\}}$$

Example Program - Verified

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\begin{array}{l}
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\left(\ell_1 \leftarrow\ !\,\ell_1 + 2 \parallel \ell_2 \leftarrow\ !\,\ell_2 + 2\right); \\
\mathbf{assert}(!\,\ell_1 + !\,\ell_2 = 4)
\end{array}
$$

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$$
\begin{array}{l}
\{\mathsf{True}\} \\
\mathtt{\textbf{let}}\ \ell_1 = \mathtt{\textbf{ref}}\, 0\ \mathtt{\textbf{in}} \\
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$$

Example Program - Verified

$\{\mathsf{True}\}$
$\mathtt{let}\ \ell_1 = \mathtt{ref}\,0\ \mathtt{in}$ // HT-LET, HT-ALLOC
$\{\ell_1 \mapsto 0\}$
$\mathtt{let}\ \ell_2 = \mathtt{ref}\,0\ \mathtt{in}$
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\mathbf{let}\ \ell_2 = \mathbf{ref}\,0\ \mathbf{in} & //\ \textsc{Ht-let}, \textsc{Ht-alloc}, \textsc{Ht-frame} \\
\{\ell_1 \mapsto 0 * \ell_2 \mapsto 0\} & \\
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$\{\mathsf{True}\}$

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$\{\ell_1 \mapsto 0\}$

$\mathbf{let}\ \ell_2 = \mathbf{ref}\,0\ \mathbf{in}$ // HT-LET, HT-ALLOC, HT-FRAME

$\{\ell_1 \mapsto 0 * \ell_2 \mapsto 0\}$

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// HT-SEQ, HT-PAR

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But What About Channels?

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Goal: Program does not crash
Sub-Goal: Hoare triples for channel primitives

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$\{???\}\ \mathbf{new\_chan}\,()\ \{???\}$

Ht-send
$\{???\}\ c.\mathbf{send}(v)\ \{???\}$

Ht-recv
$\{???\}\ c.\mathbf{recv}()\ \{???\}$

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Key Idea: Separate channel endpoint ownership à la Session Types

Actris

Hinrichsen et al.

Actris

Channel Endpoint Ownership: $c \rightarrowtail p$

Actris

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Dependent Separation Protocols: $\mathbf{!}\,\langle v \rangle.\, p \mid \mathbf{?}\langle v \rangle.\, p \mid \textbf{end}$

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Example: $\mathbf{!}\,\langle 40 \rangle.\, \mathbf{?}\langle 42 \rangle.\, \textbf{end}$

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Example: $\mathbf{!}\,\langle 40 \rangle.\, \mathbf{?}\langle 42 \rangle.\, \textbf{end}$

Rules:

Ht-send

$$\{c \rightarrowtail \mathbf{!}\,\langle v \rangle.\, p\}\; c.\mathtt{send}(v)\; \{c \rightarrowtail p\}$$

Ht-recv

$$\{c \rightarrowtail \mathbf{?}\langle v \rangle.\, p\}\; c.\mathtt{recv}()\; \{w.\, w = v * c \rightarrowtail p\}$$

Actris

Channel Endpoint Ownership: $c \rightarrowtail p$

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Example: $\mathbf{!}\,\langle 40 \rangle.\, \mathbf{?}\langle 42 \rangle.\, \mathbf{end}$

Duality: $\overline{\mathbf{!}\,\langle v \rangle.\, p} = \mathbf{?}\langle v \rangle.\, \overline{p}$ $\quad \overline{\mathbf{?}\langle v \rangle.\, p} = \mathbf{!}\,\langle v \rangle.\, \overline{p}$ $\quad \overline{\mathbf{end}} = \mathbf{end}$

Rules:

Ht-send
$\{c \rightarrowtail \mathbf{!}\,\langle v \rangle.\, p\}\; c.\mathbf{send}(v)\; \{c \rightarrowtail p\}$

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$\{c \rightarrowtail \mathbf{?}\langle v \rangle.\, p\}\; c.\mathtt{recv}()\; \{w.\, w = v * c \rightarrowtail p\}$

