Multris:
Functional Verification of Multiparty Message Passing in Separation Logic

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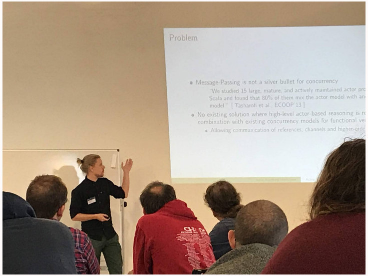
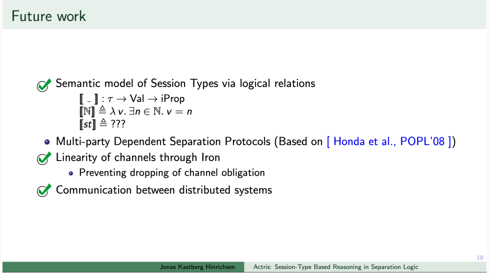
Me, Actris, and The Iris Workshop





[POPL'20] Actris, *1st Iris Workshop*
[CPP'21] Semantic Session Types
[LMCS'22] Actris 2.0, *2nd Iris Workshop*
[ICFP'23a] Actris in Distributed Systems, *2nd/3rd Iris Workshop (Léon/Me)*
[ICFP'23b] MiniActris, *3rd Iris Workshop (Jules)*
[POPL'24] LinearActris

Multris = Multiparty Actris

Actris = Verification system for message passing in Iris

Message Passing

Well-structured approach to writing concurrent (/distributed) programs

- Individual components behave as individual actors
- Actors interact based on predetermined global protocol
- We consider reliable channels: Messages are never duplicated or reordered

Message passing is not a silver bullet

- Often mixed with other programming mechanisms
  - Such as: shared memory, higher-order functions, recursion
- Many bugs happen when these mechanisms intersect
- We want functional verification that spans these intersections

Actris: program logic for verifying message passing programs

- Actris (via Iris) supports all of the above

But what about multiparty message passing?

Multiparty Message Passing

Multiparty message passing

- Message passing with dependent interactions between multiple actors
- Like a game of telephone! Or leader election

Dependencies are hard to get right

- Few results exists for functional verification
- Multiple unsound results in the literature

Idea: Modify Actris to support multiparty message passing

- Inheriting verification alongside other programming mechanisms
- Inheriting foundationally proven soundness theorem (via Iris)

Scope: Synchronous message passing in shared memory

- Synchronous: Sender and receiver block until exchange
- Shared memory: Channels implemented via references in ML-like language

Multiparty Message Passing in Shared Memory

Multiparty channels in shared memory:

$\textbf{new\_chan}(n)$	Creates a multiparty channel with n parties, returning a tuple $(c_0, \ldots, c_{(n-1)})$ of endpoints
$c_i[j].\textbf{send}(v)$	Sends a value v via endpoint c_i to party j (synchronously)
$c_i[j].\textbf{recv}()$	Receives a value via endpoint c_i from party j

Example Program: Roundtrip

$$
\begin{array}{l}
\textbf{let}\,(c_0, c_1, c_2) = \textbf{new\_chan}(3)\ \textbf{in} \\
\textbf{fork}\ \{\textbf{let}\,x = c_1[0].\textbf{recv}()\ \textbf{in}\ c_1[2].\textbf{send}(x+1)\}\,; \\
\textbf{fork}\ \{\textbf{let}\,x = c_2[1].\textbf{recv}()\ \textbf{in}\ c_2[0].\textbf{send}(x+1)\}\,; \\
c_0[1].\textbf{send}(40);\textbf{let}\,x = c_0[2].\textbf{recv}()\ \textbf{in}\ \textbf{assert}(x = 42)
\end{array}
$$

Safety and Functional Correctness

Example Program: Roundtrip

$$\begin{array}{l}
\mathtt{let}\,(c_0, c_1, c_2) = \mathtt{new_chan}(3)\ \mathtt{in} \\
\mathtt{fork}\ \{\mathtt{let}\, x = c_1[0].\mathtt{recv}()\ \mathtt{in}\, c_1[2].\mathtt{send}(x+1)\}\,; \\
\mathtt{fork}\ \{\mathtt{let}\, x = c_2[1].\mathtt{recv}()\ \mathtt{in}\, c_2[0].\mathtt{send}(x+1)\}\,; \\
c_0[1].\mathtt{send}(40);\ \mathtt{let}\, x = c_0[2].\mathtt{recv}()\ \mathtt{in}\ \mathtt{assert}(x = 42)
\end{array}$$

Goal: Prove crash-freedom (safety) and verify asserts (functional correctness)

Safety	Functional Correctness
Type systems	Program logics
Multiparty session types	???
$c_0 : \mathbf{!}[1]\mathbb{Z}.\,\mathbf{?}[2]\mathbb{Z}.\,\mathbf{end}$ $c_1 : \mathbf{?}[0]\mathbb{Z}.\,\mathbf{!}[2]\mathbb{Z}.\,\mathbf{end}$ $c_2 : \mathbf{?}[1]\mathbb{Z}.\,\mathbf{!}[0]\mathbb{Z}.\,\mathbf{end}$	???

! is send, **?** is receive

Key Idea

Prior Work: Binary protocols

- **Session Types:** $!\mathbb{Z}.\,?\mathbb{Z}.\,\textbf{end}$
- **Actris protocols:** $!\,(x:\mathbb{Z})\,\langle x\rangle.\,?\langle x+2\rangle.\,\textbf{end}$

Key Idea: Multiparty protocols!

