

**Stripping multiple laterals, one step at a time.
Recovering intuitive specifications with the
“step modality”!**

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Ghost theories and the later modality (▷)

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Ghost theories and the later modality (\triangleright)

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Recent developments of Iris extend later-based expressivity of ghost theories, but the intuition of using them arguably lacks behind.

Logical Steps (\triangleright) vs Program Steps (\rightsquigarrow)

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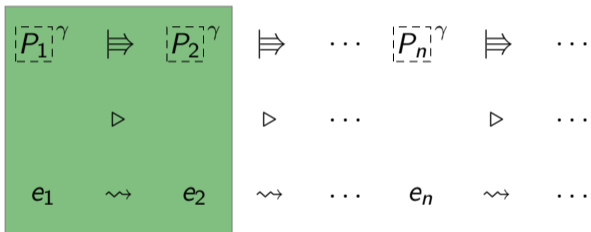
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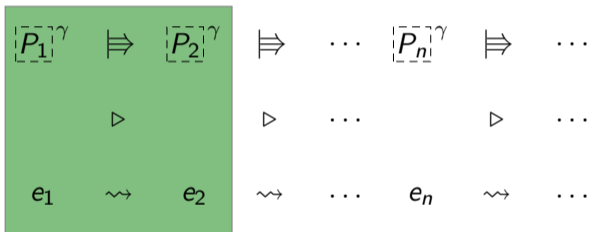
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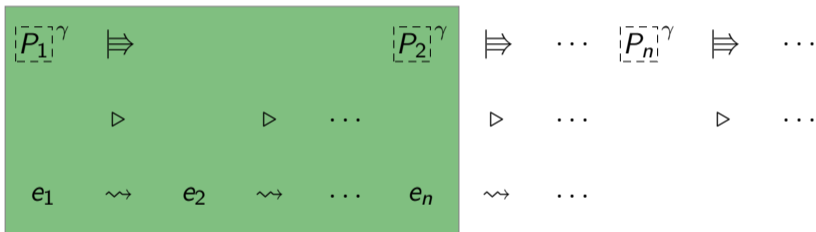


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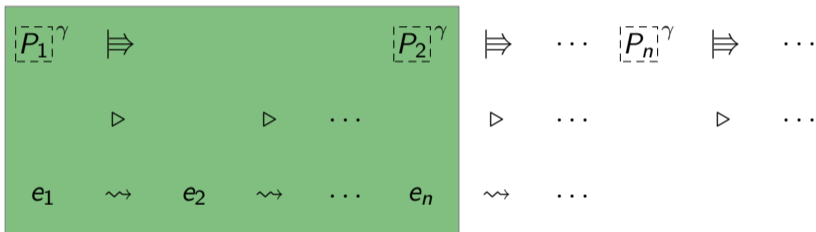


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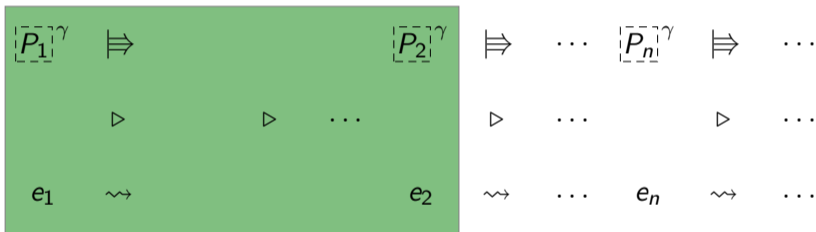


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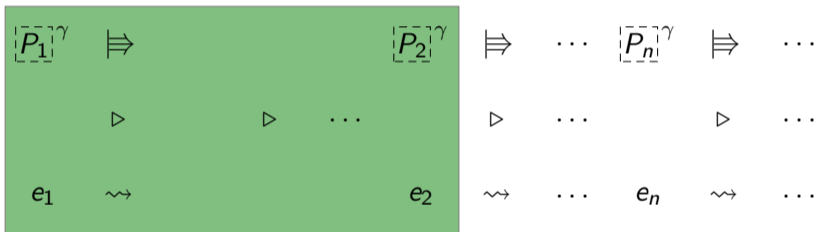


