A Logical Basis for the Verification of Message-Passing Programs

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Dutch Formal Methods Day
April 16, 2024

UNIFYING
C•RRECTNESS FOR
C•MMUNICATING
S•FTWARE

My Group's Research: Keywords (and Slogans)

Concurrency Theory, Message-Passing, Programming Languages, Verification

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Today An overview in two parts

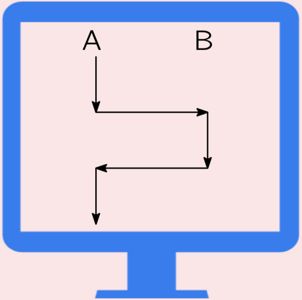
- A gentle introduction to session types
- Runtime verification based on session types (presented in RV'23)

Part I

Session Types for Message-Passing Concurrency

When is a Program Correct?

Sequential Programs



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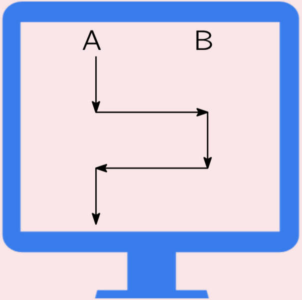

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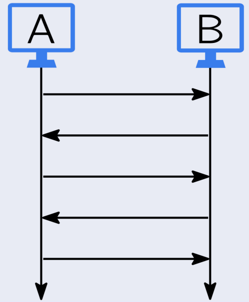

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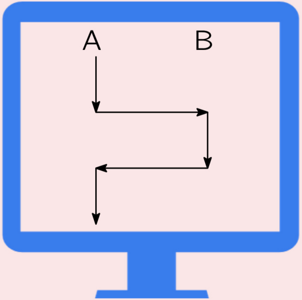

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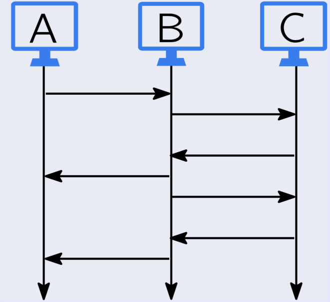
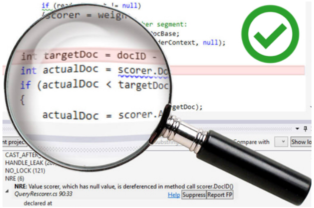


“Programs always respect their intended protocols”

Type Systems: From Data to Behaviors

- Can detect bugs before programs are run
- Present in many programming languages
- A sound notion of correctness

  A program is either correct or incorrect



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HANDLE_LEAK (2

NO_LOCK (121)

NRE (6)

NRE: Value scorer, which has null value, is dereferenced in method call scorer.DocID()

QueryRescorer.cs 90:33

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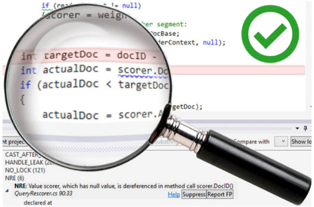

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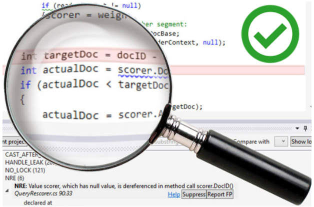

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Sequential Languages

- **Data type systems** classify values in a program
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Concurrent Languages

- **Behavioral type systems** classify protocols in a program
- Example: “first send username, then receive true/false, finally close”
- A typical bug: sending messages in the wrong order

Protocols as Session Types

Session types uniformly describe protocols in terms of

- communication actions (input and output)
- labeled choices (offers and selections)
- sequential composition
- recursion

Session protocols are attached to **interaction devices**:

- channel endpoints
- channels in languages like Go
- π-calculus names
- $\cdots$

Sequentiality in types goes **hand-in-hand** with sequentiality in processes

Example: A Two-Buyer Protocol

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bruna

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4’. In case 3(b) Alice is in charge of gracefully concluding the conversation.

The Syntax of Session Types

$S ::=$	$!U;S$	**output** value of type U, continue as S
$\mid$	$?U;S$	**input** value of type U, continue as S
$\mid$	$\&\{l_i : S_i\}_{i \in I}$	**offer** a selection between $S_1, \ldots, S_n$
$\mid$	$\oplus\{l_i : S_i\}_{i \in I}$	**select** between $S_1, \ldots, S_n$
$\mid$	$\mu t.S \mid t$	**recursion**
$\mid$	$\mathtt{end}$	**terminated protocol**

(Labels $l_1, \ldots, l_n$ are pairwise different.)

