Towards a Hybrid Verification Methodology for Communication Protocols (Short Paper)*

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Abstract. We present our preliminary work towards a comprehensive solution for the hybrid (static + dynamic) verification of open distributed systems, using session types. We automate a solution for binary sessions where one endpoint is statically checked, and the other endpoint is dynamically checked by a monitor acting as an intermediary between typed and untyped components. We outline our theory, and illustrate a tool that automatically synthesises type-checked session monitors, based on the Scala language and its session programming library (lchannels).

Keywords: Session types · Static and dynamic verification · Monitors.

1 Introduction

Session Types \cite{27,12,13} have emerged as a central formalism for the verification of concurrent and distributed programs. Session-types-based analysis ensures that a program correctly implements some predetermined communication protocol, stipulating the desired exchange of messages \cite{16,4}. The analysis is typically performed statically, via type checking, before the programs are deployed. However, full static analysis is not always possible (e.g., when the source code of third-party programs and components is unavailable); in such cases, session types are checked at runtime via monitors \cite{10,17,6,19}. We view these approaches as two extremes on a continuum: our aim is to develop practical hybrid (static and dynamic) verification methodologies and tools for distributed programs in open settings. In particular, our aim is to verify distributed systems where:

\begin{enumerate}[(i)]
\item we make no assumptions on how messages are delivered between components;
\item the components available prior-deployment are checked statically; and
\item the components that are unavailable for checking prior-deployment are verified at runtime, by deploying autogenerated, type-checked monitors.
\end{enumerate}

To achieve this aim, we present a methodology with three key features, presented as contributions in this paper:

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F1. Open systems are prone to malicious attacks and data corruption. Thus, we describe protocols via augmented session types including runtime data assertions (reminiscent of interaction refinements [18]), and synthesise monitors that automate such data checks. Unlike [18], our monitors are independent, type-checked processes, that can be deployed over any network.

F2. We develop a tool that, given a session type \( S \), can synthesise the Scala code of (1) a type-checked monitor that verifies at run-time whether an interaction abides by \( S \) (aim \([iii] \)), and (2) the signatures usable to implement a process that interacts according to \( S \), in a correct-by-construction manner (aim \([iii] \)).

F3. Our monitor synthesis can abstract over low-level communication protocols, bridging across a variety of message transports (e.g., TCP/IP, REST, etc.): this is key to facilitate the interaction with third-party (untyped) components in open systems (aim \([i] \)); this is also unlike previous work on session monitoring (theoretical \([9] \) or practical \([19] \)) that focus on a specific technology and runtime system, or assume a centralised message routing medium.

2 Binary Sessions with Assertions

A session type defines the intended behaviour of a participant that communicates with another over a channel. Our work is based on session types with assertions:

Assertions \[ A := v_1 = v_2 | v_1 = v_2 | A_1 \& \& A_2 | !A | \ldots \] 

Base types \[ B := \text{Int} | \text{Str} | \text{Boolean} | \ldots \] 

Session types \[ R, S := &_{i \in I} ? \lambda_i(V_i : B_i)[A_i],S_i | \oplus_{i \in I}! \lambda_i(V_i : B_i)[A_i],S_i \] 

\[ | \text{rec } X.S | X | \text{end} \] (with \( I \neq \emptyset \), \( 1, 1 \) pairwise distinct)

We assume a set of base types \( B \), and introduce payload identifiers \( V \) (with their types) and assertions \( A \) (i.e., predicates on payload values). Branching (or external choice) \( &_{i \in I} ? \lambda_i(V_i : B_i)[A_i],S_i \) requires the participant to receive one message of the form \( \lambda_i(v_i) \), where \( v_i \) is of (base) type \( B_i \) for some \( i \in I \); the value \( v_i \) (i.e., the message payload) is bound to the variable \( V_i \) in the continuation. If the assertion \( A_i[v_i/v_i] \) holds, the participant must proceed according to the continuation type \( S_i[v_i/v_i] \), but if the assertion fails, a violation is raised. Selection (or internal choice) \( \oplus_{i \in I}! \lambda_i(V_i : B_i)[A_i],S_i \) requires the participant to choose and send one message \( \lambda_i(v_i) \) where \( v_i \) is of (base) type \( B_i \) for some \( i \in I \); a violation is raised if the assertion \( A_i[v_i/v_i] \) does not hold, otherwise the protocol proceeds as \( S_i[v_i/v_i] \). The recursive session type \( \text{rec } X.S \) binds the recursion variable \( X \) in \( S \) (we assume guarded recursion), while \( \text{end} \) is the terminated session. For brevity, we often omit \( \oplus \) and \& for singleton choices, end, and trivial assertions (i.e., true). A process implementing a session type \( S \) can correctly interact with a process implementing the dual type of \( S \), denoted \( S \) — where each selection (resp. branching) of \( S \) is a branching (resp. selection), with the same choices:

\[ &_{i \in I} ? \lambda_i(V_i : B_i)[A_i],S_i = \oplus_{i \in I}! \lambda_i(V_i : B_i)[A_i],S_i \quad \text{end} = \text{end} \quad \text{X} = \text{X} \]

\[ \oplus_{i \in I}! \lambda_i(V_i : B_i)[A_i],S_i = &_{i \in I} ? \lambda_i(V_i : B_i)[A_i],S_i \quad \text{rec } X.S = \text{rec } X.S \]
Example 1. The type $S_{\text{login}}$ below describes the protocol of a server handling authorised logins. Notice that the type uses two assertion predicates:
- $\text{validAuth()}$ checks if an OAuth2-style token \cite{21} authorises a given user;
- $\text{validId()}$ checks whether an authentication id is correct for a given user.

$$S_{\text{login}} = \text{rec } X.\ !\text{Login}(uname:\text{Str}, pwd:\text{Str}, tok:\text{Str})[\text{validAuth}(uname, tok)]$$

$$\oplus \{!\text{Success}(id:\text{Str})[\text{validId}(id, uname)], R, !\text{Retry}().X\}$$

The server waits to receive $\text{Login}(uname:\text{Str}, pwd:\text{Str}, tok:\text{Str})$, where $tok$ is a token obtained by the client from an authorisation service. Once received, the values of $uname$ and $tok$ are passed to the the predicate $\text{validAuth}()$ which checks whether $tok$ contains a desired cryptographically-signed authorisation for $uname$: if it evaluates to $\text{true}$, the server can either send $\text{Success}$ including an $id$, or $\text{Retry}$. If the server chooses the former, then $id$ and $uname$ must be validated by $\text{validId}()$: if it succeeds, the message is sent and the server continues along session type $R$. If the server chooses to send $\text{Retry}$, the session loops.

3 Design and Implementation

We now give an overview (§3.2) and an example-driven tour (§3.3) of our methodology; but first, we summarise the toolkit underlying its implementation (§3.1).

3.1 Background: Session Programming with $1\text{channels}$

$1\text{channels}$ \cite{21,24,21} is a library implementation of session types in the Scala programming language. Its API is inspired by the continuation-passing encoding of session types into the linear $\pi$-calculus \cite{9}. $1\text{channels}$ allows to implement a program that communicates according to a session type $S$ by (1) translating $S$ into a set of Continuation-Passing Style Protocol classes (CPSPc), capturing the order of send/receive operations in $S$; and (2) communicating via “one-shot” channel objects, having type $\text{Out}[A]$ or $\text{In}[A]$ — where $A$ is a CPSP class. We show an example of CPSPc in §3.3. The main payoffs of $1\text{channels}$ are that (1) the CPSP classes restrict the usage the $\text{In}[A]/\text{Out}[A]$ channel objects to receive/send messages according to $S$, letting the Scala compiler check safety (i.e., only messages allowed by $S$ are sent) and exhaustiveness (i.e., all inputs allowed by $S$ are handled); and (2) the library provides run-time linearity enforcement: e.g., if a “one-shot” channel object is used twice to send messages, then the program is not advancing along $S$, hence $1\text{channels}$ discards the message and raises an error.

3.2 Hybrid Verification via Static and Dynamic Checking

We now illustrate how our methodology is implemented, as a tool \cite{7} targeting the Scala programming language. Consider the scenario on the right: a client $C$ exchanges messages with a server $Srv$ over a network. $Srv$ implements the session type $S_{\text{login}}$ outlined in Example 1 and expects each client $C$ to follow the dual, $S_{\text{login}}^*$. However, in an open system, we cannot guarantee that $C$ abides by $S_{\text{login}}^*$. 
Our approach is outlined on the left. The accessible participant \( S_{\text{login}} \) is \textit{statically} checked, and the behaviour of the inaccessible participant \( C \) is \textit{dynamically} monitored at runtime. Given \( S_{\text{login}} \), the synthesiser \( \text{Synth} \) generates (1) the Continuation-Passing-Style Protocol classes (CPSPc) for representing \( S_{\text{login}} \) in Scala and \( 1\text{channels} \) (see \S 3.1), and (2) the source code of a runtime monitor (Mon), based on the CPSPc above. Below are the CPSPc generated from \( S_{\text{login}} \) by our synthesiser: notably, they can be used to write a type-checked version of \( Srv \).

