Tango: Declarative Semantics for Multiagent Communication Protocols

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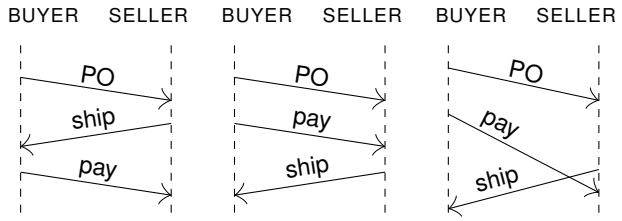
Abstract

To build a decentralized multiagent system whose member agents are not coupled to each other's decision making requires a flexible communication protocol. Information-based protocol languages capture a protocol in terms of causality and integrity constraints based on the information exchanged by the agents. Thus, they enable highly flexible enactments in which the agents proceed asynchronously and messages may be arbitrarily reordered. However, the existing semantics for such languages can produce a large number of protocol enactments, which makes verification of a protocol property intractable. This paper formulates a protocol semantics declaratively via inference rules that determine when a message emission or reception becomes enabled during an enactment, and its effect on the local state of an agent. This representation enables heuristics for determining when alternative extensions of a current enactment would be equivalent, thereby helping produce parsimonious models and yielding improved protocol verification methods.

1 Introduction

We consider a decentralized multiagent system in which autonomous agents communicate through message passing. Such multiagent systems find natural application in settings such as commerce and the Internet of Things where multiple parties interoperate autonomously with minimal coupling.

A crucial challenge is to specify, verify, and implement multiagent systems in terms of high-level concepts such as norms and other organizational constructs [Günay *et al.*, 2015; Jiang *et al.*, 2015; El Menshawy *et al.*, 2011]. However, in a decentralized setting, the high-level concepts can become entwined with details of message flow. In this context, a data-driven approach [Montali *et al.*, 2014] can unite meanings with operations and processing [De Masellis *et al.*, 2017]. We adopt BSPL (the Blindingly Simple Protocol Language) [Singh, 2011], which precisely expresses the information to be exchanged between agents. Thus, it yields enactments as flexible as possible given causal and integrity constraints that naturally encode meanings [Chopra *et al.*, 2020]. However, the current BSPL semantics [Singh, 2012] and its variants produce a combinatorial explosion of enactments, which exacerbates the complexity of formal verification.



(a) Shipment first (b) Payment first (c) Concurrent

Figure 1: Some possible equivalent enactments of *Purchase*.

Let us describe the problem and solution informally. An *enactment (of a protocol)* is what may happen when it is instantiated—which messages are sent and received in what order by what participant. Consider a *Purchase* protocol. A role BUYER sends *PO* (a purchase order specifying item and price) to a role SELLER, who responds to *PO* with *ship* (of that item). BUYER sends *pay* of price in *PO*. Notice that *ship* and *pay* are independent but each depends on *PO*. Figure 1 shows some enactments of *Purchase* for a single transaction.

To capture decentralization, each enactment is modeled as a vector of histories, one history per role [Singh, 2012]. We term two enactments *equivalent* if they reflect the "same" information and decision making at each role. Representing multiple equivalent enactments does not enhance the protocol properties verified but exacerbates verification complexity.

A protocol may produce multiple equivalent enactments for three main reasons. One, *flexibility*. Figure 1's enactments differ only with respect to the ordering of *pay* and *ship*—precisely the ordering that is *irrelevant* in the protocol. From BUYER's perspective, *PO* must precede *ship* and *pay* but their order of occurrence is irrelevant. From SELLER's perspective, *PO* must precede *ship* but how *ship* and *pay* are ordered is irrelevant. Two, the *infrastructure*. For example, under FIFO, SELLER would observe *PO* before *pay*, but either order is acceptable without FIFO. Three, the *architecture*. Specifically, decentralization means there is no central controller that can force an agent to observe messages in a particular order.

To verify the correctness of a protocol, one would check properties such as liveness and safety by generating a model

from the protocol and verifying the property in the model. Flexible protocols with many possible enactments may produce a large model that is consequently hard to verify.