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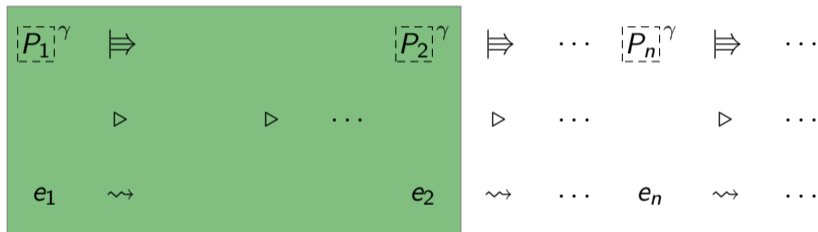


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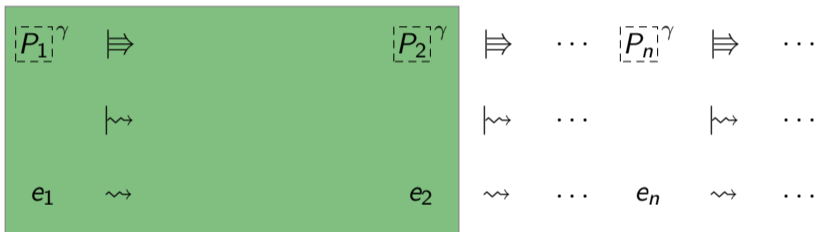
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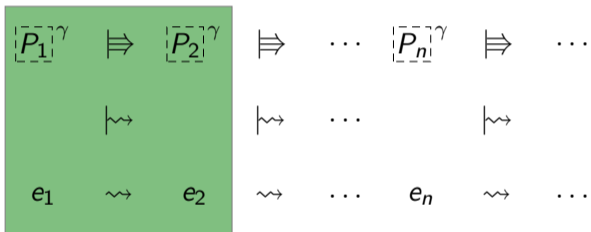
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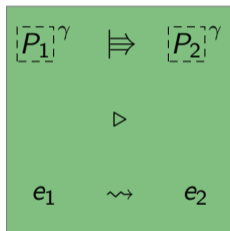
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Everything in the talk is mechanised as a *shallow embedding* on top of Iris

A story told in multiple steps

The first step



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Intuition: How do we explain the use of this pattern?

“Dont worry, just take a step”

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We can resolve a later every step

HT-LATER-FRAME

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

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We can resolve a later every step, and we can always update ghost state

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A historically accepted intuition for step-indexed logics

But what if there are multiple lateres?



An extension of Actris 1.0, that imposed an iterated number of laterers in the send rule, relative to inbound buffer \vec{v}_2 :

$$\frac{\text{PROTO-SEND-L} \quad \text{prot_ctx } \chi \vec{v}_1 \vec{v}_2 \quad \text{prot_own}_l \chi (! \vec{x} : \vec{\tau} \langle v \rangle \{P\}. \text{prot}) \quad P[\vec{t}/\vec{x}]}{\Rightarrow \triangleright^{|\vec{v}_2|} \text{prot_ctx } \chi (\vec{v}_1 \cdot [v[\vec{t}/\vec{x}]]) \vec{v}_2 * \text{prot_own}_l \chi (\text{prot}[\vec{t}/\vec{x}])}$$

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Intuition: How do we present this use???

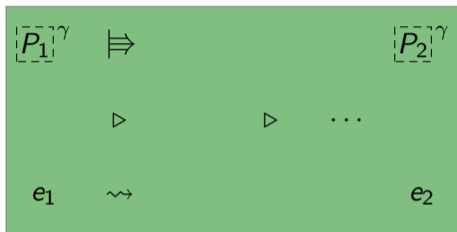
The need for skip instructions. The rules `PROTO-SEND-L` and `PROTO-SEND-R` from Figure 20 contain a number of later modalities (\triangleright) proportional to the other endpoint's buffer. As explained in § 9.3 these later modalities are the consequence of having to perform a number of case analyses on the subprotocol relation, which is defined using guarded recursion, and thus contains a later modality for each recursive unfolding.