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Two separate protocols, with Alice "leading" the interactions:

- A session type for Seller (in its interaction with Alice):

$$S_{\mathsf{SA}} = \ ?\mathtt{book};\, !\mathtt{quote};\, \& \begin{cases} \mathsf{buy}: & ?\mathtt{paym};\, ?\mathtt{address};\, !\mathtt{ok};\, \mathsf{end} \\ \mathsf{cancel}: & ?\mathtt{thanks};\, !\mathtt{bye};\, \mathsf{end} \end{cases}$$

- A session type for Alice (in its interaction with Bob):

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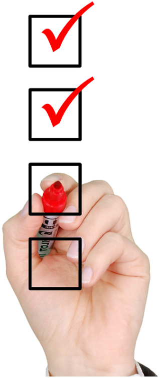
Note:

- The above protocols are specified in the **binary** setting
- Session types have been developed also in the more general **multiparty** setting

Example: A Two-Buyer Protocol

Desiderata for the implementations of Alice, Bob, and Seller:

- **Fidelity** – they **follow the intended protocol**.
  - Alice doesn't continue the transaction if Bob can't contribute
  - Alice chooses among the options provided by Seller



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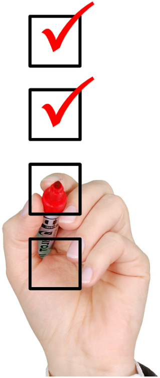
- **Safety** – they don't feature **communication errors**.
  - Seller always returns an integer when Alice requests a quote



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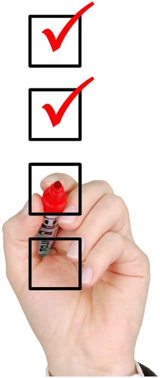

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- **Safety** – they don't feature **communication errors**.
- **Deadlock-Freedom** – they do not **"get stuck"** while running the protocol.
  - Alice eventually receives an answer from Bob on his contribution.

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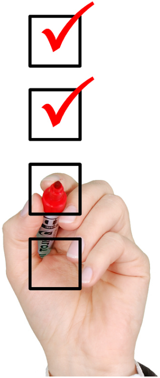

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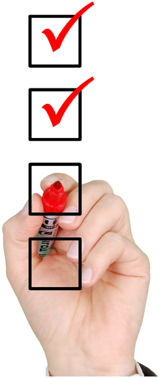

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Correctness follows from the interplay of these properties.
Hard to enforce, especially when actions are "scattered around" in source programs.

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  - the dual of input is output (and vice versa)
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- Also, Alice's implementation should conform to both $\overline{S_{\mathsf{SA}}}$ and S_{AB}.

Propositions as Sessions

Concurrency		**Logic**
session types	↔	linear logic propositions
π-calculus processes	↔	proofs
process communication	↔	cut elimination

- All four correctness properties hold "for free"
- Firm justification for seminal work on session types
- Reference framework for expressiveness
- Canonical platform for extensions (e.g., sharing)

Part II

Runtime Verification Based on Session Types

In A Nutshell

- A verification methodology based on **routers**, protocol descriptions synthesized from multiparty protocols.
- Combining and improving existing techniques, leveraging on propositions-as-sessions. Validated with a practical implementation.
- **Key idea**: Routers enrich local descriptions by capturing intra-participant dependencies.
- Routers be can used for **static verification** (type systems, SCP'22) and also in a **dynamic verification** setup (RV'23).

Multiparty Session Types

- A **global type** provides the entire protocol's specification for multiple participants. Participant implementations communicate with each other, without a coordinator.
- A simple authorization protocol:

$$G_{\mathsf{auth}} = \mu X.s!c\{\mathsf{login}.c!a(\mathsf{passwd}).a!s(\mathsf{succ}).X \ ,\ \mathsf{quit}.\mathsf{end}\}$$

Three participants: client (c), server (s), authorization server (a)

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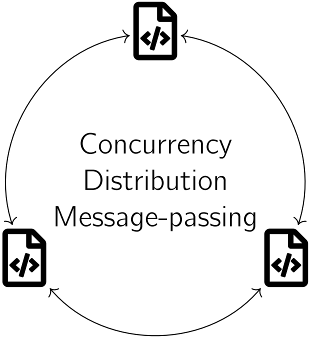
  Three participants: client (c), server (s), authorization server (a)
- The global type is projected onto **local types**, one per participant, which provide a basis for static or dynamic verification.
- Note: not all conceivable global types are projectable onto local types.

