Multris:
Functional Verification of Multiparty Message Passing in Separation Logic

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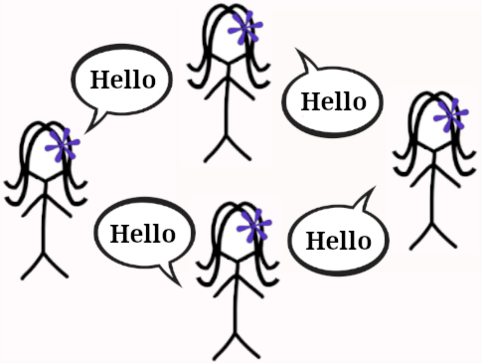
Multiparty Message Passing



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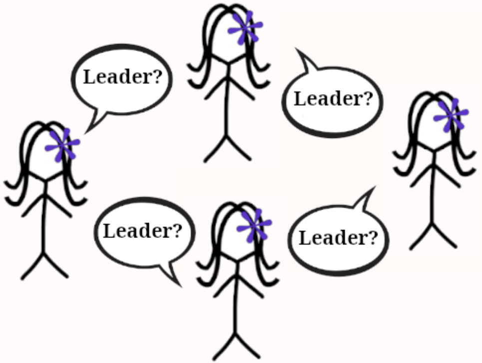

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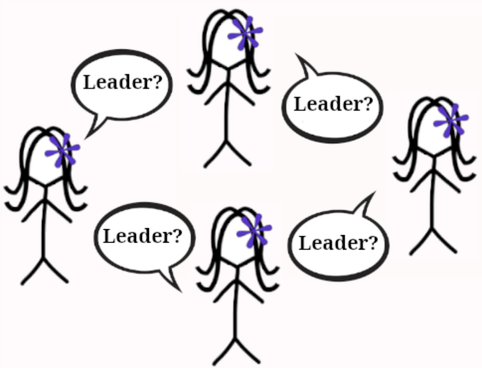

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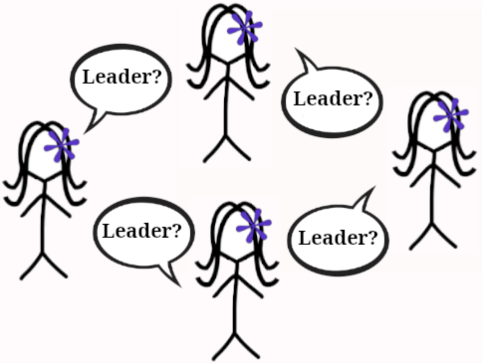

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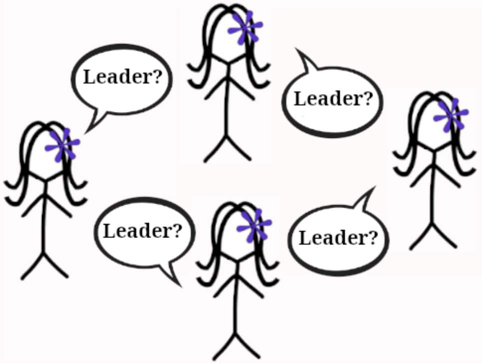

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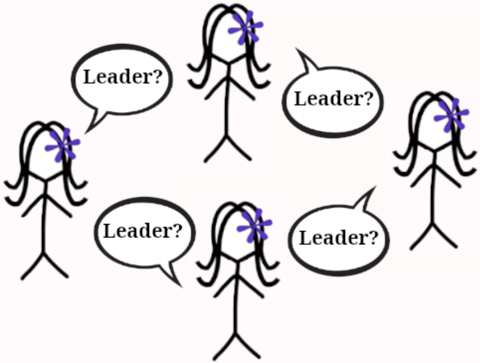
Warrants functional verification