- **Multiparty Session Types:** $![i]\mathbb{Z}.\,?[j]\mathbb{Z}.\,\textbf{end}$
- **Multiparty Actris protocols:** $!\,[i]\,(x:\mathbb{Z})\,\langle x\rangle.\,?[j]\,\langle x+2\rangle.\,\textbf{end}$

Example Program: Roundtrip

$$c_0[1].\mathbf{send}(40);\,\mathbf{let}\,x = c_0[2].\mathbf{recv}()\,\mathbf{in}\,\mathbf{assert}(x = 42)$$

Challenge: How to guarantee consistent global communication?

Challenge

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$$\begin{array}{l}
\texttt{let}\,(c_0, c_1, c_2) = \texttt{new_chan}(3)\,\texttt{in} \\
\texttt{fork}\ \{\texttt{let}\,x = c_1[0].\texttt{recv}()\,\texttt{in}\,c_1[2].\texttt{send}(x+1)\}\,; \\
\texttt{fork}\ \{\texttt{let}\,x = c_2[1].\texttt{recv}()\,\texttt{in}\,c_2[0].\texttt{send}(x+1)\}\,; \\
c_0[1].\texttt{send}(40); \texttt{let}\,x = c_0[2].\texttt{recv}()\,\texttt{in}\ \texttt{assert}(x = 42)
\end{array}$$

Prior work: Syntactic duality

$$\begin{array}{lcl}
c_0 & : & ![1]\mathbb{Z}.\,?[2]\mathbb{Z}.\,\mathbf{end} \\
c_1 & : & ?[0]\mathbb{Z}.\,![2]\mathbb{Z}.\,\mathbf{end} \\
c_2 & : & ?[1]\mathbb{Z}.\,![0]\mathbb{Z}.\,\mathbf{end}
\end{array}$$

This work: Semantic duality

$$\begin{array}{l}
c_0 \rightarrowtail\ !\,[1]\,(x:\mathbb{Z})\,\langle x\rangle.\,?[2]\,\langle x+2\rangle.\,\mathbf{end} \\
c_1 \rightarrowtail\ ?[0]\,(x:\mathbb{Z})\,\langle x\rangle.\,!\,[2]\,\langle x+1\rangle.\,\mathbf{end} \\
c_2 \rightarrowtail\ ?[1]\,(x:\mathbb{Z})\,\langle x\rangle.\,!\,[0]\,\langle x+1\rangle.\,\mathbf{end}
\end{array}$$

Key Idea: Define and prove consistency via separation logic!

Contributions

Multiparty Actris protocols

- Rich specification language for describing multiparty message passing
- Protocol consistency defined and proven in separation logic

Foundational functional verification via Multris

- Program logic for verifying multiparty message passing in Iris
- Support for language-parametric instantiation of Multiparty Actris

Verification of suite of multiparty programs

- Increasingly intricate variations of the roundtrip program
- Chang and Roberts ring leader election algorithm

Full mechanisation in Coq

- With tactic support for channels primitives and protocol consistency

Roadmap of this talk

Tour of Multiparty Actris

- Multiparty dependent separation protocols and protocol consistency
- Program logic rules
- Verification of suite of roundtrip variations

Verification of Chang and Roberts ring leader election algorithm

- Overview of algorithm
- Ring leader election protocol
- Verification of algorithm

Language-parametricity of Multiparty Actris

- Multiparty Actris ghost theory

Conclusion and Future Work

Tour of Multiparty Actris

Roundtrip Example

Roundtrip program:

$$
\begin{array}{l}
\mathbf{let}\,(c_0, c_1, c_2) = \mathbf{new\_chan}(3)\,\mathbf{in} \\
\mathbf{fork}\ \{\mathbf{let}\,x = c_1[0].\mathbf{recv}()\,\mathbf{in}\,c_1[2].\mathbf{send}(x+1)\}\,; \\
\mathbf{fork}\ \{\mathbf{let}\,x = c_2[1].\mathbf{recv}()\,\mathbf{in}\,c_2[0].\mathbf{send}(x+1)\}\,; \\
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\end{array}
$$

Goal: Prove crash-freedom (safety) and verify asserts (functional correctness)

Multiparty Actris

Channel endpoint ownership: $c \rightarrowtail p$

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

Example: $\mathbf{!}\,[1]\,(x:\mathbb{Z})\,\langle x\rangle.\,\mathbf{?}[2]\,\langle x+2\rangle.\,\mathbf{end}$

Rules:

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

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

HT-NEW
$$\{\textsc{consistent}\ \vec{p} * |\vec{p}| = n+1\}\ \mathtt{new\_chan}(|\vec{p}|)\ \{(c_0,\ldots,c_n).\,c_0 \rightarrowtail \vec{p}_0 * \ldots * c_n \rightarrowtail \vec{p}_n\}$$

Protocol Consistency

For any synchronised exchange from i to j, given the binders of i, we must:

1. Instantiate the binders of j
2. Prove equality of exchanged values
3. Prove protocol consistency where i and j are updated to their respective tails

Repeat until no more synchronised exchanges exist.

$$\frac{(\forall i, j.\ \texttt{semantic\_dual}\ \vec{p}\ i\ j)}{\textsc{consistent}\ \vec{p}}*$$

$$\frac{\vec{p}_i = \mathbf{!}\,[j]\,(\vec{x_1} : \vec{\tau_1})\,\langle v_1 \rangle.\, p_1 \mathrel{-\!\!*} \vec{p}_j = \mathbf{?}[i]\,(\vec{x_2} : \vec{\tau_2})\,\langle v_2 \rangle.\, p_2 \mathrel{-\!\!*} \\ \forall \vec{x_1} : \vec{\tau_1}.\ \exists \vec{x_2} : \vec{\tau_2}.\ v_1 = v_2 * \triangleright(\textsc{consistent}\ (\vec{p}[i := p_1][j := p_2]))}{\texttt{semantic\_dual}\ \vec{p}\ i\ j}*$$