We contribute Tango, an approach for a protocol semantics that identifies how messages tangle with each other and produces a "small" model for a protocol that contains all the relevant variety exhibited by its enactments. The message entanglements help us determine when two enactments are semantically equivalent (satisfy or violate the same properties), and provide a basis for reducing redundancy in a model. We contribute an algorithm for generating small models of protocols that ensures correctness. We show empirically that our algorithm produces smaller models and verifies correctness of sample protocols much faster than previous work.

2 Background: Information-Based Protocols

We now introduce the core ideas of information-based protocols using BSPL [Singh, 2011]. Listing 1 shows an example protocol. Each protocol involves roles (here, B and S); these roles are adopted by agents when the protocol is enacted. The parameters specify the information to be computed: think of these as forming a relational schema, each instance of which corresponds to a complete enactment of the protocol.

```
1 protocol PO Pay Cancel Ship {
2   roles B, S
3   parameters out ID key, out item, out price,
        out outcome
4   private pDone, gDone, rescind
5
6   B ↦ S: PO [out ID key, out item, out price]
7
8   B ↦ S: cancel [in ID key, nil pDone, nil
        gDone, out rescind]
9   B ↦ S: pay [in ID key, in price, in item,
        out pDone]
10
11  S ↦ B: ship [in ID key, in item, nil
        rescind, out gDone]
12  S ↦ B: cancelAck [in ID key, in rescind, nil
         gDone, out outcome]
13  S ↦ B: payAck [in ID key, in pDone, out
        outcome]
14 }
```

Listing 1: Protocol for purchase with cancellation.

BSPL specifies interactions in terms of *causality* and *integrity* constraints. Message emissions are causally constrained by dependencies between their parameters. Each message schema lists parameters adorned ⌜in⌝, ⌜out⌝, or ⌜nil⌝, and at least one ⌜key⌝. The sender must already know the binding for each ⌜in⌝ parameter, not know the binding for any ⌜out⌝ or ⌜nil⌝ parameter, and create a binding for each ⌜out⌝ but not for any ⌜nil⌝ parameter.

To send *PO*, B introduces new bindings for ID, item and price. These new bindings enable B to send *cancel* and *pay*. However, sending *pay* disables *cancel*, because *cancel* has pDone adorned ⌜nil⌝. Similarly, receiving *ship* prevents B from sending *cancel*, and receiving *cancel* prevents S from sending *ship*; it is *reception* that disables those messages, not emission, because each agent acts only on local knowledge. Thus, there is a race condition when B sends *cancel*: the PO is canceled only if S receives *cancel* before sending *ship*.

Integrity requires that each parameter have at most one binding in an enactment, as identified by the key parameters. In *PO Pay Cancel Ship*, each binding of ID identifies a unique enactment, in which there can only be one binding for item, price, and so on. Hence, ⌜out⌝ parameters are mutually exclusive; S cannot send both *cancelAck* and *payAck* in the same enactment, because both bind outcome. If all enactments of a protocol satisfy integrity, we say that the protocol is *safe*. *PO Pay Cancel Ship* is safe because none of its parameters can be bound by more than one role in an enactment.

A protocol is *live* if every enactment can produce bindings for all public parameters (assuming no message loss). *PO Pay Cancel Ship* is live, because *PO* binds ID, item, and price. Both *cancelAck* and *payAck* bind outcome; in every enactment, at least one them is enabled, completing the enactment.

BSPL semantics [Singh, 2012] maps each protocol to a set of *history vectors* comprising one sequential history for each of its roles. A history vector H is $[H_1; H_2; \ldots]$, where each H_i is a sequence of observations $[o_1^i, o_2^i, \ldots]$ made by role r_i. There is no ordering across histories. One history vector progresses to another as any of the roles append an enabled observation to its observation sequence.

Below, $x!m$ (e.g., B!*pay*) means the emission of m by x; and $x?m$ (e.g., S?*pay*) means the reception of m by x. For a message of the form $x \mapsto y$, if $y?m$ appears in y's sequence in a vector, $x!m$ also appears in x's sequence in a prior vector.

