Dependent Session Protocols in Separation Logic from First Principles

A Separation Logic Proof Pearl

Jules Jacobs
Radboud University Nijmegen

Jonas Kastberg Hinrichsen
Aarhus University

Robbert Krebbers
Radboud University Nijmegen

Message Passing Concurrency

Message passing concurrency:

- Well-structured approach to writing concurrent programs
- Threads as services and clients
- Used in Go, Scala, C#, and more

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Session types	(Actris) dependent session protocols
$!\mathbb{Z}.\,?\mathbb{Z}.\,\textbf{end}$	$!\,\langle 40\rangle.\,?\langle 42\rangle.\,\textbf{end}$
Minimalist versions exists (Kobayashi et al., Dardha et al.)	Actris employs heavy machinery *Minimalist version is the **goal** of this work*

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Actris dependent session protocols:

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

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Actris dependent session protocols:

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Actris dependent session protocols:

$$c_1 \rightarrowtail \mathbf{!}\,(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle \ell \rangle \{\ell \mapsto x\}.\, \mathbf{?}\langle () \rangle \{\ell \mapsto (x+2)\}.\,\mathbf{end}$$
$$c_2 \rightarrowtail \mathbf{?}(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle \ell \rangle \{\ell \mapsto x\}.\, \mathbf{!}\,\langle () \rangle \{\ell \mapsto (x+2)\}.\,\mathbf{end}$$

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Actris has many more features:

- Built on top of the Iris higher-order concurrent separation logic framework
  - Allows reasoning about mutable references, locks, and more
- Advanced message passing features
  - Channels as messages, recursive protocols, subprotocols (cf. subtyping)
- Fully mechanised on top of Iris in Coq

Motivation

Observation: Actris is founded upon heavy machinery

- Implementation via custom bi-directional buffers
- Protocols via custom step-indexed recursive domain equation
- Specifications and proofs via custom higher-order ghost state

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Question: How far can we get with a simpler approach?

Start from first principles:

- Mutable references ***instead of*** bi-directional buffers
- Higher-order invariants ***instead of*** custom recursive domain equation
- First-order ghost state ***instead of*** higher-order ghost state

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Start from first principles:

- Mutable references ***instead of*** bi-directional buffers
- Higher-order invariants ***instead of*** custom recursive domain equation
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All of these features are readily available in Iris!

MiniActris: a Proof Pearl Version of Actris

Key ideas:

1. Build one-shot channels on mutable references
   - With higher-order one-shot protocols via Iris's higher-order invariants
2. Build session channels on one-shot channels (Kobayashi et al., Dardha et al.)
   - With dependent session protocols via nested one-shot protocols
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Contributions:

1. A three layered approach to the implementation and specification of channels
   - One-shot channels → functional session channels → imperative session channels
2. Recovering Actris-style specifications for imperative session channels
   - Without custom recursive domain equations or higher-order ghost state
3. A minimalistic mechanisation in **less than 1000 lines** of Coq & Iris code

Outline of Presentation

In the rest of this talk we will cover:

- Layer 1: One-shot channels
- Layer 2: Functional session channels
- Layer 3: Imperative session channels
- Additional features
- Concluding remarks

Layer 1: One-Shot Channels

Layer 1: One-Shot Channels (Implementation)

One-shot channel primitives:

$$\begin{aligned}
\texttt{new1}\,() &\triangleq \texttt{ref None} \\
\texttt{send1}\,c\,v &\triangleq c \leftarrow \texttt{Some}\,v \\
\texttt{recv1}\,c &\triangleq \texttt{match}\ !\,c\ \texttt{with} \\
&\qquad \mid \texttt{None} \Rightarrow \texttt{recv1}\,c \\
&\qquad \mid \texttt{Some}\,v \Rightarrow \texttt{free}\,c;\ v \\
&\qquad \texttt{end}
\end{aligned}$$

Example program:

$$\begin{aligned}
&\texttt{let}\ c = \texttt{new1}\,()\ \texttt{in} \\
&\texttt{fork}\ \{\texttt{let}\ \ell = \texttt{ref}\ 42\ \texttt{in}\ \texttt{send1}\,c\,\ell\}\,; \\
&\texttt{let}\ \ell = \texttt{recv1}\,c\ \texttt{in}\ \texttt{assert}(!\,\ell = 42)
\end{aligned}$$

Layer 1: One-Shot Channels (Specifications)

Protocols and channel permissions:

Protocols: $p ::= (\mathsf{Send}, \Phi) \mid (\mathsf{Recv}, \Phi) \quad \text{where} \quad \Phi : \mathsf{Val} \to \mathsf{Prop}$

Duality: $\overline{(\mathsf{Send}, \Phi)} \triangleq (\mathsf{Recv}, \Phi) \qquad \overline{(\mathsf{Recv}, \Phi)} \triangleq (\mathsf{Send}, \Phi)$

Permission: $c \rightarrowtail p$

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(Hoare triple) specifications:

$$\{\mathsf{True}\}\ \mathbf{new1}\,()\ \{c.\, c \rightarrowtail p * c \rightarrowtail \overline{p}\}$$

$$\{c \rightarrowtail (\mathsf{Send}, \Phi) * \Phi\, v\}\ \mathbf{send1}\, c\, v\ \{\mathsf{True}\}$$

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Example program:

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Protocol:

$$\begin{array}{l}\Phi\,v \triangleq v \mapsto 42 \\ c \rightarrowtail (\mathsf{Send}, \Phi) \\ c \rightarrowtail (\mathsf{Recv}, \Phi)\end{array}$$

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One-shot specifications proven sound with standard Iris methodology.

$$c \rightarrowtail (\mathit{tag}, \Phi) \triangleq \ldots$$

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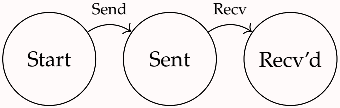

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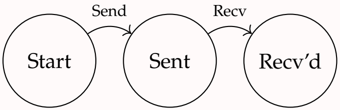

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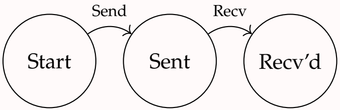

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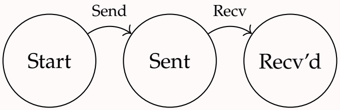

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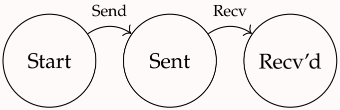

$$\mathsf{chan\_inv}\ c \triangleq (\underbrace{c \mapsto \texttt{None}}_{\text{(1) initial state}}) \vee (\underbrace{\exists v.\, c \mapsto \texttt{Some}\, v \qquad\qquad}_{\text{(2) message sent, but not yet received}}) \vee (\underbrace{\qquad\qquad}_{\text{(3) final state}})$$

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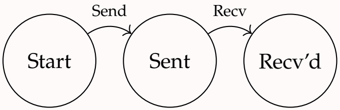

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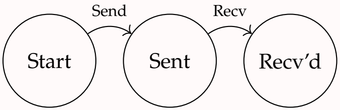

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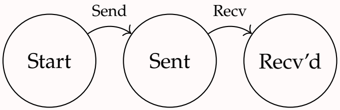

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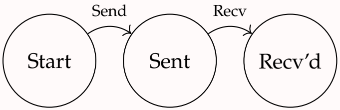

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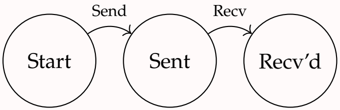

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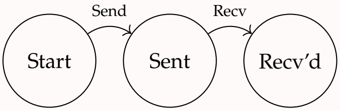

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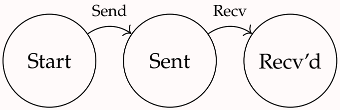

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$$c \rightarrowtail (tag, \Phi) \triangleq \exists \gamma_s, \gamma_r.\ \boxed{\mathsf{chan\_inv}\ \gamma_s\ \gamma_r\ c\ \Phi} * \triangleright \begin{cases} \mathsf{tok}\ \gamma_s & \text{if } tag = \mathsf{Send} \\ \mathsf{tok}\ \gamma_r & \text{if } tag = \mathsf{Recv} \end{cases}$$