Protocol Consistency - Example

Protocol consistency example:

$$\vec{p}_0 := \mathbf{!}\,[1]\,(x : \mathbb{Z})\,\langle x \rangle.\,\mathbf{?}[2]\,\langle x + 2 \rangle.\,\mathbf{end}$$
$$\vec{p}_1 := \mathbf{?}[0]\,(x : \mathbb{Z})\,\langle x \rangle.\,\mathbf{!}\,[2]\,\langle x + 1 \rangle.\,\mathbf{end}$$
$$\vec{p}_2 := \mathbf{?}[1]\,(x : \mathbb{Z})\,\langle x \rangle.\,\mathbf{!}\,[0]\,\langle x + 1 \rangle.\,\mathbf{end}$$

Protocol consistency:

$$\frac{(\forall i, j.\ \texttt{semantic\_dual}\ \vec{p}\ i\ j)}{\textsc{consistent}\ \vec{p}}*$$

$$\frac{\begin{array}{c}\vec{p}_i = \mathbf{!}\,[j]\,(\vec{x_1} : \vec{\tau_1})\,\langle v_1 \rangle.\,p_1 \mathrel{-\!\!*} \vec{p}_j = \mathbf{?}[i]\,(\vec{x_2} : \vec{\tau_2})\,\langle v_2 \rangle.\,p_2 \mathrel{-\!\!*} \\ \forall \vec{x_1} : \vec{\tau_1}.\ \exists \vec{x_2} : \vec{\tau_2}.\ v_1 = v_2 * \triangleright(\textsc{consistent}\ (\vec{p}[i := p_1][j := p_2]))\end{array}}{\texttt{semantic\_dual}\ \vec{p}\ i\ j}*$$

Roundtrip Example - Verified

Roundtrip program:

$$\begin{array}{l}\mathtt{let}\,(c_0, c_1, c_2) = \mathtt{new\_chan}(3)\,\mathtt{in} \\ \mathtt{fork}\ \{\mathtt{let}\,x = c_1[0].\mathtt{recv}()\,\mathtt{in}\,c_1[2].\mathtt{send}(x+1)\}\,; \\ \mathtt{fork}\ \{\mathtt{let}\,x = c_2[1].\mathtt{recv}()\,\mathtt{in}\,c_2[0].\mathtt{send}(x+1)\}\,; \\ c_0[1].\mathtt{send}(40);\,\mathtt{let}\,x = c_0[2].\mathtt{recv}()\,\mathtt{in}\ \mathtt{assert}(x = 42)\end{array}$$

Protocols:

$$\begin{array}{l}c_0 \rightarrowtail\ ![1]\,(x:\mathbb{Z})\,\langle x\rangle.\,?[2]\,\langle x+2\rangle.\,\mathbf{end} \\ c_1 \rightarrowtail\ ?[0]\,(x:\mathbb{Z})\,\langle x\rangle.\,![2]\,\langle x+1\rangle.\,\mathbf{end} \\ c_2 \rightarrowtail\ ?[1]\,(x:\mathbb{Z})\,\langle x\rangle.\,![0]\,\langle x+1\rangle.\,\mathbf{end}\end{array}$$

Verified Safety!

Roundtrip Reference Example

Roundtrip reference program:

$$\begin{array}{l}
\mathbf{let}\,(c_0, c_1, c_2) = \mathbf{new_chan}(3)\,\mathbf{in} \\
\mathbf{fork}\ \{\mathbf{let}\,\ell = c_1[0].\mathbf{recv}()\,\mathbf{in}\,\ell \leftarrow (!\,\ell + 1); c_1[2].\mathbf{send}(\ell)\}\,; \\
\mathbf{fork}\ \{\mathbf{let}\,\ell = c_2[1].\mathbf{recv}()\,\mathbf{in}\,\ell \leftarrow (!\,\ell + 1); c_2[0].\mathbf{send}()\}\,; \\
\mathbf{let}\,\ell = \mathbf{ref}\,40\,\mathbf{in}\,c_0[1].\mathbf{send}(\ell); c_0[2].\mathbf{recv}(); \mathbf{let}\,x = !\,\ell\,\mathbf{in}\,\mathbf{assert}(x = 42)
\end{array}$$

Goal: Prove crash-freedom (safety) and verify asserts (functional correctness)

Multiparty Actris with Resources

Protocols: $\mathbf{!}\,[i]\,(\vec{x}:\vec{\tau})\langle v\rangle\{P\}.\,p \mid \mathbf{?}\,[i]\,(\vec{x}:\vec{\tau})\langle v\rangle\{P\}.\,p$

Example: $\mathbf{!}\,[1]\,(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle \ell\rangle\{\ell \mapsto x\}.\,\mathbf{?}[2]\,\langle ()\rangle\{\ell \mapsto (x+2)\}.\,\mathbf{end}$

Rules:

HT-SEND

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

HT-RECV

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

HT-NEW

$$\{\textsc{consistent}\;\vec{p} * |\vec{p}| = n+1\}\;\mathtt{new\_chan}(|\vec{p}|)\;\{(c_0,\ldots,c_n).\, c_0 \rightarrowtail \vec{p}_0 * \ldots * c_n \rightarrowtail \vec{p}_n\}$$