To eliminate these later modalities, we instrument the code of the `send` function with the `skipN (llength r)` instruction, which performs a number of skips equal to the size of the other endpoint's buffer r . The `skipN` instruction has the following specification:

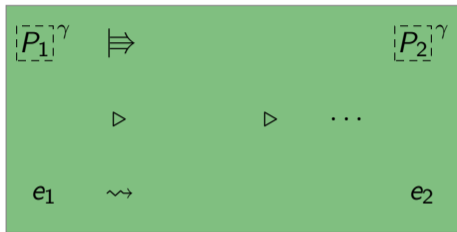
$$\{\triangleright^n P\} \text{ skipN } n \{P\}$$

Instrumentation with skip instructions is used often in work on step-indexing, see *e.g.*, [SSB16; GST⁺20]. Instrumentation is needed because current step-indexed logics like Iris unify physical/program steps and logical steps, *i.e.*, for each physical/program step at most one later can be eliminated from the hypotheses. In recent work by Svendsen *et al.* [SSB16], Matsushita and Jourdan [MJ20], and Spies *et al.* [SGG⁺21] more liberal versions of step-indexing have been proposed, but none of these versions of step-indexing have been integrated into the main Coq development of Iris and HeapLang.

But what if you can only take one step?



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E.g. if you have to put your ghost state in an invariant:

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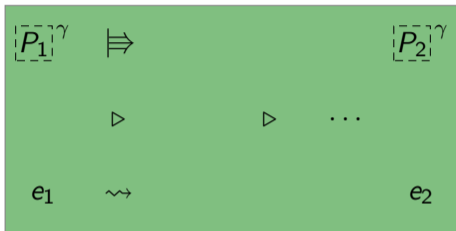


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Invariants impose that we *must* strip all laterals during a single step.

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NB: Invariant mask details are omitted in this talk.

Stripping multiple layers during a single physical step

[Matsushita et. al, 2022] extends Iris to allow stripping layers corresponding to total number of steps taken at every step, tracked via *time receipts* ($\times n$)

Stripping multiple layers during a single physical step

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Stripping multiple laterals during a single physical step

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We can then track the relevant step count lower bounds in our invariant:

$$\text{prot_ctx} \times \chi \vec{v}_1 \vec{v}_2 \triangleq \text{prot_ctx} \chi \vec{v}_1 \vec{v}_2 * \times |\vec{v}_1| * \times |\vec{v}_2| \quad \boxed{\exists \vec{v}_1, \vec{v}_2. \text{prot_ctx} \times \chi \vec{v}_1 \vec{v}_2 * \dots}$$

Stripping multiple laterers during a single physical step

[Matsushita et. al, 2022] extends Iris to allow stripping laterers corresponding to total number of steps taken at every step, tracked via *time receipts* ($\times n$):

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We can then track the relevant step count lower bounds in our invariant:

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Expressivity: Can use the send rule at every step, as we can strip all the necessary laterers using Ht-step-frame, and update the step count lower bounds in tandem with our ghost state using Ht-step-incr!

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Intuition: ...?

$$\begin{array}{c}
\text{HT-STEP-GET} \\
\frac{\{P * \times 0\} \langle ip; e \rangle \{\Phi\}}{\{P\} \langle ip; e \rangle \{\Phi\}}
\end{array}
\qquad
\begin{array}{c}
\text{HT-STEP-INCR} \\
\frac{\{P\} \langle ip; e \rangle \{w. Q\}}{\{P * \times n\} \langle ip; e \rangle \{w. Q * \times n + 1\}}
\end{array}
\qquad
\begin{array}{c}
\text{HT-STEP-FRAME} \\
\frac{\{P\} \langle ip; e \rangle \{w. Q\}}{\{P * \times n * \triangleright^n R\} \langle ip; e \rangle \{w. Q * R\}}
\end{array}
\qquad
\begin{array}{c}
\text{STEP-DUP} \\
\frac{\times n}{\times n * \times n}
\end{array}$$

Fig. 12. The mechanism for stripping multiple lateres. We require e to be an atomic expression.