Dynamic Approach



Concurrency
Distribution
Message-passing

- Multiparty session types (MPSTs): **protocols** for distributed message-passing.
- MPSTs enable useful runtime verification techniques. They rely on usual notions of well-formedness, which **limits their applicability**.
- Many practical protocols **not supported** by existing RV techniques: e.g., our running example, **s**erver requests **c**lient to login through **a**uthorization service.
- Existing techniques require **too much information** about components.

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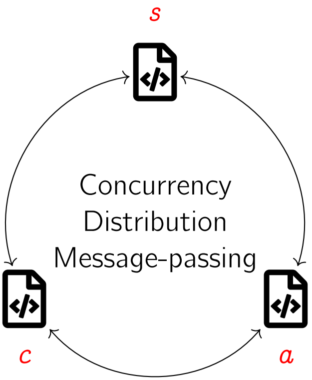

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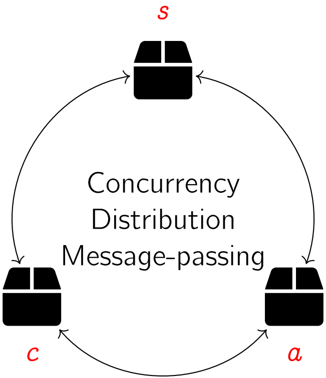
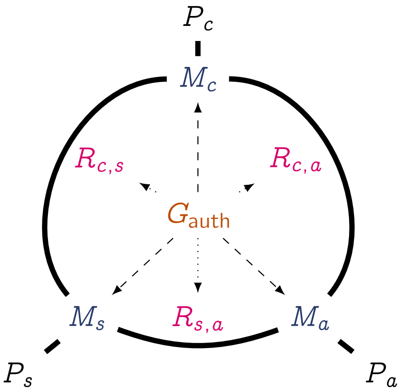


- New approach to **runtime** verification of distributed components using MPSTs as **monitors** to verify **protocol conformance**.
- Support **expressive** class of protocols.
- Components with **unknown** specification but **observable** message-passing behavior.
- LTSs with **minimal assumptions**: “blackboxes”.
- Contributions:
  - Verification framework.
  - Compositional verification.
  - Protocol conformance and **transparency**.
  - Prototype implementation.

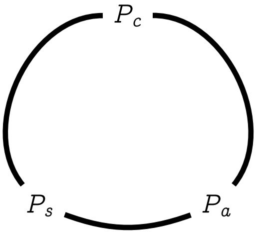
Dynamic Verification: Setup



We use the global type (multiparty protocol) in different ways:

- Obtain local views for verifying protocol conformance
- Synthesize monitors for each participant
- Detect additional coordination messages

Our Setup: Blackboxes



- Each blackbox assumed to belong to a protocol **participant**: e.g., P_c.
- Blackboxes exchange messages **asynchronously** through buffers: e.g., $\langle c : P_c : \vec{m} \rangle$.
- Messages carry **data** or **choices** to resolve **branching**.

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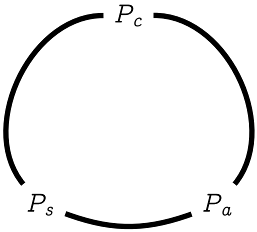

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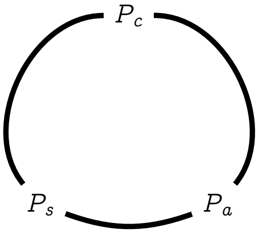

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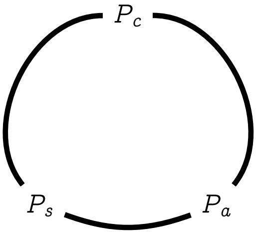

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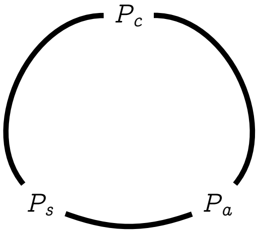

