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
CORRECTNESS FOR
COMMUNICATING
SOFTWARE
My Group’s Research: Keywords (and Slogans)

Concurrency Theory, Message-Passing, Programming Languages, Verification
My Group’s Research: Keywords (and Slogans)

Concurrency Theory, Message-Passing, Programming Languages, Verification

- **Type systems**
  
  *Slogan:* Well-typed programs can’t go wrong (Milner)
My Group’s Research: Keywords (and Slogans)

Concurrency Theory, Message-Passing, Programming Languages, Verification

- **Type systems**
  *Slogan:* Well-typed programs can’t go wrong (Milner)

- **Session types** for communication correctness
  *Slogan:* What and when should be sent through a channel
My Group’s Research: Keywords (and Slogans)

Concurrency Theory, Message-Passing, Programming Languages, Verification

- **Type systems**
  *Slogan:* Well-typed programs can’t go wrong (Milner)

- **Session types** for communication correctness
  *Slogan:* What and when should be sent through a channel

- **Process calculi**
  *Slogan:* The $\pi$-calculus treats processes like the $\lambda$-calculus treats functions

- **Propositions as sessions**
My Group’s Research: Keywords (and Slogans)

Concurrency Theory, Message-Passing, Programming Languages, Verification

- **Type systems**
  *Slogan:* Well-typed programs can’t go wrong (Milner)

- **Session types** for communication correctness
  *Slogan:* What and when should be sent through a channel

- **Process calculi**
  *Slogan:* The $\pi$-calculus treats processes like the $\lambda$-calculus treats functions

- **Propositions as sessions**

**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?

"Programs produce outputs that are consistent with their input"
When is a Program Correct?

**Sequential Programs**

"Programs produce outputs that are consistent with their input"

**Concurrent Programs**

"Programs always respect their intended protocols"
When is a Program Correct?

Sequential Programs

- Programs produce outputs that are consistent with their input

Concurrent Programs

- 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
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

Sequential Languages

- **Data type systems** classify values in a program
- Examples: Integers, strings of characters
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

Sequential Languages

- **Data type systems** classify values in a program
- Examples: Integers, strings of characters

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
- $\pi$-calculus names
- ...  

Sequentiality in types goes **hand-in-hand** with sequentiality in processes
Example: A Two-Buyer Protocol

Alice and Bob cooperate in buying a book from Seller:

1. Alice sends a book title to Seller, who sends a quote back.
2. Alice checks whether Bob can contribute in buying the book.
3. Alice uses the answer from Bob to interact with Seller, either:
   a) completing the payment and arranging delivery details
   b) canceling the transaction
4. In case 3(a) Alice contacts Bob to get his address, and forwards it to Seller.
4’. In case 3(b) Alice is in charge of gracefully concluding the conversation.
Example: A Two-Buyer Protocol

Alice and Bob cooperate in buying a book from Seller:

1. Alice sends a book title to Seller, who sends a quote back.
Example: A Two-Buyer Protocol

Alice and Bob cooperate in buying a book from Seller:

1. Alice sends a book title to Seller, who sends a quote back.
2. Alice checks whether Bob can contribute in buying the book.
Example: A Two-Buyer Protocol

Alice and Bob cooperate in buying a book from Seller:

1. Alice sends a book title to Seller, who sends a quote back.
2. Alice checks whether Bob can contribute in buying the book.
3. Alice uses the answer from Bob to interact with Seller, either:
   a) completing the payment and arranging delivery details
   b) canceling the transaction
Example: A Two-Buyer Protocol

Alice and Bob cooperate in buying a book from Seller:

1. Alice sends a book title to Seller, who sends a quote back.
2. Alice checks whether Bob can contribute in buying the book.
3. Alice uses the answer from Bob to interact with Seller, either:
   a) completing the payment and arranging delivery details
   b) canceling the transaction
4. In case 3(a) Alice contacts Bob to get his address, and forwards it to Seller.
Example: A Two-Buyer Protocol

Alice and Bob cooperate in buying a book from Seller:

1. Alice sends a book title to Seller, who sends a quote back.

2. Alice checks whether Bob can contribute in buying the book.

3. Alice uses the answer from Bob to interact with Seller, either:
   a) completing the payment and arranging delivery details
   b) canceling the transaction