The shared logical context can then be captured as the following Iris invariant:

$$\exists Tl, Tr, Rl, Rr. \text{auth_list } \chi_{Tl} Tl * \text{auth_list } \chi_{Tr} Tr * \text{auth_list } \chi_{Rl} Rl * \text{auth_list } \chi_{Rr} Rr * \\
\text{prot_ctx } \chi_{\text{chan}} (Tl - Rr) (Tr - Rl) * Rr \leq_p Tl * Rl \leq_p Tr * \times |Tl| * \times |Tr|$$

Stripping multiple lateres. In Iris, and thus Aneris, one can strip a later whenever a step of computation is taken. Conventionally the intuition is that one step equates stripping one later. However, recent discoveries [Matsushita et al. 2022; Mével et al. 2019; Spies et al. 2022] uncovered various methods for stripping *multiple* lateres per step. Based on these discoveries we extended Aneris with a similar, albeit more simplistic, mechanism as presented in Figure 12. The mechanism lets us strip multiple lateres during one physical step, based on the amount of steps that has been taken thus far. The rule `HT-STEP-GET` lets us track a new lower bound of steps taken thus far $\times 0$, and `HT-STEP-INCR` allows us to increase it by one, every time a step is taken. Crucially, the rule `HT-STEP-FRAME` lets us frame resources under an amount of lateres corresponding to the lower bound

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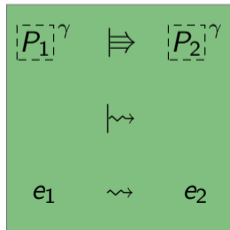


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Solution: Introducing the step modality!

$$| \rightsquigarrow P$$

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Recovers the intuition that we can get P *after taking a single step*:

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Intentionally mimics the semantics of the original later- and update-stripping rules:

$$\frac{\text{HT-LATER-FRAME} \quad \{P\} e \{w. Q\}}{\{P * \triangleright R\} e \{w. Q * R\}}$$

$$\frac{\text{HT-CSQ-VS} \quad P \equiv P' \quad \{P'\} e \{w. Q'\} \quad \forall w. Q' \equiv Q}{\{P\} e \{w. Q\}}$$

Step-based Actris Ghost Theory

Instead of ghost theories that expose verification details (such as later):

$$\frac{\text{PROTO-SEND-L} \quad \text{prot_ctx } \chi \vec{v}_1 \vec{v}_2 \quad \text{prot_own}_l \chi (! \vec{x} : \vec{\tau} \langle v \rangle \{P\}. \text{prot}) \quad P[\vec{t}/\vec{x}]}{\Rightarrow^{| \vec{v}_2 |} \text{prot_ctx } \chi (\vec{v}_1 \cdot [v[\vec{t}/\vec{x}]]) \vec{v}_2 * \text{prot_own}_l \chi (\text{prot}[\vec{t}/\vec{x}])}$$

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We can now have high-level patterns that hide such details:

$$\frac{\text{STEP-PROTO-SEND-L} \quad \triangleright \text{prot_ctx}_\delta \chi \vec{v}_1 \vec{v}_2 \quad \triangleright \text{prot_own}_l \chi (! \vec{x} : \vec{\tau} \langle v \rangle \{P\}. \text{prot}) \quad \triangleright P[\vec{t}/\vec{x}]}{\mapsto \text{prot_ctx}_\delta \chi (\vec{v}_1 \cdot [v[\vec{t}/\vec{x}]]) \vec{v}_2 * \text{prot_own}_l \chi (\text{prot}[\vec{t}/\vec{x}])}$$

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Expressivity: Can be applied at every step!