Actris

Channel Endpoint Ownership: $c \rightarrowtail p$

Dependent Separation Protocols: $\mathbf{!}\,\langle v \rangle .\, p \mid \mathbf{?}\langle v \rangle .\, p \mid \mathbf{end}$

Example: $\mathbf{!}\,\langle 40 \rangle .\, \mathbf{?}\langle 42 \rangle .\, \mathbf{end}$

Duality: $\overline{\mathbf{!}\,\langle v \rangle .\, p} = \mathbf{?}\langle v \rangle .\, \overline{p} \qquad \overline{\mathbf{?}\langle v \rangle .\, p} = \mathbf{!}\,\langle v \rangle .\, \overline{p} \qquad \overline{\mathbf{end}} = \mathbf{end}$

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Ht-send
$\{c \rightarrowtail \mathbf{!}\,\langle v \rangle .\, p\}\; c.\mathtt{\textbf{send}}(v)\; \{c \rightarrowtail p\}$

Ht-recv
$\{c \rightarrowtail \mathbf{?}\langle v \rangle .\, p\}\; c.\mathtt{\textbf{recv}}()\; \{w.\, w = v * c \rightarrowtail p\}$

Ht-new
$\{\mathsf{True}\}\; \mathtt{\textbf{new\_chan}}\,()\; \{(c_1, c_2).\, c_1 \rightarrowtail p * c_2 \rightarrowtail \overline{p}\}$

Example Channel Program - Verified

Example Program:

$$\begin{array}{l}\mathtt{let}\,(c_1, c_2) = \mathtt{new\_chan}\,()\,\mathtt{in}\\ \left(\begin{array}{l||l} c_1.\mathtt{send}(40); & \mathtt{let}\,x = c_2.\mathtt{recv}()\,\mathtt{in}\\ \mathtt{let}\,y = c_1.\mathtt{recv}()\,\mathtt{in} & c_2.\mathtt{send}(x+2)\\ \mathtt{assert}(y = 42) & \end{array}\right)\end{array}$$

Example Channel Program - Verified

Example Program:

$$
\begin{array}{l}
\texttt{let}\,(c_1, c_2) = \texttt{new\_chan}\,()\,\texttt{in} \\
\left(\begin{array}{l}
c_1.\texttt{send}(40); \\
\texttt{let}\,y = c_1.\texttt{recv}()\,\texttt{in} \\
\texttt{assert}(y = 42)
\end{array}
\;\middle\|\;
\begin{array}{l}
\texttt{let}\,x = c_2.\texttt{recv}()\,\texttt{in} \\
c_2.\texttt{send}(x + 2) \\
\\
\end{array}\right)
\end{array}
$$

Protocols:

$$c_1 \rightarrowtail \mathbf{!}\,\langle 40\rangle.\,\mathbf{?}\langle 42\rangle.\,\mathbf{end}$$

$$c_2 \rightarrowtail \mathbf{?}\langle 40\rangle.\,\mathbf{!}\,\langle 42\rangle.\,\mathbf{end}$$

Example Channel Program - Verified

Example Program:

$$
\begin{array}{l}
\texttt{let}\,(c_1, c_2) = \texttt{new\_chan}\,()\,\texttt{in} \\
\left(\begin{array}{l||l}
c_1.\texttt{send}(40); & \texttt{let}\,x = c_2.\texttt{recv}()\,\texttt{in} \\
\texttt{let}\,y = c_1.\texttt{recv}()\,\texttt{in} & c_2.\texttt{send}(x + 2) \\
\texttt{assert}(y = 42) &
\end{array}\right)
\end{array}
$$

Protocols:

$$
\begin{array}{l}
c_1 \rightarrowtail \mathbf{!}\,\langle 40 \rangle.\,\mathbf{?}\langle 42 \rangle.\,\mathbf{end} \\
c_2 \rightarrowtail \mathbf{?}\langle 40 \rangle.\,\mathbf{!}\,\langle 42 \rangle.\,\mathbf{end}
\end{array}
$$