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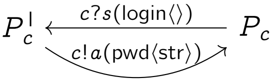

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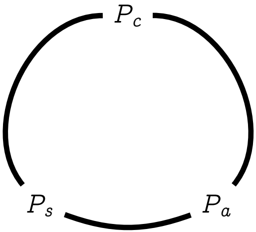

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$$\begin{tikzcd} P_c^{\mathsf{l}} \arrow[r, bend right, "c!a(\mathsf{pwd}\langle \mathsf{str} \rangle)"'] & P_c \arrow[l, "c?s(\mathsf{login}\langle\rangle)"'] \arrow[r, "c?s(\mathsf{quit}\langle\rangle)"] & P_c^{\mathsf{q}} \end{tikzcd}$$

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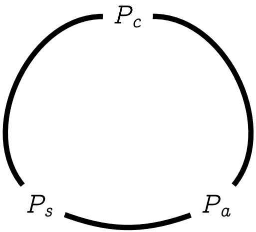

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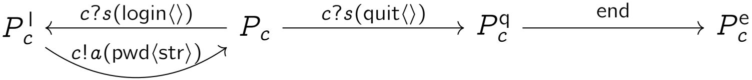
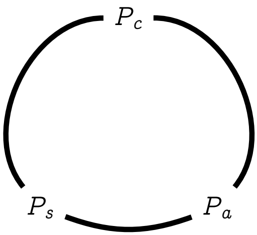
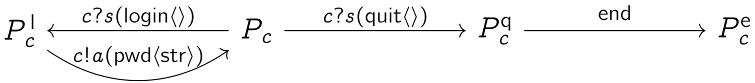


Our Setup: Blackboxes

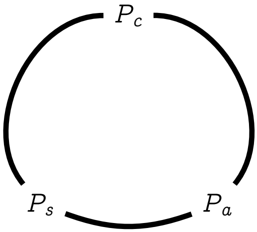


- Each blackbox assumed to belong to a protocol **participant**: e.g., P_c.
- Blackboxes exchange messages **asynchronously** through buffers: e.g., $\langle c : P_c : \vec{m} \rangle$.
- Messages carry **data** or **choices** to resolve **branching**.



$\langle c : P_c : s!c(\mathsf{quit}\langle\rangle) \rangle$

Our Setup: Blackboxes

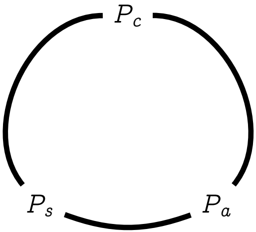


- Each blackbox assumed to belong to a protocol **participant**: e.g., P_c.
- Blackboxes exchange messages **asynchronously** through buffers: e.g., $\langle c : P_c : \vec{m} \rangle$.
- Messages carry **data** or **choices** to resolve **branching**.

$$\begin{tikzcd}
P_c^{\mathsf{!}} \arrow[r, bend right, "c!a(\mathsf{pwd}\langle\mathsf{str}\rangle)"'] & P_c \arrow[l, "c?s(\mathsf{login}\langle\rangle)"'] \arrow[r, "c?s(\mathsf{quit}\langle\rangle)"] & P_c^{\mathsf{q}} \arrow[r, "\mathsf{end}"] & P_c^{\mathsf{e}}
\end{tikzcd}$$

$$\langle c : P_c : s!c(\mathsf{quit}\langle\rangle) \rangle \xrightarrow{c?s(\mathsf{quit}\langle\rangle)} \langle c : P_c^{\mathsf{q}} : \varepsilon \rangle$$

Our Setup: Blackboxes



- Each blackbox assumed to belong to a protocol **participant**: e.g., P_c.
- Blackboxes exchange messages **asynchronously** through buffers: e.g., $\langle c : P_c : \vec{m} \rangle$.
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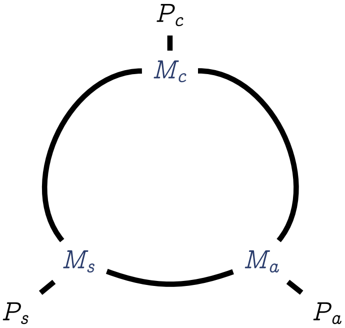
\end{tikzcd}$$

$$\begin{tikzcd}
\langle c : P_c : s!c(\mathsf{quit}\langle\rangle)\rangle \arrow[r, "c?s(\mathsf{quit}\langle\rangle)"] & \langle c : P_c^{\mathsf{q}} : \varepsilon\rangle \arrow[r, "\mathsf{end}"] & \langle c : P_c^{\mathsf{e}} : \varepsilon\rangle
\end{tikzcd}$$

