Global Types for Dynamic Checking of Protocol Conformance of Multi-Agent Systems

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Italian Conference on Theoretical Computer Science, Varese, September 19-21, 2012

Outline

1. Background on multi-agent systems
2. Previous work (Declarative Agent Languages and Technologies - DALT 2012, Ancona, Drossopoulou, Mascardi)
3. Global types: formalization
4. Expressive power of global types (by examples)
5. An extension to enhance the expressive power (not in the paper)
6. Conclusion and future work

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Multi-agent systems (MASs)

- industrial-strength technology for integrating and coordinating heterogeneous systems
- intrinsically distributed nature, asynchronous message passing
- agent-oriented programming languages are typically dynamically typed

Jason

- AgentSpeak: a logic-based agent-oriented programming language, based on the belief-desire-intention (BDI) software model
- Jason: open source interpreter for an extended version of AgentSpeak, supporting a Prolog-like language for specifying agents behavior
- communication model: speech-act based, with performatives (a.k.a. illocutionary forces)

Sending actions in Jason

```
.send(recipient,performative,content)
```

- *recipient*: the *id* of the agent that will receive the message
- *performative*: specifies the semantics/aim of the message

  tell untell achieve unachieve tell-how untell-how ask-if ask-all ask-how

- *content*: a (possibly empty) set of atoms or plans

Outline

Protocols and multi-agent systems

A protocol represents an agreement on how participating agents [systems] interact with each other. Without a protocol, it is hard to do a meaningful interaction: participants simply cannot communicate effectively.

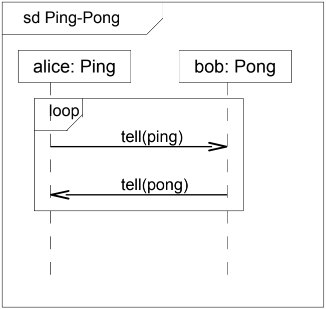
[From the manifesto of Scribble, a language to describe application-level protocols among communicating systems initially designed by Kohei Honda and Gary Brown, `http://www.jboss.org/scribble/`]

Protocol specification

Interaction diagrams in FIPA AUML

- specify the behavior of a system from a global point of view
- suitable for humans, but not for verification

A first example: ping-pong protocol



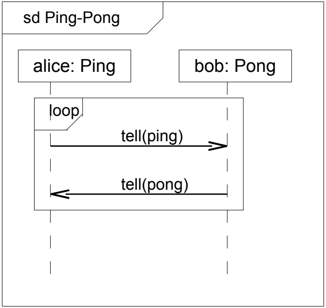
[FIPA Modeling: Interaction Diagrams,
`http://www.auml.org/auml/documents/ID-03-07-02.pdf`]

Protocol specification: a formal approach

protocol =
(possibly infinite) set of (possibly infinite) sequences of sending actions

Example 1: ping-pong protocol

```
msg(alice,bob,tell,ping) msg(bob,alice,tell,pong)
     msg(alice,bob,tell,ping) msg(bob,alice,tell,pong) ...
```



Protocols as global types

Example 1: ping-pong protocol

`PingPong` = α_1:α_2:`PingPong`

- where α_1 sending action type corresponding to `msg(alice,bob,`**`tell`**`,ping)`
- where α_2 sending action type corresponding to `msg(bob,alice,`**`tell`**`,pong)`
- sending action types = monadic predicates

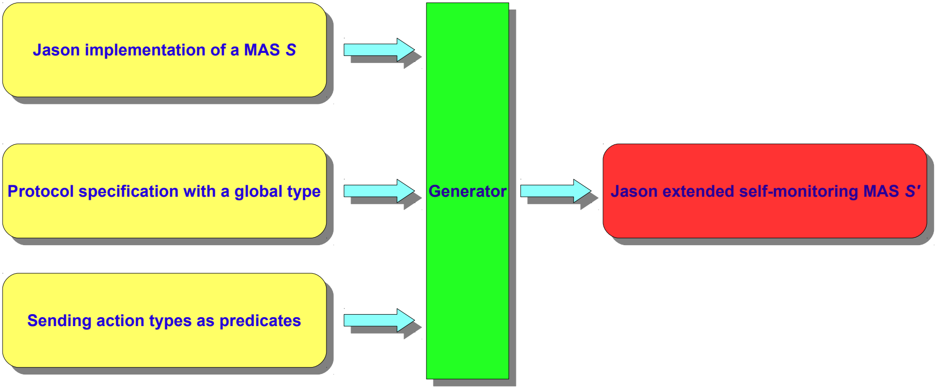
Global types as Prolog cyclic terms

- Modern Prolog systems (and Jason as well) support cyclic terms (a.k.a. regular or rational terms)
- Example: the unification problem