3 Semantic Tableaux for Protocols

A protocol *configuration* corresponds to a state of the world as the protocol is enacted. A configuration comprises the local knowledge of each role in the protocol as well as the contents of every communication channel (i.e., between each pair of roles). Given the message emissions and receptions at each role, a message that has been sent but not (yet) received is in the corresponding channel. In an initial configuration, no observations have occurred, thus no messages are in transit, and each role knows exactly the ⌜in⌝ parameters of the protocol. Each protocol enactment goes through a series of configurations where the transition from each configuration to the next respects causality and no role emits a message that would locally cause integrity violation. (Our example protocols have no ⌜in⌝ parameters and can be enacted standalone—without needing any other protocols to provide the ⌜in⌝ parameters.)

Semantic tableaux [D'Agostino *et al.*, 1999; Fitting, 1999] are a way to organize a proof as a tree where inference rules determine how one node leads to another node. Here, tableaux capture the notion of transition for generating a model of a protocol, as needed for our protocol semantics.

Each *branch* or sequence of nodes beginning from the root of a tableau has a natural semantic interpretation as a possible protocol enactment. A tableau is thus a model of a protocol, i.e., the set of its enactments. The tableaux we define lend themselves to natural reasoning to eliminate redundant branches, thereby compressing the model of a protocol.

We adopt propositional logic with its usual rules. Below, m is a message schema $x \mapsto y$: $m[\vec{p}_I, \vec{p}_O, \vec{p}_N]$, where

$L_x m$	Message m has been observed by x
$K_x p$	Binding for parameter p is known to x
$U_x p$	Binding for parameter p is still unknown to x
$x \mapsto y\colon m$	Message m, x to y; detailed with $\vec{p}_I, \vec{p}_O, \vec{p}_N$
$m_i \Vdash m_j$	m_i is a possible enabler of m_j
$m_i \dashv\Vdash m_j$	m_i disables m_j

Table 1: Notation summarized.

$\vec{p}_I, \vec{p}_O, \vec{p}_N$ are sets of its parameters respectively adorned ⌜in⌝, ⌜out⌝, and ⌜nil⌝. The modalities K_x and U_x capture that role x knows or does not know parameter bindings, and L_x that x observes the emission or reception of a message.

3.1 Knowledge and Observations

Initially, each role knows bindings for exactly the set of ⌜in⌝ parameters of the protocol (the empty set for self-contained protocols). What is known to each role grows monotonically because parameter bindings are immutable, and the emission and reception of each message adds to a role's knowledge.

$L_x m$ means role x has observed message m. In BSPL, the only observations are local, i.e., emissions or receptions. Chaining back a role's observations to the root gives us its history in reverse. This is crucial in relating nodes to history vectors and tableaux to sets of history vectors [Singh, 2012].

The $K_x p$ assertions in a tableau node together characterize a protocol configuration. U_x expresses which bindings are (so far) unknown to x. Each transition involves an observation and the associated increase in the knowledge of the observing role. The BSPL treatment of ⌜out⌝ and ⌜nil⌝ parameters at emission relies upon their bindings being unknown. To capture this increase in knowledge, we delete $U_x p$ assertions simultaneously with when we infer $K_x p$ assertions. Repeated deletion of a $U_x p$ assertion has no additional effect.

An instance of $x \mapsto y\colon m[\vec{p}_I, \vec{p}_O, \vec{p}_N]$ is enabled for emission by x if and only if x knows $\vec{p}_I$ but does not know $\vec{p}_O$ or $\vec{p}_N$. Concomitantly with the emission, the sender produces and comes to know the bindings for $\vec{p}_O$.

$$\frac{K_x\vec{p}_I \qquad U_x\vec{p}_O \qquad U_x\vec{p}_N}{L_x(x \mapsto y\colon m[\vec{p}_I, \vec{p}_O, \vec{p}_N]) \qquad K_x\vec{p}_O \qquad \cancel{U_x\vec{p}_O}}$$

Upon the sender observing a message, the message enters the communication channel from its sender to its receiver. A message from x to y is enabled for reception by y if and only if x has observed sending that message. Concomitantly, y comes to know the bindings for $\vec{p}_I$ and $\vec{p}_O$.

$$\frac{L_x(r = x \mapsto y\colon m[\vec{p}_I, \vec{p}_O, \vec{p}_N])}{L_y r \qquad K_y\vec{p}_I \qquad K_y\vec{p}_O \qquad \cancel{U_y\vec{p}_I} \qquad \cancel{U_y\vec{p}_O}}$$

3.2 Generating Branches

Whether a message is enabled for emission may depend upon its sender not knowing bindings of some parameters. Hence, enablement is transient; it is computed within this inference rule but not stored as an assertion in the tableau. For completeness, we must ensure that each enabled message is observed on some tableau branch growing from a configuration.