Protocol Consistency with Resources

For any synchronised exchange from i to j, given the binders and resources of i:

1. Instantiate the binders of j
2. Prove equality of exchanged values and the resources of j
3. Prove protocol consistency where i and j are updated to their respective tails

Repeat until no more synchronised exchanges exist.

$$\frac{(\forall i, j.\ \texttt{semantic\_dual}\ \vec{p}\ i\ j)}{\textsc{consistent}\ \vec{p}}*$$

$$\frac{\begin{array}{c}\vec{p}_i = \mathbf{!}\,[j]\,(\vec{x_1} : \vec{\tau_1})\langle v_1\rangle\{P_1\}.\, p_1 \twoheadrightarrow \vec{p}_j = \mathbf{?}\,[i]\,(\vec{x_2} : \vec{\tau_2})\langle v_2\rangle\{P_2\}.\, p \twoheadrightarrow \\ \forall \vec{x_1} : \vec{\tau_1}.\, P_1 \twoheadrightarrow \exists \vec{x_2} : \vec{\tau_2}.\, v_1 = v_2 * P_2 * \triangleright(\textsc{consistent}\ (\vec{p}[i := p_1][j := p_2]))\end{array}}{\texttt{semantic\_dual}\ \vec{p}\ i\ j}*$$

Protocol Consistency with Resources - Example

Protocol consistency example:

$$\vec{p}_0 := \mathbf{!}\,[1]\,(\ell : \mathrm{Loc}, x : \mathbb{Z})\,\langle \ell \rangle \{\ell \mapsto x\}.\, \mathbf{?}[2]\,\langle () \rangle \{\ell \mapsto (x+2)\}.\,\mathbf{end}$$
$$\vec{p}_1 := \mathbf{?}[0]\,(\ell : \mathrm{Loc}, x : \mathbb{Z})\,\langle \ell \rangle \{\ell \mapsto x\}.\, \mathbf{!}\,[2]\,\langle \ell \rangle \{\ell \mapsto (x+1)\}.\,\mathbf{end}$$
$$\vec{p}_2 := \mathbf{?}[1]\,(\ell : \mathrm{Loc}, x : \mathbb{Z})\,\langle \ell \rangle \{\ell \mapsto x\}.\, \mathbf{!}\,[0]\,\langle () \rangle \{\ell \mapsto (x+1)\}.\,\mathbf{end}$$

Protocol consistency:

$$\frac{(\forall i, j.\ \texttt{semantic\_dual}\ \vec{p}\ i\ j)}{\textsc{consistent}\ \vec{p}}\,*$$

$$\frac{\begin{array}{c}\vec{p}_i = \mathbf{!}\,[j]\,(\vec{x_1} : \vec{\tau_1})\,\langle v_1 \rangle \{P_1\}.\,p_1 \twoheadrightarrow \vec{p}_j = \mathbf{?}[i]\,(\vec{x_2} : \vec{\tau_2})\,\langle v_2 \rangle \{P_2\}.\,p_2 \twoheadrightarrow \\ \forall \vec{x_1} : \vec{\tau_1}.\, P_1 \twoheadrightarrow \exists \vec{x_2} : \vec{\tau_2}.\, v_1 = v_2 * P_2 * \triangleright(\textsc{consistent}\ (\vec{p}[i := p_1][j := p_2]))\end{array}}{\texttt{semantic\_dual}\ \vec{p}\ i\ j}\,*$$

Roundtrip Reference Example - Verified

Roundtrip reference program:

$$\begin{array}{l}
\texttt{let}\,(c_0, c_1, c_2) = \texttt{new_chan}(3)\,\texttt{in} \\
\texttt{fork}\,\{\texttt{let}\,\ell = c_1[0].\texttt{recv}()\,\texttt{in}\,\ell \leftarrow (!\,\ell + 1); c_1[2].\texttt{send}(\ell)\}\,; \\
\texttt{fork}\,\{\texttt{let}\,\ell = c_2[1].\texttt{recv}()\,\texttt{in}\,\ell \leftarrow (!\,\ell + 1); c_2[0].\texttt{send}()\}\,; \\
\texttt{let}\,\ell = \texttt{ref}\,40\,\texttt{in}\,c_0[1].\texttt{send}(\ell); c_0[2].\texttt{recv}(); \texttt{let}\,x = !\,\ell\,\texttt{in}\,\texttt{assert}(x = 42)
\end{array}$$

Protocols:

$$\begin{array}{l}
c_0 \rightarrowtail \mathbf{!}\,[1]\,(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle \ell \rangle \{\ell \mapsto x\}.\,\mathbf{?}[2]\,\langle () \rangle \{\ell \mapsto (x + 2)\}.\,\mathbf{end} \\
c_1 \rightarrowtail \mathbf{?}[0]\,(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle \ell \rangle \{\ell \mapsto x\}.\,\mathbf{!}\,[2]\,\langle \ell \rangle \{\ell \mapsto (x + 1)\}.\,\mathbf{end} \\
c_2 \rightarrowtail \mathbf{?}[1]\,(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle \ell \rangle \{\ell \mapsto x\}.\,\mathbf{!}\,[0]\,\langle () \rangle \{\ell \mapsto (x + 1)\}.\,\mathbf{end}
\end{array}$$

Protocol Consistency - Recursion

Protocols are contractive in the tail:

$$\mu rec.\, !\,[1]\,(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle \ell \rangle\{\ell \mapsto x\}.\, ?[2]\,\langle () \rangle\{\ell \mapsto (x+2)\}.\, rec$$

