A Critical Examination of Languages for Specifying Interaction Protocols for Decentralized Social Machines

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Abstract

Important Web applications are social machines in that they involve interoperation among autonomous parties through the Web. We particularly focus on decentralized social machines that reflect the autonomy of their participants in infrastructure that avoids a central provider or authority. A social machine can be effectively specified via an interaction protocol that specifies how participants engage with each other by sending and receiving messages.

The importance of decentralization in modern applications has driven research into languages for specifying interaction protocols. However, despite their shared objectives, current languages differ significantly in their—often complex—technical details.

We contribute a comparative evaluation of these languages over criteria geared toward social machines that incorporate three crucial aspects: (i) information—to express social meaning via instances, correlation, and integrity; (ii) flexible enactments—to enable autonomy via concurrency and extensibility—that are also causally valid; and (iii) asynchrony—to avoid hidden coupling. We show how the underlying abstractions and assumptions of the various languages fare on these criteria.

1 Introduction

Important Web applications are conceptually decentralized in that they involve interactions among autonomous parties [9, 17, 18]. Such applications arise in domains such as e-commerce, health, banking, finance, entertainment, and so on. For example, purchasing a book involves interactions between buyers, sellers, payment enablers such as credit card companies and banks, and shippers. Crucially, these applications feature the social meaning of interaction, as reflected, for example, in the commitments between the parties.

Supporting a decentralized application requires specifying the appropriate interaction protocol for that application. An interaction protocol specifies the rules of engagement between the parties in an application. Specifically, it constrains how a party may emit messages to another and possibly how it may receive messages from others. A key benefit of the protocol abstraction for decentralization is that it decouples the parties by providing a basis for interoperability that is independent of implementation.

Current software practice does not do justice to decentralization. In current practice, decentralized applications are realized in software via API-based integration of Web services. For example, in the purchase scenario, the seller’s service implementation would invoke both the shipping and payment services based on information provided by a buyer. Notably, current approaches leave the social meaning entirely epiphenomenal to the software [17]. The expansion of the Internet of Things (IoT)—typically energy constrained [43]—across settings where the “things” belong to different users and organizations highlights the limitations of Web-based (request-response) service computing. As a case in point, the major IoT protocols [33, 38, 47]...
Figure 1: A social machine as an sociotechnical system (STS), schematically. A protocol and its overlaid social meanings specify the STS. The agents enact the protocol by sending and receiving messages over a communication infrastructure. An agent’s computation has two main parts: (1) internal decision making and (2) public computation in enacting the protocol. Generally, an STS has two or more agents; the figure shows only two to reduce clutter.

all assume asynchronous communication. That is, as asynchronous protocols spread, current programming approaches interfere with decentralization.

Notably, in Berners-Lee’s vision [9], decentralized applications would be realized as social machines. A social machine is in essence a computer-supported social system. In a social machine, humans would engage each other creatively in social processes (that is, under, social constraints) and leave mundane administrative tasks to computers. Sambra et al. [33] introduce Solid, a recent approach for realizing social machines. However, Solid does not go far enough. It decentralizes the data but assumes the application is conceptually centralized. More importantly, although it supports representing data semantics, it leaves interaction semantics hidden within application code. The first step toward supporting interaction semantics to specify the engagements between social entities (human and organizations) via protocols. Other work on social machines, e.g., by Smart et al. [41], too inadequately supports decentralization.

1.1 Social Machines as Sociotechnical Systems

The foregoing motivates a natural mapping of social machines to sociotechnical systems (STS) comprising social and technical entities coexisting and interacting [17]. In an STS, each agent is an autonomous locus of control and represents a social entity, such as a person or organization. Agents interact on the basis of the relevant interaction protocols by sending and receiving messages, which helps decouple their knowledge and decision making.

Figure [1] describes an STS schematically. Agents enact a protocol via messaging, realized over a communication infrastructure. Notably, an STS is decentralized—there is no distinguished locus of computation. Thus, the protocol is realized entirely by the agents performing their respective parts of it.

Communication is via asynchronous messaging. This is in line with practical communication infrastructures such as the Internet, IoT, and programming paradigms for building distributed systems such as the actor model [1, 20, 27], which give prominence to asynchronous messaging for organizing decoupled computations. Notably, the actor model does not assume message ordering, which later approaches (including some discussed in this paper) do.

An agent embodies the—typically private—decision-making policies (including knowledge bases) of the party it represents, indicating heterogeneity. Each agent’s part in the protocol is seen in the history of messages observed (sent or received) by the agent. An agent’s decision making determines the messages it sends but not its receptions. Any observation though must agree with, that is, be compliant with, the protocol. We refer to the determination of compliance as the agent’s public computation; it is based solely on its history and nothing else.

The public computation component is effectively a protocol layer that mediates between the communication infrastructure and an agent’s decision making, effectively decoupling them. A consequence of this decoupling is that decision-making can be entirely event-driven, where an event corresponds to an aggregation
of one or more observations in the agent’s history. This is evocative of Saltzer et al.’s classic end-to-end principle—protocol-specific reasoning happens in its own layer realized at the appropriate endpoints.