Our desired tableaux would have a branch for each enactment. To this end, there is a choice between all allowed observations by any of the roles. For completeness, we must consider all choices. Let C be a configuration comprising all assertions of the form (for each role, parameter, and message) $K_x p$, $U_x p$, and $L_x m$, and define the following.

- $\mathbf{E}_x = \{\langle x, e\rangle | e = x \mapsto y\colon m[\vec{p}_I, \vec{p}_O, \vec{p}_N]$ and $K_x\vec{p}_I$ and $U_x\vec{p}_O$ and $U_x\vec{p}_N\}$.
- $\mathbf{R}_y = \{\langle y, r\rangle | r = x \mapsto y\colon m[\ldots]$ and $L_x r\}$.
- $\mathbf{L} = \bigcup_x \mathbf{E}_x \cup \bigcup_y \mathbf{R}_y$, the enabled observations in C.

Then, this metarule captures all branches in the tableau:

$$\frac{C}{L_z m | \ldots |, \text{ where each } \langle z, m\rangle \in \mathbf{L}}$$

3.3 Generating Enactments from Tableaux

Each branch of a tableau, as generated from the inference rules above, respects the causal structure of BSPL as well as local consistency for the emissions made by a role.

Each branch leading to a configuration corresponds to a unique history vector in the BSPL semantics. Specifically, for each role x, we identify the observation sequence of x as the list of all the L_x statements in the order in which they occur from the root to a given configuration. The history (of some role) changes any time there is an $L_x m$ assertion. The rest of the tableau, i.e., between consecutive $L_x m$ and $L_y m'$ assertions, is for reasoning about the same state.

3.4 Verifying Correctness Properties

Properties of interest, e.g., liveness and safety, are concerned with the reachability or otherwise of a configuration through an enactment. They are expressed via propositional combinations of local knowledge states of the roles and the observations made by the roles.

We assert a property at the root. A branch ends when no more observations are enabled. A consistent branch that ends provides an example for the property at the root. A branch that hits a contradiction is *closed*; a tableau closes if all its branches close, which indicates the property is inconsistent and its negation is proved. The situation is more nuanced here because the $L_x m$ assertions indicate the passage of time.

For liveness, we require each public parameter of the protocol to be known to at least one role. A liveness violation occurs precisely when at least one of the parameters remains unknown to each role that emits a message with an ⌜out⌝ on that parameter. For example, in Listing 1, $\neg K_{\text{B}}$ ID $\vee \neg K_{\text{B}}$ item $\vee \neg K_{\text{B}}$ price $\vee \neg K_{\text{S}}$ outcome. A consistent ended branch is a counterexample: some parameter is unknown. But if every branch closes, liveness is *established*.

For safety, let m_1 and m_2 be two messages that conflict by having the same ⌜out⌝ parameter. If both messages were to be emitted, we would have conflicting bindings for the parameter, reflecting an integrity violation. A safety violation occurs for any such pair of messages—a disjunction of conjunctions of expressions $L_x m_1$ and $L_y m_2$, where $x \neq y$, x sends m_1, and y sends m_2. Listing 1 has no such case since both *cancelAck* and *payAck*, which conflict on outcome, are sent by S. For illustration, let's augment Listing 1 with

```
S ↦ B: getLost [in ID key, out rescind]
```

Then, the safety violation of the resulting protocol would occur if and only if L_{B} *cancel* $\wedge$ L_{S} *getLost can* hold. The negation of this property means that safety is preserved. We place the negated property, $\neg L_{\text{B}}$ *cancel* $\vee$ $\neg L_{\text{S}}$ *getLost*, at the root of the tableau. If any branch of the tableau closes, i.e., runs into a contradiction, we determine that safety is *violated*.