4. In case 3(a) Alice contacts Bob to get his address, and forwards it to Seller.

4'. In case 3(b) Alice is in charge of gracefully concluding the conversation.
The Syntax of Session Types

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

(Labels \(l_1, \ldots, l_n\) are pairwise different.)
Example: A Two-Buyer Protocol

Two separate protocols, with Alice “leading” the interactions:

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

  \[ S_{SA} = \ ?book; \ !quote; \ & \ \{ \begin{align*}
  \text{buy} : & \ ?\text{paym}; \ ?\text{address}; \ !\text{ok}; \ \text{end} \\
  \text{cancel} : & \ ?\text{thanks}; \ !\text{bye}; \ \text{end}
  \end{align*} \ & \end{equation} \]

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

  \[ S_{AB} = \ !\text{cost}; \ & \ \{ \begin{align*}
  \text{share} : & \ ?\text{address}; \ !\text{ok}; \ \text{end} \\
  \text{close} : & \ !\text{bye}; \ \text{end}
  \end{align*} \ & \end{equation} \]
Example: A Two-Buyer Protocol

Two separate protocols, with Alice “leading” the interactions:

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

  \[ S_{SA} = \ ?book; \ !quote; \ & \begin{cases} \text{buy} : \ \ ?paym; \ ?address; \ !ok; \ \text{end} \\ \text{cancel} : \ \ ?thanks; \ !bye; \ \text{end} \end{cases} \]

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

  \[ S_{AB} = \ !cost; \ & \begin{cases} \text{share} : \ \ ?address; \ !ok; \ \text{end} \\ \text{close} : \ !bye; \ \text{end} \end{cases} \]

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
Example: A Two-Buyer Protocol

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

- **Fidelity** – they follow the intended protocol.
- **Safety** – they don’t feature communication errors.
  - Seller always returns an integer when Alice requests a quote
Example: A Two-Buyer Protocol

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

- **Fidelity** – they *follow the intended protocol*.
- **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.
Example: A Two-Buyer Protocol

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

- **Fidelity** – they follow the intended protocol.
- **Safety** – they don’t feature communication errors.
- **Deadlock-Freedom** – they do not “get stuck” while running the protocol.
- **Termination** – they do not engage in infinite behavior (that may prevent them from completing the protocol).
Example: A Two-Buyer Protocol

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

- **Fidelity** – they follow the intended protocol.
- **Safety** – they don’t feature communication errors.
- **Deadlock-Freedom** – they do not “get stuck” while running the protocol.
- **Termination** – they do not engage in infinite behavior (that may prevent them from completing the protocol)

Correctness follows from the interplay of these properties. **Hard to enforce**, especially when actions are “scattered around” in source programs.
Example: A Two-Buyer Protocol

Implementations for Alice, Bob, Seller should be **compatible**.
Example: A Two-Buyer Protocol

Implementations for Alice, Bob, Seller should be compatible.

- **Duality** relates session types with opposite behaviors.
  - the dual of input is output (and vice versa)
  - branching is the dual of selection (and vice versa)
Example: A Two-Buyer Protocol

Implementations for Alice, Bob, Seller should be **compatible**.

- **Duality** relates session types with opposite behaviors.
  - the dual of input is output (and vice versa)
  - branching is the dual of selection (and vice versa)

- Recall that $S_{AB}$ describes Alice’s viewpoint in her interaction with Bob:

  $$S_{AB} = !\text{cost}; &\left\{\begin{array}{l}
  \text{share} : \ ?\text{address}; \ !\text{ok}; \ \text{end} \\
  \text{close} : \ !\text{bye}; \ \text{end}
  \end{array}\right.$$ 

- Given this, Bob’s implementation should conform to $\bar{S}_{AB}$, the dual of $S_{AB}$:

  $$\bar{S}_{AB} = ?\text{cost}; \oplus\left\{\begin{array}{l}
  \text{share} : \ !\text{address}; \ ?\text{ok}; \ \text{end} \\
  \text{close} : \ ?\text{bye}; \ \text{end}
  \end{array}\right.$$
Example: A Two-Buyer Protocol

Implementations for Alice, Bob, Seller should be **compatible**.