Layer 2: Functional Session Channels

Functional session channel primitives *(Kobayashi et al., Dardha et al.)*:

$$\texttt{new}\,() \triangleq \texttt{new1}\,()$$
$$\texttt{send}\,c\,v \triangleq \texttt{let}\,c' = \texttt{new1}\,()\,\texttt{in}\,\texttt{send1}\,c\,(v, c');\ c'$$
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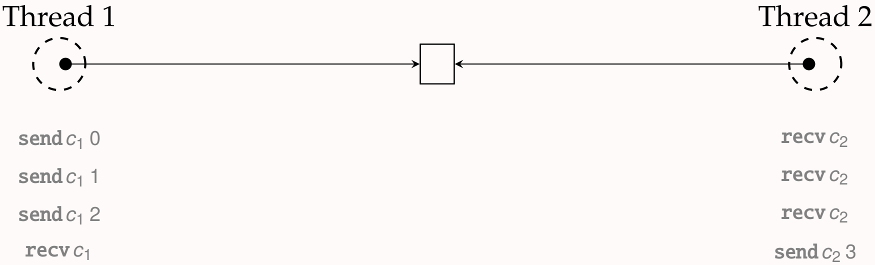
Emerging polarised bi-directional linked list:



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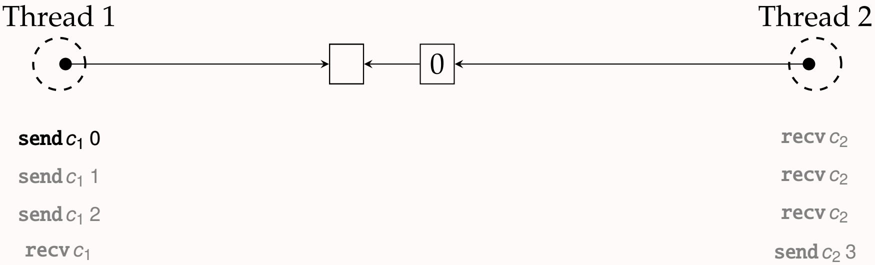

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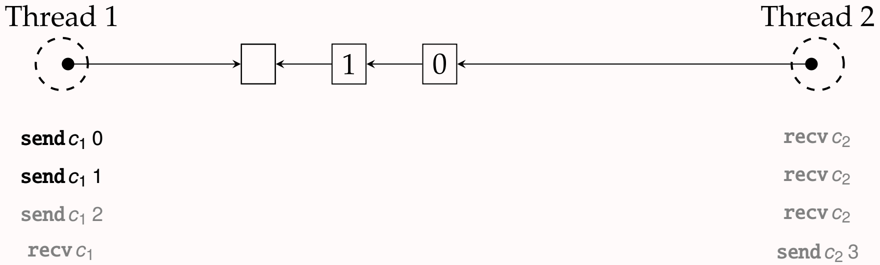

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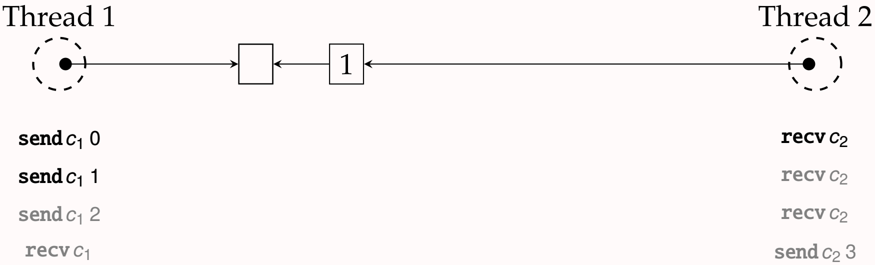

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$\texttt{send}\,c_1\,1$	$\texttt{recv}\,c_2$
$\texttt{send}\,c_1\,2$	$\texttt{recv}\,c_2$
$\texttt{recv}\,c_1$	$\texttt{send}\,c_2\,3$

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$$\mathbf{!}\,\langle w \rangle.\, p \triangleq (\mathsf{Send}, \lambda(v, c').\, v = w * c' \rightarrowtail \overline{p})$$

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Specifications:

$$\begin{aligned}\{\mathsf{True}\}\;&\mathtt{new}\,()\;\{c.\,c \rightarrowtail p * c \rightarrowtail \overline{p}\} \\ \{c \rightarrowtail (\mathbf{!}\,(x : \tau)\,\langle w\rangle\{P\}.\,p) * P\,t\}\;&\mathtt{send}\,c\,(w\,t)\;\{c'.\,c' \rightarrowtail p\,t\} \\ \{c \rightarrowtail (\mathbf{?}\,(x : \tau)\,\langle w\rangle\{P\}.\,p)\}\;&\mathtt{recv}\,c\;\{(v, c').\,\exists(x:\tau).\,v = (w\,x) * P\,x * c' \rightarrowtail p\,x\}\end{aligned}$$

