

Verification of Communicating Data-Driven Web Services*

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ABSTRACT

We study the verification of compositions of Web Service peers which interact asynchronously by exchanging messages. Each peer has access to a local database and reacts to user input and incoming messages by performing various actions and sending messages. The reaction is described by queries over the database, internal state, user input and received messages. We consider two formalisms for specification of correctness properties of compositions, namely Linear Temporal First-Order Logic and Conversation Protocols. For both formalisms, we map the boundaries of verification decidability, showing that they include expressive classes of compositions and properties. We also address modular verification, in which the correctness of a composition is predicated on the properties of its environment.

1. INTRODUCTION

Recent years have witnessed the proliferation of Web services powered by an underlying database and interacting with human users and with peer Web services. Examples include e-commerce sites, scientific and other domain-specific portals, e-government, and data-driven Web services. The development of such services is facilitated by the emergence of high-level specification tools which automatically generate the code implementing the Web service (a commercially successful representative is WebML [7]). Besides increasing developer productivity, high-level specification tools create opportunities for automatic verification. Such verification leads to increased confidence in the service's correctness by addressing the most likely source of errors—the specification itself—as opposed to the less likely errors in the well-maintained automatic code generator.

In prior work [13], we studied as a first step the verification of isolated Web services which interact only with external users (through a Web browser interface). Many settings however require services to interact with each other, typically by exchanging messages. For instance, even seemingly self-contained e-commerce Web sites place calls to an external Web service to charge a credit card. Similarly, a bank's loan management application exchanges

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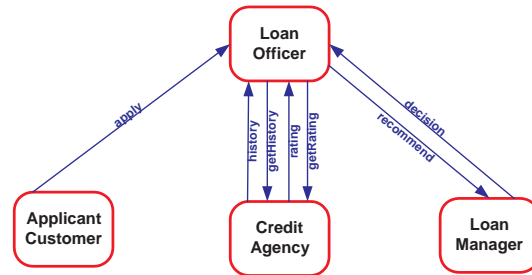


Figure 1: Bank loan application

messages with a credit reporting agency's Web service.

In this paper, we present a significant extension of our verification work to compositions of Web services (also called *peers*), which interact by asynchronous message exchange. The peers receive both input from their users (through the Web interface) and messages from other peers. They react by updating their internal state, by sending messages (such as a credit check request to a credit agency's Web service) or by performing actions (such as the generation of a notification letter). Each peer's reaction is a function of the current contents of the database, state, user input and received messages. We illustrate a composition below.

EXAMPLE 1.1 Consider a bank's loan application process involving the applicant customer, the loan officer, his manager, and the credit reporting agency (as shown in Figure 1). Applicant, loan officer and manager play their part in the process using Web interfaces running on top of the Web services \mathcal{A} , \mathcal{O} , \mathcal{M} respectively. The credit reporting agency provides the Web service \mathcal{CR} .

The officer's Web service \mathcal{O} , for instance,

- receives application messages from the customer's Web service;
- allows the officer to view details about the applicant, available in the bank's customer database;
- allows the officer to request the customer's credit history, obtained via a message from \mathcal{CR} , which retrieves the information by querying its own local database;
- allows the officer to input his recommendation of acceptance or denial;
- sends a message with the recommendation, as well as the customer data and credit history to the Web service \mathcal{M} , which allows the manager to input her final decision, returned as a message to \mathcal{O} ;
- generates notification letters for customers.

As a sample correctness property, we'd like to ensure that the composition satisfies bank policy, according to which the officer may

make an unsupervised decision granting loans to applicants with excellent credit rating and denying them to those with poor rating. All other credit ratings require the manager’s involvement. We show in this paper how such properties are expressed and automatically verified. \square

A *run* is a sequence of snapshots through which the collection of peers evolves during the interaction with users and with each other. The correctness of a composition is specified by properties which express requirements on individual run snapshots (using First-Order Logic), as well as the temporal relationship among these snapshots. Verification involves searching for runs which violate the property. We are interested in *sound and complete* verification, which produces a counterexample run if and only if the property is violated.

We consider two formalisms for property specification, namely First-Order Linear Temporal Logic and Conversation Protocols. Conversation protocols were introduced in [17] as a generalization of an industrial standard (IBM’s conversation support project [19]). Classical conversation protocols are concerned only with the sequence of message names observed during the interaction. In this paper, we extend them with awareness of the message contents.

Contributions. For both property formalisms, we map the boundaries of verification decidability. In particular, we explore various semantics for message-based communication (singleton versus set messages, lossy versus perfect communication channels, bounded versus unbounded received message queues). We also identify syntactic restrictions on the peer and property specifications which, under appropriate communication semantics, guarantee decidability of verification in PSPACE. This complexity is the best one can hope for given that propositional LTL verification of finite-state Mealy machines is PSPACE-complete [9]. We show that our restrictions are quite tight: even slight relaxations thereof lead to undecidability. When the composition consists of a single peer with no message channels, the restrictions degenerate to the notion of *input-boundedness* from [13]. We demonstrated the expressivity of input-bounded peer specifications in [12] by modeling significant parts of four well-known database-powered Web sites (demo available at [1]). The favorable experimental results obtained in [12] for verification of individual input-bounded services suggest that similarly good performance can be expected for compositions.

Finally, we address modular verification, in which the correctness of a subset of the peers is checked when the full specification of the other peers is not available and the only knowledge about them is declared as properties of their message input-output behavior. Modular verification is useful when some peers are provided by autonomous parties unwilling to disclose implementation details, or when verification of a partially specified composition is desired.

Relationship to Software Verification. In the broader context of software verification, our work addresses sound and complete automatic verification of a novel class of reactive systems communicating asynchronously. The systems are infinite-state because the underlying database and user input values are not fixed in advance. This is a departure from most existing research, which focuses on communicating finite-state systems (called CFSMs in [6, 2, 3], and *e-compositions* in the context of Web services, as surveyed in [22, 23, 24, 21]). Conventional wisdom in software verification holds that sound and complete verification of infinite-state systems is infeasible, prescribing instead the approach of finite-state abstraction followed by classical finite-state model checking. In the data-driven Web service scenario we consider, data values are first-class citizens and abstracting them away is not satisfactory. For instance, abstraction would allow us to check that upon receiving *some* credit score request, the reporting agency sends *some* re-

ply message, but preclude us from requiring the reply to reflect the customer’s database record. To handle data-driven compositions and data-aware correctness properties, we employ a novel mix of model-checking and database/logic techniques. Our results suggest that the data-driven composition scenario with peer specifications based on database queries is particularly well-suited to automatic verification, in contrast to general-purpose software verification.

Paper Outline. The remainder of the paper is organized as follows. Section 2 introduces our formalism for specification of data-driven peers and compositions. Sections 3 and 4 study the verification of properties expressed by Linear Temporal First-Order Logic, respectively Conversation Protocols. We address modular verification in Section 5. We present related work in Section 6 and conclude in Section 7. All proofs are shown in Appendix ??.

2. PEERS AND COMPOSITIONS

We describe a framework for the specification of compositions, starting from the individual Web services (called peers) involved in a composition. Peers communicate with each other by sending and receiving messages via one-way channels implemented by *message queues*. Each queue is associated with a unique sender who places messages into the queue, and a unique receiver who consumes messages from it in FIFO order. The queue is called an *out-queue* by the sender and an *in-queue* by the receiver. The queues are classified into *flat queues* and *nested queues*. Flat queues deliver single-tuple messages, e.g. the age and social security number of a given customer. Nested queues transport messages consisting of a set of tuples, e.g. the set of books written by an author. Notice that, by modeling communication channels with queues, we assume that messages arrive in the same order they were sent.

Each peer consists of

- an underlying database that remains fixed throughout the interaction with the environment;¹
- a set of state relations that are updated throughout the interaction;
- a set of input relations which capture the input provided by the user who picks among a set of options generated by the peer.
- a set of action relations modeling the performed actions (e.g. the sending of a notification letter is modeled as the insertion of a tuple into the letter table)
- a set of in-queues through which the Web service receives messages;
- a set of out-queues used to send messages;
- a set of rules specifying the reaction to user input and received messages.