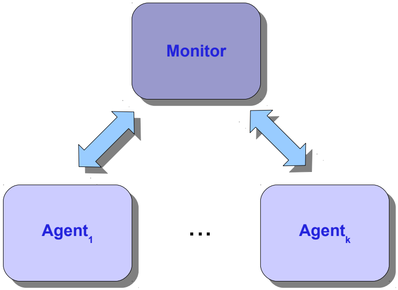
  ```
  PingPong = ping:pong:PingPong.
  ```

  succeeds with the answer `PingPong = ping:pong:PingPong`
- Regular terms naturally support recursive types
- Regular Prolog terms: a very compact representation of protocol specifications through global types
- Protocols can be easily manipulated and exchanged by agents

Automatic generation of a self-monitoring MAS



Centralized monitor agent



- protocol conformance dynamically checked by a monitor agent *M*
- other agents ask *M* permission to send their messages
- the monitor notifies all failures
- the monitor checks responsiveness of the agents

Outline

Global types

The set of regular terms defined on the following constructors:

- λ (empty sequence), representing the singleton set $\{\epsilon\}$ containing the empty sequence ϵ.
- $\alpha{:}\tau$ (*seq*), representing the set of all sequences whose first element is a sending action matching type α, and the remaining part is a sequence in the set represented by τ.
- $\tau_1 + \tau_2$ (*choice*), representing the union of the sequences of τ_1 and τ_2.
- $\tau_1 | \tau_2$ (*fork*), representing the set obtained by shuffling the sequences in τ_1 with the sequences in τ_2 .
- $\tau_1 \cdot \tau_2$ (*concat*), representing the set of sequences obtained by concatenating the sequences of τ_1 with those of τ_2.

Contractive global types

A global type τ is *contractive* if it does not contain paths whose nodes can only be constructors in $\{+, |, \cdot\}$ (such paths are necessarily infinite).

Examples:

- a contractive type: $\texttt{T1} = (\lambda + \alpha\texttt{:T1})$
- a non contractive type: $\texttt{T2} = \lambda + (\texttt{T2} \mid \texttt{T2}) + (\texttt{T2} \cdot \texttt{T2})$

Transition rules

- $\mathcal{T}$ contractive global types, $\mathcal{A}$ sending actions
- total function $\delta{:}\mathcal{T} \times \mathcal{A} \rightarrow \mathcal{P}_{fin}(\mathcal{T})$
- $\tau_1 \xrightarrow{a} \tau_2$ means $\tau_2 \in \delta(\tau_1, a)$

$$(\text{seq})\frac{}{\alpha{:}\tau \xrightarrow{a} \tau}\ a{\in}\alpha \qquad (\text{choice-l})\frac{\tau_1 \xrightarrow{a} \tau_1'}{\tau_1 + \tau_2 \xrightarrow{a} \tau_1'} \qquad (\text{choice-r})\frac{\tau_2 \xrightarrow{a} \tau_2'}{\tau_1 + \tau_2 \xrightarrow{a} \tau_2'}$$

$$(\text{fork-l})\frac{\tau_1 \xrightarrow{a} \tau_1'}{\tau_1|\tau_2 \xrightarrow{a} \tau_1'|\tau_2} \qquad (\text{fork-r})\frac{\tau_2 \xrightarrow{a} \tau_2'}{\tau_1|\tau_2 \xrightarrow{a} \tau_1|\tau_2'}$$

$$(\text{cat-l})\frac{\tau_1 \xrightarrow{a} \tau_1'}{\tau_1 \cdot \tau_2 \xrightarrow{a} \tau_1' \cdot \tau_2} \qquad (\text{cat-r})\frac{\tau_2 \xrightarrow{a} \tau_2'}{\tau_1 \cdot \tau_2 \xrightarrow{a} \tau_2'}\ \epsilon(\tau_1)$$

Definition of $\epsilon(\_)$

$\epsilon(\tau)$ holds if and only if τ contains λ

$$(\epsilon\text{-seq})\frac{}{\epsilon(\lambda)} \qquad (\epsilon\text{-lchoice})\frac{\epsilon(\tau_1)}{\epsilon(\tau_1 + \tau_2)} \qquad (\epsilon\text{-rchoice})\frac{\epsilon(\tau_2)}{\epsilon(\tau_1 + \tau_2)}$$

$$(\epsilon\text{-fork})\frac{\epsilon(\tau_1) \quad \epsilon(\tau_2)}{\epsilon(\tau_1 | \tau_2)} \qquad (\epsilon\text{-cat})\frac{\epsilon(\tau_1) \quad \epsilon(\tau_2)}{\epsilon(\tau_1 \cdot \tau_2)}$$

Interpretation of global types

Run

A *run* ρ for τ_0 is a sequence $\tau_0 \xrightarrow{a_0} \tau_1 \xrightarrow{a_1} \ldots \xrightarrow{a_{n-1}} \tau_n \xrightarrow{a_n} \tau_{n+1} \xrightarrow{a_{n+1}} \ldots$ of valid transitions such that

- either the sequence is infinite,
- or it terminates with the type τ_k (with $k \geq 0$) s.t. $\epsilon(\tau_k)$.