4 Reducing the Tableau

Recall that in BSPL, each role executes serially (i.e., is single threaded) but the various roles can proceed concurrently. Our interleaved expansion of a tableau is adequate for representing concurrent enactments because BSPL decouples observations by different roles. Therefore, any set of concurrent observations can be realized by interleaving them without any intervening observations from outside of that set.

Theorem 1. *Each history vector corresponds to at least one possible branch in a tableau for that protocol.*

Proof Sketch. Each step on a tableau branch involves one inference rule being applied. A history vector is built inductively starting from a vector of empty histories. When the inductive step involves exactly one role sending or receiving a message, the corresponding inference rule generates the node that corresponds to the new vector.

When roles act concurrently, the effect equals that of interleavings of individual steps, which are captured by our tableau construction. Consider a history vector $[H_x; H_y]$ for a protocol with two roles, x and y. Suppose x emits m_1 and y emits m_2. Then, under true concurrency, first both emit: $[H_x, x!m_1; H_y, y!m_2]$. And next both receive: $[H_x, x!m_1, x?m_2; H_y, y!m_2, y?m_1]$. We can show that interleavings would produce configurations equivalent to those produced by concurrency, e.g., $[H_x, x!m_1; H_y]$ and $[H_x, x!m_1; H_y, x?m_1]$, which are legitimate BSPL history vectors. That is, a tableau produced without concurrency captures all history vectors in the BSPL semantics. □

4.1 How Messages Relate in a Protocol

The following intuitions underlie our approach for reducing the set of interleavings of messages to be considered in a tableau. We begin from identifying relationships between messages to construct a graph of potential incompatibilities.

Unrelated messages may occur in any order and any arbitrary ordering of them is equivalent to all orderings, so we can discard all but one of the branches in the tableau.

Necessary enabler If one message must occur before another, we need consider them only in that order. However, the tableau would unfold in the correct order and we need do nothing special to accommodate it.

Order matters If one message may disable another, we must include both possibilities in the tableau. We need to recognize such orders even if one of the messages is not presently enabled and make sure we do not prematurely eliminate viable branches from the tableau.

We consider message transmissions realized as separate observations by the sender and recipient, respectively.

Observation a *directly endows* observation b, $a \mid\!\div b$, if and only if a is a necessary precursor to b. In BSPL, b has a parameter adorned $\ulcorner\mathsf{in}\urcorner$ and a is an observation of the unique message that has the same parameter adorned $\ulcorner\mathsf{out}\urcorner$. Emissions directly endow their reception. For example, B!*pay* directly endows S?*pay*, and S?*pay* directly endows S!*payAck* because it is the only observation for S that binds pDone.

Observation a *endows* c, $a \|\!\div c$, if and only if there is a chain of one or more direct endowments from a to c.

Observation a *directly disables* observation b, $a \dashv b$, if and only if the occurrence of a disables b. In BSPL, b must have an $\ulcorner\mathsf{out}\urcorner$ or $\ulcorner\mathsf{nil}\urcorner$ parameter that a has $\ulcorner\mathsf{in}\urcorner$ or $\ulcorner\mathsf{out}\urcorner$. For example, S?*cancel* directly disables S!*ship*. An emission can be disabled by other observations by the sender, but a reception cannot be disabled [Chopra *et al.*, 2020]. Additionally, a must not endow b; otherwise, B!*pay* would be considered to disable B!*PO* since *pay* has ID $\ulcorner\mathsf{in}\urcorner$ and *PO* has ID $\ulcorner\mathsf{out}\urcorner$; but clearly *pay* depends on *PO* and cannot disable it.

Observation a *directly enables* observation b, $a \vdash b$, if and only if a is a potential precursor to b. In BSPL, b is the reception for an emission a, or is an emission that has a parameter adorned $\ulcorner\mathsf{in}\urcorner$ and a is observed by the sender and has the same parameter adorned $\ulcorner\mathsf{out}\urcorner$ or $\ulcorner\mathsf{in}\urcorner$. Emissions directly enable the corresponding reception observation at the recipient, and both emissions and receptions can enable emissions at the sender. For example, B!*pay* directly enables S?*pay*, S?*pay* directly enables S!*payAck*, and B!*PO* enables B!*pay*.