The rules specify how the set of current user input choices is generated, and how the Web service reacts to the user’s input and/or to the arrival of messages. The reaction is a function of the current contents of the database, state, user input and received messages, and it involves updating the state, performing actions (such as the placement of an order) and sending messages (such as a credit check request to a credit agency’s Web service). Formally, we have:

DEFINITION 2.1. A Web service (or peer) \mathcal{W} is a tuple $\langle \mathbf{D}, \mathbf{S}, \mathbf{I}, \mathbf{A}, \mathbf{Q}_{in}, \mathbf{Q}_{out}, \mathcal{R} \rangle$, where:

- $\mathbf{D}, \mathbf{S}, \mathbf{I}, \mathbf{A}, \mathbf{Q}_{in}, \mathbf{Q}_{out}$ are relational schemas called, respectively, *database, state, input, action, in-queue and out-queue schemas*. The sets of relation symbols of the schemas are disjoint (but they may share constant symbols). The queue

¹We do not claim that the peer’s database does not change; we simply regard the changing part of the database as state.

schemas are partitioned into a flat and a nested part: $\mathbf{Q}_{\text{in}} = \mathbf{Q}_{\text{in}}^f \cup \mathbf{Q}_{\text{in}}^n$ and $\mathbf{Q}_{\text{out}} = \mathbf{Q}_{\text{out}}^f \cup \mathbf{Q}_{\text{out}}^n$.

We require \mathbf{S} to include, for each in-queue Q , a propositional state empty_Q indicating if the queue Q is empty, referred to as a queue state. (Note that queue states are only available for in-queues, since we assume out-queues are located at the recipients of sent messages and thus their state is not accessible by the peer.) We also denote by \mathbf{Prev}_I the relational vocabulary $\{\text{prev}_I \mid I \in \mathbf{I}\}$, where prev_I has the same arity as I (intuitively, prev_I refers to the most recent non-empty input to I).

Finally, \mathcal{R} is a set of rules containing the following:

- For each input relation $I \in \mathbf{I}$ of arity $k > 0$, an input rule

$$\text{Options}_I(\bar{x}) \leftarrow \varphi_I(\bar{x})$$

where Options_I is a relation of arity k , \bar{x} is a k -tuple of distinct variables, and $\varphi_I(\bar{x})$ is an FO formula over schema $\mathbf{D} \cup \mathbf{S} \cup \mathbf{Prev}_I \cup \mathbf{Q}_{\text{in}}$, with free variables \bar{x} .

- For each state relation $S \in \mathbf{S}$ that is not a queue state, one, both, or none of the following state rules:

- an insertion rule $S(\bar{x}) \leftarrow \varphi_S^+(\bar{x})$,
- a deletion rule $\neg S(\bar{x}) \leftarrow \varphi_S^-(\bar{x})$,

where the arity of S is k , \bar{x} is a k -tuple of distinct variables, and $\varphi_S^+(\bar{x})$, $\varphi_S^-(\bar{x})$ are FO formulas over schema $\mathbf{D} \cup \mathbf{S} \cup \mathbf{I} \cup \mathbf{Prev}_I \cup \mathbf{Q}_{\text{in}}$, with free variables \bar{x} .

- For each action relation $A \in \mathbf{A}$, an action rule

$$A(\bar{x}) \leftarrow \varphi_A(\bar{x})$$

where the arity of A is k , \bar{x} is a k -tuple of distinct variables, and $\varphi_A(\bar{x})$ is an FO formula over schema $\mathbf{D} \cup \mathbf{S} \cup \mathbf{I} \cup \mathbf{Prev}_I \cup \mathbf{Q}_{\text{in}}$, with free variables \bar{x} .

- For each out-queue relation $Q \in \mathbf{Q}_{\text{out}}$, one send rule

$$Q(\bar{x}) \leftarrow \varphi_Q(\bar{x})$$

where the arity of Q is k , \bar{x} is a k -tuple of distinct variables, and $\varphi_Q(\bar{x})$ is an FO formula over schema $\mathbf{D} \cup \mathbf{S} \cup \mathbf{I} \cup \mathbf{Prev}_I \cup \mathbf{Q}_{\text{in}}$, with free variables \bar{x} .

Intuitively, the input rules specify a set of options to be presented to users, from which they can pick at most one tuple to input. This feature corresponds to menus in user interfaces. At every point in time, input J contains the current input tuple and prev_J contains the most recent previous non-empty input to J . The state rules specify the tuples to be inserted or deleted from state relations (with conflicts given no-op semantics, as seen below). If no rule is specified for a given state relation, the state remains unchanged. The action rules specify the actions to be taken in response to the input. The send rules specify the tuples used to construct the message. For nested queues, all tuples yielded by one firing of the send rule are collected into one message. Flat queues are intended to be used when the send rule is known to yield a single tuple. If several tuples are generated, then at most one of them is non-deterministically placed into the queue and the others are dropped.

Remark. *Syntactic sugar* The above allows us to simulate various syntactic sugar on individual peers as done in [13] (such as a notion of a current Web page; rules governing the transition to the next page; inputs for buttons and HTML links; etc.). For simplicity, we abstract syntactic sugar and focus on modeling the distributed

communication aspect of the composition.

Notation To improve readability, in the following we display any relation R in the specification of service \mathcal{W} , depending on whether it belongs to $\mathcal{W}.\mathbf{I}$, $\mathcal{W}.\mathbf{D}$, $\mathcal{W}.\mathbf{S}$, $\mathcal{W}.\mathbf{A}$, $\mathcal{W}.\mathbf{Q}_{\text{in}}$ and $\mathcal{W}.\mathbf{Q}_{\text{out}}$, as \mathbf{R} , $\underline{\mathbf{R}}$, R , \mathbf{R} , $\mathbf{?R}$ and $\mathbf{!R}$, respectively.

EXAMPLE 2.2 We specify the loan officer’s peer \mathcal{O} from Example 1.1. \mathcal{O} ’s schema is given as:

$$\begin{aligned} \mathcal{O}.\mathbf{D} &= \{\underline{\text{customer}}(cId, ssn, name)\} \\ \mathcal{O}.\mathbf{I} &= \{\text{reccom}(cId, recommendation)\} \\ \mathcal{O}.\mathbf{S} &= \{\text{application}(cId, loan), \\ &\quad \text{awaitsHist}(cId, ssn, name, loan, rating), \\ &\quad \text{awaitsMgr}(cId, ssn, name, loan, rating, \\ &\quad \quad \quad \text{account, balance})\} \\ \mathcal{O}.\mathbf{A} &= \{\text{letter}(cId, name, loan, decision)\} \\ \mathcal{O}.\mathbf{Q}_{\text{in}}^f &= \{\text{apply}(cId, loan), \text{decision}(cId, dec), \\ &\quad \text{rating}(ssn, category)\} \\ \mathcal{O}.\mathbf{Q}_{\text{in}}^n &= \{\text{history}(ssn, account, balance)\} \\ \mathcal{O}.\mathbf{Q}_{\text{out}}^f &= \{\text{getRating}(ssn), \text{getHistory}(ssn)\} \\ \mathcal{O}.\mathbf{Q}_{\text{out}}^n &= \{\text{recommend}(cId, loan, decision, rating, \\ &\quad \quad \quad \text{account, balance})\} \end{aligned}$$

We show some of \mathcal{O} ’s rules below. \mathcal{O} runs on top of a customer database which records each customer’s id, ssn and name. The input reccom allows the officer to provide an approval or denial recommendation for any customer, by picking from a menu generated by input rule (1). Upon arrival of an application message, \mathcal{O} reacts automatically, without the officer’s involvement, as follows. The application message is saved in the *application* state (rule (2)) and a credit rating request message is sent to the credit agency peer \mathcal{CR} (rule (3)). Notice how the customer database is consulted to translate the bank-specific customer id to the ssn required by the credit agency’s Web service. On receipt of a message rating a customer’s credit as “excellent”, an approval letter is generated (4). Customers with “poor” rating get denial letters (5). For all other ratings, a message is sent to request the credit history details, namely the list of open accounts and their balance (rule (7)). In addition, the customer’s information and rating are recorded in the state *awaitsHist* (rule (8)), where they await the response of \mathcal{CR} . Upon its receipt, the complete customer information gathered so far is recorded in the state *awaitsMgr* (rule (9)). The subsequent input of a recommendation by the officer triggers the sending of a recommendation message to the manager’s Web service \mathcal{M} (rule (10)). \mathcal{M} ’s reply causes an appropriate letter-writing action (6).