In an STS, social meaning of interaction is specified in terms of commitments, prohibitions, and other kinds of norms that apply between the agents. For example, the social meaning of an Offer from a seller to a buyer for some item for some price may be specified as creating a commitment from the seller to the buyer that if the buyer sends Payment for the price and specifies a delivery address by some deadline, then the seller will ship the item to the address by some deadline. Notice the correlation of information that weaves through the commitment. For example, the price in the Payment is the price in the Offer. Further, every distinct Offer by the seller counts as creating a distinct commitment. Social meanings inform decision making and each agent computes them in a decentralized manner solely from its history.

1.2 Challenges in Specifying Protocols

As Figure I shows, protocols lie at the heart of an STS. Specification languages for protocols are therefore crucial in engineering STSs. Starting with informal languages such as UML interaction, many languages for specifying protocols have been proposed over the last two decades, and in communities as diverse as programming languages, Web services, and multiagent systems. These languages make different assumptions and provide varying capabilities for specifying protocols. However, today, we lack generally clear evaluation criteria or use cases for protocol languages. Any set of evaluation criteria would necessarily be incomplete, but what would constitute an informative set that sheds light upon the theoretical foundations for protocols?

To answer this question, we turn to some central challenges in specifying interaction protocols. A central challenge in specifying interaction protocols for STSs is how to enable the specification of flexible protocols that agents can correctly enact in a decentralized manner, that is, based solely on local knowledge and accommodating asynchrony. This challenge captures the essence of what drives most theoretical work on protocol languages. The difficulty is that flexibility, which includes important aspects such as concurrency and extensibility (support for enacting multiple protocols), is in tension with correctness in asynchronous communication.

Another central, but overlooked, challenge is how protocols support the computation of social meaning. Notably, social meaning necessarily involves information, for example, item, price, address, and an identifier for offers in the foregoing example. Further, this information must originate in the communications between the agents. As in workflows, modeling information is essential to capturing application-level meaning.

1.3 Contributions, Novelty, and Significance

We make the three technical contributions. One, based on the foregoing, we motivate three broad categories of criteria for evaluating languages for specifying protocols: how public computations are achieved and how they interface with the layers above and below.

Information model. Does the language support an adequate information model to capture social meaning? At a minimum, does the information model support instances (of messages and protocols), correlation of information, and information integrity?

Enactment. How well does a language support flexible correct enactments? Specifically, how well does a language support concurrent and extensible enactments? Focusing on correctness, how well does a language characterize causally valid enactments?

Operational environment. What guarantees does a language require from the environment. For example, does it require synchrony or ordered delivery of messages?

Two, using these criteria, we undertake a comparative evaluation of selected approaches. We focus on state-of-the-art languages. Specifically, we evaluate each approach with respect to the same criteria by specifying (as best possible) the same scenarios.

Three, so as to understand better the differences between the approaches, we tease out the architectural assumptions underlying the various approaches.

The paper’s overarching contribution is developing and applying unified evaluation criteria for protocol languages. Its significance lies in bringing forth the information models, semantics, and operational and architectural assumptions underlying protocol languages. Doing so not only provides a unified framework for understanding protocols and protocol languages but also clarifies requirements for STSs and yields guidance.
on research into protocols. Its novelty arises from the absence, currently, of such a framework. Notably, this paper focuses on essential representational criteria and plays down contingent features such as current tool support or popularity.

**Organization.** The rest of the paper is organized as follows. Section 2 gives an overview of the languages we select for the evaluation. Although protocols have been studied for well over two decades, the selected approaches represent modern treatments of the challenges outlined above. Section 3 analyzes how the selected approaches fare against the information criteria. Section 4 analyzes how they fare against criteria related to flexibility and correctness. Section 5 analyzes them for infrastructure-related assumptions. Section 6 builds upon Section 5 to tease out the architectural models underlying the approaches. Section 7 presents our conclusions, touching upon points and criteria of potential interest that lie outside the scope of the present examination. It also discusses some future directions.

## 2 Overview of Selected Approaches

Well-known early approaches for protocol specification [22, 30, 34, 44] emphasized graphical notation but did not have a clear formal semantics. Some formal approaches supported specifying and verifying logic-based or control-flow based protocols [12, 24, 32] but did not address asynchronous communication or decentralization. Some other approaches addressed **conformance** of agents with protocols that took decentralization into account [5, 7, 8, 20, 31].

We select protocol specification languages that are recent and represent diverse doctrines. We introduce their main ideas via a common scenario in which a buyer **B** requests an item from a seller **S**, who responds with a price. **B** may accept or reject the offer. Rejection ends the enactment. If **B** accepts, **S** instructs warehouse **W** to ship the item, following which **W** delivers it to **B**.