Table 2 summarizes direct enablement and disablement relationships between observations based on what parameters occur in them. It is possible syntactically to have a protocol with two messages that both enable and disable each other.

	$\ulcorner\mathsf{in}\urcorner\ \mathsf{p} \in b$	$\ulcorner\mathsf{out}\urcorner\ \mathsf{p} \in b$	$\ulcorner\mathsf{nil}\urcorner\ \mathsf{p} \in b$
$\ulcorner\mathsf{in}\urcorner\ \mathsf{p} \in a$	$x?a \vdash\ y!b$	$x?a \dashv\ y!b$	$x?a \dashv\ y!b$
$\ulcorner\mathsf{out}\urcorner\ \mathsf{p} \in a$	$x\,?a \vdash\ y!b$	$x\,?a \dashv\ y!b$	$x\,?a \dashv\ y!b$
$\ulcorner\mathsf{nil}\urcorner\ \mathsf{p} \in a$	–	–	–

Table 2: Direct enablement or disablement by a of b. The interrobang, as in $x\,?\,a$, indicates that x may either emit or receive a; b is always an emission. Here, $p \in m$ indicates parameter p occurs in message schema m; x and y may be the same or different roles.

Observation a *enables* observation c, $a \|\!- c$, if and only if there is a chain of one or more direct enablements from a to c. Thus, enablement is an upper bound in that not all the enabling messages for c would be needed as precursors of c, and some of which may be mutually disabling.

Observation a *tangles with* observation c, $a \dashv\!\| c$, if and only if (1) a does not endow c; and (2) a directly disables c or a directly disables a message b where b enables c. That is, a tangles with the causal precursors of any message it disables. Considering causal precursors helps us identify entanglement even when a message does not directly disable another.

Two observations are *incompatible* if and only if at least one is an emission and one of them tangles with the other.

We consider observations to be *sensitive* if they can directly disable or be directly disabled by a potential observa-

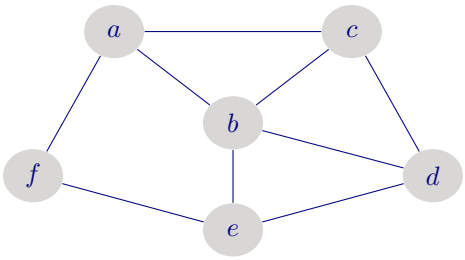


Figure 2: Incompatible observations placed in a graph.

tion. Such observations must be handled carefully to ensure that all enactments are covered.

4.2 Compatible Sets of Observations

We now compute compatible sets of observations that are enabled in a particular configuration. As explained above, the reception of a message that has been sent is always enabled. Emissions are enabled based on the knowledge state of the emitting role.

Given the set of messages enabled in a configuration, identify incompatible pairs of observations. Then, partition the messages into *compatible sets* such that (1) no observation is incompatible with another within the same compatible set and (2) each compatible set contains an observation that is incompatible with an observation in another compatible set.

For correctness, we consider both orders for any pair of incompatible observations. We can arbitrarily reorder observations within a compatible set with no effect on correctness—desirable for reducing the number of generated orders.

We capture the incompatibilities as an undirected graph, i.e., with observations as vertices and edges as incompatibilities. We reduce the problem of identifying a suitable partition to graph coloring. Since minimal graph coloring is NP-Hard, we apply a greedy approach that ensures the observations assigned the same color are compatible though the different colors may not necessarily reflect true incompatibilities. We slightly enhance Brélaz's [1979] approach below.

- Sort vertices in order of decreasing degree.
- Assign a color to each vertex that is not assigned to its neighbors, generating a new color only if necessary.
- In variation from Brélaz, choose a color that (1) has the highest cardinality; (2) within such, the color whose vertex of highest degree has the smallest degree; (3) within such, the color whose vertex of highest degree in the full protocol incompatibility graph has the smallest degree. We posit that this choice pushes the coloring toward an imbalanced distribution of vertices, which would tend to lower the number of branches to be added to a tableau.