$$\begin{aligned} \text{Options}_{\text{reccom}}(id, rec) &\leftarrow \exists ssn, name \underline{\text{customer}}(id, ssn, name) \\ &\quad \wedge (rec = \text{“approve”} \vee rec = \text{“deny”}) \end{aligned} \quad (1)$$

$$\text{application}(id, loan) \leftarrow \mathbf{?}\text{apply}(id, loan) \quad (2)$$

$$\begin{aligned} \mathbf{!}\text{getRating}(ssn) &\leftarrow \exists id, loan, name \mathbf{?}\text{apply}(id, loan) \\ &\quad \wedge \underline{\text{customer}}(id, ssn, name) \end{aligned} \quad (3)$$

$$\begin{aligned} \text{letter}(id, name, loan, dec) &\leftarrow \exists ssn \underline{\text{customer}}(id, ssn, name) \\ &\quad \wedge \text{application}(id, loan) \\ &\quad \wedge [\mathbf{?}\text{rating}(ssn, \text{“excellent”}) \wedge dec = \text{“approved”} \end{aligned} \quad (4)$$

$$\quad \vee \mathbf{?}\text{rating}(ssn, \text{“poor”}) \wedge dec = \text{“denied”} \quad (5)$$

$$\quad \vee \mathbf{?}\text{decision}(id, dec)] \quad (6)$$

$$\begin{aligned} \text{!getHistory}(ssn) &\leftarrow \exists r \text{?rating}(ssn, r) & (7) \\ &\wedge \neg(r = \text{"excellent"} \vee r = \text{"poor"}) \end{aligned}$$

$$\begin{aligned} \text{awaitsHist}(id, ssn, name, l, r) &\leftarrow \text{?rating}(ssn, r) \wedge \\ &\neg(r = \text{"excellent"} \vee r = \text{"poor"}) \wedge \text{application}(id, l) \\ &\wedge \text{!customer}(id, ssn, name) \end{aligned} \quad (8)$$

$$\begin{aligned} \text{awaitsMgr}(id, ssn, name, loan, rating, acc, bal) &\leftarrow \\ &\text{?history}(ssn, acc, bal) \\ &\wedge \text{awaitsHist}(id, ssn, name, loan, rating) \end{aligned} \quad (9)$$

$$\begin{aligned} \text{!recommend}(id, ssn, name, loan, rec, rating, acc, bal) &\leftarrow \\ \text{reccom}(id, rec) & \\ \wedge \text{awaitsMgr}(id, loan, ssn, name, rating, acc, bal) & \end{aligned} \quad (10)$$

□

We next define the notion of a configuration of a Web service, and the transition relation among configurations. Informally, a configuration consists of the fixed database, the contents of the message queues, as well as the states, previous and current inputs, and actions. To formalize the usage of message queues, we first introduce the following notation, allowing us to refer to the first and last message in each in-queue. Suppose Q^{in} is an instance of the in-queues, i.e. a mapping associating to each $R \in \mathbf{Q}_{in}$ a finite sequence of instances of R . Given Q^{in} , we define the relational instances $f(Q^{in})$ and $l(Q^{in})$, both of schema \mathbf{Q}_{in} , holding the first, respectively last messages from all queues. Thus, if $R \in \mathbf{Q}_{in}^f$ ($Q^{in}(R)$ is a flat queue), then $f(Q^{in})(R)$ and $l(Q^{in})(R)$ contain each a singleton tuple which is the first, resp. last message in $Q^{in}(R)$. If $R \in \mathbf{Q}_{in}^n$, $f(Q^{in})(R)$ and $l(Q^{in})(R)$ contain the set of tuples making up the first, resp. last message of $Q^{in}(R)$. If $Q^{in}(R)$ is empty so are $f(Q^{in})(R)$ and $l(Q^{in})(R)$.

DEFINITION 2.3. Let $\mathcal{W} = \langle \mathbf{D}, \mathbf{S}, \mathbf{I}, \mathbf{A}, \mathbf{Q}_{in}, \mathbf{Q}_{out}, \mathcal{R} \rangle$ be a Web service. A configuration of \mathcal{W} is a tuple $\langle D, S, I, P, A, Q^{in}, Q^{out} \rangle$ where the database D is an instance of \mathbf{D} , the state S is an instance of \mathbf{S} , the input I is an instance of \mathbf{I} , the previous input P is an instance of \mathbf{Prev}_I , and the action A is an instance of \mathbf{A} . Additionally, Q^{in} (Q^{out}) associates to each $R \in \mathbf{Q}_{in}$ ($R \in \mathbf{Q}_{out}$) a finite sequence $Q^{in}(R)$ ($Q^{out}(R)$) of instances of R . We refer to Q^{in} and Q^{out} respectively as instances of the in-queues and out-queues. For each $R \in \mathbf{Q}_{in}$, the queue state empty $_R$ is true iff the sequence associated to R by Q^{in} is empty. Finally, for each relation R in \mathbf{I} of arity $k > 0$, $I(R) \subseteq \{v\}$ for some $v \in \text{Options}_R$, where Options_R is the result of evaluating φ_R on $D, S, f(Q^{in})$, and P ; if R has arity zero (so R is a propositional state), then $I(R)$ is a truth value such that $I(R) \rightarrow \text{Options}_R$.

We next define the transition relation of a Web service. This relation defines for every current configuration of the Web service its legal successor configurations, reachable in one atomic step.

DEFINITION 2.4. Let $\mathcal{W} = \langle \mathbf{D}, \mathbf{S}, \mathbf{I}, \mathbf{A}, \mathbf{Q}_{in}, \mathbf{Q}_{out}, \mathcal{R} \rangle$ be a Web service and $C_i = \langle D_i, S_i, I_i, P_i, A_i, Q_i^{in}, Q_i^{out} \rangle$, a configuration of \mathcal{W} . A configuration

$$C_{i+1} = \langle D_{i+1}, S_{i+1}, I_{i+1}, P_{i+1}, A_{i+1}, Q_{i+1}^{in}, Q_{i+1}^{out} \rangle$$

of \mathcal{W} is a legal successor configuration of C_i iff:

- $D_i = D_{i+1}$ i.e. the database remains unchanged. We will denote it with D .

- for each relation $prev_R$ in \mathbf{Prev}_I , $P_{i+1}(prev_R) = I_i(R)$ if $I_i(R) \neq \emptyset$, and $P_{i+1}(prev_R) = P_i(prev_R)$ otherwise.
- for each relation S in \mathbf{S} that is not a queue state, $S_{i+1}(S)$ is the result of evaluating

$$\begin{aligned} &(\varphi_S^+(\bar{x}) \wedge \neg\varphi_S^-(\bar{x})) \vee \\ &(S(\bar{x}) \wedge \varphi_S^-(\bar{x}) \wedge \varphi_S^+(\bar{x})) \vee \\ &(S(\bar{x}) \wedge \neg\varphi_S^-(\bar{x}) \wedge \neg\varphi_S^+(\bar{x})) \end{aligned}$$

on $D, S_i, f(Q_i^{in}), I_i$, and P_i , where $\varphi_S^\epsilon(\bar{x})$ is taken to be false if it is not provided ($\epsilon \in \{+, -\}$). In particular, S remains unchanged if no insertion or deletion rule is specified for it.

- for each relation A in \mathbf{A} , $A_{i+1}(A)$ is the result of evaluating φ_A on $D, S_i, f(Q_i^{in}), I_i$, and P_i .
- for each relation R in \mathbf{Q}_{out} , let m_R denote the result of evaluating φ_R on $D, S_i, f(Q_i^{in}), I_i$, and P_i . If $R \in \mathbf{Q}_{out}^n$, $Q_{i+1}^{out}(R)$ is obtained by enqueueing m_R into $Q_i^{out}(R)$. If $R \in \mathbf{Q}_{out}^f$, then if m_R is non-empty, $Q_{i+1}^{out}(R)$ is obtained by enqueueing into $Q_i^{out}(R)$ a singleton containing a non-deterministically picked tuple from m_R . If m_R is empty, $Q_{i+1}^{out}(R) = Q_i^{out}(R)$ so the queue remains unchanged.
- for each relation R in \mathbf{Q}_{in} , if R is mentioned in the set of rules \mathcal{R} , the corresponding new in-queue $Q_{i+1}^{in}(R)$ is obtained by dequeuing the first message from $Q_i^{in}(R)$. Otherwise, $Q_{i+1}^{in}(R) = Q_i^{in}(R)$.