### 2.1 Multiparty Session Types: Scribble

In Scribble [49], a protocol is an ordering of constituent protocols (bottoming out at individual message specifications) using constructs such as sequence, choice, and iteration. Scribble assumes communication between pairs of participants is asynchronous but ordered over FIFO channels. Listing 1 highlights its salient features. Notice that in case a **Reject** happens, Scribble requires a further message (**NoShip** to **W**), else **W** is unable to distinguish the **Accept** branch from the **Reject** and is therefore unable to terminate [29]. We return to the significance of this message in Section 7.

**Listing 1:** Three-party **Purchase** in Scribble.

```plaintext
protocol Purchase (role B, role S, role W) {
  Item (string) from B to S;
  Price (int) from S to B;
  choice at B {
    Accept () from B to S;
    Ship () from S to W;
    Deliver () from W to B;
  } or {
    Reject () from B to S;
    NoShip () from S to W;
  }
}
```

Given a protocol, Scribble yields *projections* for each role. A role’s projection represents the local protocol-related computations performed by the role. Ideally, the computations realized jointly by all projections of a protocol should exactly be the computations of the protocol (as we shall see, this is not always the case). Scribble’s [37] tools generate these projections. Scribble is based on multiparty session types [28].
2.2 Multiparty Session Types: Trace Expressions

Castagna et al. [14], Ancona et al. [3], and Ferrando et al. [21] exemplify this approach. Hereon, we refer to this approach as Trace. We follow Castagna et al.’s [14] variant for concreteness as they give clear rules for determining projections of protocols. Here, \( \text{x} \xrightarrow{m} \text{y} \) means that \( \text{x} \) sends message \( m \) to \( \text{y} \); ‘;’ denotes sequence, ‘\( \lor \)’ denotes mutually exclusive choice, and ‘\( \land \)’ denotes shuffle (order-preserving interleaving). Trace assumes pairwise-FIFO communication. Listing 2 shows how our purchase example may be rendered in Trace.

Listing 2: Three-party Purchase protocol in Trace.

```
| B          | Item | S ; S | Price | B |
|------------|------|-------|-------|---|
| (B Accept, S ; S Ship, W ; W Deliver, B) \lor B Reject, S |
```

2.3 HAPN

HAPN [46] is a graphical protocol language. As Figure 2 shows, nodes represent states; they can also reference other protocols to compose them. Edges can have complex annotations, supporting the specification of message transmissions, guard expressions, and changes to state. HAPN specifies the computations of a protocol in terms of state machines. It assumes synchronous communication [46, p. 61] and does not give a method for projecting a protocol to local perspectives (although it acknowledges their need).

HAPN provides methods to flatten a hierarchical protocol into simple protocols and finite state machines for verification.

2.4 BSPL

BSPL [39, 40] and Splée [16], which extends BSPL, are exemplars of information-based languages, which are declarative and eschew specifying ordering between messages. In BSPL, a protocol specifies an information object. Each protocol enactment fills out an instance of this object. A protocol specifies two kinds of constraints on the messages a role can observe: causality or information flow constraints between protocols and integrity or consistency constraints on any object.

Listing 3: Three-party Purchase in BSPL.

```
Purchase {
role B, S, W
parameter out ID key, out item, out price, out d, out OK
B \rightarrow S: RFQ[ out ID, out item ]
S \rightarrow B: Offer[ in ID, in item, out price ]
B \rightarrow S: Accept[ in ID, in item, in price, out d, out addr ]
B \rightarrow S: Reject[ in ID, in item, in price, out d, out OK ]
S \rightarrow W: Ship[ in ID, in item, in addr ]
W \rightarrow B: Deliver[ in ID, in item, in addr, out OK ]
}
```

In Listing 3, B requests a quote from S for a specific item, and initiates an enactment uniquely identified by key ID. The ‘out’ annotations on ID and item mean that in sending RFQ, B produces bindings for those parameters. The ‘in’ annotations on ID and item in the Offer message indicate that S needs to know these parameters before S can send Offer. B can either accept or reject the offered price, but not both, because
both messages produce a “decision” (as d), and integrity requires a parameter to have at most one binding. An accept message includes the buyer’s address, so S can send shipping instructions to warehouse W. An enactment is complete when all public “out” parameters are bound, so either Reject or Deliver can complete Purchase. Notice that S cannot send Ship if Reject happens as it does not know addr.

The projection of a BSPL protocol to a role is a protocol containing only those messages that involve the specified role. For example, the projection of Purchase for W consists only of Ship and Deliver.

3 Information Model

We denote protocol enactments via sequence diagrams, as in Figure 3, where each agent’s lifeline captures its history.

3.1 Protocol Instances

A protocol language must support enacting a protocol multiple times, each a new instance, and linking or correlating the messages corresponding to one instance.

Scenario. A seller and buyer may interact repeatedly where the buyer sends an RFQ for some item and the seller responds with a matching offer. Figure 3 illustrates some enactments involving multiple protocol instances. To distinguish the instances and correlate messages within an instance, the messages contain identifiers (‘1’ and ‘2’).