Goal complete: Program verified safe to execute for any scheduling

Example Channel Program - Verified

Example Program:

$$\texttt{let}\,(c_1, c_2) = \texttt{new\_chan}\,()\,\texttt{in}$$
$$\left(\begin{array}{l} c_1.\texttt{send}(40); \\ \texttt{let}\; y = c_1.\texttt{recv}()\;\texttt{in} \\ \texttt{assert}(y = 42) \end{array} \middle\| \begin{array}{l} \texttt{let}\; x = c_2.\texttt{recv}()\;\texttt{in} \\ c_2.\texttt{send}(x + 2) \\ \end{array}\right)$$

Protocols:

$$c_1 \rightarrowtail \,!\,\langle 40\rangle.\, ?\langle 42\rangle.\, \textbf{end}$$
$$c_2 \rightarrowtail \,?\langle 40\rangle.\, !\,\langle 42\rangle.\, \textbf{end}$$

Goal complete: Program verified safe to execute for any scheduling
Problem: Protocols too restrictive; right thread works for any integer

Actris with Quantifiers

Dependent Separation Protocols: $\mathbf{!}\,(\vec{x}:\vec{\tau})\langle v\rangle.\,p \mid \mathbf{?}\,(\vec{x}:\vec{\tau})\langle v\rangle.\,p \mid \mathbf{end}$

Example: $\mathbf{!}\,(x:\mathbb{Z})\,\langle x\rangle.\,\mathbf{?}\langle x+2\rangle.\,\mathbf{end}$

Duality: $\overline{\mathbf{!}\,(\vec{x}:\vec{\tau})\langle v\rangle.\,p} = \mathbf{?}\,(\vec{x}:\vec{\tau})\langle v\rangle.\,\overline{p}$ $\qquad$ $\overline{\mathbf{?}\,(\vec{x}:\vec{\tau})\langle v\rangle.\,p} = \mathbf{!}\,(\vec{x}:\vec{\tau})\langle v\rangle.\,\overline{p}$

Rules:

Ht-send

$$\{c \rightarrowtail \mathbf{!}\,(\vec{x}:\vec{\tau})\langle v\rangle.\,p\}\; c.\mathbf{send}(v[\vec{t}/\vec{x}])\; \{c \rightarrowtail p[\vec{t}/\vec{x}]\}$$

Ht-recv

$$\{c \rightarrowtail \mathbf{?}\,(\vec{x}:\vec{\tau})\langle v\rangle.\,p\}\; c.\mathbf{recv}()\; \{w.\, \exists(\vec{t}:\vec{\tau}).\, w = v[\vec{t}/\vec{x}] * c \rightarrowtail p[\vec{t}/\vec{x}]\}$$

Example Channel Program - Quantifiers

Example Program:

$$\begin{array}{l}
\mathbf{let}\,(c_1, c_2) = \mathbf{new\_chan}\,()\,\mathbf{in} \\
\left(\begin{array}{l} c_1.\mathbf{send}(40); \\ \mathbf{let}\, y = c_1.\mathbf{recv}()\,\mathbf{in} \\ \mathbf{assert}(y = 42) \end{array} \middle\| \begin{array}{l} \mathbf{let}\, x = c_2.\mathbf{recv}()\,\mathbf{in} \\ c_2.\mathbf{send}(x + 2) \\ \end{array}\right)
\end{array}$$

Example Channel Program - Quantifiers

Example Program:

$$\texttt{let}\,(c_1, c_2) = \texttt{new\_chan}\,()\ \texttt{in}$$
$$\left(\begin{array}{l} c_1.\texttt{send}(40); \\ \texttt{let}\, y = c_1.\texttt{recv}()\ \texttt{in} \\ \texttt{assert}(y = 42) \end{array} \middle\| \begin{array}{l} \texttt{let}\, x = c_2.\texttt{recv}()\ \texttt{in} \\ c_2.\texttt{send}(x + 2) \\ \ \end{array}\right)$$