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Observation: *Dependent session protocol definitions rely on higher-order invariants*

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Nested invariants *are readily supported by Iris*

Layer 3: Imperative Channels

Layer 3: Imperative Channels (Motivation and Implementation)

Functional channels are inconvenient:

$$\mathbf{let}\, c = \mathbf{send}\, c\, v\ \mathbf{in}\ \mathbf{recv}\, c$$

We instead want:

$$c.\mathbf{send}(v);\, c.\mathbf{recv}()$$

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Solution: Imperative channels

$$\begin{aligned} \texttt{new\_chan}\,() &\triangleq \texttt{let}\, c = \texttt{new}\,()\, \texttt{in}\, (\texttt{ref}\, c, \texttt{ref}\, c) \\ c.\texttt{send}(v) &\triangleq c \leftarrow \texttt{send}\, (!\, c)\, v \\ c.\texttt{recv}() &\triangleq \texttt{let}\, (v, c') = \texttt{recv}\, !\, c\, \texttt{in}\, c \leftarrow c';\, v \end{aligned}$$

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$$c.\mathbf{recv}() \triangleq \mathbf{let}\,(v, c') = \mathbf{recv}\, !\, c\, \mathbf{in}\, c \leftarrow c';\, v$$

With this we can write the program from the introduction:

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

Layer 3: Imperative Channels (Specifications)

Imperative channel endpoint ownership:

$$c \overset{\mathsf{imp}}{\rightarrowtail} p \triangleq \exists (c' : \mathsf{Val}).\, c \mapsto c' * c' \rightarrowtail p$$

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Actris specifications:

$$\{\mathsf{True}\}\ \mathbf{new\_chan}\,()\ \{(c_1, c_2).\, c_1 \xrightarrowtail{\text{imp}} p * c_2 \xrightarrowtail{\text{imp}} \overline{p}\}$$

$$\{c \xrightarrowtail{\text{imp}} (\mathbf{!}\,(x : \tau)\,\langle w \rangle \{P\}.\, p) * P\ t\}\ c.\mathbf{send}(w\ t)\ \{c \xrightarrowtail{\text{imp}} p\ t\}$$

$$\{c \xrightarrowtail{\text{imp}} (\mathbf{?}(x : \tau)\,\langle w \rangle \{P\}.\, p)\}\ c.\mathbf{recv}()\ \{v.\, \exists (x : \tau).\, v = (w\ x) * P\ x * c \xrightarrowtail{\text{imp}} p\ x\}$$

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Proof of specifications is trivial reasoning about references

Layer 3: Imperative Channels (Proof of Example)

Program from introduction:

$$\mathtt{let}\,(c_1, c_2) = \mathtt{new\_chan}\,()\,\mathtt{in}$$
$$\mathtt{fork}\ \{\mathtt{let}\,\ell = c_2.\mathtt{recv}()\,\mathtt{in}\,\ell \leftarrow (!\,l + 2); c_2.\mathtt{send}(())\}\,;$$
$$\mathtt{let}\,\ell = \mathtt{ref}\,40\,\mathtt{in}\,c_1.\mathtt{send}(\ell); c_1.\mathtt{recv}(); \mathtt{assert}(!\,\ell = 42)$$

Protocols:[1]

$$c_1 \overset{\mathsf{imp}}{\rightarrowtail} \mathbf{!}\,(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle \ell \rangle \{\ell \mapsto x\}.\, \mathbf{?}\langle () \rangle \{\ell \mapsto (x+2)\}.\, \mathbf{?end}$$
$$c_2 \overset{\mathsf{imp}}{\rightarrowtail} \mathbf{?}(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle \ell \rangle \{\ell \mapsto x\}.\, \mathbf{!}\,\langle () \rangle \{\ell \mapsto (x+2)\}.\, \mathbf{!end}$$

Actris specifications:

$$\{\mathsf{True}\}\ \mathtt{new\_chan}\,()\ \{(c_1, c_2).\, c_1 \overset{\mathsf{imp}}{\rightarrowtail} p * c_2 \overset{\mathsf{imp}}{\rightarrowtail} \overline{p}\}$$
$$\{c \overset{\mathsf{imp}}{\rightarrowtail} (\mathbf{!}\,(x : \tau)\,\langle w \rangle \{P\}.\, p) * P\ t\}\ c.\mathtt{send}(w\ t)\ \{c \overset{\mathsf{imp}}{\rightarrowtail} p\ t\}$$
$$\{c \overset{\mathsf{imp}}{\rightarrowtail} (\mathbf{?}(x : \tau)\,\langle w \rangle \{P\}.\, p)\}\ c.\mathtt{recv}()\ \{v.\, \exists (x : \tau).\, v = (w\ x) * P\ x * c \overset{\mathsf{imp}}{\rightarrowtail} p\ x\}$$