Our Setup: Monitors



- **Monitoring** to shield the system against **unexpected behavior**.
- Monitors: FSMs describing sequences of **expected** incoming/outgoing messages.
- **Forwards** expected messages between its blackbox and other monitored blackboxes.
- Unexpected messages result in **error state**.
- **Monitored blackboxes**: e.g., $[\langle c : P_c : \vec{m} \rangle : M_c : \vec{n}]$.
- Broadcast messages to **coordinate** blackboxes to support **more expressive** protocols.

Networks of monitored blackboxes (1/2)

$$\langle c : P_c : s!c(\mathsf{quit}\langle\rangle)\rangle \xrightarrow{c?s(\mathsf{quit}\langle\rangle)} \langle c : P_c^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\mathsf{end}} \langle c : P_c^{\mathsf{e}} : \varepsilon\rangle$$

$$\langle s : P_s : \varepsilon\rangle \xrightarrow{s!c(\mathsf{quit}\langle\rangle)} \langle s : P_s^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\mathsf{end}} \langle s : P_s^{\mathsf{e}} : \varepsilon\rangle$$

Networks of monitored blackboxes (1/2)

$$\langle c : P_c : s!c(\mathsf{quit}\langle\rangle)\rangle \xrightarrow{c?s(\mathsf{quit}\langle\rangle)} \langle c : P_c^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\mathsf{end}} \langle c : P_c^{\mathsf{e}} : \varepsilon\rangle$$

$$\langle s : P_s : \varepsilon\rangle \xrightarrow{s!c(\mathsf{quit}\langle\rangle)} \langle s : P_s^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\mathsf{end}} \langle s : P_s^{\mathsf{e}} : \varepsilon\rangle$$

$$M_c = c?s\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\} \qquad M_s = s!c\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\}$$

Networks of monitored blackboxes (1/2)

$$\frac{\begin{array}{c} \langle c : P_c : s!c(\mathsf{quit}\langle\rangle)\rangle \xrightarrow{c?s(\mathsf{quit}\langle\rangle)} \langle c : P_c^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\mathsf{end}} \langle c : P_c^{\mathsf{e}} : \varepsilon\rangle \\ \langle s : P_s : \varepsilon\rangle \xrightarrow{s!c(\mathsf{quit}\langle\rangle)} \langle s : P_s^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\mathsf{end}} \langle s : P_s^{\mathsf{e}} : \varepsilon\rangle \end{array}}{[\langle c : P_c : \varepsilon\rangle : c?s\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\} : \varepsilon] \quad \mid \quad [\langle s : P_s : \varepsilon\rangle : s!c\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\} : \varepsilon]}$$

Networks of monitored blackboxes (1/2)

$$
\begin{array}{c}
\langle c : P_c : s!c(\mathsf{quit}\langle\rangle)\rangle \xrightarrow{c?s(\mathsf{quit}\langle\rangle)} \langle c : P_c^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\quad\mathsf{end}\quad} \langle c : P_c^{\mathsf{e}} : \varepsilon\rangle \\
\langle s : P_s : \varepsilon\rangle \xrightarrow{s!c(\mathsf{quit}\langle\rangle)} \langle s : P_s^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\quad\mathsf{end}\quad} \langle s : P_s^{\mathsf{e}} : \varepsilon\rangle \\
\hline
\end{array}
$$

$$
\begin{array}{l}
[\langle c : P_c : \varepsilon\rangle : c?s\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\} : \varepsilon] \quad \mid \quad [\langle s : P_s : \varepsilon\rangle : s!c\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\} : \varepsilon] \\
\qquad\qquad \downarrow\tau \\
[\langle c : P_c : \varepsilon\rangle : c?s\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\} : s!c(\mathsf{quit}\langle\rangle)] \quad \mid \quad [\langle s : P_s^{\mathsf{q}} : \varepsilon\rangle : \mathsf{end} : \varepsilon]
\end{array}
$$