Protocols:

$$c_1 \rightarrowtail\, !\,(x : \mathbb{Z})\,\langle x \rangle.\, ?\langle x + 2 \rangle.\, \textbf{end}$$
$$c_2 \rightarrowtail\, ?(x : \mathbb{Z})\,\langle x \rangle.\, !\,\langle x + 2 \rangle.\, \textbf{end}$$

Example Channel Program - Quantifiers

Example Program:

$$\begin{array}{l}\texttt{let}\,(c_1, c_2) = \texttt{new\_chan}\,()\,\texttt{in}\\ \left(\begin{array}{l} c_1.\texttt{send}(40);\\ \texttt{let}\,y = c_1.\texttt{recv}()\,\texttt{in}\\ \texttt{assert}(y = 42) \end{array} \;\middle\|\; \begin{array}{l} \texttt{let}\,x = c_2.\texttt{recv}()\,\texttt{in}\\ c_2.\texttt{send}(x+2)\\ \end{array}\right)\end{array}$$

Protocols:

$$c_1 \rightarrowtail\, !\,(x : \mathbb{Z})\,\langle x\rangle.\, ?\langle x+2\rangle.\,\mathbf{end}$$

$$c_2 \rightarrowtail\, ?(x : \mathbb{Z})\,\langle x\rangle.\, !\,\langle x+2\rangle.\,\mathbf{end}$$

Goal complete: Right thread now modularly compose with arbitrary clients

Example Reference Program

Example Program:

$$\mathtt{let}\,(c_1, c_2) = \mathtt{new\_chan}\,()\ \mathtt{in}$$
$$\left(\begin{array}{l||l} \mathtt{let}\ \ell = \mathtt{ref}\ 40\ \mathtt{in} & \mathtt{let}\ \ell = c_2.\mathtt{recv}()\ \mathtt{in} \\ c_1.\mathtt{send}(\ell); & \ell \leftarrow\ !\,\ell + 2; \\ c_1.\mathtt{recv}(); & c_2.\mathtt{send}() \\ \mathtt{assert}(!\,\ell = 42) & \end{array}\right)$$

$\ell \mapsto v$: Ownership of reference ℓ pointing to v

$\{\mathsf{True}\}\ \mathtt{ref}\,v\ \{\ell.\ \ell \mapsto v\}$ $\quad$ $\{\ell \mapsto v\}\ !\,v\ \{w.\ w = v * \ell \mapsto v\}$ $\quad$ $\{\ell \mapsto v\}\ \ell \leftarrow w\ \{\ell \mapsto w\}$

Example Reference Program

Example Program:

$$\begin{array}{l}\mathbf{let}\,(c_1, c_2) = \mathbf{new\_chan}\,()\ \mathbf{in} \\ \left(\begin{array}{l}\mathbf{let}\,\ell = \mathbf{ref}\,40\ \mathbf{in} \\ c_1.\mathbf{send}(\ell); \\ c_1.\mathbf{recv}(); \\ \mathbf{assert}(!\,\ell = 42)\end{array} \middle\| \begin{array}{l}\mathbf{let}\,\ell = c_2.\mathbf{recv}()\ \mathbf{in} \\ \ell \leftarrow !\,\ell + 2; \\ c_2.\mathbf{send}() \\ \\ \end{array}\right)\end{array}$$

Protocols?

$$c_1 \rightarrowtail \mathbf{!}\,(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle \ell \rangle.\,\mathbf{?}\langle () \rangle.\,\mathbf{end}$$

$$c_2 \rightarrowtail \mathbf{?}(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle \ell \rangle.\,\mathbf{!}\,\langle () \rangle.\,\mathbf{end}$$

$\ell \mapsto v$: Ownership of reference ℓ pointing to v

$\{\mathsf{True}\}\ \mathbf{ref}\,v\ \{\ell.\,\ell \mapsto v\}$ $\quad \{\ell \mapsto v\}\ !\,v\ \{w.\,w = v * \ell \mapsto v\}$ $\quad \{\ell \mapsto v\}\ \ell \leftarrow w\ \{\ell \mapsto w\}$