Notice that we employ a “snapshot” semantics, in the sense that at each step all rules are simultaneously interpreted over the current configuration. In particular, all occurrences of $R \in \mathbf{Q}_{in}$ in \mathcal{R} refer to the same first message in q_R . Also notice that a message sent in the current configuration i is enqueued at the receiver in the successor configuration $i + 1$. Furthermore, since \mathcal{W} ’s out-queues are some other peers’ in-queues, \mathcal{W} side-effects the receiver’s queues upon transitioning to the successor configuration.

We next define the syntax and semantics of a composition of Web services.

DEFINITION 2.5. A composition is a set of Web services $\mathcal{C} = \{\mathcal{W}_i\}_{1 \leq i \leq n}$ such that $\mathcal{W}_i.\mathbf{Q}_{in} \cap \mathcal{W}_j.\mathbf{Q}_{in} = \emptyset$ and $\mathcal{W}_i.\mathbf{Q}_{out} \cap \mathcal{W}_j.\mathbf{Q}_{out} = \emptyset$ for $i \neq j$, so each queue is an output (input) queue for at most one peer. We say that \mathcal{C} is closed if $\bigcup_{i=1}^n \mathcal{W}_i.\mathbf{Q}_{in} = \bigcup_{i=1}^n \mathcal{W}_i.\mathbf{Q}_{out}$, otherwise it is open. We refer to the composition members as peers.

Intuitively, a composition is closed if every peer’s in-queue is some other peer’s out-queue and conversely, so that no input messages are received from or sent outside the composition.

Since we are interested in verifying the correctness of a composition’s behavior, we describe the latter via the notion of “run” of a closed composition. Essentially, a run is a sequence of snapshots through which the composition evolves. Each snapshot specifies the current configuration of each peer. We consider only serialized runs, i.e. runs in which at every step precisely one peer performs a transition.

DEFINITION 2.6. Let \mathcal{C} be a closed composition $\{\mathcal{W}_j\}_{1 \leq j \leq n}$ and $\bar{D} = \{D_j\}_{1 \leq j \leq n}$ be database instances where each D_j is an instance of $\mathcal{W}_j.\mathbf{D}$. A run of \mathcal{C} over \bar{D} is an infinite sequence $\{(k_i, \langle C_i^j \rangle_{j \in [1, n]})\}_{i \geq 0}$, where $k_i \in [1, n]$ and C_i^j is a configuration of peer \mathcal{W}_j , such that:

- for each $j \in [1, n]$, the state, action, previous input and queues of C_0^j are empty and its database is D_j ;
- for each $i \geq 0$, $j, l \in [1, n]$ and for each $R \in \mathcal{W}_j \cdot \mathbf{Q}_{\text{out}} \cap \mathcal{W}_l \cdot \mathbf{Q}_{\text{in}}$, the queues associated to R in C_i^j and C_i^l are identical;
- for each $i \geq 0$,
 - (i) $C_{i+1}^{k_i}$ is a legal successor configuration of $C_i^{k_i}$ for peer \mathcal{W}_{k_i} , and
 - (ii) for each $1 \leq l \leq n$ with $l \neq k_i$, the database, input, previous input, state and actions of C_{i+1}^l and C_i^l coincide, and so do the queues for each $R \in (\mathcal{W}_l \cdot \mathbf{Q}_{\text{in}} \setminus \mathcal{W}_{k_i} \cdot \mathbf{Q}_{\text{out}} \cup \mathcal{W}_l \cdot \mathbf{Q}_{\text{out}} \setminus \mathcal{W}_{k_i} \cdot \mathbf{Q}_{\text{in}})$.

We say that (only) peer \mathcal{W}_{k_i} moves at step i . $\langle C_i^j \rangle_{1 \leq j \leq n}$ is called the snapshot at step i .

Intuitively, at step i in the run, only the peer \mathcal{W}_{k_i} moves while the others wait their turn. While waiting, their configurations are preserved, except for the queues which are updated by peer \mathcal{W}_{k_i} . These are the queues into which \mathcal{W}_{k_i} sends, and from which \mathcal{W}_{k_i} receives.

Lossy and perfect channels The semantics of Web compositions as defined above assumes that channels are *perfect*, i.e. all messages sent across a channel are received. This is modeled by enqueueing each sent message into the corresponding in-queue. In practice however, channels are often *lossy*, i.e. messages may be lost in transit. Indeed, this is reflected in the models used in standard work on communicating finite-state automata [2, 3]. We can also define a variant of the semantics for Web compositions that captures lossy channels, by non-deterministically allowing sent messages to not be enqueueing in the corresponding in-queue. We refer to such Web compositions as *Web compositions with lossy channels*, and to the Web compositions defined above as *Web compositions with perfect channels*. As we shall see, many of the results depend on whether channels are lossy or perfect.

There are many ways in which the correctness of a composition can be specified. We investigate two alternatives next: temporal logic (Section 3) and conversation protocols (Section 4).

3. LTL-FO PROPERTIES

The correctness of a composition is specified by statements which can express the properties of individual run snapshots (using First-Order Logic), as well as the temporal relationship among these snapshots (using Linear Temporal Logic operators). We call these statements LTL-FO properties.

DEFINITION 3.1. (Inspired by [14, 4, 27]) *The language LTL-FO (first-order linear-time temporal logic) is obtained by closing FO under negation, disjunction, and the following formula formation rule: If φ and ψ are formulas, then $\mathbf{X}\varphi$ and $\varphi\mathbf{U}\psi$ are formulas. Free and bound variables are defined in the obvious way. The universal closure of an LTL-FO formula $\varphi(\bar{x})$ with free variables \bar{x} is the formula $\forall \bar{x}\varphi(\bar{x})$. An LTL-FO sentence is the universal closure of an LTL-FO formula.*

Note that quantifiers cannot be applied to formulas containing temporal operators, except by taking the universal closure of the entire formula, yielding an LTL-FO sentence.

Composition Schema. Let $\mathcal{C} = \{\mathcal{W}_j\}_{1 \leq j \leq n}$ be a composition. Properties of runs are expressed over the *composition schema* of \mathcal{C} which consists of

- the union of all peer schemas in which each relation is qualified by the name of its peer:
 $\mathcal{C} \cdot \mathbf{Y} = \bigcup_{j=1}^n \{\mathcal{W}_j \cdot R \mid R \in \mathcal{W}_j \cdot \mathbf{Y}\}$ for each
 $\mathbf{Y} \in \{\mathbf{I}, \text{prev}_{\mathbf{I}}, \mathbf{S}, \mathbf{A}, \mathbf{Q}_{\text{in}}, \mathbf{Q}_{\text{in}}^f, \mathbf{Q}_{\text{in}}^n, \mathbf{Q}_{\text{out}}, \mathbf{Q}_{\text{out}}^f, \mathbf{Q}_{\text{out}}^n\}$;
- the set of propositional states $\{\text{move}_{\mathcal{W}} \mid \mathcal{W} \in \mathcal{C}\}$. Intuitively, at every step of a run, $\text{move}_{\mathcal{W}}$ holds iff \mathcal{W} is the moving peer at that step.

Semantics of LTL-FO Properties. Let $\psi = \forall \bar{x}\varphi(\bar{x})$ be an LTL-FO sentence over the above schema. We say that the composition \mathcal{C} satisfies $\forall \bar{x}\varphi(\bar{x})$ (denoted $\mathcal{C} \models \psi$) iff every run ρ of \mathcal{C} satisfies ψ . Let $\rho = \{\rho_i\}_{i \geq 0}$ be a run of \mathcal{C} over databases \bar{D} , and let $\rho_{\geq j}$ denote $\{\rho_i\}_{i \geq j}$, for $j \geq 0$. Note that $\rho = \rho_{\geq 0}$. Let $\text{Dom}(\rho)$ be the active domain of ρ , i.e. the set of all elements occurring in relations or as constants in ρ . The run ρ satisfies $\forall \bar{x}\varphi(\bar{x})$ (denoted $\rho \models \forall \bar{x}\varphi(\bar{x})$) iff for each valuation ν of \bar{x} in $\text{Dom}(\rho)$, $\rho_{\geq 0}$ satisfies $\varphi(\nu(\bar{x}))$. The latter is defined by structural induction on the formula: An FO sentence ψ is satisfied by $\rho_i = (k_i, \langle C_i^j \rangle_{1 \leq j \leq n})$ if the structure ρ'_i satisfies ψ , where ρ'_i is obtained from ρ_i by

- replacing the instance q of in-queues in ρ_i with the relational instance $f(q)$;
- replacing the instance q of out-queues of ρ_i with the relational instance $l(q)$;
- setting the propositional state $\text{move}_{\mathcal{W}_{k_i}}$ to *true* and $\text{move}_{\mathcal{W}}$ for $\mathcal{W} \neq \mathcal{W}_{k_i}$ to *false*.