Networks of monitored blackboxes (1/2)

$$
\begin{array}{c}
\langle c : P_c : s!c(\text{quit}\langle\rangle)\rangle \xrightarrow{c?s(\text{quit}\langle\rangle)} \langle c : P_c^{\text{q}} : \varepsilon\rangle \xrightarrow{\quad\text{end}\quad} \langle c : P_c^{\text{e}} : \varepsilon\rangle \\
\langle s : P_s : \varepsilon\rangle \xrightarrow{s!c(\text{quit}\langle\rangle)} \langle s : P_s^{\text{q}} : \varepsilon\rangle \xrightarrow{\quad\text{end}\quad} \langle s : P_s^{\text{e}} : \varepsilon\rangle \\
\hline
\end{array}
$$

$$
\begin{array}{l}
[\langle c : P_c : \varepsilon\rangle : c?s\{\!\{\text{quit}\langle\rangle.\text{end}\}\!\} : \varepsilon] \quad | \quad [\langle s : P_s : \varepsilon\rangle : s!c\{\!\{\text{quit}\langle\rangle.\text{end}\}\!\} : \varepsilon] \\
\qquad\qquad \downarrow_{\tau} \\
[\langle c : P_c : \varepsilon\rangle : c?s\{\!\{\text{quit}\langle\rangle.\text{end}\}\!\} : s!c(\text{quit}\langle\rangle)] \quad | \quad [\langle s : P_s^{\text{q}} : \varepsilon\rangle : \text{end} : \varepsilon] \\
\qquad\qquad \downarrow_{\tau} \\
[\langle c : P_c : s!c(\text{quit}\langle\rangle)\rangle : \text{end} : \varepsilon] \quad | \quad [\langle s : P_s^{\text{q}} : \varepsilon\rangle : \text{end} : \varepsilon]
\end{array}
$$

Networks of monitored blackboxes (1/2)

$$\langle c : P_c : s!c(\mathsf{quit}\langle\rangle)\rangle \xrightarrow{c?s(\mathsf{quit}\langle\rangle)} \langle c : P_c^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\quad\mathsf{end}\quad} \langle c : P_c^{\mathsf{e}} : \varepsilon\rangle$$

$$\langle s : P_s : \varepsilon\rangle \xrightarrow{s!c(\mathsf{quit}\langle\rangle)} \langle s : P_s^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\quad\mathsf{end}\quad} \langle s : P_s^{\mathsf{e}} : \varepsilon\rangle$$

$$[\langle c : P_c : \varepsilon\rangle : c?s\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\} : \varepsilon] \quad | \quad [\langle s : P_s : \varepsilon\rangle : s!c\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\} : \varepsilon]$$

$$\downarrow\tau$$

$$[\langle c : P_c : \varepsilon\rangle : c?s\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\} : s!c(\mathsf{quit}\langle\rangle)] \quad | \quad [\langle s : P_s^{\mathsf{q}} : \varepsilon\rangle : \mathsf{end} : \varepsilon]$$

$$\downarrow\tau$$

$$[\langle c : P_c : s!c(\mathsf{quit}\langle\rangle)\rangle : \mathsf{end} : \varepsilon] \quad | \quad [\langle s : P_s^{\mathsf{q}} : \varepsilon\rangle : \mathsf{end} : \varepsilon]$$

$$\downarrow\tau$$

$$[\langle c : P_c^{\mathsf{q}} : \varepsilon\rangle : \mathsf{end} : \varepsilon] \quad | \quad [\langle s : P_s^{\mathsf{q}} : \varepsilon\rangle : \mathsf{end} : \varepsilon]$$

Networks of monitored blackboxes (1/2)

$$\langle c : P_c : s!c(\mathsf{quit}\langle\rangle)\rangle \xrightarrow{c?s(\mathsf{quit}\langle\rangle)} \langle c : P_c^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\quad\mathsf{end}\quad} \langle c : P_c^{\mathsf{e}} : \varepsilon\rangle$$

$$\langle s : P_s : \varepsilon\rangle \xrightarrow{s!c(\mathsf{quit}\langle\rangle)} \langle s : P_s^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\quad\mathsf{end}\quad} \langle s : P_s^{\mathsf{e}} : \varepsilon\rangle$$

$$[\langle c : P_c : \varepsilon\rangle : c?s\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\} : \varepsilon] \quad \mid \quad [\langle s : P_s : \varepsilon\rangle : s!c\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\} : \varepsilon]$$