Example Reference Program

Example Program:

$$\begin{array}{l}
\mathtt{let}\,(c_1, c_2) = \mathtt{new\_chan}\,()\,\mathtt{in}\\
\left(\begin{array}{l} \mathtt{let}\,\ell = \mathtt{ref}\,40\,\mathtt{in}\\ c_1.\mathtt{send}(\ell);\\ c_1.\mathtt{recv}();\\ \mathtt{assert}(!\,\ell = 42)\end{array} \middle\| \begin{array}{l} \mathtt{let}\,\ell = c_2.\mathtt{recv}()\,\mathtt{in}\\ \ell \leftarrow !\,\ell + 2;\\ c_2.\mathtt{send}()\\ \\ \end{array}\right)
\end{array}$$

Protocols?

$$c_1 \rightarrowtail \mathbf{!}\,(\ell : \mathrm{Loc}, x : \mathbb{Z})\,\langle \ell \rangle.\,\mathbf{?}\langle () \rangle.\,\mathbf{end}$$

$$c_2 \rightarrowtail \mathbf{?}(\ell : \mathrm{Loc}, x : \mathbb{Z})\,\langle \ell \rangle.\,\mathbf{!}\,\langle () \rangle.\,\mathbf{end}$$

Problem: Implicit transfer of control not possible to capture

---

$\ell \mapsto v$: Ownership of reference ℓ pointing to v

$\{\mathrm{True}\}\ \mathtt{ref}\,v\ \{\ell.\ \ell \mapsto v\}\quad \{\ell \mapsto v\}\ !\,v\ \{w.\ w = v * \ell \mapsto v\}\quad \{\ell \mapsto v\}\ \ell \leftarrow w\ \{\ell \mapsto w\}$

Example Reference Program

Example Program:

$$\begin{array}{l}
\mathtt{let}\,(c_1, c_2) = \mathtt{new\_chan}\,()\;\mathtt{in} \\
\left(\begin{array}{l||l}
\mathtt{let}\;\ell = \mathtt{ref}\,40\;\mathtt{in} & \mathtt{let}\;\ell = c_2.\mathtt{recv}()\;\mathtt{in} \\
c_1.\mathtt{send}(\ell); & \ell \leftarrow {!}\,\ell + 2; \\
c_1.\mathtt{recv}(); & c_2.\mathtt{send}() \\
\mathtt{assert}({!}\,\ell = 42) &
\end{array}\right)
\end{array}$$

Protocols?

$$c_1 \rightarrowtail \mathbf{!}\,(\ell : \mathrm{Loc}, x : \mathbb{Z})\,\langle \ell \rangle.\,\mathbf{?}\langle () \rangle.\,\mathbf{end}$$

$$c_2 \rightarrowtail \mathbf{?}(\ell : \mathrm{Loc}, x : \mathbb{Z})\,\langle \ell \rangle.\,\mathbf{!}\,\langle () \rangle.\,\mathbf{end}$$

Problem: Implicit transfer of control not possible to capture

Key Idea: Resources in protocols

$\ell \mapsto v$: Ownership of reference ℓ pointing to v

$\{\mathrm{True}\}\;\mathtt{ref}\,v\;\{\ell.\,\ell \mapsto v\}\quad \{\ell \mapsto v\}\;{!}\,v\;\{w.\,w = v * \ell \mapsto v\}\quad \{\ell \mapsto v\}\;\ell \leftarrow w\;\{\ell \mapsto w\}$

Actris with Resources

Dependent Separation Protocols: $\mathbf{!}\,(\vec{x}:\vec{\tau})\langle v\rangle\{P\}.\,p \mid \mathbf{?}\,(\vec{x}:\vec{\tau})\langle v\rangle\{P\}.\,p \mid \mathbf{end}$

Example: $\mathbf{!}\,(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle \ell\rangle\{\ell \mapsto x\}.\,\mathbf{?}\langle ()\rangle\{\ell \mapsto (x+2)\}.\,\mathbf{end}$