Intuitively, an in-queue symbol Q used in an LTL-FO formula is taken to refer to the first message of Q , currently available as an input message, and an out-queue symbol Q refers to the message most recently added to the queue Q . Note that, in order to refer to the output messages generated at step i , one has to refer to the last messages of the out-queues at step $i + 1$.

The semantics of Boolean operators is the obvious one. The meaning of the temporal operators \mathbf{X}, \mathbf{U} is the following (where \models denotes satisfaction and $j \geq 0$):

- $\rho_{\geq j} \models \mathbf{X}\varphi$ iff $\rho_{\geq j+1} \models \varphi$,
- $\rho_{\geq j} \models \varphi\mathbf{U}\psi$ iff $\exists k \geq j$ such that $\rho_{\geq k} \models \psi$ and $\rho_{\geq l} \models \varphi$ for $j \leq l < k$.

Observe that the above temporal operators can simulate all commonly used operators, including \mathbf{B} (before), \mathbf{G} (always) and \mathbf{F} (eventually). Indeed, $\varphi\mathbf{B}\psi$ (“ φ must hold *before* ψ fails”) is equivalent to $\neg(\neg\varphi\mathbf{U}\neg\psi)$; $\mathbf{G}\varphi$ (“ φ *generally* holds”) is equivalent to *false* $\mathbf{B}\varphi$; $\mathbf{F}\varphi$ (“ φ *finally* holds”) is expressible as *true* $\mathbf{U}\varphi$. We use the above operators as shorthand in LTL-FO formulas whenever convenient.

EXAMPLE 3.2 LTL-FO sentences can express many interesting properties of compositions. For instance, property (11) below states that every received application message from an applicant found in the customer database will eventually result in either an approval or a denial letter.

$$\begin{aligned} & \forall id, l, name, ssn \mathbf{G} \\ & [(\mathcal{O} \cdot ?\text{apply}(id, l) \wedge \mathcal{O} \cdot \text{customer}(id, ssn, name)) \\ & \quad \rightarrow \mathbf{F} \\ & \quad (\mathcal{O} \cdot \text{letter}(id, name, l, \text{“denied”}) \\ & \quad \vee \mathcal{O} \cdot \text{letter}(id, name, l, \text{“approved”}))] \end{aligned} \quad (11)$$

The following requires loans to be approved only for applicants with excellent credit rating or for those previously cleared by the

manager.

$$\begin{aligned} & \forall id, name, loan \mathbf{G} \\ & [(\exists ssn \mathcal{CR}. \text{!rating}(ssn, \text{“excellent”}) \wedge \mathcal{O}. \text{!customer}(id, ssn, name) \\ & \quad \vee \mathcal{M}. \text{!decision}(id, \text{“approved”})) \\ & \quad \mathbf{B} \\ & \quad \neg \mathcal{O}. \text{letter}(id, name, loan, \text{“approved”})] \end{aligned}$$

□

3.1 Decidable Verification

In this section we establish two restrictions under which verification is decidable for a significant class of compositions with lossy channels. These restrictions will be justified in Section 3.2, where we show that even modest relaxations lead to undecidability. The first restriction is syntactic and is called *input-boundedness*. The second is of a semantic nature, assuming *bounded-length queues*.

Input-boundedness is a natural restriction inspired by the observation that each peer is driven by the user input and by the incoming messages. Essentially, we require that quantified variables range only over the active domain of the current inputs, the previous inputs and the first messages of flat (but not nested!) queues. This restriction is enforced syntactically as follows.

The set of *input-bounded* FO formulas over a composition \mathcal{C} 's schema is obtained by replacing in the definition of FO the quantification formation rule with the following:

- if φ is an input-bounded formula, α is an atom using a relational symbol from $\mathcal{C}.I \cup \mathcal{C}.Prev_I \cup \mathcal{C}.Q_{in}^f \cup \mathcal{C}.Q_{out}^f$, $\bar{x} \subseteq free(\alpha)$, and $\bar{x} \cap free(\beta) = \emptyset$ for every state, action or nested in-queue atom β in φ , then $\exists \bar{x}(\alpha \wedge \varphi)$ and $\forall \bar{x}(\alpha \rightarrow \varphi)$ are input-bounded formulas.

A peer is input-bounded iff

1. all state, action, and send rules into nested queues are given by input-bounded formulas, and
2. all input rules, as well as all send rules into flat queues use \exists^* FO formulas in which all state and nested queue atoms are ground.

An LTL-FO sentence over the composition schema is input-bounded iff all of its FO subformulas are input-bounded.

EXAMPLE 3.3 Peer \mathcal{O} in Example 2.2 is input-bounded, and so are the properties in Example 3.2. Examples for non-input-bounded properties can be found in [13]. □

For the particular case when the composition consists of a single peer without any message queues, the above restriction degenerates to the notion of input-bounded Web service from [13]. To show that input-bounded specifications of individual peers cover a large class of applications, we have modeled significant parts of a computer shopping Web site similar to the Dell computer shopping site, an airline reservation site similar to Expedia, an online bookstore in the spirit of Barnes & Noble, and a sports Web site on the Motorcycle Grand Prix (all published at [1]).

As it turns out, for proper compositions the syntactic input-boundedness restriction is insufficient to yield decidability. We need to make the further assumption that the queues are bounded. We say that a composition has *k-bounded queues* if each queue may simultaneously contain at most k messages. Messages arriving when the receiver's in-queue is full are simply dropped. With these restrictions, we can state our main decidability result:

THEOREM 3.4. *It is decidable whether an input-bounded composition with k -bounded queues and lossy channels satisfies an input-bounded LTL-FO property. Furthermore, the problem is PSPACE-complete for schemas with fixed bound on the arity, and EXPSpace otherwise.*

The proof is outlined in Appendix ???. It essentially consists in a non-trivial PTIME-reduction to the problem of verifying input-bounded properties of compositions consisting of a single peer with no queues. In addition, the peer can inspect, for each input I , the k previous non-empty inputs to I , using relations $prev_I^i$ for $1 \leq i \leq k$ (instead of just the immediately previous non-empty input $prev_I$, as in our definition of a peer). We refer to peers with this ability as peers with k -lookback. The decidability of verification for peers with k -lookback is shown by adapting and extending Theorem 3.5 in [13], as follows.

LEMMA 3.5. (follows from [13]) *It is decidable, given a composition $\mathcal{C} = \{\mathcal{W}\}$ where \mathcal{W} is an input-bounded peer with k -lookback and no message queues and an input-bounded LTL-FO property φ , whether \mathcal{C} satisfies φ . The problem is PSPACE-complete for schemas with fixed bound on the arity, and EXPSpace otherwise.*

Remarks Transmission delays In our model of compositions, we assumed instantaneous transmission of messages (that are not lost) by having each message be enqueued immediately after being sent. The model and results can be easily adapted to model arbitrary transmission delays, as long as the capacity of each channel is bounded. In the simulation of the composition by a single peer, the transmission delays can be captured by partitioning each in-queue into a received portion followed by an in-transit portion, and triggering the transition of a message from the in-transit portion to the received portion using a new propositional input turned on non-deterministically by a dummy user. The decidability does not extend to channels with unbounded capacity. Indeed, this is similar to having unbounded queues, for which verification is undecidable (see Corollary 3.6).

Perfect nested message channels Theorem 3.4 assumes that all channels are lossy. It turns out that the result still holds if nested message channels are perfect, and flat message channels are lossy.