Within a compatible set, observations do not conflict so we consider them in an arbitrary order. Across compatible sets, observations may conflict so we generate branches in the tableau to capture each order of incompatible observations.

Suppose the observation incompatibilities are as Figure 2 shows. A possible partition is $\{\{b, f\}, \{a, d\}, \{c, e\}\}$.

4.3 Reduction of Proof Orders

In a configuration C, compute $\mathbf{L}$ as defined above; the set of pairs of roles and their enabled observations in C.

From any nonsensitive observations in $\mathbf{L}$, select one by an arbitrary ordering such as alphabetically by name, or maximum degree in the incompatibility graph; order does not matter for correctness, but may influence the number of branches.

If only sensitive observations are enabled at C, generate a subgraph of the protocol's incompatibility graph limited to observations in $\mathbf{L}$. Identify compatible sets of the subgraph as described above. Create one branch of the tableau for each compatible set, each branch to begin from the an arbitrarily selected observation of that compatible set.

Preferentially handling nonsensitive observations first is not essential to correctness, but can sometimes reduce the number of branches that are introduced by a conflict and makes the branching occur closer to the actual conflict so the tree is easier to understand.

4.4 Correctness of the Method

Since we showed in Theorem 1 that all history vectors (enactments) have a corresponding tableau, we need only to show that a reduced tableau covers all the branches of the full tableau up to equivalence.

Definition 1. *Two tableau branches are* equivalent *if they contain the same observations, regardless of order. Such branches must induce the same knowledge for each role.*

Theorem 2. *If T_P is a full tableau for protocol P and R_P is a reduced tableau constructed according to the above rules, then every maximal branch in T_P is equivalent to some branch in R_P.*

Proof Sketch. Suppose B_T is a maximal branch in T_P, i.e., a valid sequence of observations that does not enable any additional observations. Suppose also that B_T is not equivalent to any branch B_R in R_P. Then, there must be some point, D where B_T diverges from R_P; that is, observations on B_T up to D form subsequences of the observations on some branch in R_P. This point may be the empty branch. Let Q be the set of maximal branches in R_P such that each branch in B_T is equivalent to some branch in Q.

Case 1. B_T ends prematurely, so that all branches in Q are strict supersequences and thus not equivalent. But this is impossible because B_T is maximal, so the configuration induced by its observations cannot enable any additional observations.

Case 2. B_T is extended by some observation not in any branch in Q. After divergence, B_T is extended by some observation o that is not in any branch in Q. Thus, since the branches in Q are maximal, and contain every observation in B_T prior to o (thus everything necessary to enable o), every branch in Q must contain some observation o' that directly disables o. According to the rules of construction, sensitive observations are delayed until some sensitive event must be chosen, and then partitioned into incompatible sets which each form a new branch. Thus, at the point that o' is selected, since o is enabled, it must be placed in an incompatible set, and thus end up on some other branch, contradicting the premise that no branch in Q contains o. Thus, every maximal branch in T_P is equivalent to some branch in R_P. □

Protocol	No Branch Reductions			Tango		
	Nodes	Branches	Time	Nodes	Branches	Time
PO Pay Cancel Ship (Listing 1)	1,495	490	655 ms	22	4	8 ms
Block Contra (in online supplement)	1,802	612	636 ms	14	2	8 ms
Independent (in online supplement)	453	90	157 ms	11	1	3 ms
NetBill [Sirbu, 1998], Bliss version [Singh, 2014]	4,097	1,246	2,688 ms	62	8	38 ms
HL7 Create Lab Order [Christie *et al.*, 2018]	59,259	17,814	70,953 ms	69	14	76 ms

Table 3: Performance comparison between full paths [Christie *et al.*, 2020] and reduced (Tango) approaches on a well-known payment protocol (NetBill) and a healthcare standard (HL7) protocol as well as on conceptually challenging protocols such as Block Contra.

5 Performance Evaluation

Figure 3 shows a graphical representation of the entire tableau computed for Listing 1, with the observations as transitions. Partitions are shown at nodes where only sensitive observations are enabled. When checking a property, the construction process would stop as soon as a counterexample is found.