Figure 3: Multiple instances of a protocol are enacted between a buyer and seller.

We might consider using the infrastructure (e.g., AMQP [2] headers) to support correlation: messages with the same identifier are part of the same protocol instance. However, relying on the infrastructure has significant drawbacks. First, it causes tight coupling with the infrastructure. Second, the required correlation may go beyond whatever the infrastructure supports. For example, AMQP identifiers are ineffective for describing one-to-many relationships, which require composite identifiers. Third, an implementation must satisfy integrity constraints, e.g., uniqueness of AMQP identifiers, without language support.

Alternatively, implementations could insert identifiers into the messages: without protocol support that would be worse for interoperation, in being ad hoc, than relying on the infrastructure.

Either way, relying on implementations and infrastructure to do protocol-specific reasoning is a violation of the end to end principle [35].

Listings 4 and 5 are possible specifications in Scribble and Trace respectively, and Figure 4 in HAPN. These specifications lack a way to specify instances since they provide no way to designate a parameter as a key. This would be the case even if ID were introduced in both RFQ and Offer.
Listing 4: Offers for RFQs in Scribble.

```
protocol Pricing (role B, role S) {
  RFQ(item: string) from B to S;
  Offer(price: string) from S to B;
}
```

Listing 5: Offers for RFQs in Trace.

```
B -> S: RFQ(item)  P -> S: Offer(item, price)
   /bind(item, item)  /bind(price, price)
```

Figure 4: Pricing in HAPN.

In essence, the enactments in Figure 3 are not supported in these languages: instances must be managed by using extra-protocol logic, which results in tight coupling of the agents. Scribble does refer to an implementation construct (conversation, [49, p. 11]), which is evidence of limited support.

In contrast, BSPL supports the specification of instances via key parameters of protocols. Listing 6 shows a BSPL protocol that supports all the enactments in Figure 3.

Listing 6: Pricing in BSPL.

```
protocol Pricing {
  role B, S
  parameter out ID key, out item, out price
  B -> S: RFQ[out ID, out item]
  S -> B: Offer[in ID, out price]
}
```

3.2 Information Integrity

An essential function of a protocol is to help agents compute information objects based on which they can compute relevant social meanings in their STS. For example, Pricing supports an information model with the schema Pricing(ID, item, price), with the integrity constraint that ID is the key.

Scribble and Trace do not support information models. Messages are opaque containers: their names matter but content does not. Consider the Scribble protocol in Listing 7, a variant of Listing 4—Offer has a parameter item. An enactment of an instance where item has different values in RFQ and Offer is correct, even though it violates integrity. Notably, see their FSM and listing [49, pp. 10–11], neither of which refers to a parameter journey, even though journey is part of protocol specification.

Listing 7: Alternative Offers for RFQs in Scribble.

```
protocol Alt-Pricing (role B, role S) {
  RFQ(item: string) from B to S;
  Offer(item, price: string) from S to B;
}
```

HAPN partially guarantees information integrity. Once a variable is bound in an enactment, as item is at state $s_1$ in Figure 4, any message attempting to use that variable with a different value is invalid and does not result in a state transition. HAPN’s ‘unbind’ does not compromise integrity under its assumptions of synchronicity and shared state; all agents would simultaneously see any updates, and would never have inconsistent bindings. However, HAPN does not ensure integrity when implementing the protocol in a decentralized asynchronous environment, expecting the designer to check for realizability and fix any problems arising.

BSPL supports an information model, as Listing 6 shows.
4 Flexible Enactments and Causal Validity

The criteria here concern the challenges of decentralized enactments of protocols.

4.1 Concurrency

To support autonomy, we should constrain an agent only as essential to the enactment of a protocol. In particular, we should allow agents to act concurrently when doing so would not violate correctness.

**Scenario.** B sends Request to S to ship some item. After sending Request, B may send Payment. After receiving Request, S may send Shipment. That is, Payment and Shipment are not mutually ordered.

This scenario is natural in case of reciprocal commitments: B commits to S that if Shipment occurs, B will send a Payment and S commits to B that if Payment occurs, S will send a Shipment [48].

Figure 5 shows possible enactments of one protocol instance, eliding the parameters.

![Figure 5: Three possible enactments of Purchase.](image)

Listing 8 gives a Trace protocol specification that appears to capture the scenario.

**Listing 8: Attempt to capture Figure 5 in Trace.**

```plaintext
B \text{Request} \rightarrow S ; (B \text{Payment} \rightarrow S \land S \text{Shipment} \rightarrow B)
```

The shortcomings of Listing 8 become apparent when determining its projections. Following Trace [14, p. 14], we eliminate \( \land \) from Listing 8 to obtain the equivalent Listing 9.