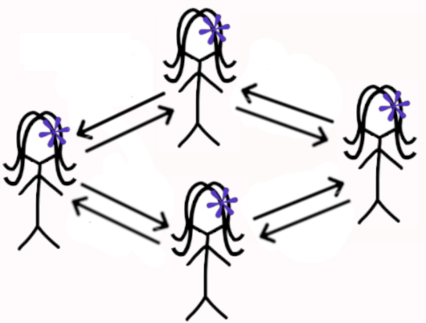
- No results that supports all the above
- We want validation in a mechanised theorem prover



Our Setting of Multiparty Message Passing

Message passing over bi-directional channels with distinct channel endpoints

- Each endpoint correspond to one party



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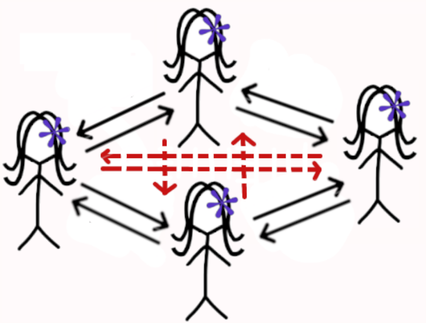

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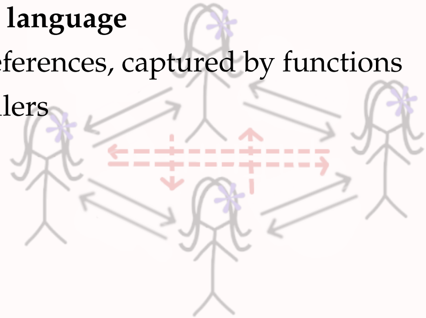
- Similar to Go channels and BSD socket handlers



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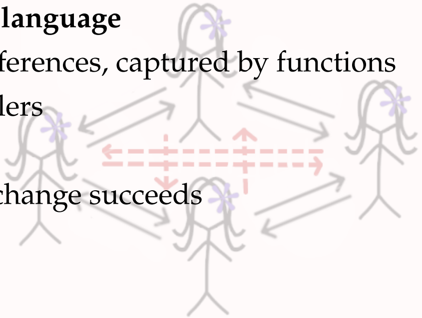

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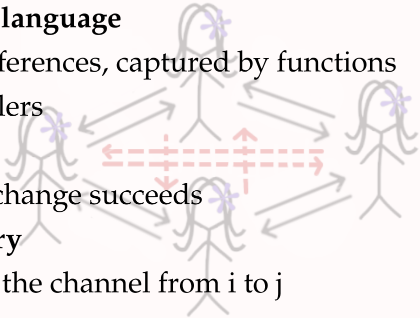
Implementation via references in shared memory

- Implemented as an N x N matrix where i,j is the channel from i to j



Multiparty Message Passing in Shared Memory

Multiparty channels API:

new_chan(n)	Creates a multiparty channel with n parties, returning a tuple $(c_0, \ldots, c_{(n-1)})$ of endpoints
$c_i[j]$.**send**(v)	Sends a value v via endpoint c_i to party j (synchronously)
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Binary	Session Types	Dependent separation protocols

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Key Idea

Prior work:

- **Safety (Multiparty):** $\mathbf{!}[1]\mathbb{Z}.\,\mathbf{?}[2]\mathbb{Z}.\,\textbf{end}$

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This work: Semantic duality

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

Key Idea: Define and prove consistency via separation logic!

Contributions

Multiparty dependent separation protocols (MDSPs)

- Rich specification language for describing multiparty message passing
- Protocol consistency defined in terms of semantic duality, proven in separation logic

Multris separation logic

- Separation logic for verifying multiparty communication via MDSPs
- Support for language-parametric instantiation of Multris

Verification of suite of multiparty programs

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

Full mechanisation in Rocq

- With tactic support for protocol consistency and channel primitives

Roadmap of this talk

Separation Logic Primer

- Operational semantics
- Hoare triples
- Separation logic

Tour of the Multris separation logic

- Multiparty dependent separation protocols and protocol consistency
- Verification rules for multiparty channels
- Verification of suite of roundtrip variations