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Expressivity: Can be applied at every step!

Intuition: How do we explain this specification to newcomers (and reviewers)?

“Dont worry, just take a step”

The Session Escrow Pattern [ICFP'23] (Conditionally Accepted)

Derived abstractions may hide the number of laterals that needs to be stripped

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$$P, Q ::= \dots \mid \text{ses_own}_1 \chi \ n \ m \ \text{prot} \mid \text{ses_own}_r \chi \ n \ m \ \text{prot} \mid \\ \text{ses_idx}_1 \chi \ i \ v \mid \text{ses_idx}_r \chi \ i \ v \mid \dots$$

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$$\text{ses_own}_1 \chi n m \text{ prot} \triangleq \boxed{\exists \vec{v}_1, \vec{v}_2. \text{prot_ctx}_\delta \chi \vec{v}_1 \vec{v}_2 * \dots} * \dots$$
$$\text{ses_own}_r \chi n m \text{ prot} \triangleq \boxed{\exists \vec{v}_1, \vec{v}_2. \text{prot_ctx}_\delta \chi \vec{v}_1 \vec{v}_2 * \dots} * \dots$$

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IDEAL-SESSION-ESCROW-SEND

$$\frac{\text{ses_own}_1 \chi n m (!(\vec{x}:\vec{\tau}) \langle v \rangle \{P\}. \text{prot}) \quad P[\vec{t}/\vec{x}]}{\text{ses_own}_1 \chi (n+1) m (\text{prot}[\vec{t}/\vec{x}]) * \text{ses_idx}_1 \chi n (v[\vec{t}/\vec{x}])}$$

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NAIVE-SESSION-ESCROW-SEND

$$\frac{\text{ses_own}_1 \chi n m (! (\vec{x} : \vec{\tau}) \langle v \rangle \{P\}. \text{prot}) \quad P[\vec{t}/\vec{x}]}{\Rightarrow \triangleright^{???} \text{ses_own}_1 \chi (n+1) m (\text{prot}[\vec{t}/\vec{x}]) * \text{ses_idx}_1 \chi n (v[\vec{t}/\vec{x}])}$$

The Session Escrow Pattern [ICFP'23] (Conditionally Accepted)

Derived abstractions may hide the number of laterals that needs to be stripped:

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$$\text{ses_own}_r \chi n m \text{ prot} \triangleq \boxed{\exists \vec{v}_1, \vec{v}_2. \text{prot_ctx}_\delta \chi \vec{v}_1 \vec{v}_2 * \dots} * \dots$$

SESSION-ESCROW-SEND-L

$$\frac{\text{ses_own}_1 \chi n m (! (\vec{x} : \vec{\tau}) \langle v \rangle \{ P \}. \text{prot}) \quad P[\vec{t} / \vec{x}]}{\rightsquigarrow \text{ses_own}_1 \chi (n + 1) m (\text{prot}[\vec{t} / \vec{x}]) * \text{ses_idx}_1 \chi n (v[\vec{t} / \vec{x}])}$$

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SESSION-ESCROW-SEND-L

$$\frac{\text{ses_own}_1 \chi n m (! (\vec{x} : \vec{\tau}) \langle v \rangle \{ P \}. \text{prot}) \quad P[\vec{t}/\vec{x}]}{\rightsquigarrow \text{ses_own}_1 \chi (n+1) m (\text{prot}[\vec{t}/\vec{x}]) * \text{ses_idx}_1 \chi n (v[\vec{t}/\vec{x}])}$$

This ghost theory is virtually *inexpressible* without the step modality

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SESSION-ESCROW-SEND-L

$$\frac{\text{ses_own}_1 \chi n m (! (\vec{x} : \vec{\tau}) \langle v \rangle \{ P \}. \text{prot}) \quad P[\vec{t}/\vec{x}]}{\rightsquigarrow \text{ses_own}_1 \chi (n+1) m (\text{prot}[\vec{t}/\vec{x}]) * \text{ses_idx}_1 \chi n (v[\vec{t}/\vec{x}])}$$