Protocols:

$$\begin{aligned}
\vec{p}_0 &= \mu rec.\, !\,[1]\,(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle \ell \rangle\{\ell \mapsto x\}.\, ?[2]\,\langle () \rangle\{\ell \mapsto (x+2)\}.\, rec \\
\vec{p}_1 &= \mu rec.\, ?[0]\,(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle \ell \rangle\{\ell \mapsto x\}.\, !\,[2]\,\langle \ell \rangle\{\ell \mapsto (x+1)\}.\, rec \\
\vec{p}_2 &= \mu rec.\, ?[1]\,(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle \ell \rangle\{\ell \mapsto x\}.\, !\,[0]\,\langle () \rangle\{\ell \mapsto (x+1)\}.\, rec
\end{aligned}$$

Recursion via Löb induction (▷):

$$\frac{\begin{array}{c}\vec{p}_i = !\,[j]\,(\vec{x_1} : \vec{\tau_1})\,\langle v_1 \rangle\{P_1\}.\, p_1 \twoheadrightarrow \vec{p}_j = ?[i]\,(\vec{x_2} : \vec{\tau_2})\,\langle v_2 \rangle\{P_2\}.\, p_2 \twoheadrightarrow \\ \forall \vec{x_1} : \vec{\tau_1}.\, P_1 \twoheadrightarrow \exists \vec{x_2} : \vec{\tau_2}.\, v_1 = v_2 * P_2 * \triangleright(\textsc{consistent}\,(\vec{p}[i := p_1][j := p_2]))\end{array}}{\texttt{semantic\_dual}\ \vec{p}\ i\ j}*$$

Protocol Consistency - Framing

Consider the replacement of process 1 with a forwarder:

$$\texttt{let}\, v = c_1[0].\mathbf{recv}()\, \texttt{in}\, c_1[1].\mathbf{send}(v)$$

Protocols:

$$\begin{aligned}
\vec{p}_0 &= \mu rec.\, \mathbf{!}\,[1]\,(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle \ell \rangle \{\ell \mapsto x\}.\, \mathbf{?}[2]\,\langle () \rangle \{\ell \mapsto (x+1)\}.\, rec \\
\vec{p}_1 &= \mu rec.\, \mathbf{?}[0]\,(v : \mathsf{Val})\,\langle v \rangle.\, \mathbf{!}\,[2]\,\langle v \rangle.\, rec \\
\vec{p}_2 &= \mu rec.\, \mathbf{?}[1]\,(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle \ell \rangle \{\ell \mapsto x\}.\, \mathbf{!}\,[0]\,\langle () \rangle \{\ell \mapsto (x+1)\}.\, rec
\end{aligned}$$

Protocol consistency owns resources while in transit:

$$\frac{\begin{array}{c}\vec{p}_i = \mathbf{!}\,[j]\,(\vec{x_1} : \vec{\tau_1})\,\langle v_1 \rangle \{P_1\}.\, p_1 \mathrel{-\!\!*} \vec{p}_j = \mathbf{?}[i]\,(\vec{x_2} : \vec{\tau_2})\,\langle v_2 \rangle \{P_2\}.\, p_2 \mathrel{-\!\!*} \\ \forall \vec{x_1} : \vec{\tau_1}.\, P_1 \mathrel{-\!\!*} \exists \vec{x_2} : \vec{\tau_2}.\, v_1 = v_2 * P_2 * \triangleright(\textsc{consistent}\,(\vec{p}[i := p_1][j := p_2]))\end{array}}{\texttt{semantic\_dual}\, \vec{p}\; i\; j}*$$

Protocol Consistency - Branching

Consider the extension of process 1 with a rerouter:

$$\texttt{let}\,(v,b) = c_1[0].\texttt{recv}()\ \texttt{in}\ c_1[\texttt{if}\ b\ \texttt{then}\ 2\ \texttt{else}\ 3].\texttt{send}(v)$$

Protocols:

$$\begin{aligned}
\vec{p}_0 &= \mu rec.\,![1]\,(\ell : \mathsf{Loc}, x : \mathbb{Z}, b : \mathbb{B})\,\langle(\ell, b)\rangle\{\ell \mapsto x\}.\\
&\qquad\qquad ?[\texttt{if}\ b\ \texttt{then}\ 2\ \texttt{else}\ 3]\,\langle()\rangle\{\ell \mapsto (x+1)\}.\,rec\\
\vec{p}_1 &= \mu rec.\,?[0]\,(v : \mathsf{Val}, b : \mathbb{B})\,\langle(v, b)\rangle.\,![\texttt{if}\ b\ \texttt{then}\ 2\ \texttt{else}\ 3]\,\langle v\rangle.\,rec\\
\vec{p}_2, \vec{p}_3 &= \mu rec.\,?[1]\,(\ell : \mathsf{Loc}, x : \mathbb{Z})\,\langle\ell\rangle\{\ell \mapsto x\}.\,![0]\,\langle()\rangle\{\ell \mapsto (x+1)\}.\,rec
\end{aligned}$$