Conclusion and Future Work

Separation Logic Primer

Operational Semantics

HeapLang: Untyped OCaml-like language

$$
\begin{aligned}
v, w \in \mathsf{Val} &::= z \mid \mathbf{true} \mid \mathbf{false} \mid () \mid \ell \mid \lambda x.\, e \\
e \in \mathsf{Expr} &::= v \mid x \mid e_1\ e_2 \mid \mathbf{let}\, x = e_1\ \mathbf{in}\, e_2 \mid e_1; e_2 \mid \\
&\quad \mathbf{ref}\, e \mid !\, e \mid e_1 \leftarrow e_2 \mid \\
&\quad (e_1 \parallel e_2) \mid \mathbf{assert}(e) \mid \ldots
\end{aligned}
$$

Operational Semantics

HeapLang: Untyped OCaml-like language

$$
\begin{aligned}
v, w \in \mathsf{Val} &::= z \mid \mathbf{true} \mid \mathbf{false} \mid () \mid \ell \mid \lambda x.\, e \\
e \in \mathsf{Expr} &::= v \mid x \mid e_1\ e_2 \mid \mathbf{let}\ x = e_1\ \mathbf{in}\ e_2 \mid e_1 ; e_2 \mid \\
&\quad \mathbf{ref}\ e \mid !\, e \mid e_1 \leftarrow e_2 \mid \\
&\quad (e_1 \parallel e_2) \mid \mathbf{assert}(e) \mid \ldots
\end{aligned}
$$

Example program:

$$
\begin{array}{l}
\mathbf{let}\ \ell_1 = \mathbf{ref}\ 0\ \mathbf{in} \\
\mathbf{let}\ \ell_2 = \mathbf{ref}\ 0\ \mathbf{in} \\
\big(\ell_1 \leftarrow !\,\ell_1 + 2 \parallel \ell_2 \leftarrow !\,\ell_2 + 2\big)\,; \\
\mathbf{assert}(!\,\ell_1 + !\,\ell_2 = 4)
\end{array}
$$

Operational Semantics

HeapLang: Untyped OCaml-like language

$$\begin{aligned} v, w \in \mathsf{Val} &::= z \mid \mathbf{true} \mid \mathbf{false} \mid () \mid \ell \mid \lambda x.\, e \\ e \in \mathsf{Expr} &::= v \mid x \mid e_1\, e_2 \mid \mathbf{let}\, x = e_1\, \mathbf{in}\, e_2 \mid e_1 ; e_2 \mid \\ &\quad\ \mathbf{ref}\, e \mid !\, e \mid e_1 \leftarrow e_2 \mid \\ &\quad\ (e_1 \parallel e_2) \mid \mathbf{assert}(e) \mid \ldots \end{aligned}$$

Example program:

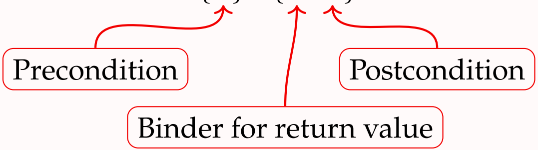
$$\begin{array}{l} \mathbf{let}\, \ell_1 = \mathbf{ref}\, 0\, \mathbf{in} \\ \mathbf{let}\, \ell_2 = \mathbf{ref}\, 0\, \mathbf{in} \\ \big(\ell_1 \leftarrow !\, \ell_1 + 2 \parallel \ell_2 \leftarrow !\, \ell_2 + 2\big)\, ; \\ \mathbf{assert}(!\, \ell_1 + !\, \ell_2 = 4) \end{array}$$

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

Hoare Triples

Hoare triples for partial functional correctness:

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



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 and knowledge about the state

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.

Separation Logic

Separation logic: propositions assert ownership and knowledge about the state

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.