$$\downarrow_{\tau}$$

$$[\langle c : P_c : \varepsilon\rangle : c?s\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\} : s!c(\mathsf{quit}\langle\rangle)] \quad \mid \quad [\langle s : P_s^{\mathsf{q}} : \varepsilon\rangle : \mathsf{end} : \varepsilon]$$

$$\downarrow_{\tau}$$

$$[\langle c : P_c : s!c(\mathsf{quit}\langle\rangle)\rangle : \mathsf{end} : \varepsilon] \quad \mid \quad [\langle s : P_s^{\mathsf{q}} : \varepsilon\rangle : \mathsf{end} : \varepsilon]$$

$$\downarrow_{\tau}$$

$$[\langle c : P_c^{\mathsf{q}} : \varepsilon\rangle : \mathsf{end} : \varepsilon] \quad \mid \quad [\langle s : P_s^{\mathsf{q}} : \varepsilon\rangle : \mathsf{end} : \varepsilon]$$

$$\downarrow_{\mathsf{end}}$$

$$\downarrow_{\mathsf{end}}$$

$$[\langle c : P_c^{\mathsf{e}} : \varepsilon\rangle : \checkmark : \varepsilon] \quad \mid \quad [\langle s : P_s^{\mathsf{e}} : \varepsilon\rangle : \checkmark : \varepsilon]$$

Networks of monitored blackboxes (2/2)

$$\langle c : P_c : s!c(\mathsf{quit}\langle\rangle)\rangle \xrightarrow{c?s(\mathsf{quit}\langle\rangle)} \langle c : P_c^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\qquad\mathsf{end}\qquad} \langle c : P_c^{\mathsf{e}} : \varepsilon\rangle$$

$$\langle s : P_s : \varepsilon\rangle \xrightarrow{s!c(\mathsf{quit}\langle\rangle)} \langle s : P_s^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\qquad\mathsf{end}\qquad} \langle s : P_s^{\mathsf{e}} : \varepsilon\rangle$$

$$M_c = c?s\{\!\{\mathsf{login}\langle\rangle \ldots\}\!\} \qquad\qquad M_s = s!c\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\}$$

Networks of monitored blackboxes (2/2)

$$\frac{\begin{array}{c}\langle c : P_c : s!c(\mathsf{quit}\langle\rangle)\rangle \xrightarrow{c?s(\mathsf{quit}\langle\rangle)} \langle c : P_c^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\mathsf{end}} \langle c : P_c^{\mathsf{e}} : \varepsilon\rangle \\ \langle s : P_s : \varepsilon\rangle \xrightarrow{s!c(\mathsf{quit}\langle\rangle)} \langle s : P_s^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\mathsf{end}} \langle s : P_s^{\mathsf{e}} : \varepsilon\rangle\end{array}}{[\langle c : P_c : \varepsilon\rangle : c?s\{\!\{\mathsf{login}\langle\rangle \ldots\}\!\} : \varepsilon] \quad \mid \quad [\langle s : P_s : \varepsilon\rangle : s!c\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\} : \varepsilon]}$$

Networks of monitored blackboxes (2/2)

$$\frac{\begin{array}{c} \langle c : P_c : s!c(\mathsf{quit}\langle\rangle)\rangle \xrightarrow{c?s(\mathsf{quit}\langle\rangle)} \langle c : P_c^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\quad\mathsf{end}\quad} \langle c : P_c^{\mathsf{e}} : \varepsilon\rangle \\ \langle s : P_s : \varepsilon\rangle \xrightarrow{s!c(\mathsf{quit}\langle\rangle)} \langle s : P_s^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\quad\mathsf{end}\quad} \langle s : P_s^{\mathsf{e}} : \varepsilon\rangle \end{array}}{\begin{array}{l} [\langle c : P_c : \varepsilon\rangle : c?s\{\!\{\mathsf{login}\langle\rangle \ldots\}\!\} : \varepsilon] \quad | \quad [\langle s : P_s : \varepsilon\rangle : s!c\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\} : \varepsilon] \\ \qquad\qquad\quad \downarrow\tau \\ [\langle c : P_c : \varepsilon\rangle : c?s\{\!\{\mathsf{login}\langle\rangle \ldots\}\!\} : s!c(\mathsf{quit}\langle\rangle)] \quad | \quad [\langle s : P_s^{\mathsf{q}} : \varepsilon\rangle : \mathsf{end} : \varepsilon] \end{array}}$$