We can do case analysis on the binders:

$$\frac{\begin{array}{c}\vec{p}_i = ![j]\,(\vec{x_1} : \vec{\tau_1})\,\langle v_1\rangle\{P_1\}.\,p_1 \mathrel{-\!\!*} \vec{p}_j = ?[i]\,(\vec{x_2} : \vec{\tau_2})\,\langle v_2\rangle\{P_2\}.\,p_2 \mathrel{-\!\!*}\\ \forall \vec{x_1} : \vec{\tau_1}.\, P_1 \mathrel{-\!\!*} \exists \vec{x_2} : \vec{\tau_2}.\, v_1 = v_2 * P_2 * \triangleright(\textsc{consistent}\ (\vec{p}[i := p_1][j := p_2]))\end{array}}{\texttt{semantic\_dual}\ \vec{p}\ i\ j}\,*$$

Benchmark:
Chang and Roberts
Ring Leader Election

Leader Election

Consider n uniquely identifiable actors in a network

Leader election is an algorithm that upon satisfies:

- **Uniqueness:** There is exactly one actor that considers itself as leader
- **Agreement:** All other actors know who the leader is
- **Termination:** The algorithm finishes in finite time*

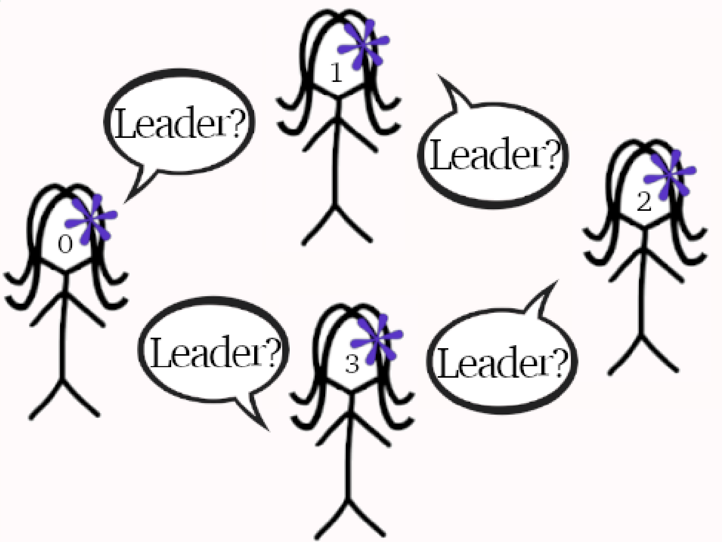
Goal: Prove **uniqueness** and **agreement**

Observation: We prove partial correctness so **termination** is out of scope

We lift the properties to functional correctness as:

- **Uniqueness:** The leader can proceed with elevated permissions (resources)
- **Agreement:** Participants following interaction can depend on knowing leader

Chang and Roberts Ring Leader Election - Overview



Chang and Roberts Ring Leader Election - Algorithm

Consider n actors, with unique id's, arranged in a ring

- Ex1: $0 \rightarrow 1, 1 \rightarrow 2, 2 \rightarrow 0$
- Ex2: $0 \rightarrow 2, 2 \rightarrow 1, 1 \rightarrow 0$

Actors are tagged as participating or not; everyone starts untagged

- Tag as participating whenever any message is sent

Message types are election(i') **(1)** and elected(i') **(2)**

Received election(i') messages are compared to the receivers id i and

- If $i' > i$, send election(i') **(1.1)**
- If $i' = i$, we are elected, send elected(i) **(1.2)**
- If we are not participating, send election(i) **(1.3)**
- If we are already participating, do nothing **(1.4)**

Received elected(i') messages are compared to the participants id i and

- If $i' = i$, terminate by returning i' **(2.1)**
- If $i' \neq i$, send elected(i'), and terminate by returning i' **(2.2)**

Chang and Roberts Ring Leader Election - Implementation

We encode election(i) as $\mathbf{inl}\ i$ and elected(i) as $\mathbf{inr}\ i$.
We write i_l and i_r for the left and right participants of participant i.
The leader election process can then be implemented as follows:

$$
\begin{aligned}
&\text{process}\ c\ i \ \triangleq\ \mathbf{rec}\ \mathit{rec}\ \mathit{isp} = \\
&\quad \mathbf{match}\ c[i_r].\mathbf{recv}()\ \mathbf{with} \\
&\quad \mid \mathbf{inl}\ i' \Rightarrow \mathbf{if}\ i < i'\ \mathbf{then}\ c[i_l].\mathbf{send}(\mathbf{inl}\ i');\ \mathit{rec}\ \mathbf{true} && (\mathbf{1.1}) \\
&\qquad\qquad\quad \mathbf{else\ if}\ i = i'\ \mathbf{then}\ c[i_l].\mathbf{send}(\mathbf{inr}\ i);\ \mathit{rec}\ \mathbf{false} && (\mathbf{1.2}) \\
&\qquad\qquad\quad \mathbf{else\ if}\ \mathit{isp}\ \mathbf{then}\ \mathit{rec}\ \mathbf{true} && (\mathbf{1.3}) \\
&\qquad\qquad\quad \mathbf{else}\ c[i_l].\mathbf{send}(\mathbf{inl}\ i);\ \mathit{rec}\ \mathbf{true} && (\mathbf{1.4}) \\
&\quad \mid \mathbf{inr}\ i' \Rightarrow \mathbf{if}\ i = i'\ \mathbf{then}\ i' && (\mathbf{2.1}) \\
&\qquad\qquad\quad \mathbf{else}\ c[i_l].\mathbf{send}(\mathbf{inr}\ i');\ i' && (\mathbf{2.2}) \\
&\quad \mathbf{end}
\end{aligned}
$$

Chang and Roberts Ring Leader Election - Validation

Procedure for starting the election:

$$\text{init } c\ i \triangleq c[i_l].\mathtt{send}(\mathtt{inl}\ i);\ \text{process } c\ i\ \mathtt{true}$$