- **Duality** relates session types with opposite behaviors.
  - the dual of input is output (and vice versa)
  - branching is the dual of selection (and vice versa)

- Recall that $S_{AB}$ describes Alice’s viewpoint in her interaction with Bob:
  \[
  S_{AB} = !\text{cost}; \& \begin{cases} 
  \text{share} : \ ?\text{address}; !\text{ok}; \text{end} \\
  \text{close} : \ !\text{bye}; \text{end}
  \end{cases}
  \]

- Given this, Bob’s implementation should conform to $\overline{S_{AB}}$, the dual of $S_{AB}$:
  \[
  \overline{S_{AB}} = ?\text{cost}; \oplus \begin{cases} 
  \text{share} : \ !\text{address}; ?\text{ok}; \text{end} \\
  \text{close} : \ ?\text{bye}; \text{end}
  \end{cases}
  \]

- Also, Alice’s implementation should conform to both $\overline{S_{SA}}$ and $S_{AB}$. 
Propositions as Sessions

Concurrency  Logic
session types $\leftrightarrow$ linear logic propositions
$\pi$-calculus processes $\leftrightarrow$ proofs
process communication $\leftrightarrow$ 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 can be 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:

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

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

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

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.
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, server requests client to login through authorization service.

Existing techniques require **too much information** about components.
Dynamic Approach

- 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, server requests client to login through authorization service.
- Existing techniques require **too much information** about components.
Dynamic Approach: Overview

- 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.
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., $\langle c : P_c : m \rangle$.
- Messages carry data or choices to resolve branching.
Our Setup: Blackboxes

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

\[
P_c \xleftarrow{c?} P_c
\]
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**.

\[
\begin{align*}
P_c & \xrightarrow{c?s(\text{login}() \rangle} P_c
\end{align*}
\]
Our Setup: Blackboxes

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

$$
P_c \xleftrightarrow{\text{c?} \text{s(login\{\})}} P_c
\xleftrightarrow{\text{c!} \text{a(pwd\{str\})}} P_c
$$
Our Setup: Blackboxes

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

▶ Each blackbox assumed to belong to a protocol participant: e.g., $P_c$.

▶ Blackboxes exchange messages asynchronously through buffers: e.g., $\langle c : P_c : \bar{m} \rangle$.

▶ Messages carry data or choices to resolve branching.

\[
\begin{align*}
&P_c \xleftarrow{c? s(\text{login}())} P_c \xrightarrow{c! a(\text{pwd}(\text{str}))} P_c \xrightarrow{c? s(\text{quit}())} P^q \xrightarrow{\text{end}} P^e
\end{align*}
\]
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.

\[
\begin{align*}
\langle c : P_c : s!c(\text{login}) \rangle & \quad P_c \\
\langle \  \ c!a(\text{pwd}(\text{str})) \quad P_c \quad c?s(\text{login}) \rangle & \quad P_c \\
\langle \  \ c?s(\text{quit}) \quad P^q_c \quad \text{end} \quad P^e_c \rangle
\end{align*}
\]

\[
\langle c : P_c : s!c(\text{quit}) \rangle
\]
Our Setup: Blackboxes

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

$$
\begin{align*}
& P_c \xleftarrow{c？s(\text{login}())} P_c \xrightarrow{c！a(\text{pwd}(\text{str}))} P_c \xrightarrow{c？s(\text{quit}())} P^q_c \xrightarrow{\text{end}} P^e_c \\
& \langle c : P_c : s！c(\text{quit}()) \rangle \xrightarrow{c？s(\text{quit}())} \langle c : P^q_c : \varepsilon \rangle
\end{align*}
$$
Our Setup: Blackboxes

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

\[
\begin{align*}
P_c & \xleftarrow{c?s(login\langle\rangle)} P_c \xrightarrow{c!a(pwd\langle str \rangle)} P_c \xrightarrow{c?s(quit\langle\rangle)} P^q_c \xrightarrow{\text{end}} P^e_c \\
\langle c : P_c : s!c(quit\langle\rangle) \rangle & \xrightarrow{c?s(quit\langle\rangle)} \langle c : P^q_c : \varepsilon \rangle \xrightarrow{\text{end}} \langle c : P^e_c : \varepsilon \rangle
\end{align*}
\]
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., \([⟨c : P_c : \vec{m}⟩ : M_c : \vec{n}⟩]\).
- Broadcast messages to *coordinate* blackboxes to support *more expressive* protocols.
Networks of monitored blackboxes (1/2)