1 case class Login(uname: String, pwd: String, tok: String)(val cont: Out[Choice1])
2 sealed abstract class Choice1
3 case class Success(id: String)(val cont: Out[R]) extends Choice1
4 case class Retry()(val cont: Out[Choice1]) extends Choice1
5 case class R(...) // This is the continuation of the session (omitted)

The messages sent from \( Srv \) to \( C \) (and \textit{vice versa}) must pass through the monitor \( \text{Mon} \). As \( Srv \) and \( \text{Mon} \) use \( 1\text{channels} \) to interact, they are statically typed according to \( S_{\text{login}} \) and \( S_{\text{login}} \); instead, there is no assumption on the interaction between \( \text{Mon} \) and \( C \): it is handled by a user-supplied \textit{connection manager} (CM), which acts as a \textit{translator} and \textit{gatekeeper} by transforming messages from the transport protocol supported by \( C \) to the \( \text{Mon} \)'s CPSP classes, and \textit{vice versa}. Hence, \( \text{CM} \) provides a message transport abstraction for \( \text{Mon} \) and \( Srv \): to support new clients and message transports, only \( \text{CM} \) needs extending.

When the monitor is initialised, it invokes \( \text{CM} \) to set up the communication channel with client \( C \), through a suitable message transport: \textit{e.g.}, in the case of TCP/IP, \( \text{CM} \) creates a socket and initialises the I/O buffers. Each message sent from \( Srv \) to \( \text{Mon} \) via \( 1\text{channels} \) is analysed by \( \text{Mon} \), and if it conforms to \( S_{\text{login}} \) and its assertions, it is translated by \( \text{CM} \) and forwarded to \( C \). Dually, each message sent from \( C \) to \( \text{Mon} \) is translated by \( \text{CM} \) and analysed by \( \text{Mon} \), and if it conforms to \( S_{\text{login}} \) and its assertions, it is forwarded to \( Srv \). \( \text{Mon} \)'s assertion checks provide additional verification against incorrect values from \( Srv \) or \( C \).

### 3.3 A Step-by-step Example

To illustrate our approach and implementation, we now follow the message exchanges prescribed by \( S_{\text{login}} \), showing how they engage with the elements of our design. Roughly, \( \text{Mon} \) acts as a state machine: it transitions by receiving and forwarding messages between \( Srv \) and \( \text{CM} \), abiding by the type \( S_{\text{login}} \) and its dual. \( \text{CM} \), in turn, provides a \texttt{send/receive} interface to \( \text{Mon} \), and delivers messages to/from client \( C \). The monitor also maintains a mapping, called \texttt{payloads}, that associates the payload identifiers of \( S_{\text{login}} \) to their current values.

```scala
1 val loginK = "\" LOGIN \(.+) \(.+) \(.+) \" \\".r
2 def receive(): Any = inBuf.readLine() match {
3 case loginK(uname, pwd, tok) => Login(uname, pwd, tok)(null)
4 case other => other
5 }
```

We begin with the login request sent from a client over TCP/IP. The client’s message is initially handled by the
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connection manager \texttt{CM}, which provides a \texttt{receive} method like the one shown above: it is invoked by \texttt{Mon} to retrieve messages. When invoked, \texttt{receive} checks the socket input buffer \texttt{inBuf}: if a new supported message is found (line 3, where the message matches the regex \texttt{loginR}), the corresponding CPSP class is returned to the monitor; otherwise, the unaltered message is returned (line 4).

On the left is the synthesised code for \texttt{Mon} that handles the beginning of $S_{\text{login}}$. The monitor invokes \texttt{CM}'s method \texttt{receive} (shown above) to retrieve the latest message (line 2). Depending on the type of message, the monitor will perform a series of actions. By default, a catch-all case (line 9) handles any messages violating the protocol. If \texttt{Login} is received, the monitor initially invokes the function \texttt{validateAuth()} with the values of \texttt{uname} and \texttt{tok}: \textit{i.e.}, the assertion predicate in $S_{\text{login}}$ corresponds to a Scala function (imported from a user-supplied library). If the function returns \texttt{true}, the message is forwarded to the server \texttt{Srv} (line 5), otherwise the monitor logs the violation and halts. The function used to forward the message (\texttt{!!}), which is part of \texttt{lchannels}, returns a continuation channel that is stored in \texttt{cont}. The value of \texttt{uname} is stored in a mapping (line 6) since it is used later on in $S_{\text{login}}$. Finally, the monitor moves to the next state, by calling the synthesised method \texttt{sendChoice1}, passing \texttt{cont} to continue the protocol.

On the left is the synthesised code of \texttt{Mon} that handles the server's response to the client. According to $S_{\text{login}}$, the server can choose to send either \texttt{Success} or \texttt{Retry}; correspondingly, the monitor waits to receive either of the options from \texttt{Srv}, using the function ? from \texttt{lchannels} (line 2).