Closed program example of election:

$$\begin{array}{l}
\text{ring_ref_prog } n \triangleq \\
\quad \mathtt{let}\ \ell = \mathtt{ref}\ 42\ \mathtt{in} \\
\quad \mathtt{let}\ (c_0, \ldots, c_{n-1}) = \mathtt{new_chan}(n)\ \mathtt{in} \\
\quad \mathtt{for}(i = 1 \ldots (n-1)) \left\{ \mathtt{fork} \left\{ \begin{array}{l} \mathtt{let}\ i' = \text{process } c_i\ i\ \mathtt{false}\ \mathtt{in} \\ \mathtt{if}\ i' = i\ \mathtt{then}\ \mathtt{free}\ \ell\ \mathtt{else}\ () \end{array} \right\} \right\}; \\
\quad \mathtt{let}\ i' = \text{init } c_0\ 0\ \mathtt{in}\ \mathtt{if}\ i' = 0\ \mathtt{then}\ \mathtt{free}\ \ell\ \mathtt{else}\ ()
\end{array}$$

Goal: Verify that only one leader is elected (no use-after-free)

Chang and Roberts Ring Leader Election - Protocol

We can define the ring leader election protocol as:

$$\mathsf{ring\_prot}(i:\mathbb{N})(P:\mathsf{iProp})(p:\mathbb{N}\to\mathsf{iProto}):\mathbb{B}\to\mathsf{iProto}\triangleq\mu\mathit{rec}.\,\lambda(\mathit{isp}:\mathbb{B}).$$

$$\&[i_r]\left\{\begin{array}{lll}\mathtt{inl}(i':\mathbb{N})\langle i'\rangle & \Rightarrow \mathtt{if}\ i<i'\ \mathtt{then}\ !\,[i_l]\,\langle\mathtt{inl}\ i'\rangle.\,\mathit{rec}\ \mathtt{true} & (\mathbf{1.1})\\ & \quad\mathtt{else\ if}\ i=i'\ \mathtt{then}\ !\,[i_l]\,\langle\mathtt{inr}\ i\rangle.\,\mathit{rec}\ \mathtt{false} & (\mathbf{1.2})\\ & \quad\mathtt{else\ if}\ \mathit{isp}\ \mathtt{then}\ \mathit{rec}\ \mathtt{true} & (\mathbf{1.3})\\ & \quad\mathtt{else}\ !\,[i_l]\,\langle\mathtt{inl}\ i\rangle.\,\mathit{rec}\ \mathtt{true} & (\mathbf{1.4})\\ \mathtt{inr}(i':\mathbb{N})\langle i'\rangle\{i=i'\Rightarrow P\} & \Rightarrow \mathtt{if}\ i=i'\ \mathtt{then}\ p\ i' & (\mathbf{2.1})\\ & \quad\mathtt{else}\ !\,[i_l]\,\langle\mathtt{inr}\ i'\rangle.\,p\ i' & (\mathbf{2.2})\end{array}\right\}$$

This lets us verify the following spec for the ring leader process:

$$\{c\rightarrowtail\mathsf{ring\_prot}\ i\ P\ p\ \mathit{isp}\}\ \mathsf{process}\ c\ i\ \mathit{isp}\ \{i'.\,c\rightarrowtail(p\ i')*(i=i'\Rightarrow P)\}$$

Chang and Roberts Ring Leader Election - Init

The protocol for starting an election is an extension of the ring protocol:

$$\begin{aligned}&\mathsf{init\_prot}(i : \mathbb{N})(P : \mathsf{iProp})(p : \mathbb{N} \to \mathsf{iProto}) : \mathsf{iProto} \triangleq \\ &\quad \mathbf{!}\,[i_l]\,\langle \mathtt{inl}\ i\rangle\{P\}.\ \mathsf{ring\_prot}\ i\ P\ p\ \mathtt{true}\end{aligned}$$

With the initial message we yield the P resource to the network.

With this protocol we can prove the following specification for the starting process:

$$\{c \rightarrowtail (\mathsf{init\_prot}\ i\ P\ p) * P\}\ \mathsf{init}\ c\ i\ \{i'.\ c \rightarrowtail (p\ i') * (i = i' \Rightarrow P)\}$$

Chang and Roberts Ring Leader Election - Leader Uniqueness

$$\begin{array}{l}
\mathsf{ring_ref_prog}\ n \triangleq \\
\quad \mathtt{let}\ \ell = \mathtt{ref}\ 42\ \mathtt{in} \\
\quad \mathtt{let}\ (c_0, \ldots, c_{n-1}) = \mathtt{new_chan}(n)\ \mathtt{in} \\
\quad \mathtt{for}(i = 1 \ldots (n-1)) \left\{ \mathtt{fork} \left\{ \begin{array}{l} \mathtt{let}\ i' = \mathsf{process}\ c_i\ i\ \mathtt{false}\ \mathtt{in} \\ \mathtt{if}\ i' = i\ \mathtt{then}\ \mathtt{free}\ \ell\ \mathtt{else}\ () \end{array} \right\} \right\}; \\
\quad \mathtt{let}\ i' = \mathsf{init}\ c_0\ 0\ \mathtt{in}\ \mathtt{if}\ i' = 0\ \mathtt{then}\ \mathtt{free}\ \ell\ \mathtt{else}\ ()
\end{array}$$