**Listing 9: A Trace transformation of protocol in Listing 8.**

```plaintext
B \text{Request} \rightarrow S ; (B \text{Payment} \rightarrow S \lor S \text{Shipment} \rightarrow B)
```

Listing 9 is unprojectable because the choice is controlled by different parties—either B pays or S ships. Specifically, the projections must interpret \( \lor \) as external choice (choosing) for one agent and an internal choice (following) for another. Listing 10 arbitrarily gives the external choice (denoted +) to B and the internal choice (denoted \( \oplus \)) to S (the reverse is equally good since the situation is symmetric). However, this provides only the illusion of choice, because choosing to receive causes deadlock; the agent arbitrarily given the internal choice must send first, enabling only one of the two desired enactments.

**Listing 10: Hypothetical local projections in Trace that illustrate the difficulty with choice.**

```plaintext
B : S! \text{Request} . (S? \text{Shipment} . S! \text{Payment}) + (S! \text{Payment} . S? \text{Shipment})
S : B? \text{Request} . (B! \text{Shipment} . B? \text{Payment}) \oplus (B? \text{Payment} . B! \text{Shipment})
```

Castagna et al. formalize properties of sequentiality and knowledge for choice under which Listing 10 is invalid because of the nonlocal choice between Payment and Shipment.

Scribble shares Trace’s limitations. Listing 11 shows how we might model the scenario in Scribble. Scribble tooling rejects the protocol as ill-formed because the choice is at B but one of the alternatives triggers with an action by S.

**Listing 11: Encode in Scribble.**

```scribble
protocol FlexiblePurchase (role B, role S) {
  Request() from B to S;
  choice at B {
    Payment() from B to S;
  }
}
```
Some research branches of Scribble [19] have included a parallel operator, which however is absent from the main Scribble language and implementation. The parallel operator would manifest as nonlocal choice—just as Trace’s ∧, as shown above since ∧ is in essence a parallel operator.

Figure 6’s HAPN protocol captures only the first two enactments, not the concurrent one, because HAPN assumes synchrony.

Listing 12 gives a BSPL protocol. It supports the enactment in Figure 5c because after B sends Request, it has the information needed to send Payment and, upon receiving Request, S has the information needed to send Shipment.

4.2 Extensibility

In general, an agent may participate in multiple protocols (each representing a MAS). Extensibility means that enactments of multiple protocols could be interleaved. It would be unreasonable if the correct enactment of one protocol rules out enactments of any other protocols. Therefore, a protocol language should support extensibility.

Scenario. S and B engage in enactments of Pricing. In addition, S engages with provider P in enactments of Catalog to obtain information about the newest products. Pricing and Catalog have nothing to do with each other.

Figure 7 shows an enactment for the scenario. If the protocol language did not support extensibility, the enactment would be deemed incorrect.
Listing 13: \textit{Catalog} in Trace.

| $S$ | Query $\rightarrow$ $P$; $P$ | Newest $\rightarrow$ $S$ |

Trace’s semantics is in tension with extensibility. Listing 13 gives a specification of \textit{Catalog} in Trace. \textit{Pricing} is as specified before, in Listing 5. Castagna et al. promote a correctness criterion \textit{fitness}, which says that an agent correctly implements a protocol only if it observes no message that is not in the protocol. That means to correctly implement \textit{Pricing}, $S$ must not observe any message from \textit{Catalog} and to correctly implement \textit{Catalog}, $S$ must not observe any message from \textit{Pricing}. In other words an agent cannot implement both and be correct. In essence, fitness with one protocol rules out enacting other protocols. Moreover, fitness goes against the idea that implementations in general may do more [5].

A plausible way to interleave interactions from two protocols in Trace is to compose them. Listing 14 shows a composition of \textit{Pricing} and \textit{Catalog}. Then fitness of $S$ with respect to the protocol is not a problem. However, requiring explicit composition to satisfy fitness would create a large unwieldy protocol with unrelated interactions. It would prevent any organizational abstraction. For example, the protocol by which an organization trades with others will have to be composed with all the internal protocols within the organization. Composition for fitness is therefore an unrealistic requirement.

Listing 14: \textit{Catalog}+\textit{Pricing} in Trace.

\[(B \text{ RFQ} \rightarrow S \land S \text{ Offer} \rightarrow B) \land (S \text{ Query} \rightarrow P \land P \text{ Newest} \rightarrow S)\]

Interestingly, following the analysis of Listing 8, Listing 14 turns out to be unprojectable. Specifically, it involves a nonlocal choice ($S$ sends \textit{Query} or $B$ sends \textit{RFQ}). We conclude that Trace’s support for extensibility is limited.

Scribble’s support for extensibility is limited too. Each protocol generates a set of projections distinct from those of other protocols, which rules out observing messages from other protocols [49, FSM on p. 10]. However, protocols may be composed explicitly as in Trace. Further, each protocol is enacted in its own universe, a session or a \textit{conversation} [49, listing on p. 11]. Making the assumption of separate universes, though, complicates the implementation of agents. Consider an agent that plays two roles in a protocol. The agent would have to implement two projections (one for each role), which would render the implementation incorrect with respect to each projection—even in the same universe. This criticism applies to Trace as well: Castagna et al. say [14, p. 10] “each participant is uniquely identified by a role.”