\[
\langle c : P_c : s!c(\text{quit}{\langle\rangle}) \rangle \xrightarrow{c?s(\text{quit}{\langle\rangle})} \langle c : P^q_c : \varepsilon \rangle \xrightarrow{\text{end}} \langle c : P^e_c : \varepsilon \rangle
\]

\[
\langle s : P_s : \varepsilon \rangle \xrightarrow{s!c(\text{quit}{\langle\rangle})} \langle s : P^q_s : \varepsilon \rangle \xrightarrow{\text{end}} \langle s : P^e_s : \varepsilon \rangle
\]
Networks of monitored blackboxes (1/2)

\[
\begin{align*}
\langle c : P_c : s!c(\text{quit} \langle \rangle) \rangle \xrightarrow{c?s(\text{quit} \langle \rangle)} & \langle c : P_c : \varepsilon \rangle \xrightarrow{\text{end}} \langle c : P_c^e : \varepsilon \rangle \\
\langle s : P_s : \varepsilon \rangle \xrightarrow{s!c(\text{quit} \langle \rangle)} & \langle s : P_s^q : \varepsilon \rangle \xrightarrow{\text{end}} \langle s : P_s^e : \varepsilon \rangle
\end{align*}
\]

\[
M_c = c?s\{\text{quit} \langle \rangle . \text{end}\} \quad M_s = s!c\{\text{quit} \langle \rangle . \text{end}\}
\]
Networks of monitored blackboxes (1/2)

\[
\begin{align*}
\langle c : P_c : s!c\langle \text{quit} \rangle \rangle & \xrightarrow{c?s\langle \text{quit} \rangle} \langle c : P_c^q : \varepsilon \rangle \xrightarrow{\text{end}} \langle c : P_c^e : \varepsilon \rangle \\
\langle s : P_s : \varepsilon \rangle & \xrightarrow{s!c\langle \text{quit} \rangle} \langle s : P_s^q : \varepsilon \rangle \xrightarrow{\text{end}} \langle s : P_s^e : \varepsilon \rangle
\end{align*}
\]
Networks of monitored blackboxes (1/2)

\[
\begin{align*}
\langle c : P_c : s!c(\text{quit}\langle\rangle)\rangle & \xrightarrow{c?s(\text{quit}\langle\rangle)} \langle c : P^q_c : \varepsilon \rangle \xrightarrow{\text{end}} \langle c : P^e_c : \varepsilon \rangle \\
\langle s : P_s : \varepsilon \rangle & \xrightarrow{s!c(\text{quit}\langle\rangle)} \langle s : P^q_s : \varepsilon \rangle \xrightarrow{\text{end}} \langle s : P^e_s : \varepsilon \rangle
\end{align*}
\]

\[
\begin{align*}
[\langle c : P_c : \varepsilon \rangle : c?s\{\text{quit}\langle\rangle.\text{end}\} : \varepsilon] & \mid [\langle s : P_s : \varepsilon \rangle : s!c\{\text{quit}\langle\rangle.\text{end}\} : \varepsilon] \\
\downarrow\tau & \\
[\langle c : P_c : \varepsilon \rangle : c?s\{\text{quit}\langle\rangle.\text{end}\} : s!c(\text{quit}\langle\rangle)] & \mid [\langle s : P^q_s : \varepsilon \rangle : \text{end} : \varepsilon]
\end{align*}
\]
Networks of monitored blackboxes (1/2)

\[
\begin{align*}
\langle c : P_c : s!c(\text{quit}()) \rangle & \xrightarrow{c?s(\text{quit}())} \langle c : P^q_c : \varepsilon \rangle \xrightarrow{\text{end}} \langle c : P^e_c : \varepsilon \rangle \\
\langle s : P_s : \varepsilon \rangle & \xrightarrow{s!c(\text{quit}())} \langle s : P^q_s : \varepsilon \rangle \xrightarrow{\text{end}} \langle s : P^e_s : \varepsilon \rangle
\end{align*}
\]