Enables modular reasoning, through disjointness:

Ht-frame

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

Hoare Triples for Seperation Logic

Hoare triples for references:

Ht-alloc
$\{\mathsf{True}\}\ \mathtt{ref}\, v\ \{\ell.\ \ell \mapsto v\}$

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

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

Hoare Triples for Seperation Logic

Hoare triples for references:

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

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

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

Hoare triples for structural expressions:

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

HT-ASSERT
$$\frac{\{P\}\ e\ \{w.\ w = \mathtt{true} * Q\}}{\{P\}\ \mathtt{assert}(e)\ \{Q\}}$$

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

$$\mathbf{let}\ \ell_1 = \mathbf{ref}\ 0\ \mathbf{in}$$
$$\mathbf{let}\ \ell_2 = \mathbf{ref}\ 0\ \mathbf{in}$$
$$\big(\ell_1 \leftarrow !\,\ell_1 + 2 \parallel \ell_2 \leftarrow !\,\ell_2 + 2\big)\,;$$
$$\mathbf{assert}(!\,\ell_1 + !\,\ell_2 = 4)$$

Example Program - Verified

$$\{\mathsf{True}\}$$
$$\mathbf{let}\ \ell_1 = \mathbf{ref}\ 0\ \mathbf{in}$$
$$\mathbf{let}\ \ell_2 = \mathbf{ref}\ 0\ \mathbf{in}$$
$$(\ell_1 \leftarrow !\,\ell_1 + 2 \parallel \ell_2 \leftarrow !\,\ell_2 + 2)\,;$$
$$\mathbf{assert}(!\,\ell_1 + !\,\ell_2 = 4)$$
$$\{\mathsf{True}\}$$

Example Program - Verified

$\{\mathsf{True}\}$

$\mathbf{let}\ \ell_1 = \mathbf{ref}\ 0\ \mathbf{in}$ // HT-LET, HT-ALLOC

$\{\ell_1 \mapsto 0\}$

$\mathbf{let}\ \ell_2 = \mathbf{ref}\ 0\ \mathbf{in}$

$(\ell_1 \leftarrow !\,\ell_1 + 2 \parallel \ell_2 \leftarrow !\,\ell_2 + 2)\,;$

$\mathbf{assert}(!\,\ell_1 + !\,\ell_2 = 4)$

$\{\mathsf{True}\}$

Example Program - Verified

$\{\mathsf{True}\}$

$\texttt{let}\ \ell_1 = \texttt{ref}\ 0\ \texttt{in}$ // HT-LET, HT-ALLOC

$\{\ell_1 \mapsto 0\}$

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

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

$\left(\ell_1 \leftarrow !\,\ell_1 + 2 \;\middle\|\; \ell_2 \leftarrow !\,\ell_2 + 2\right);$

$\texttt{assert}(!\,\ell_1 + !\,\ell_2 = 4)$

$\{\mathsf{True}\}$

Example Program - Verified

$$
\begin{array}{ll}
\{\mathsf{True}\} & \\
\mathbf{let}\ \ell_1 = \mathbf{ref}\ 0\ \mathbf{in} & //\ \textsc{Ht-let}, \textsc{Ht-alloc} \\
\{\ell_1 \mapsto 0\} & \\
\mathbf{let}\ \ell_2 = \mathbf{ref}\ 0\ \mathbf{in} & //\ \textsc{Ht-let}, \textsc{Ht-alloc}, \textsc{Ht-frame} \\
\{\ell_1 \mapsto 0 * \ell_2 \mapsto 0\} & \\
\left(\begin{array}{l} \{\ell_1 \mapsto 0\} \\ \ell_1 \leftarrow\ !\,\ell_1 + 2 \end{array} \middle\| \begin{array}{l} \{\ell_2 \mapsto 0\} \\ \ell_2 \leftarrow\ !\,\ell_2 + 2 \end{array} \right); & //\ \textsc{Ht-seq}, \textsc{Ht-par} \\
\mathbf{assert}(!\,\ell_1 + !\,\ell_2 = 4) & \\
\{\mathsf{True}\} &
\end{array}
$$

Example Program - Verified

$\{\mathsf{True}\}$

$\texttt{let}\ \ell_1 = \texttt{ref}\ 0\ \texttt{in}$ // Ht-let, Ht-alloc

$\{\ell_1 \mapsto 0\}$

$\texttt{let}\ \ell_2 = \texttt{ref}\ 0\ \texttt{in}$ // Ht-let, Ht-alloc, Ht-frame