HAPN’s state-machine semantics rules out interleavings with other protocols. However, protocols support composition. Therefore, we conclude limited support for extensibility in HAPN.

BSPL fully supports extensibility. In fact, BSPL formalization refers to a universe of discourse, which for an agent would be any communications it observes. Listing 6 and Listing 15 give \textit{Pricing} and \textit{Catalog} in BSPL. An agent may be $S$ in both protocols and interleave their enactment. Further, an agent can play more than one role in any protocol.

Listing 15: \textit{Catalog} in BSPL.

\begin{verbatim}
Catalog {
  role S, P
  parameter out qID key, out req, out products
  S => P: Query[out qID, out req]
  P => S: Newest[in qID, in req, out products]
}
\end{verbatim}

4.3 Causal Validity

Protocols should be causally valid: they should support all enactments that respect information causality and support none that do not.

\textit{Scenario.} B sends an \textit{RFQ} for an item to $S$ following which (provider) $P$ sends \textit{Stock} for the item to S. We interpret following with respect to $S$, which alone observes both events. Figure 8 shows a desired and an undesired enactment.

Listings 16 and 17 show how Figure 8 may be captured in Scribble and Trace, respectively.

Listing 16: \textit{StockAfterRFQ} protocol in Scribble along with its projections as generated by Scribble tooling.
Figure 8: Scenario cannot be guaranteed.

(a) Desired enactment.

(b) Undesired enactment.

Figure 9: StockAfterRFQ in HAPN, starting from $s_0$.

Listing 18 shows how Figure 8a might be specified in BSPL. Instead of modeling the ordering, it specifies the causal dependency that in order to supply a binding for item, P needs to know that binding, thereby preventing Figure 8b.
Listing 18: Causally valid but nonlive protocol.

\[
\text{StockAfterRFQ} \{ \\
\quad \text{role } B, S, P \\
\quad \text{parameter out ID key, out item, out supplied} \\
\quad B \rightarrow S: \text{RFQ}[\text{out ID, out item}] \\
\quad P \rightarrow S: \text{Stock}[\text{in ID, in item, out supplied}] \\
\}
\]

Listing 18 is not enactable as-is because it provides no way of conveying ID and item to P, information P needs to know to send Stock. However, there is a qualitative difference between the flaws of the BSPL and other specifications. For the BSPL specification, missing information shows up as the appropriate consequence, namely, that agents cannot enact the protocol to completion. A consequence is that agents can enact Listing 18 provided it is composed with another protocol that communicates ID and item to P. The Trace and Scribble specifications though have a fatal flaw: they can produce erroneous enactments that their projections do not support.

Castagna et al.’s analysis [14, p. 4] suggests that RFQ and Stock may be treated as independent actions and therefore we might compose them using not ‘;’ but ‘\&’. However, Stock and Request are not independent. Interestingly, if two communications were independent, we could specify the information flow in BSPL to capture that, as shown in Listing 19 and they would be unordered.

Listing 19: Independent Stock and RFQ.

\[
\text{Independent RFQ} \{ \\
\quad \text{role } B, S \\
\quad \text{parameter out rID key, out ritem} \\
\quad B \rightarrow S: \text{RFQ}[\text{out rID, out ritem}] \\
\}
\]

\[
\text{Independent Stock} \{ \\
\quad \text{role } S, P \\
\quad \text{parameter out sID key, out site m, out supplied} \\
\quad P \rightarrow S: \text{Stock}[\text{out sID, out site m, out supplied}] \\
\}
\]

5 Operational Environment

The criteria here concern the environments in which protocols specified by a language can operate.

5.1 Asynchronous Communication

Whereas synchronous communication couples a sender and receiver (they must be ready to receive and send at the same time), asynchronous communication does not. Asynchrony is supported by the Internet and promotes decentralization: agents do not need to know of each other’s states or wait for each other. Scribble, Trace, and BSPL support asynchrony but HAPN [46, p. 61] does not.

5.2 Unordered Communication

A consequence of the end-to-end principle [35] is that a protocol should not rely on message ordering guarantees from the communication infrastructure since the appropriate constraints are to be checked in an upper layer. Relying on such guarantees naturally limits the kinds of communication infrastructures upon which a protocol may be used. More importantly, as we show below, ordering guarantees are inadequate for ensuring the correct enactment of even simple protocols.

To see why relying on message ordering is tempting, consider the Trace protocol and its projections in Listing 20. Of the enactments in Figure 5, the protocol supports solely the enactment in Figure 5b in which Payment is received before Shipment is sent. This implies that messages cannot arrive out of order, and
is why Trace requires pairwise first-in first-out or FIFO communication channels between agents. Scribble requires FIFO channels as well.