\[
\begin{align*}
[\langle c : P_c : \varepsilon \rangle : c?s\{$\text{quit}()$.\text{end}$\} : \varepsilon] & \quad | \quad [\langle s : P_s : \varepsilon \rangle : s!c\{$\text{quit}()$.\text{end}$\} : \varepsilon] \\
\downarrow \tau & \\
[\langle c : P_c : \varepsilon \rangle : c?s\{$\text{quit}()$.\text{end}$\} : s!c(\text{quit}())] & \quad | \quad [\langle s : P^q_s : \varepsilon \rangle : \text{end} : \varepsilon] \\
\downarrow \tau & \\
[\langle c : P_c : s!c(\text{quit}()) \rangle : \text{end} : \varepsilon] & \quad | \quad [\langle s : P^q_s : \varepsilon \rangle : \text{end} : \varepsilon]
\end{align*}
\]
Networks of monitored blackboxes (1/2)

\[
\begin{align*}
\langle c : P_c : s!c(\text{quit}()) \rangle &\xrightarrow{c?s(\text{quit}())} \langle c : P^q_c : \varepsilon \rangle \xrightarrow{\text{end}} \langle c : P^e_c : \varepsilon \rangle \\
\langle s : P_s : \varepsilon \rangle &\xrightarrow{s!c(\text{quit}())} \langle s : P^q_s : \varepsilon \rangle \xrightarrow{\text{end}} \langle s : P^e_s : \varepsilon \rangle
\end{align*}
\]
Networks of monitored blackboxes (1/2)

\[
\begin{align*}
\langle c : P_c : s!c(\text{quit}) \rangle & \xrightarrow{c?s(\text{quit})} \langle c : P_c^q : \varepsilon \rangle \xrightarrow{\text{end}} \langle c : P_c^e : \varepsilon \rangle \\
\langle s : P_s : \varepsilon \rangle & \xrightarrow{s!c(\text{quit})} \langle s : P_s^q : \varepsilon \rangle \xrightarrow{\text{end}} \langle s : P_s^e : \varepsilon \rangle
\end{align*}
\]

\[
\begin{align*}
\left[ \langle c : P_c : \varepsilon \rangle : c?s\{\text{quit}.\text{end}\} : \varepsilon \right] & \quad | \quad \left[ \langle s : P_s : \varepsilon \rangle : s!c\{\text{quit}.\text{end}\} : \varepsilon \right] \\
\downarrow \tau & \quad | \quad \downarrow \tau \\
\left[ \langle c : P_c : \varepsilon \rangle : c?s\{\text{quit}.\text{end}\} : s!c(\text{quit}) \rangle \right] & \quad | \quad \left[ \langle s : P_s^q : \varepsilon \rangle : \text{end} : \varepsilon \right] \\
\downarrow \tau & \quad | \quad \downarrow \tau \\
\left[ \langle c : P_c^q : \varepsilon \rangle : \text{end} : \varepsilon \right] & \quad | \quad \left[ \langle s : P_s^q : \varepsilon \rangle : \text{end} : \varepsilon \right] \\
\downarrow \text{end} & \quad | \quad \downarrow \text{end} \\
\left[ \langle c : P_c^e : \varepsilon \rangle : \checkmark : \varepsilon \right] & \quad | \quad \left[ \langle s : P_s^e : \varepsilon \rangle : \checkmark : \varepsilon \right]
\end{align*}
\]
Networks of monitored blackboxes (2/2)

\[ \langle c : P_c : s!c(\text{quit}()) \rangle \xrightarrow{c?s(\text{quit}())} \langle c : P^q_c : \varepsilon \rangle \xrightarrow{\text{end}} \langle c : P^e_c : \varepsilon \rangle \]

\[ \langle s : P_s : \varepsilon \rangle \xrightarrow{s!c(\text{quit}())} \langle s : P^q_s : \varepsilon \rangle \xrightarrow{\text{end}} \langle s : P^e_s : \varepsilon \rangle \]

\[ M_c = c?s\{\text{login}(), \ldots \} \]

\[ M_s = s!c\{\text{quit}().\text{end}\} \]
Networks of monitored blackboxes (2/2)

\[
\begin{align*}
\langle c \triangledown P_c : s!c(\text{quit}()) \rangle & \xrightarrow{c?s(\text{quit}())} \langle c \triangledown P^q_c : \varepsilon \rangle \xrightarrow{\text{end}} \langle c \triangledown P^e_c : \varepsilon \rangle \\
\langle s \triangledown P_s : \varepsilon \rangle & \xrightarrow{s!c(\text{quit}())} \langle s \triangledown P^q_s : \varepsilon \rangle \xrightarrow{\text{end}} \langle s \triangledown P^e_s : \varepsilon \rangle
\end{align*}
\]
Networks of monitored blackboxes (2/2)