We verify the program for 3 participants with the following protocols:

$$c_0 \rightarrowtail \mathbf{end}$$

$$c_1 \rightarrowtail \mathbf{end}$$

$$c_2 \rightarrowtail \mathbf{end}$$

We can thus verify: $\{\mathsf{True}\}\ \mathsf{ring\_ref\_prog}\ 3\ \{\mathsf{True}\}$

Chang and Roberts Ring Leader Election - Leader Agreement

$$
\begin{aligned}
&\mathsf{ring\_del\_prog}\ n \triangleq \\
&\quad \mathtt{let}\ (c_0, \ldots, c_n) = \mathtt{new\_chan}(n+1)\ \mathtt{in} \\
&\quad \mathtt{fork}\ \{\mathtt{let}\ i' = c_n[0].\mathtt{recv}()\ \mathtt{in}\ \mathtt{for}(i = 1 \ldots (n-1))\ \{\mathtt{assert}(c_n[i].\mathtt{recv}() = i')\}\}\ ; \\
&\quad \mathtt{for}(i = 1 \ldots (n-1))\ \{\mathtt{fork}\ \{\mathtt{let}\ i' = \mathsf{process}\ c_i\ i\ \mathtt{false}\ \mathtt{in}\ c_i[n].\mathtt{send}(i')\}\}\ ; \\
&\quad \mathtt{let}\ i' = \mathsf{init}\ c_0\ 0\ \mathtt{in}\ c_0[n].\mathtt{send}(i')
\end{aligned}
$$

We verify the program for 3 participants and 1 central coordinator:

$$
\begin{aligned}
c_0 &\rightarrowtail \mathbf{end} \\
c_1 &\rightarrowtail \mathbf{end} \\
c_2 &\rightarrowtail \mathbf{end} \\
c_3 &\rightarrowtail \mathbf{end}
\end{aligned}
$$

We can thus verify: $\{\mathsf{True}\}\ \mathsf{ring\_del\_prog}\ 3\ \{\mathsf{True}\}$

Language Parametricity of Multiparty Actris

Multiparty Actris Ghost Theory

We prove language-generic ghost theory rules:

PROTO-ALLOC
$$\frac{\textsc{consistent}\ \vec{p}}{\Rrightarrow \exists \chi.\ \mathsf{prot\_ctx}\ \chi\ |\vec{p}| * \mathop{\ast}_{i \mapsto p \in \vec{p}} \mathsf{prot\_own}\ \chi\ i\ p}$$

PROTO-VALID
$$\frac{\mathsf{prot\_ctx}\ \chi\ n \qquad \mathsf{prot\_own}\ \chi\ i\ p}{i < n}$$

PROTO-STEP
$$\frac{\begin{array}{c}\mathsf{prot\_ctx}\ \chi\ n \qquad P_1[\vec{t_1}/\vec{x_1}] \\ \mathsf{prot\_own}\ \chi\ i\ (\mathbf{!}\,[j]\,(\vec{x_1} : \vec{\tau_1})\,\langle v_1\rangle\{P_1\}.\, p_1) \qquad \mathsf{prot\_own}\ \chi\ j\ (\mathbf{?}[i]\,(\vec{x_2} : \vec{\tau_2})\,\langle v_2\rangle\{P_2\}.\, p_2)\end{array}}{\begin{array}{c}\Rrightarrow \triangleright \exists (\vec{t_2} : \vec{\tau_2}).\ \mathsf{prot\_ctx}\ \chi\ * \mathsf{prot\_own}\ \chi\ i\ (p_1[\vec{t_1}/\vec{x_1}]) * \mathsf{prot\_own}\ \chi\ j\ (p_2[\vec{t_2}/\vec{x_2}]) * \\ (v_1[\vec{t_1}/\vec{x_1}]) = (v_2[\vec{t_2}/\vec{x_2}]) * P_2[\vec{t_2}/\vec{x_2}]\end{array}}$$

One can then define $c \rightarrowtail p$ and prove Hoare triple rules for a given language using the ghost theory

- Such as Ht-send, Ht-recv, and Ht-new

Conclusion and Future Work

Conclusion

Dependent multiparty protocols are non-trivial to prove sound

- Mismatched dependencies (quantifiers) makes syntactic analysis difficult
- Fullfillment of received resources is tricky

Concurrent separation logic (Iris) is a good fit for multiparty protocols

- Quantifier scopes enable inherent tracking of dependencies
- Separation logic enables framing of resources
- Integration with other features readily available

Automation of protocol consistency proofs is warranted

- Deterministic (often synchronous) protocols are barely manageable
- Brute-force procedure allows for some automation
- Asynchronous protocols would require more efficient techniques

Future Work

Additional features

- Asynchronous communication

More scalable methodology for proving protocol consistency

- Abstraction and Modularity via separation logic
- Automation via model checking?

Semantic Multiparty Session Type System

- Investigate correspondences with syntactic protocol consistency

Deadlock freedom guarantees

- Leverage connectivity graphs for multiparty communication

Multiparty Actris for distributed systems

- Leverage Aneris

And much more?: RefinedActris, Verified Secure MPC, Non-interference, ...

$$
\begin{aligned}
&\mathbf{!}\,[1]\,\langle\text{“Thank you”}\rangle\{\texttt{MultrisOverview}\}.\\
&\mu rec.\,\mathbf{?}[1]\,(q : \texttt{Question i})\,\langle q\rangle\{\texttt{AboutMultris}\;q\}.\\
&\qquad\mathbf{!}\,[i]\,(a : \texttt{Answer})\,\langle a\rangle\{\texttt{Insightful}\;q\;a\}.\,rec
\end{aligned}
$$