Listing 20: A Trace protocol and its projections.

```
// Protocol
B Request → S; B Payment → S; S Shipment → B
// Projections
B: S! Request . S! Payment . S? Shipment
S: B Request . B? Payment . B! Shipment
```

Requiring pairwise FIFO channels seems innocuous at first glance. TCP supports FIFO as does AMQP. However, protocols for lightweight communications (e.g., for IoT) or fast interactions (e.g., in financial transactions) cannot support FIFO. And, FIFO is inadequate for settings of more than two parties as the following scenario demonstrates.

Scenario. In an indirect-payment purchase protocol, after receiving an Offer B sends Accept to S and then Instruct (a payment instruction) to bank K. Upon receiving Instruct, B does a funds Transfer to S.

Figure 10 shows two enactments for this scenario. In Figure 10a S receives Accept before Transfer whereas in Figure 10b S receives it after Transfer. Both enactments satisfy pairwise FIFO. The enactments illustrate that even with FIFO ordering, asynchrony makes ordering indeterminate for protocols involving more than two agents.

The BSPL specification in Listing 21 specifies a protocol that supports both enactments in Figure 10.

Listing 21: Indirect payment protocol in BSPL.

```
Indirect Payment {
  role B, S, K // K is bank
  parameter out ID key, out item, out price, out acc, out inst, out OK

  S → B: Offer [out ID, out item, out price]
  B → S: Accept [in ID, in item, in price, in acc]
  B → K: Instruct [in ID, in price, in acc, out inst]
  K → S: Transfer [in ID, in price, in inst, out OK]
}
```

Listing 22 is an attempt to capture the scenario in Trace. Following Trace [14, p. 16], this protocol is not well-formed, which means that the correctness of its projections, also given in Listing 22, cannot be guaranteed. Specifically, the projection for S expects Accept before Transfer and therefore does not support the enactment in Figure 10a which may arise despite using FIFO channels.

Listing 22: A plausible indirect payment protocol and its projections in Trace.

```
// Protocol
S Offer → B; B Accept → S; B Instruct → K; K Transfer → S
// Projections
B: S? Offer . S! Accept . K! Instruct
S: B! Offer . B? Accept . K? Transfer
K: B? Instruct . S! Transfer
```
Listing 23 gives a Scribble protocol to capture the scenario. The projections given are produced by Scribble tooling, which verifies the specification. The projections are analogous to the Trace projections in Listing 22; in particular, S cannot receive Transfer before Accept; it blocks on the reception of Accept on the channel from B even if Transfer may have arrive earlier on the channel from K. Effectively, the projection reorders the receptions of the two messages. The listing shows S’s projection (other roles’ projections are elided).

Listing 23: Indirect payment in Scribble.

```srs
protocol IndirectPayment (role S, role C, role B) {
  Offer() from S to B;
  Accept() from B to S;
  Instruct() from B to K;
  Transfer() from K to S;
}

projection IndirectPayment\_S (role B, role S, role K) {
  Offer() to B;
  Accept() from B;
  Transfer() from K;
}
```

Reordering messages as Scribble does has the following undesirable consequences.

**Delay.** Treating receive as an action means an agent blocks on a reception. This means that the reception of messages that have arrived earlier is unnecessarily delayed. By contrast, in the architecture of Figure 1, reception is not an agent action: As messages arrive from the infrastructure, and provided they pass compliance, they are made available to the agent and added to its history.

**Deadlock.** Blocking paves the way for deadlocks. For example, imagine a scenario where an agent is waiting for \( m_1 \) to arrive, with \( m_2 \) already in its buffer waiting to be received by the agent. If \( m_2 \) disables the emission of \( m_1 \), then the agent is deadlocked.

**Interference with social meaning.** Social meaning is computed based on the messages observed by an agent. Not reading messages that have arrived unnecessarily delays this computation. In the example of Figure 10, if Transfer means that the seller becomes unconditionally committed to ship the goods offered to the buyer by some deadline, it would be foolish to ignore it waiting for an Accept whose arrival may well be meaningless after the arrival of Transfer.

What the foregoing scenario shows is that despite the FIFO assumption, both Scribble and Trace (unnecessarily) rule out realistic message orders that are simply the result of asynchrony. Making message delivery assumptions stronger than FIFO, e.g., causal delivery [11], will not address this problem. We return to this point in Section 6 where we induce the architectural assumptions underlying these languages.

We omit HAPN since it does not even support asynchrony.

### 6 Architecture and Programming

Why the differences between the approaches? The answer lies in the differences in their architectural models. BSPL’s architectural model is described accurately by Figure 1.

The architectural model for multiparty session types (both Scribble and Trace) is shown in Figure 11 and it differs in important ways from the one in Figure 1.

Besides the FIFO channels assumption, a notable difference is the absence of a public computation layer. In session types, a protocol yields a projection for each agent that determines the order of an agent’s actions (sending and receiving) over the relevant communication channels. In effect, projections are agent specifications. As we saw above, however, the order of an agent’s actions may be inconsistent with the order of message arrivals, which leads to problems such as delays, deadlocks, and interference with social meaning, as discussed above.