Duality: $\overline{\mathbf{!}\,(\vec{x}:\vec{\tau})\langle v\rangle\{P\}.\,p} = \mathbf{?}\,(\vec{x}:\vec{\tau})\langle v\rangle\{P\}.\,\overline{p}$ $\qquad$ $\overline{\mathbf{?}\,(\vec{x}:\vec{\tau})\langle v\rangle\{P\}.\,p} = \mathbf{!}\,(\vec{x}:\vec{\tau})\langle v\rangle\{P\}.\,\overline{p}$

Rules:

Ht-send

$$\left\{c \rightarrowtail \mathbf{!}\,(\vec{x}:\vec{\tau})\langle v\rangle\{P\}.\,p * P[\vec{t}/\vec{x}]\right\}\; c.\mathbf{send}(v[\vec{t}/\vec{x}])\; \left\{c \rightarrowtail p[\vec{t}/\vec{x}]\right\}$$

Ht-recv

$$\{c \rightarrowtail \mathbf{?}\,(\vec{x}:\vec{\tau})\langle v\rangle\{P\}.\,p\}\; c.\mathbf{recv}()\; \left\{w.\, \exists(\vec{t} : \vec{\tau}).\, w = v[\vec{t}/\vec{x}] * c \rightarrowtail p[\vec{t}/\vec{x}] * P[\vec{t}/\vec{x}]\right\}$$

Example Reference Program - Verified

Example Program:

$$\begin{array}{l}
\mathbf{let}\,(c_1, c_2) = \mathbf{new\_chan}\,()\,\mathbf{in} \\
\left(\begin{array}{l}
\mathbf{let}\,\ell = \mathbf{ref}\,40\,\mathbf{in} \\
c_1.\mathbf{send}(\ell); \\
c_1.\mathbf{recv}(); \\
\mathbf{assert}(!\,\ell = 42)
\end{array}
\middle\|
\begin{array}{l}
\mathbf{let}\,\ell = c_2.\mathbf{recv}()\,\mathbf{in} \\
\ell \leftarrow !\,\ell + 2; \\
c_2.\mathbf{send}() \\
\\
\end{array}\right)
\end{array}$$

Protocols:

$$c_1 \rightarrowtail \mathbf{!}\,(\ell : \mathrm{Loc}, x : \mathbb{Z})\,\langle \ell \rangle \{\ell \mapsto x\}.\,\mathbf{?}\langle () \rangle \{\ell \mapsto (x+2)\}.\,\mathbf{end}$$

$$c_2 \rightarrowtail \mathbf{?}(\ell : \mathrm{Loc}, x : \mathbb{Z})\,\langle \ell \rangle \{\ell \mapsto x\}.\,\mathbf{!}\,\langle () \rangle \{\ell \mapsto (x+2)\}.\,\mathbf{end}$$

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$\{\mathrm{True}\}\ \mathbf{ref}\,v\ \{\ell.\,\ell \mapsto v\} \quad \{\ell \mapsto v\}\ !\,v\ \{w.\,w = v * \ell \mapsto v\} \quad \{\ell \mapsto v\}\ \ell \leftarrow w\ \{\ell \mapsto w\}$

Beyond This Talk

And Much More

Sample of additional Actris features:

Exchanging channels: $\mathbf{!}\,(c : \mathsf{Chan}, p : \mathsf{iProto})\,\langle c \rangle \{c \rightarrowtail \mathbf{!}\,\langle 42 \rangle .\, p\} .\, \mathbf{end}$

And Much More

Sample of additional Actris features:

Exchanging channels: $\mathbf{!}\,(c : \mathsf{Chan}, p : \mathsf{iProto})\,\langle c\rangle\{c \rightarrowtail \mathbf{!}\,\langle 42\rangle.\,p\}.\,\mathbf{end}$

Recursion: $\mu(p : \mathsf{iProto}).\,\mathbf{!}\,(c : \mathsf{Chan})\,\langle c\rangle\{c \rightarrowtail \mathbf{!}\,\langle 42\rangle.\,p\}.\,p$