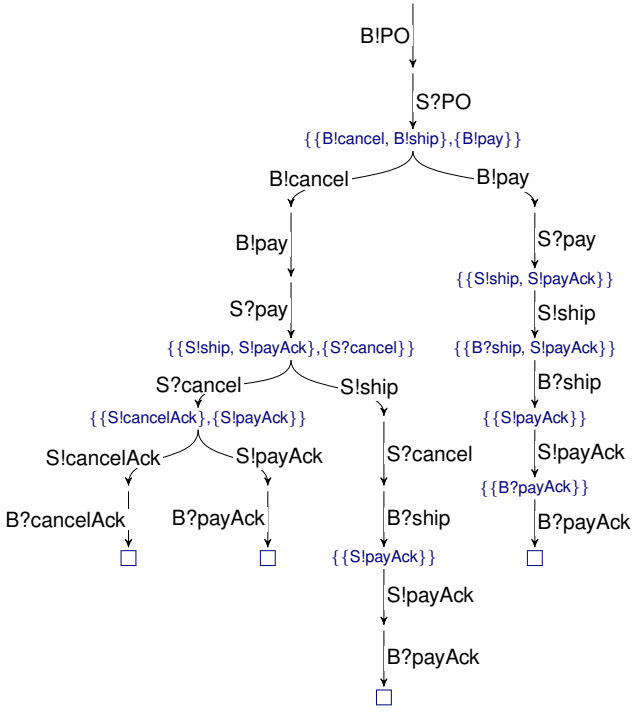


Figure 3: Entire tableau structure for *PO Pay Cancel Ship*.

We have implemented Tango in Python, and compared it with existing BSPL verification tools. All experiments were performed on the same Linux laptop, a Thinkpad T460 with an Intel i7-6600U CPU and 16GB of DDR3 RAM. In our experiments, observations are sorted alphabetically by message name and nonsensitive observations are handled first.

Table 3 shows the total number of nodes (representing configurations or states), branches, and elapsed time for several sample protocols, including the examples in this paper. The columns labeled *No Branch Reductions* describe the prior approach for BSPL [Christie *et al.*, 2020]. The columns labeled *Tango* result from our method.

In addition to the *PO Order Cancel Ship* protocol, we show the results for two protocols (listings in the online supplement; link in Section 7) that illustrate important cases for our evaluation. *Block+Contra* exhibits subtle race conditions that confound a naïve method. *Independent* shows an ideal case for tableau reduction where there is a direct causal chain that can lead to a combinatorial explosion for a naïve method.

6 Discussion

The engineering of interacting agents is an evergreen theme in multiagent systems [Mazouzi *et al.*, 2002; Damiani *et al.*, 2012]. The connection of interactions with high-level representations, both cognitive [Boissier *et al.*, 2019] and social [Baldoni *et al.*, 2015], from the standpoint of engineering multiagent systems remains crucial. A well-designed protocol would decouple its agents, helping cope with the complexity of verifying or testing them separately [Winikoff and Cranefield, 2014] and composing the results. BSPL makes it possible to specify flexible protocols that decouple the agents as much as possible given causality and integrity constraints.

BSPL is unique in its support for asynchrony and flexibility, and thus in its need for reduced models. Christie *et al.* [2020] introduce protocol refinement to support re-verifying a BSPL protocol after substituting a component protocol in a large composition. But their models simulate each interleaving of observations as a distinct enactment, thereby exploding combinatorially. Protocol languages such as trace expressions [Ferrando *et al.*, 2019] that do not express the information exchanged (and associated causality and integrity constraints) do not enable the optimizations we described, since they do not make clear which message emissions and receptions can be reordered without affecting the meaning.

Tango's contribution includes fast (polynomial time) heuristics that help avoid generating a too-large tableau. A valuable enhancement of Tango would be to identify optimizations for protocols that are generated from meaning specifications as in Clouseau [Singh and Chopra, 2020].

7 Reproducibility

Our source code, examples, and instructions are available publicly in an online supplement at https://gitlab.com/masr/.

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