3.2 Boundaries of Verification Decidability

We have shown in Section 3.1 that we can soundly and completely verify a significant and expressive class of compositions and properties. It is natural to ask whether the restrictions of Theorem 3.4 are truly necessary. In this section we show that this is indeed the case, in the sense that minimally relaxing any single restriction leads to undecidability. The proofs are all in Appendix ??.

We first investigate the assumptions pertaining to the boundedness of queues and lossyness of channels. We immediately obtain the following as consequences of prior work on peers which are communicating finite-state machines (CFSM) with queues holding propositional messages: verification is undecidable for unbounded queues, whether they are perfect (Brand and Zafiropulo [6]) or lossy (Abdulla and Jonson [2]):

COROLLARY 3.6. (of [6, 2]) *It is undecidable to determine if an input-bounded property is satisfied by an input-bounded composition \mathcal{C} with unbounded queues, regardless of whether they are lossy or perfect.*

According to Corollary 3.6, the unbounded-queue assumption alone suffices to cause undecidability. Theorem 3.7 below provides the

complementary result, showing that the perfect-queue assumption is sufficient for undecidability even when all queues are bounded. This result highlights the impact of data-awareness on the verification problem. Contrast it with the finite-state case, in which the composition of CFSMs via bounded, perfect queues is easily reducible to a single FSM, for which verification is decidable.

THEOREM 3.7. *It is undecidable whether an input-bounded property is satisfied by an input-bounded composition with no nested queues and 1-bounded, perfect flat queues.*

Recall that the semantics of sending into flat queues requires a message to be non-deterministically picked whenever the send rule generates several candidates. We consider a plausible alternative semantics in which the generation of multiple candidate messages is treated as a run-time error, in the sense that no message is sent and an error flag is set instead. To this end, we extend the schema of each peer \mathcal{W} with a propositional state $error_R$ for each flat out-queue $R \in \mathcal{W}.\mathbf{Q}_{out}^f$. This state is appropriately set by the legal successor relation and it can be consulted by the peer rules and the properties. We say that the flat queues in this peer flavor have *deterministic send rules*.

THEOREM 3.8. *It is undecidable whether an input-bounded property is satisfied by an input-bounded composition of peers with no nested queues, and 1-bounded lossy flat queues with deterministic send rules.*

We next consider a list of minor relaxations of the syntactic input-boundedness restriction (Section 3.1). First, we focus on the restriction disallowing quantified variables to appear in nested queue atoms. Notice that a consequence of this restriction is the impossibility to test emptiness of messages received via nested queues: if $R \in \mathcal{W}.\mathbf{Q}_{in}^n$, $\exists \bar{x} ?\mathbf{R}(\bar{x})$ checks the non-emptiness of the message received along queue q_R . Also notice that this test is legal if $R \in \mathbf{Q}_{in}^f$. Consider a relaxation of input-boundedness allowing access to a built-in predicate $empty(?R)$ that is set to true iff the first message in q_R is non-empty. We show that this is enough to yield undecidability, even if the emptiness tests are only used in formulating the property to be verified.

THEOREM 3.9. *It is undecidable whether an input-bounded property with emptiness tests on nested messages is satisfied by an input-bounded composition \mathcal{C} with 1-bounded queues (lossy or perfect).*

A second restriction imposed by input-boundedness requires the nested queue atoms appearing in input and in flat queue send rules to be *ground* (contain terms constructed only of constants, no variables). Its removal leads to undecidability.

THEOREM 3.10. *It is undecidable whether an input-bounded property is satisfied by a composition \mathcal{C} with 1-bounded queues and lossy flat queues, where \mathcal{C} is input-bounded except for allowing non-ground nested in-queue atoms in input rules, or in flat queue send rules.*

4. CONVERSATION PROTOCOLS

The most prominent kind of correctness property for compositions considered in previous work is the notion of (*finite-state*) *conversation protocol*. It requires that the sequence of messages as observed by some global observer belongs to an ω -regular language accepted by a Büchi automaton. The notion was introduced by Fu, Bultan and Su [17], as a generalization of an earlier version proposed by an industrial standard (IBM’s conversation support project [19]) for the model of communicating finite-state machines (CFSMs) sending and receiving propositional messages via queues.

Conversation protocols of the above flavor can also be verified for our compositions. We refer to such protocols as “data-agnostic”, because they ignore the contents of messages, checking only the sequence of observed message *names*. For instance, in our running example, a data-agnostic protocol would require any **getHistory** message to be followed by a **history** message. Alternatively, we may consider a “data-aware” extension of conversation protocols, where the contents of messages is taken into account in the specification of the protocol. We first show how data-agnostic protocols can be verified for compositions, then consider data-aware protocols.

In the context of lossy channels and bounded queues, several semantics for conversation protocols are possible. One is to ignore dropped messages and only consider messages actually being enqueued. Intuitively, this places the observer of messages at the recipients. We refer to this semantics as *observer-at-recipient*. An alternative would be to observe all sent messages, regardless of whether or not they are enqueued. This corresponds to placing the observer at the source of sent messages. We refer to this semantics as *observer-at-source*. We first consider data-agnostic conversation protocols with observer-at-recipient semantics.

Let \mathcal{C} be a composition and $\Sigma = \mathcal{C}.\mathbf{Q}_{out}$. A data-agnostic conversation protocol for \mathcal{C} is a pair (Σ, \mathcal{B}) where \mathcal{B} is a Büchi automaton over alphabet Σ .² Satisfaction of (Σ, \mathcal{B}) by \mathcal{C} under the observer-at-recipient semantics is defined as follows. Let $\rho = \{\rho_i\}_{i \geq 0}$ be a run of \mathcal{C} . We first define the set of propositions Q in Σ satisfied by each configuration of the run. The configuration ρ_0 satisfies no proposition Q . A configuration ρ_i , $i > 0$, satisfies Q if a new message is placed in the queue for Q in the transition from ρ_{i-1} to ρ_i . Let $\sigma(\rho_i)$ provide the subset of Σ satisfied by ρ_i , $i \geq 0$. The run ρ satisfies the protocol iff $\{\sigma(\rho_i)\}_{i \geq 0}$ is accepted by \mathcal{B} . The composition \mathcal{C} satisfies the protocol (Σ, \mathcal{B}) iff every run of \mathcal{C} satisfies the protocol. Clearly, data-agnostic conversation protocols for our infinite-state compositions strictly generalize conversation protocols for finite-state systems.

EXAMPLE 4.1 Since Büchi automata are strictly more expressive than LTL [28, 9], conversation protocols include properties expressible in LTL. For presentation simplicity, we illustrate an LTL-expressible protocol which, in our running example, requires each credit rating request message **getRating** to be followed by a **rating** reply:

$$\mathbf{G}(\mathbf{getRating} \rightarrow \mathbf{F rating}).$$

□

THEOREM 4.2. *It is decidable whether an input-bounded composition with bounded queues and lossy channels satisfies a data-agnostic conversation protocol with observer-at-recipient semantics. The problem is PSPACE-complete for schemas with bounded arity, and EXSPACE otherwise.*

Note that PSPACE decidability is reasonable as far as verification goes, given that LTL verification of finite-state (Mealy) machines is already PSPACE-complete [9].

Suppose we wish to verify protocols under the alternative observer-at-source semantics. Unfortunately, verification is undecidable in this case.

²A Büchi automaton is a finite-state automaton accepting infinite sequences iff they drive the automaton to visit some final state infinitely often [28].

THEOREM 4.3. *It is undecidable, given an input-bounded composition \mathcal{C} with bounded queues and lossy channels, and a data-agnostic conversation protocol (Σ, \mathcal{B}) with observer-at-source semantics, whether \mathcal{C} satisfies (Σ, \mathcal{B}) .*

We next consider data-aware conversation protocols. In view of Theorem 4.3, we only consider protocols with observer-at-recipient semantics, which is assumed by default. The data-aware protocols generalize finite-state protocols, the data-agnostic protocols discussed above, and also input-bounded LTL-FO properties over the schema $\mathcal{C}.\mathbf{Q}_{\text{out}}$. We show the decidability of checking compliance of a composition with respect to the resulting protocol.