And Much More

Sample of additional Actris features:

Exchanging channels: $\mathbf{!}\,(c : \mathsf{Chan}, p : \mathsf{iProto})\,\langle c\rangle\{c \rightarrowtail \mathbf{!}\,\langle 42\rangle.\,p\}.\,\mathbf{end}$

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Exchanging closures: $\mathbf{!}\,(f : \mathsf{Val}, \Phi : \mathsf{Val} \to \mathsf{iProp})\,\langle f\rangle\{(\{\mathsf{True}\}\, f\, ()\, \{w.\Phi\, w\})\}.$
$\mathbf{?}(w : \mathsf{Val})\,\langle w\rangle\{\Phi\, w\}.\,\mathbf{end}$

And Much More

Sample of additional Actris features:

Exchanging channels: $\mathbf{!}\,(c : \mathsf{Chan}, p : \mathsf{iProto})\ \langle c\rangle\{c \rightarrowtail \mathbf{!}\,\langle 42\rangle .\, p\}.\ \mathbf{end}$

Recursion: $\mu(p : \mathsf{iProto}).\ \mathbf{!}\,(c : \mathsf{Chan})\ \langle c\rangle\{c \rightarrowtail \mathbf{!}\,\langle 42\rangle .\, p\}.\, p$

Exchanging closures: $\mathbf{!}\,(f : \mathsf{Val}, \Phi : \mathsf{Val} \to \mathsf{iProp})\ \langle f\rangle\{(\{\mathsf{True}\}\ f\ ()\ \{w.\Phi\ w\})\}.$
$\mathbf{?}(w : \mathsf{Val})\ \langle w\rangle\{\Phi\ w\}.\ \mathbf{end}$

Verified programs:

- Distributed merge-sort
- Distributed load-balancing mapper
- Shared-memory Map-Reduce
- Remote procedure calls
- Distributed locks

And Much More

Sample of additional Actris features:

Exchanging channels: $\mathbf{!}\,(c : \mathsf{Chan}, p : \mathsf{iProto})\,\langle c\rangle\{c \rightarrowtail \mathbf{!}\,\langle 42\rangle\,.\,p\}\,.\,\mathbf{end}$

Recursion: $\mu(p : \mathsf{iProto})\,.\,\mathbf{!}\,(c : \mathsf{Chan})\,\langle c\rangle\{c \rightarrowtail \mathbf{!}\,\langle 42\rangle\,.\,p\}\,.\,p$

Exchanging closures: $\mathbf{!}\,(f : \mathsf{Val}, \Phi : \mathsf{Val} \to \mathsf{iProp})\,\langle f\rangle\{(\{\mathsf{True}\}\ f\ ()\ \{w.\Phi\ w\})\}\,.$
$\mathbf{?}(w : \mathsf{Val})\,\langle w\rangle\{\Phi\ w\}\,.\,\mathbf{end}$

Verified programs:

- Distributed merge-sort
- Distributed load-balancing mapper
- Shared-memory Map-Reduce
- Remote procedure calls
- Distributed locks

Fully validated and mechanized in Iris in Coq up to operational semantics

The Actris Line of Work

[POPL'20] Actris (This talk)

- Dependent separation protocols
- Actris for shared memory message passing

The Actris Line of Work

[POPL'20] Actris (This talk)

- Dependent separation protocols
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[CPP'21] Semantic Session Type System [Distinguished Paper Award]

- Semantic session types: $!A.\,S \triangleq !\,(v : \mathsf{Val})\,\langle v \rangle \{A\ v\}.\,S$

The Actris Line of Work

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[LMCS'22] Actris 2.0

- Language-parametric validation of Actris rules
- Subprotocols: $!\,(x : \mathbb{Z})\, \langle x \rangle.\, ?\langle x + 2 \rangle.\, \mathbf{end} \quad \sqsubseteq \quad !\, \langle 40 \rangle.\, ?\langle 42 \rangle.\, \mathbf{end}$