This ghost theory is virtually *inexpressible* without the step modality

- ▶ Inexpressible without explicitly mentioning the later-stripping mechanism

*So how do we derive
step-based ghost theories?*

Step modality proof interface

The step modality admits a step-based version of the time receipt mechanism:

$$\begin{array}{c} \text{STEP-TIME-GET} \\ \vdash \delta 0 \end{array}$$

$$\begin{array}{c} \text{STEP-TIME-INCR} \\ \delta n \\ \hline \vdash \delta (n + 1) \end{array}$$

$$\begin{array}{c} \text{STEP-TIME-FRAME} \\ \delta n \quad \dashv\vdash^{(n+1)} P \\ \hline \vdash P \end{array}$$

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 \hline
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 \qquad
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 \text{STEP-TIME-INCR} \\
 \Delta n \\
 \hline
 \vdash \Delta (n + 1)
 \end{array}
 \qquad
 \begin{array}{c}
 \text{STEP-TIME-FRAME} \\
 \Delta n \quad \text{FID} \Rightarrow^{(n+1)} P \\
 \hline
 \vdash P
 \end{array}$$

Additionally, the step modality enjoys a mix of the later and update modality rules:

$$\begin{array}{c}
 \text{STEP-INTRO} \\
 P \\
 \hline
 \vdash P
 \end{array}
 \qquad
 \begin{array}{c}
 \text{STEP-MONO} \\
 P \vdash Q \\
 \hline
 \vdash P \vdash \vdash Q
 \end{array}
 \qquad
 \begin{array}{c}
 \text{STEP-SEP-COMM} \\
 \vdash P \quad \vdash Q \\
 \hline
 \vdash P * Q
 \end{array}
 \qquad
 \begin{array}{c}
 \text{STEP-UPD} \\
 \text{FID} \vdash \vdash \text{FID} P \\
 \hline
 \vdash P
 \end{array}
 \qquad
 \begin{array}{c}
 \text{STEP-LATER} \\
 \triangleright P \\
 \hline
 \vdash P
 \end{array}$$

Vertical modularity of the step modality

The step modality properties lets us derive step-based ghost theories on top of the time receipt later-stripping mechanism

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$$\frac{\text{STEP-TIME-FRAME} \quad \mathbb{X} n \quad \mathbb{E} \Rightarrow^{(n+1)} P}{\mathbb{X} P} \quad \wedge \quad \frac{\text{STEP-TIME-INCR} \quad \mathbb{X} n}{\mathbb{X} (n+1)}$$

Vertical modularity of the step modality

The step modality properties lets us derive step-based ghost theories on top of the time receipt later-stripping mechanism:

$$\begin{array}{c}
 \text{STEP-TIME-FRAME} \quad \text{STEP-TIME-INCR} \\
 \frac{\mathbb{X} n \quad \mathbb{E} \Rightarrow^{(n+1)} P}{\rightsquigarrow P} \quad \wedge \quad \frac{\mathbb{X} n}{\rightsquigarrow \mathbb{X} (n+1)} \quad \wedge \\
 \\
 \text{PROTO-SEND-L} \\
 \frac{\text{prot_ctx } \chi \quad \vec{v}_1 \quad \vec{v}_2 \quad \text{prot_own}_l \chi \quad (! \vec{x} : \vec{\tau} \langle v \rangle \{ P \}. \text{prot}) \quad P[\vec{t}/\vec{x}]}{\mathbb{E} \triangleright^{|\vec{v}_2|} \text{prot_ctx } \chi \quad (\vec{v}_1 \cdot [v[\vec{t}/\vec{x}]]) \quad \vec{v}_2 * \text{prot_own}_l \chi \quad (\text{prot}[\vec{t}/\vec{x}])}
 \end{array}$$