Networks of monitored blackboxes (2/2)

$$\langle c : P_c : s!c(\mathsf{quit}\langle\rangle)\rangle \xrightarrow{c?s(\mathsf{quit}\langle\rangle)} \langle c : P_c^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\qquad\mathsf{end}\qquad} \langle c : P_c^{\mathsf{e}} : \varepsilon\rangle$$

$$\langle s : P_s : \varepsilon\rangle \xrightarrow{s!c(\mathsf{quit}\langle\rangle)} \langle s : P_s^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\qquad\mathsf{end}\qquad} \langle s : P_s^{\mathsf{e}} : \varepsilon\rangle$$

$$[\langle c : P_c : \varepsilon\rangle : c?s\{\!\{\mathsf{login}\langle\rangle \ldots\}\!\} : \varepsilon] \quad | \quad [\langle s : P_s : \varepsilon\rangle : s!c\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\} : \varepsilon]$$

$$\downarrow\tau$$

$$[\langle c : P_c : \varepsilon\rangle : c?s\{\!\{\mathsf{login}\langle\rangle \ldots\}\!\} : s!c(\mathsf{quit}\langle\rangle)] \quad | \quad [\langle s : P_s^{\mathsf{q}} : \varepsilon\rangle : \mathsf{end} : \varepsilon]$$

$$\downarrow\tau$$

$$\mathsf{error}_c \quad | \quad [\langle s : P_s^{\mathsf{q}} : \varepsilon\rangle : \mathsf{end} : \varepsilon]$$

Networks of monitored blackboxes (2/2)

$$\langle c : P_c : s!c(\mathsf{quit}\langle\rangle)\rangle \xrightarrow{c?s(\mathsf{quit}\langle\rangle)} \langle c : P_c^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\quad\mathsf{end}\quad} \langle c : P_c^{\mathsf{e}} : \varepsilon\rangle$$

$$\langle s : P_s : \varepsilon\rangle \xrightarrow{s!c(\mathsf{quit}\langle\rangle)} \langle s : P_s^{\mathsf{q}} : \varepsilon\rangle \xrightarrow{\quad\mathsf{end}\quad} \langle s : P_s^{\mathsf{e}} : \varepsilon\rangle$$

$$[\langle c : P_c : \varepsilon\rangle : c?s\{\!\{\mathsf{login}\langle\rangle\ \ldots\}\!\} : \varepsilon] \quad | \quad [\langle s : P_s : \varepsilon\rangle : s!c\{\!\{\mathsf{quit}\langle\rangle.\mathsf{end}\}\!\} : \varepsilon]$$

$$\downarrow\tau$$

$$[\langle c : P_c : \varepsilon\rangle : c?s\{\!\{\mathsf{login}\langle\rangle\ \ldots\}\!\} : s!c(\mathsf{quit}\langle\rangle)] \quad | \quad [\langle s : P_s^{\mathsf{q}} : \varepsilon\rangle : \mathsf{end} : \varepsilon]$$

$$\downarrow\tau$$

$$\mathsf{error}_c \quad | \quad [\langle s : P_s^{\mathsf{q}} : \varepsilon\rangle : \mathsf{end} : \varepsilon]$$

$$\downarrow\tau$$

$$\mathsf{error}_{c,s}$$

Results

Theorem (Soundness)

If all the monitored blackboxes in a network N *satisfy a protocol* G*, then* N *behaves as specified by* G*.*

Theorem (Transparency)

If a monitored blackbox satisfies a protocol, then it is behaviorally equivalent to its contained blackbox (modulo coordination messages).

Conclusion

- Types for message-passing concurrency
- Session types: A class of behavioral types for communication correctness
- A new framework for runtime verification based on multiparty session types
- More details in our papers; see `www.jperez.nl`

Current and future work:

- Coalgebraic and coinductive approaches to session types
- Session types beyond linear logic / propositions as sessions
- Session-based concurrency implemented on Maude (rewriting logic)

A Logical Basis for the Verification of Message-Passing Programs

Jorge A. Pérez

Fundamental Computing Group
University of Groningen, The Netherlands
https://www.rug.nl/fse/fc

Dutch Formal Methods Day
April 16, 2024

UNIFYING
C•RRECTNESS FOR
C•MMUNICATING
S•FTWARE