However, the problems with the architecture in Figure 11 go deeper. The architecture is a violation of Saltzer the end to end principle [35], putting public computation in nonprotocol layers. The architecture of Figure 1 says nothing about an agent’s internals. More precisely, it indicates an agent’s decision making
Figure 11: STS using Scribble and Trace, schematically. Agents interact on the basis of local projections derived from the protocol. A projection is a control flow-based skeleton of an agent’s behavior that determines the order of its actions (sending and receiving) on the FIFO channel-based communication infrastructure. Notably, in contrast to Figure 1, a distinct public computation layer is absent.

is event driven based on its history but leaves the agent’s construction otherwise unconstrained. Being event driven means that Transfer, if it arrives before Accept, may be handled earlier. But it does not rule out legitimate possibilities. For example, even if is not sensible to do so, it allows one to construct an agent where Accept is handled before Transfer, regardless of the arrival order. The architecture of Figure 11 however requires blocking agents. To dictate an agent’s internals from a protocol not only violates heterogeneity and interaction-orientation [17] but also demonstrates implementation bias [50].

Even more fundamentally, the inconsistency between action order and arrival order in Scribble and Trace is indicative of a unitary mindset. Apparently, the idea is that there is a unique correct global order of events and all agent observations must respect this order. Thus, mutually contradictory observations, e.g., in Figure 5c, are ruled out even though they are realizable, simply because they don’t fit a unitary view.

Although session types yield projections that serve as agent specifications and can be potentially helpful to programmers, they come at too high a cost: A lack of adequate separation of the concerns of specifying protocols and specifying agents. BSPL supports interesting programming models that sacrifice none of the flexibility of BSPL protocols and in fact pave the way for declarative, event-driven programming. Stellar [25], one such programming model and its implementation (in Java), guarantees that following the model will yield compliant agent implementations.

7 Discussion

Table 1: Summary of evaluation.

| Criterion          | Scribble | Trace | HAPN | BSPL |
|--------------------|----------|-------|------|------|
| Information model  |          |       |      |      |
| Instances          | Limited  | No    | No   | Yes  |
| Integrity          | No       | No    | Limited | Yes |
| Enactment          |          |       |      |      |
| Concurrency        | No       | No    | Limited | Yes |
| Extensibility      | Limited  | Limited | Limited | Yes |
| Causal validity    | No       | No    | No   | Yes  |
| Operational environment |        |       |      |      |
| Asynchrony         | Yes      | Yes   | No   | Yes  |
| Unordering         | No       | No    | –    | Yes  |

Table 1 summarizes our findings. Our criteria are motivated by a fundamental conception of STS. Our criteria and scenarios are elementary, motivated from fundamental challenges for interaction protocols. And our selected approaches represent recent research into protocols. Our evaluation is concrete and comparative, driven by the specification of scenarios in the selected approaches, followed by their analysis. Our evaluation shows significant advantages of BSPL over the other approaches. The reason is twofold. One, a separation
of concerns. BSPL focuses solely on interactions, inducing a protocol layer to capture protocol-relevant computations, leaving agent specifications out. Two, BSPL relies on information causality to limit enactments to those which are causally valid and doesn’t eliminate any that are causally valid.

Although the kinds of scenarios used in this paper are typical of the bodies of work we examine, Scribble and Trace has investigated sociotechnical settings less fully than others. Rooted in programming language theory, the work has often been driven by orthogonal considerations originating from type theory. That may explain the lack of emphasis on information in these approaches.

Several languages boast useful advanced features such as recursion, data types, dynamic role binding, multicast, timeouts, and so on. Such features are out of scope for purposes of the present examination, which focuses on the central challenges that drive work in protocol languages. In any case, an evaluation of advanced features is unlikely to be insightful unless we can place the languages on simple common ground, as the current evaluation seeks to do.

Properties, such as liveness (termination), and their formal verification are another interesting point of difference between the approaches. Session types conflate protocol termination with agent termination—witness the NoShip message in Listing 1, which was introduced to guarantee that W (the warehouse) terminates.

BSPL takes a more modular approach in which protocol properties are verified from the protocol specification alone [40]. The liveness of a protocol in BSPL means that any enactment of the protocol would terminate under the assumptions that (1) each agent sends a message as long as some message is enabled and (2) the infrastructure delivers all messages sent. This formulation abstracts away from agent and communication infrastructure details to make liveness a property of protocols. A more thorough investigation of the properties and a discussion of their differences would be an interesting direction.

Several additional directions could potentially reap rich benefits for research into protocols for sociotechnical systems. One, institute a public repository of scenarios and their specification in various protocol languages along with their possible implementations. Two, formalize the criteria described in this paper. Three, develop a process-algebraic encoding of BSPL so as to bring the rich machinery developed for programming languages to bear upon it. Our hope is that this paper opens up a rich vein of problems that researchers interested in social machines, MAS, services, and programming languages can collaboratively study.

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