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$$\begin{array}{c}
 \text{STEP-TIME-FRAME} \quad \text{STEP-TIME-INCR} \\
 \frac{\mathbb{X} n \quad \mathbb{E} \Rightarrow^{(n+1)} P}{\rightsquigarrow P} \quad \wedge \quad \frac{\mathbb{X} n}{\rightsquigarrow \mathbb{X} (n+1)} \quad \wedge \\
 \\
 \text{PROTO-SEND-L} \\
 \frac{\text{prot_ctx } \chi \vec{v}_1 \vec{v}_2 \quad \text{prot_own}_l \chi (! \vec{x} : \vec{\tau} \langle v \rangle \{ P \}. \text{prot}) \quad P[\vec{t}/\vec{x}]}{\mathbb{E} \triangleright^{|\vec{v}_2|} \text{prot_ctx } \chi (\vec{v}_1 \cdot [v[\vec{t}/\vec{x}]]) \vec{v}_2 * \text{prot_own}_l \chi (\text{prot}[\vec{t}/\vec{x}])} \Rightarrow \\
 \\
 \text{STEP-PROTO-SEND-L} \\
 \frac{\triangleright \text{prot_ctx}_\mathbb{X} \chi \vec{v}_1 \vec{v}_2 \quad \triangleright \text{prot_own}_l \chi (! \vec{x} : \vec{\tau} \langle v \rangle \{ P \}. \text{prot}) \quad \triangleright P[\vec{t}/\vec{x}]}{\rightsquigarrow \text{prot_ctx}_\mathbb{X} \chi (\vec{v}_1 \cdot [v[\vec{t}/\vec{x}]]) \vec{v}_2 * \text{prot_own}_l \chi (\text{prot}[\vec{t}/\vec{x}])}
 \end{array}$$

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$$\frac{\text{SESSION-ESCROW-SEND} \quad \text{ses_own} \chi s n m (! (\vec{x} : \vec{\tau}) \langle v \rangle \{P\}. \text{prot}) \quad P[\vec{t}/\vec{x}]}{\vdash \text{ses_own} \chi s (n + 1) m (\text{prot}[\vec{t}/\vec{x}]) * \text{ses_idx} \chi s n (v[\vec{t}/\vec{x}])}$$

So how does it work?

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Well, one approach is...

The (simplified) step modality definition

Designed as a “frame” around the Hoare triple (/ weakest precondition):

$$\vdash P \triangleq \forall n. \mathbb{X} \bullet n \Rightarrow (\mathbb{X} \bullet n * (\Rightarrow^{(n+1)} \mathbb{X} \bullet (n+1) \Rightarrow \mathbb{X} \bullet (n+1) * P))$$

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- ▶ Prove the goal P

The step modality definition

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Language “primitive” rules should then be proven for the later-stripping mechanism of choice, e.g. the ones for time receipts (where $S \sigma n \kappa S nt \triangleq \boxtimes \bullet n * \dots$):

| | | |
|----------------------------------------------------|--------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| <p>STEP-TIME-GET</p> $\frac{}{\Vdash \boxtimes 0}$ | <p>STEP-TIME-INCR</p> $\frac{\boxtimes n}{\Vdash \boxtimes (n+1)}$ | <p>STEP-TIME-FRAME</p> $\frac{\boxtimes n \quad \boxRightarrow^{(n+1)} P}{\Vdash P}$ |
|----------------------------------------------------|--------------------------------------------------------------------|--------------------------------------------------------------------------------------|

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However, everything in this talk has been fully mechanised using it.

Mechanisation:

https://gitlab.mpi-sws.org/iris/iris/-/merge_requests/887

https://gitlab.mpi-sws.org/iris/actris/-/merge_requests/30

Some reflections on the step modality

What if the modality abstracts away necessary details? (e.g. specific number of laterals)

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Is the step modality obsolete in Transfinite Iris?

- ▶ Pretty much, yeah

Future work

Better support for invariant masks

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Looking for feedback!

- ▶ Suggestions for improvements, usefulness, etc.

STEP-QUESTIONS?

Question

|  Answer