DEFINITION 4.4. *A data-aware conversation protocol over the schema of composition \mathcal{C} is a triple $(\Sigma, \mathcal{B}, \{\varphi_\sigma\}_{\sigma \in \Sigma})$, where: Σ is a set of propositional symbols, $\{\varphi_\sigma\}_{\sigma \in \Sigma}$ is a family of FO formulas over schema $\mathcal{C}.\mathbf{Q}_{\text{out}}$, one for each symbol in Σ , and \mathcal{B} is a Büchi automaton with transitions guarded by boolean formulas over Σ .*

Intuitively, we use the symbols in $\sigma \in \Sigma$ as shorthands for formulas φ_σ over the current snapshot.

We next define the semantics of data-aware conversation protocols of the observer-at-recipient flavor. Recall that the semantics of FO formulas interprets each $Q \in \mathcal{C}.\mathbf{Q}_{\text{out}}$ as the message last placed in the queue for Q . This is consistent with the observer-at-recipient semantics for protocols.

Let \mathcal{P} be a protocol $(\Sigma, \mathcal{B}, \{\varphi_\sigma\}_{\sigma \in \Sigma})$. If each φ_σ is a sentence, a run ρ of composition \mathcal{C} satisfies \mathcal{P} iff \mathcal{B} accepts the infinite sequence obtained by computing the truth values for $\{\varphi_\sigma\}_{\sigma \in \Sigma}$ in each snapshot of ρ . If the φ_σ 's are formulas with free variables, let $\bar{x} := \bigcup_{\sigma \in \Sigma} \text{freeVars}(\varphi_\sigma)$. Denoting with $\text{Dom}(\rho)$ the active domain of ρ , ρ satisfies \mathcal{P} iff for each valuation ν of \bar{x} in $\text{Dom}(\rho)$, ρ satisfies the protocol (without free variables) $(\Sigma, \mathcal{B}, \{\varphi_\sigma(\nu(\bar{x}))\}_{\sigma \in \Sigma})$. We say that composition \mathcal{C} satisfies conversation protocol \mathcal{P} iff every run ρ of \mathcal{C} satisfies \mathcal{P} .

Note that any LTL-FO property over schema $\mathcal{C}.\mathbf{Q}_{\text{out}}$ can be expressed by a data-aware conversation protocol, while the converse is not true. This observation follows from well-known results relating the expressivity of propositional LTL and Büchi automata [28]. An example data-aware conversation protocol is property (12) in Example 5.1 below.

We say that conversation protocol $\mathcal{P} = (\Sigma, \mathcal{B}, \{\varphi_\sigma\}_{\sigma \in \Sigma})$ is *input-bounded* if each φ_σ is input bounded.

THEOREM 4.5. *It is decidable whether an input-bounded composition with bounded queues and lossy channels satisfies an input-bounded data-aware conversation protocol. The problem is PSPACE-complete for schemas with bounded arity, and EXPSpace otherwise.*

Boundary of decidability. As in the case of LTL-FO properties over the entire schema, even small relaxations of the restrictions under which the above decidability results were obtained lead to undecidability of verification. We consider relaxations similar to those in Section 3.2.

THEOREM 4.6. *The following are undecidable:*

- (i) *satisfaction of a data-agnostic protocol by an input-bounded composition with unbounded queues.*
- (ii) *satisfaction of a data-agnostic conversation protocol by an input-bounded composition with no nested queues and 1-bounded, perfect flat queues.*
- (iii) *satisfaction of a data-aware conversation protocol with ground message parameters, by an input-bounded composition with deterministic lossy flat 1-bounded queues and perfect nested 1-bounded queues.*

- (iv) *satisfaction of a data-agnostic conversation protocol augmented with emptiness tests on nested messages, by an input-bounded composition with (perfect or lossy) 1-bounded queues.*

5. MODULAR VERIFICATION

It is often useful to verify a composition \mathcal{C} in a modular fashion, i.e. to verify that a subset of its peers behaves correctly when the full specification of the other peers is not available and the only knowledge about them is declared in the form of properties of their input-output behavior. Such verification is the best one can hope for when the various peers are provided by autonomous parties unwilling to disclose the internal implementation details. Even when all peers are owned by a single party, modular verification enables the validation of a peer subset before the design of the others is completed.

Recall that a set of peers \mathcal{C} is an open composition if $\mathcal{C}.\mathbf{Q}_{\text{in}} \neq \mathcal{C}.\mathbf{Q}_{\text{out}}$. In particular, any single peer with at least one queue is an open composition. Notice that \mathcal{C} interacts with outside peers by means of the message queues in the symmetric difference $\mathcal{C}.\mathbf{Q}_{\text{in}} \Delta \mathcal{C}.\mathbf{Q}_{\text{out}} = (\mathcal{C}.\mathbf{Q}_{\text{in}} \setminus \mathcal{C}.\mathbf{Q}_{\text{out}}) \cup (\mathcal{C}.\mathbf{Q}_{\text{out}} \setminus \mathcal{C}.\mathbf{Q}_{\text{in}})$. The queues in $\mathcal{C}.\mathbf{Q}_{\text{in}} \setminus \mathcal{C}.\mathbf{Q}_{\text{out}}$ hold messages output by the environment, and are denoted $\mathcal{E}.\mathbf{Q}_{\text{out}}$, where we denote the environment with \mathcal{E} . The queues in $\mathcal{C}.\mathbf{Q}_{\text{out}} \setminus \mathcal{C}.\mathbf{Q}_{\text{in}}$ hold messages consumed by the environment, and are denoted $\mathcal{E}.\mathbf{Q}_{\text{in}}$. A *transition of the environment* modifies the queues in $\mathcal{E}.\mathbf{Q}_{\text{in}} \cup \mathcal{E}.\mathbf{Q}_{\text{out}}$ by non-deterministically removing first messages from the queues in $\mathcal{E}.\mathbf{Q}_{\text{in}}$ and enqueueing new messages in the queues in $\mathcal{E}.\mathbf{Q}_{\text{out}}$. We assume that in each run the tuples enqueued in environment transitions use values from some finite domain. A *run* of \mathcal{C} is defined by allowing, in addition to regular moves of peers in \mathcal{C} , non-deterministically interleaved transitions of the environment. These are detected by a special propositional state *move \mathcal{E}* that is true whenever a transition of the environment occurs. We omit the formal definition, which is an extension of Definition 2.6.

We next formalize the modular verification problem. An *environment* specification (spec) for \mathcal{C} is an LTL-FO formula over $\mathcal{C}.\mathbf{Q}_{\text{in}} \Delta \mathcal{C}.\mathbf{Q}_{\text{out}}$. Thus, an environment spec describes the input-output behavior of the outside peers as temporal connections between messages they receive and send.

EXAMPLE 5.1 We are interested in verifying that \mathcal{O} from Example 2.2 satisfies property (11) from Example 3.2 provided that the credit reporting agency replies to credit inquiries, and moreover returns only credit categories from a pre-defined list (ranging from “poor” to “excellent”). This is expressed as an environment specification as follows:

$$\begin{aligned} & \mathbf{G} \forall ssn [\text{?getRating}(ssn) & (12) \\ & \quad \rightarrow \\ & \quad (!\text{rating}(ssn, \text{“poor”}) \vee !\text{rating}(ssn, \text{“fair”}) \\ & \quad \vee !\text{rating}(ssn, \text{“good”}) \vee !\text{rating}(ssn, \text{“excellent”}))] \end{aligned}$$

□

Intuitively, it is natural to interpret the specification of an environment with observer-at-source semantics, independently of the properties of the channels connecting the composition \mathcal{C} with its environment. In other words, if Q is an output of the environment, an atom $Q(\bar{x})$ used in the description of the environment is true at some point in a run iff message $Q(\bar{x})$ is sent at that point by the environment. However, recall that in the context of bounded queues and lossy channels, our observer-at-recipient semantics ignores dropped messages, so $Q(\bar{x})$ is taken to be the last enqueued

message in the queue for Q . Thus, if the environment sends $Q(\bar{x})$ at step i , the only fact observable at the recipient is that, if a message is received at step $i + 1$ in queue Q , then it has to equal $Q(\bar{x})$. To correctly interpret environment specs in the context of bounded queues and lossy channels with our observer-at-recipient semantics, we translate their specification as follows. Let ψ be an environment spec. The *observer-at-recipient* translation of ψ is the formula ψ_r obtained by replacing in ψ each atom $Q(\bar{x})$ where $Q \in \mathcal{E}.\mathbf{Q}_{\text{out}}$ by $\mathbf{X}(\text{received}_Q \rightarrow Q(\bar{x}))$, where received_Q is a new propositional state that holds at step i iff the queue for Q received a new message between step $i - 1$ and i (received_Q holds either if the length of queue Q increased from step $i - 1$ to step i , or if a message was read from Q at step $i - 1$ and the length of Q stayed the same; this can be defined in terms of states and inputs already available, so received_Q is simply a convenient shorthand).