- If the server sends \texttt{Success}, including the value \texttt{id} as specified in $S_{\text{login}}$, the first case is selected (line 3). The monitor evaluates the assertion on \texttt{id} and \texttt{uname} (stored in \texttt{receiveLogin} above, and now retrieved from the \texttt{payloads} mapping): if it is satisfied, the message is sent to the client (line 5) via \texttt{CM}'s \texttt{send} method (explained below), and the monitor continues according to session type $R$. Otherwise, the monitor logs a violation and halts (line 8).
- Instead, if the server sends \texttt{Retry} (line 10), the message is forwarded directly to the client using the method \texttt{send} of the \texttt{CM} (see below); notice that there are no dynamic checks at this point, as there is no assertion after \texttt{Retry} in $S_{\text{login}}$. The monitor then goes back to the previous state \texttt{receiveLogin}.  

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```scala
1 def receiveLogin(srv: Out[Login], client: ConnManager): Unit = {
2   client.receive() match {
3     case msg @ Login(_, _, _) =>
4       if (validateAuth(msg.uname, msg.tok)) {
5         val cont = srv !! Login(msg.uname, msg.pwd, msg.tok)_
6         payloads.Login.uname = msg.uname
7         sendChoice1(msg.cont, client) // Protocol continues
8       } else { /* log and halt: Incorrect values received */ }
9     case _ => /* log and halt: Unexpected message received */
10   }
```

---

```scala
1 def sendChoice1(srv: In[Choice1], Client: ConnManager): Unit = {
2   srv ? {
3     case msg @ Success(_) =>
4       if (validateId(msg.id, payloads.Login.uname)) {
5         Client.send(msg)
6         /* Continue according to R */
7       } else {
8         /* log and halt: Sending incorrect values. */
9       }
10     case msg @ Retry() =>
11       Client.send(msg)
12       receiveLogin(msg.cont, Client)
13   }
```
Notably, unlike the synthesised code of `receiveLogin` (that handles the previous external choice), there is no catch-all case for unexpected messages from `Srv`. In fact, here we assume that `Srv` is written in Scala and `lchannels`, hence statically checked, and conforming to `Slogin`; hence, it can only send one of the expected messages (as per §3.1). The monitor only checks the assertions on `Srv`'s messages.

```scala
def send(msg: Any): Unit = msg match {
  case Success(id) => outB.write(f"SUCCESS $id\n")
  case Retry() => outB.write(f"RETRY\n")
  case _ => { close(); throw new Exception("Invalid message") }
}
```

Finally, we review the `send` method of `CM`: it translates messages from a CPSP class instance to the format accepted by the client’s transport protocol. In this case, the format is a textual representation of the session type. The catch-all case (lines 4-5) is for debugging purposes.

4 Conclusion

We presented our preliminary work on the hybrid verification of open distributed systems, based on session types with assertions and automatically synthesised monitors — with a supporting tool [7] based on the Scala programming language.

**Future work.** Our approach adheres to the “fail-fast” design methodology: if an assertion fails, the monitor logs the violation and halts. In the practice of distributed systems, “fail-fast” is advocated as an alternative to defensive programming [8]; it is also in line with existing literature on runtime verification [5].

Our further rationale for this design choice is that we intend to investigate monitorability properties of session types, along the lines of recent work [11,12], and identify any limits, in terms of what can be verified at runtime. We plan to extend our approach to multiparty sessions [14,15], in connection to existing work [22,23] based on `lchannels` and Scribble [26,28]. Finally, we plan to investigate how to handle assertion violations by adding compensations to our session types, formalising how the protocol should proceed whenever an assertion fails.

**Related Work.** The work in [6] formalises a theory of monitored (multiparty) session types, based on a global, centralised router providing a safe transport network that dispatches messages between participant processes. The main commonality with our work is that session types are used to synthesise monitors. The main differences (besides our focus on a tool implementation) are that (1) we do not assume a centralised message routing system, and consider the network adversarial (as per contribution F1) and use monitors to also protect typed participants; (2) our monitors can enforce data constraints, through assertions; and (3) in our setting, if a participant sends an invalid message, the monitor will flag violations (and stop computation) whereas [6] drops the invalid message, but will continue forwarding the rest, akin to runtime enforcement via suppressions [3].

Our protocol assertions are reminiscent of interaction refinements in [18], that are also statically generated (by an F# type provider), and dynamically enforced when messages are sent/received. However, we enforce our assertions by synthesising well-typed monitoring processes that can be deployed over a network, whereas [18] injects dynamic checks in the local executable of a process.
References