The Actris Line of Work

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[ICFP'23a] Actris in Distributed Systems

The Actris Line of Work

[POPL'20] Actris (This talk)

- Dependent separation protocols
- Actris for shared memory message passing

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[LMCS'22] Actris 2.0

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- Subprotocols: $\mathbf{!}\,(x : \mathbb{Z})\,\langle x\rangle.\,\mathbf{?}\langle x + 2\rangle.\,\mathbf{end} \quad \sqsubseteq \quad \mathbf{!}\,\langle 40\rangle.\,\mathbf{?}\langle 42\rangle.\,\mathbf{end}$

[ICFP'23a] Actris in Distributed Systems
[ICFP'23b] Minimalistic Actris (Session channels via one-shot channels)

The Actris Line of Work

[POPL'20] Actris (This talk)

- Dependent separation protocols
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[CPP'21] Semantic Session Type System [Distinguished Paper Award]

- Semantic session types: $!A.\, S \triangleq \mathbf{!}\,(v : \mathsf{Val})\,\langle v\rangle\{A\ v\}.\, S$

[LMCS'22] Actris 2.0

- Language-parametric validation of Actris rules
- Subprotocols: $\mathbf{!}\,(x : \mathbb{Z})\,\langle x\rangle.\,\mathbf{?}\langle x+2\rangle.\,\mathbf{end} \quad \sqsubseteq \quad \mathbf{!}\,\langle 40\rangle.\,\mathbf{?}\langle 42\rangle.\,\mathbf{end}$

[ICFP'23a] Actris in Distributed Systems
[ICFP'23b] Minimalistic Actris (Session channels via one-shot channels)
[POPL'24] Deadlock-freedom via Actris

The Actris Line of Work

[POPL'20] Actris (This talk)

- Dependent separation protocols
- Actris for shared memory message passing

[CPP'21] Semantic Session Type System [Distinguished Paper Award]

- Semantic session types: $!A.\,S \triangleq !\,(v : \mathsf{Val})\,\langle v\rangle\{A\;v\}.\,S$

[LMCS'22] Actris 2.0

- Language-parametric validation of Actris rules
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[ICFP'23a] Actris in Distributed Systems
[ICFP'23b] Minimalistic Actris (Session channels via one-shot channels)
[POPL'24] Deadlock-freedom via Actris

[Ongoing Work] Multiparty Actris: $!\,[i]\,(x : \mathbb{Z})\,\langle x\rangle.\,?[j]\,\langle x+2\rangle.\,\mathbf{end}$

The Actris Line of Work

[POPL'20] Actris (This talk)

- Dependent separation protocols
- Actris for shared memory message passing

[CPP'21] Semantic Session Type System [Distinguished Paper Award]

- Semantic session types: $!A.\,S \triangleq\ !\,(v : \mathsf{Val})\,\langle v \rangle \{A\ v\}.\,S$

[LMCS'22] Actris 2.0

- Language-parametric validation of Actris rules
- Subprotocols: $!\,(x : \mathbb{Z})\,\langle x \rangle.\,?\langle x + 2 \rangle.\,\mathbf{end} \quad \sqsubseteq \quad !\,\langle 40 \rangle.\,?\langle 42 \rangle.\,\mathbf{end}$

[ICFP'23a] Actris in Distributed Systems
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[Ongoing Work] Multiparty Actris: $!\,[i]\,(x : \mathbb{Z})\,\langle x \rangle.\,?[j]\,\langle x + 2 \rangle.\,\mathbf{end}$

$$
\begin{aligned}
&\mathbf{!}\,\langle \text{“Thank you”} \rangle \{ \mathtt{ActrisKnowledge} \}. \\
&\mu \mathit{rec}.\, \mathbf{?}(q : \mathtt{Question})\, \langle q \rangle \{ \mathtt{AboutActris}\; q \}. \\
&\qquad\quad \mathbf{!}\,(a : \mathtt{Answer})\, \langle a \rangle \{ \mathtt{Insightful}\; q\; a \}.\, \mathit{rec}
\end{aligned}
$$