---

[1] $\mathbf{!end} \triangleq (\mathsf{Send}, \lambda v.\, v = ())$ | $\mathbf{?end} \triangleq \overline{\mathbf{!end}}$

Additional Features of MiniActris

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Recursive protocols: $\mu p.\, \mathbf{!}\,\langle 40\rangle.\, \mathbf{?}\langle 42\rangle.\, p$

Variance subprotocols: $\mathbf{?}(n : \mathbb{N})\,\langle n\rangle.\, \mathbf{!}\,\langle n+2\rangle.\, p \;\sqsubseteq\; \mathbf{?}(x : \mathbb{Z})\,\langle x\rangle.\, \mathbf{!}\,\langle x+2\rangle.\, p$

Channel deallocation: traditional (symmetric, asymmetric) & new (closing sends)

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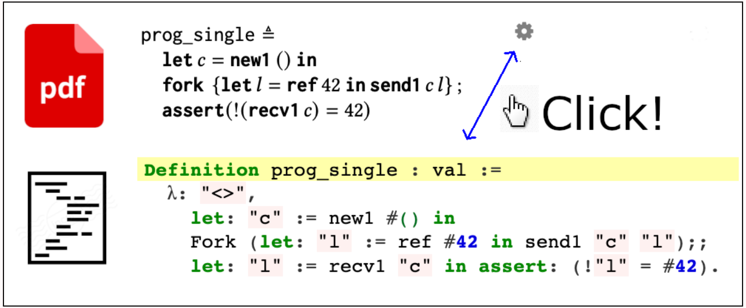
Channel deallocation: traditional (symmetric, asymmetric) & new (closing sends)

Everything mechanized in less than 1000 lines of Coq!



Concluding Remarks

Comparison with Actris

MiniActris

This work

(ICFP'23)

- **Asynchronous channels**
- **Dependent session protocols**
- **Iris separation logic**
- **Channels as messages**
- **Recursive protocols**
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Actris 1.0
Hinrichsen, Bengtson, Krebbers
(POPL'20)

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- **Asynchronous subprotocols**
- **Actris ghost theory**

Actris 1.0 (Asynchronous channels – Recursive protocols)
Hinrichsen, Bengtson, Krebbers
(POPL'20)

Actris 2.0 (Variance subprotocols – Actris ghost theory)
Hinrichsen, Bengtson, Krebbers
(LMCS'22)

Comparison with Actris

MiniActris

This work

(ICFP'23)

Asynchronous channels

Dependent session protocols

Iris separation logic

Channels as messages

Recursive protocols

Actris 1.0

Hinrichsen, Bengtson, Krebbers

(POPL'20)

Verifying Reliable Network Components in a Distributed Separation Logic with Dependent Separation Protocols

LÉON GONDELMAN, Aarhus University, Denmark
JONAS KASTBERG HINRICHSEN, Aarhus University, Denmark
MÁRIO PEREIRA, NOVA LINCS, NOVA School of Science and Technology, Portugal
AMIN TIMANY, Aarhus University, Denmark
LARS BIRKEDAL, Aarhus University, Denmark

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Actris ghost theory

Actris 2.0

Hinrichsen, Bengtson, Krebbers

(LMCS'22)

Conclusion: Sessions ♡ (Iris) Higher-Order Separation Logic

MiniActris: ***a separation logic proof pearl for verified message passing***

- Three layers: one-shot → functional → imperative
- Simple soundness proof with nested invariants
- Abundance of protocol features
- Mechanized in less than 1000 lines of Coq code

Suitable as an exercise in separation logic courses?

- One-shot channels: *suitable*
- Session channels: *within arms reach*

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

Backup Slides

Distributed MiniActris?

Conjecture: Not as elegant

- Handshake when creating new one-shot channels is non-trivial at scale
- Might be solved with session context, but then one-shots make less sense

MiniActris Ghost Theory?

Conjecture: Not feasible

- The recursion in MiniActris is tied by the references of the program
- A ghost theory solution would need to explicitly track the linked list
- Quickly ends up with similar workload as current Actris ghost theory