EXAMPLE 5.2 The observer-at-recipient translation of the environment in Example 5.1 is

$$\begin{aligned} & \mathbf{G} \forall \text{ssn} [\text{?getRating}(\text{ssn}) \rightarrow \\ & \quad \mathbf{X}(\text{received}_1 \text{rating} \rightarrow \\ & \quad (!\text{rating}(\text{ssn}, \text{"poor"}) \vee !\text{rating}(\text{ssn}, \text{"fair"}) \\ & \quad \vee !\text{rating}(\text{ssn}, \text{"good"}) \vee !\text{rating}(\text{ssn}, \text{"excellent"})))] \end{aligned}$$

(after combining several implications with $\text{received}_1 \text{rating}$ on the left-hand side). \square

The soundness of the observer-at-recipient translation can be shown formally as follows: (i) define observer-at-source runs of the environment recording the consumed and generated messages at each transition, (ii) define satisfaction of an environment spec ψ by observer-at-source runs of the environment, (iii) define the set of observer-at-recipient runs corresponding to observer-at-source runs, and (iv) show that for each environment spec ψ , the observer-at-recipient runs corresponding to the observer-at-source runs satisfying ψ are precisely those satisfying ψ_r . We omit the straightforward details here.

We are now ready to define satisfaction of a property φ under environment spec ψ . Since in a run of \mathcal{C} the environment transitions are interleaved with transitions of peers in \mathcal{C} , the property ψ describing runs of the environment must be relaxed to take into account the interleaved transitions. Intuitively, this is done by considering only configurations where $\text{move}_\mathcal{E}$ is true. In detail, for a propositional state α , we denote by \mathbf{X}^α a temporal operator whose semantics is the following:

- $\rho_{\geq j} \models \mathbf{X}^\alpha \varphi$ iff $\rho_{\geq i} \models \varphi$, where $i = \min\{m \mid m > j, \rho_m \models \alpha\}$;
- $\rho_{\geq j} \models \xi_1 \mathbf{U}^\alpha \xi_2$ iff $\exists k \geq j$ such that $\rho_k \models \alpha$ and $\rho_{\geq k} \models \xi_2$ and $\rho_{\geq m} \models \xi_1$ for every m such that $j \leq m < k$ and $\rho_m \models \alpha$.

It is clear that \mathbf{X}^α and \mathbf{U}^α can be simulated with usual LTL operators.

DEFINITION 5.3. Let \mathcal{C} be an open composition, φ an LTL-FO formula over the schema of \mathcal{C} , and ψ an environment spec for \mathcal{C} . Let $\alpha = \text{move}_\mathcal{E}$ and $\bar{\psi}$ be obtained by replacing in ψ each occurrence of the \mathbf{X} and \mathbf{U} operators with \mathbf{X}^α and \mathbf{U}^α . Let $\bar{\psi}_r$ be the observer-at-recipient translation of $\bar{\psi}$. Then \mathcal{C} satisfies φ under environment spec ψ (denoted $\mathcal{C} \models_\psi \varphi$) iff every run ρ of \mathcal{C} that satisfies $\bar{\psi}_r$ also satisfies φ .

Note that the order of the two translations, first from ψ to $\bar{\psi}$ and then from $\bar{\psi}$ to $\bar{\psi}_r$, is important and cannot be switched. Indeed,

the translation from $\bar{\psi}$ to $\bar{\psi}_r$ introduces \mathbf{X} operators that must not be replaced by \mathbf{X}^α .

Towards stating our decidability result for modular verification, we recall from Section 3 that an LTL-FO formula allows no temporal operators to appear in the scope of any quantifier. An LTL-FO sentence relaxes this restriction, being obtained by universally quantifying the free variables of an LTL-FO formula. In contrast, we say that an LTL-FO sentence is *strictly input-bounded* if no temporal operators occur in the scope of quantifiers. The environment spec (12) is strictly input-bounded.

THEOREM 5.4. *It is decidable whether an input-bounded open composition \mathcal{C} with bounded queues and lossy channels satisfies property φ under environment spec ψ , where φ is an input-bounded LTL-FO sentence and ψ is a strictly input-bounded LTL-FO sentence over $\mathcal{C}.\mathbf{Q}_{\text{in}}^f \Delta \mathcal{C}.\mathbf{Q}_{\text{out}}^f$. Moreover, the problem is PSPACE-complete for schemas of bounded arity and EXPSpace otherwise.*

As it turns out, the strictness restriction is essential; removing it leads to undecidability.

THEOREM 5.5. *It is undecidable whether an input-bounded open composition \mathcal{C} with bounded queues and lossy channels satisfies input-bounded property φ under input-bounded yet non-strict environment specifications.*

It is easy to see that strictly input-bounded LTL-FO environment specs can be expressed by input-bounded conversation protocols. It turns out that the proof of Theorem 5.4 above adapts to obtain decidability when the environment spec is given instead by an input-bounded conversation protocol with observer-at-recipient semantics.

6. RELATED WORK

In the finite-state case, it was shown in prior work that verification of communicating finite-state machines (CFSM) is undecidable for *unbounded, perfect* queues [6], and for *unbounded, lossy* queues [2]. The CFSM model is a special case of ours in which all schemas are propositional and there is no user input or database.

The body of work on compositions of communicating finite-state Web Services (sometimes called *e-compositions*) is surveyed in [22, 23, 24]. We mention a few projects here. [15] verifies that synchronous finite-state mediated composite services specified in the standard BPEL language [10] implement a Message Sequence Chart specification. The verification is performed by compiling the sequence charts into the Finite State Process notation (FSP), and invoking a propositional model checker from the LTSa toolkit. [26] proposes an approach to the verification and automated composition of finite-state web services specified using the DAML-S standard [11]. The verified properties are propositional, abstracting from the data values. They pertain to safety, liveness and deadlocks, all of which are expressible in LTL. [25] is concerned with verifying a given finite-state web service flow specified in the standard WSFL [29] by using the explicit state model checker SPIN [20]. The properties are expressed in LTL (abstracting from data content).

The line of work in [18, 16] takes into account the contents of the exchanged messages and thus transcends the purely propositional composition models described above (but assumes a pre-defined finite domain for the values, which reduces the problem to a finite-state setting). Peers are specified using finite-state automata whose transitions are guarded by boolean formulas involving the message contents. Properties are expressed in LTL. This is a particular case of the framework presented in this paper, with finite domain, no database, no user input and no nested queues (but perfect

bounded flat queues). The emphasis is not on mapping the verification boundaries, but on developing a versatile architecture allowing the exchange of XML messages without being tied to any particular standard, as well as sufficient conditions to delegate the verification task to the off-the-shelf finite-state model checker SPIN [20].

Recently, [5] has proposed a model of compositions of peers with underlying databases. The model corresponds to a particular case of the one we present here, with no user input, no nested queues, perfect flat queues, and database access restricted to key lookup only, so that at most one tuple is retrieved or updated at any given time. [5] does not address verification, focusing on automatic synthesis of a desired Web Service by “gluing together” an existing set of services.

7. CONCLUSIONS

We have studied the verification properties of compositions of data-driven peers communicating asynchronously by message exchange. We treat data values as first-class citizens, specifying each peer’s behavior with queries against its configuration. This leads to infinite-state compositions (since the database is not fixed in advance), and constitutes a departure from classical work on verification of communicating finite-state machines or, more recently, verification of finite-state Web Service compositions.

We delineate the boundaries of verification decidability by exploring a wide range of communication semantics and classes of composition and property specifications. We also consider modular verification of partially specified compositions when only the input-output behavior of their environment is known. We identify a practically appealing and fairly tight class of specifications for which verification is decidable in PSPACE (for fixed database arity), which is no worse than LTL verification of finite-state machines. Our favorable prior experiments on individual peer verification lead us to expect similar results for compositions.

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