\[
\begin{align*}
\langle c : P_c : s!c(\text{quit}()) \rangle & \xrightarrow{c?s(\text{quit}())} \langle c : P^q_c : \varepsilon \rangle \xrightarrow{\text{end}} \langle c : P^e_c : \varepsilon \rangle \\
\langle s : P_s : \varepsilon \rangle & \xrightarrow{s!c(\text{quit}())} \langle s : P^q_s : \varepsilon \rangle \xrightarrow{\text{end}} \langle s : P^e_s : \varepsilon \rangle
\end{align*}
\]

\[
\begin{align*}
[\langle c : P_c : \varepsilon \rangle : c?s\{\text{login}() \ldots\} : \varepsilon] & \quad | \quad [\langle s : P_s : \varepsilon \rangle : s!c\{\text{quit}().\text{end}\} : \varepsilon] \\
\downarrow_\tau & \\
[\langle c : P_c : \varepsilon \rangle : c?s\{\text{login}() \ldots\} : s!c(\text{quit}())] & \quad | \quad [\langle s : P^q_s : \varepsilon \rangle : \text{end} : \varepsilon]
\end{align*}
\]
Networks of monitored blackboxes (2/2)

\[
\begin{align*}
&\langle c : P_c : s!c(\text{quit}()) \rangle \xrightarrow{c?s(\text{quit}())} \langle c : P^q_c : \varepsilon \rangle \xrightarrow{\text{end}} \langle c : P^e_c : \varepsilon \rangle \\
&\langle s : P_s : \varepsilon \rangle \xrightarrow{s!c(\text{quit}())} \langle s : P^q_s : \varepsilon \rangle \xrightarrow{\text{end}} \langle s : P^e_s : \varepsilon \rangle
\end{align*}
\]

\[
\begin{align*}
&[\langle c : P_c : \varepsilon \rangle : c?s\{\text{login}() \ldots \} : \varepsilon] \mid [\langle s : P_s : \varepsilon \rangle : s!c\{\text{quit}().\text{end}\} : \varepsilon] \\
&\downarrow_\tau \\
&[\langle c : P_c : \varepsilon \rangle : c?s\{\text{login}() \ldots \} : s!c(\text{quit}())] \mid [\langle s : P^q_s : \varepsilon \rangle : \text{end} : \varepsilon] \\
&\downarrow_\tau \\
&\text{error}_c \mid [\langle s : P^q_s : \varepsilon \rangle : \text{end} : \varepsilon]
\end{align*}
\]
Networks of monitored blackboxes (2/2)

\[
\begin{align*}
\langle c : P_c : s!c{(\text{quit} \langle \rangle)} \rangle & \xrightarrow{cs{(\text{quit} \langle \rangle)}} \langle c : P^q_c : \varepsilon \rangle \xrightarrow{\text{end}} \langle c : P^e_c : \varepsilon \rangle \\
\langle s : P_s : \varepsilon \rangle & \xrightarrow{s!c{(\text{quit} \langle \rangle)}} \langle s : P^q_s : \varepsilon \rangle \xrightarrow{\text{end}} \langle s : P^e_s : \varepsilon \rangle
\end{align*}
\]

\[
\begin{align*}
\langle c : P_c : \varepsilon \rangle & : c?s\{\text{login} \langle \ldots \rangle\} : \varepsilon \quad | \quad \langle s : P_s : \varepsilon \rangle & : s!c\{\text{quit} \langle \rangle.\text{end}\} : \varepsilon \\
\downarrow_\tau & \quad | \quad \downarrow_\tau \\
\langle c : P_c : \varepsilon \rangle & : c?s\{\text{login} \langle \ldots \rangle\} : s!c{(\text{quit} \langle \rangle)} \quad | \quad \langle s : P^q_s : \varepsilon \rangle & : \text{end} : \varepsilon \\
\downarrow_\tau & \quad | \quad \downarrow_\tau \\
\text{error}_c & \quad | \quad \langle s : P^q_s : \varepsilon \rangle & : \text{end} : \varepsilon \\
\downarrow_\tau & \\
\text{error}_{c,s}
\end{align*}
\]
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