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

$$\left(\begin{array}{l} \{\ell_1 \mapsto 0\} \\ \ell_1 \leftarrow !\,\ell_1 + 2 \\ \{\ell_1 \mapsto 2\} \end{array} \middle\| \begin{array}{l} \{\ell_2 \mapsto 0\} \\ \ell_2 \leftarrow !\,\ell_2 + 2 \\ \{\ell_2 \mapsto 2\} \end{array}\right);$$

// Ht-seq, Ht-par, Ht-load, Ht-store

$\texttt{assert}(!\,\ell_1 + !\,\ell_2 = 4)$

$\{\mathsf{True}\}$

Example Program - Verified

$$\{\mathsf{True}\}$$

$$\texttt{let}\ \ell_1 = \texttt{ref}\ 0\ \texttt{in} \qquad // \textsc{Ht-let}, \textsc{Ht-alloc}$$

$$\{\ell_1 \mapsto 0\}$$

$$\texttt{let}\ \ell_2 = \texttt{ref}\ 0\ \texttt{in} \qquad // \textsc{Ht-let}, \textsc{Ht-alloc}, \textsc{Ht-frame}$$

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

$$\left(\begin{array}{l} \{\ell_1 \mapsto 0\} \\ \ell_1 \leftarrow !\,\ell_1 + 2 \\ \{\ell_1 \mapsto 2\} \end{array} \middle\| \begin{array}{l} \{\ell_2 \mapsto 0\} \\ \ell_2 \leftarrow !\,\ell_2 + 2 \\ \{\ell_2 \mapsto 2\} \end{array}\right); \qquad // \textsc{Ht-seq}, \textsc{Ht-par}, \textsc{Ht-load}, \textsc{Ht-store}$$

$$\{\ell_1 \mapsto 2 * \ell_2 \mapsto 2\}$$

$$\texttt{assert}(!\,\ell_1 + !\,\ell_2 = 4)$$

$$\{\mathsf{True}\}$$

Example Program - Verified

$$
\begin{array}{l}
\{\mathsf{True}\} \\
\texttt{let}\ \ell_1 = \texttt{ref}\ 0\ \texttt{in} \qquad // \textsc{Ht-let}, \textsc{Ht-alloc} \\
\{\ell_1 \mapsto 0\} \\
\texttt{let}\ \ell_2 = \texttt{ref}\ 0\ \texttt{in} \qquad // \textsc{Ht-let}, \textsc{Ht-alloc}, \textsc{Ht-frame} \\
\{\ell_1 \mapsto 0 * \ell_2 \mapsto 0\} \\
\left(\begin{array}{l} \{\ell_1 \mapsto 0\} \\ \ell_1 \leftarrow !\,\ell_1 + 2 \\ \{\ell_1 \mapsto 2\} \end{array} \middle\| \begin{array}{l} \{\ell_2 \mapsto 0\} \\ \ell_2 \leftarrow !\,\ell_2 + 2 \\ \{\ell_2 \mapsto 2\} \end{array} \right); \qquad // \textsc{Ht-seq}, \textsc{Ht-par}, \textsc{Ht-load}, \textsc{Ht-store} \\
\{\ell_1 \mapsto 2 * \ell_2 \mapsto 2\} \\
\texttt{assert}(!\,\ell_1 + !\,\ell_2 = 4) \qquad // \textsc{Ht-load}, \textsc{Ht-assert} \\
\{\mathsf{True}\}
\end{array}
$$

But What About Multiparty Channels?

Roundtrip program:

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

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

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Goal: Prove crash-freedom (safety) and verify asserts (functional correctness)
Sub-Goal: Hoare triples for multiparty channel primitives

Ht-new
$\{???\}\,\textbf{new\_chan}(n)\,\{???\}$

Ht-send
$\{???\}\,c[i].\textbf{send}(v)\,\{???\}$

Ht-recv
$\{???\}\,c[i].\textbf{recv}()\,\{???\}$

Tour of Multris

Multris

Channel endpoint ownership: $c \rightarrowtail p$

Multris

Channel endpoint ownership: $c \rightarrowtail p$

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

Multris

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

Multris

Channel endpoint ownership: $c \rightarrowtail p$

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

Rules:

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

Multris

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-NEW

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

HT-SEND

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

Multris

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-NEW

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

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

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

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.

Protocol Consistency

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Repeat until no more synchronised exchanges exist.

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

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

Protocol Consistency - Example

Protocol consistency example:

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

Protocol consistency:

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

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

Roundtrip Example - Verified

Roundtrip program:

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

Protocols:

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

Roundtrip Example - Verified

Roundtrip program:

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

Protocols:

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

Verified Functional Correctness!

Roundtrip Reference Example

Roundtrip reference program:

$$\mathtt{let}\,(c_0, c_1, c_2) = \mathtt{new\_chan}(3)\,\mathtt{in}$$

$$\left(\begin{array}{l} \mathtt{let}\,x = 40\,\mathtt{in} \\ \mathtt{let}\,\ell = \mathtt{ref}\,x\,\mathtt{in} \\ c_0[1].\mathtt{send}(\ell); \\ c_0[2].\mathtt{recv}(); \\ \mathtt{assert}(!\,\ell = x + 2) \end{array} \middle\| \begin{array}{l} \mathtt{let}\,\ell = c_1[0].\mathtt{recv}()\,\mathtt{in} \\ \ell \leftarrow (!\,\ell + 1); \\ c_1[2].\mathtt{send}(\ell) \\ \\ \\ \end{array} \middle\| \begin{array}{l} \mathtt{let}\,\ell = c_2[0].\mathtt{recv}()\,\mathtt{in} \\ \ell \leftarrow (!\,\ell + 1); \\ c_2[0].\mathtt{send}(\ell) \\ \\ \\ \end{array}\right)$$

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

Multris with Resources

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

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

Rules:

Ht-new

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

Ht-send

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

Ht-recv

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

Protocol Consistency with Resources

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

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.

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

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

Protocol Consistency with Resources - Example

Protocol consistency example:

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

Protocol consistency:

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

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

Roundtrip Reference Example - Verified

Roundtrip reference program:

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

Protocols:

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

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

Protocol Consistency - Recursion

Protocols are contractive in the tail:

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

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Protocol consistency example:

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

Recursion via Löb induction ($\triangleright$)

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

Protocol Consistency - Framing

Consider the replacement of process 1 with a forwarder:

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

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

Protocol Consistency - Framing

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

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

Protocol consistency owns resources while in transit:

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

Protocol Consistency - Branching

Consider the extension of process 1 with a rerouter:

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

Protocol Consistency - Branching

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

Protocol consistency example:

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

We can do case analysis on the binders:

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

Language Parametricity of Multris

Multris Ghost Theory

We defined the MDSP's via Iris's recursive domain equation solver and proved language-generic ghost theory rules based on Iris's ghost state machinery

PROTO-ALLOC

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

PROTO-VALID

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

PROTO-STEP

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

One can then define language-specific $c \rightarrowtail p$ and prove Hoare triple rules (such as HT-SEND, HT-RECV, and HT-NEW) for a given language using the ghost theory

Conclusion and Future Work

Conclusion

Dependent multiparty protocols are non-trivial to prove sound

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

Concurrent separation logic is a good fit for multiparty protocols

- Quantifier scopes enable inherent tracking of dependencies
- Separation logic enables framing of resources

Mechanisation yields crucial level of automation

- Imperative for non-trivial multiparty protocol consistency proofs

Future Work

Additional features

- Asynchronous communication/subprotocols
- Mixed choice

Semantic Multiparty Session Type System

- Investigate correspondences with syntactic protocol consistency

Better methodology for proving protocol consistency

- Abstraction and Modularity via separation logic

Deadlock freedom guarantees

- Leverage connectivity graphs for multiparty communication

Multris for distributed systems

- Leverage the Aneris separation logic

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Multris for distributed systems

- Leverage the Aneris separation logic

And much more!

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