$A(\rho)$ = sequence of sending actions $a_0 a_1 \ldots a_n \ldots$ contained in ρ.

Interpretation

$[\![\tau_0]\!] = \{A(\rho) \mid \rho \text{ is a run for } \tau_0 \}$

Results

Proposition 1

Let τ be a contractive type. Either $\epsilon(\tau)$ holds or there exist *a* and τ' s.t. $\tau \xrightarrow{a} \tau'$.

Proposition 2

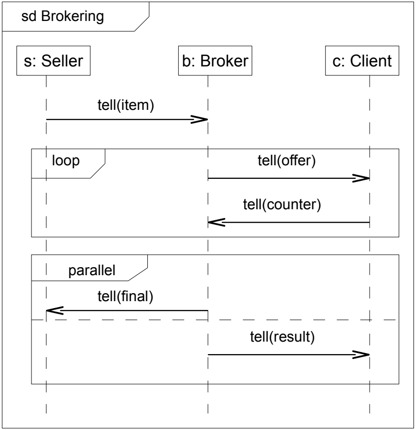
If τ is contractive and $\tau \xrightarrow{a} \tau'$ for some *a*, then τ' is contractive as well.

Corollary

If τ is contractive, then $[\![\tau]\!] \neq \emptyset$

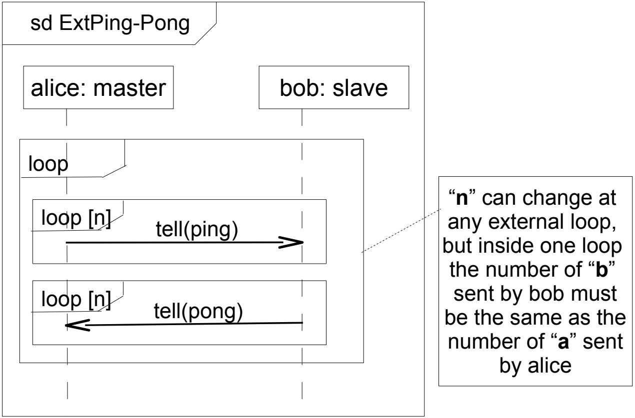
Outline

Example 2: brokering protocol




```
Brokering   = item:(Negotiation + End)
Negotiation = offer:counter:(Negotiation + End)
End         = final:λ | result:λ
```

Example 3: extended ping-pong protocol




```
Loop     = PingPong · Loop
PingPong = ping:(pong:λ + (PingPong · pong:λ))
```

Example 4: alternating bit protocol

Proposed by Deniélou and Yoshida (ESOP 2012)
Infinite sequences of the following sending action types:

- Alice sends `msg1` to Bob
- Alice sends `msg2` to Bob
- Bob sends `ack1` to Alice
- Bob sends `ack2` to Alice

Constraints (for all $n \geq 0$):

- $\texttt{msg1}_n \leq \texttt{msg2}_n \leq \texttt{msg1}_{n+1}$
- $\texttt{msg1}_n \leq \texttt{ack1}_n \leq \texttt{msg1}_{n+1}$
- $\texttt{msg2}_n \leq \texttt{ack2}_n \leq \texttt{msg2}_{n+1}$

Where α_n denotes the n-th occurrence of α in the sequence

A global type for the alternating bit protocol

```
AltBitOne = msg1:M2
AltBitTwo = msg2:M1
M2 = (((msg2:λ) | (ack1:λ)) · M1) +
     (((msg2:ack2:λ) | (ack1:λ)) · AltBitOne)
M1 = (((msg1:λ) | (ack2:λ)) · M2) +
     (((msg1:ack1:λ) | (ack2:λ)) · AltBitTwo)
```

Problems:

- quite complex type, not intuitive
- the complexity of the type grows exponentially with the number of messages

Outline

Global types and constraints

Intuition: for every correct sequence *s*

- *s* restricted to `msg1` and `ack1` is `M1A1 = msg1:ack1:M1A1`
- *s* restricted to `msg2` and `ack2` is `M2A2 = msg2:ack2:M2A2`
- *s* restricted to `msg1` and `msg2` is `M1M2 = msg1:msg2:M1M2`

But neither

`M1A1 | M2A2`

nor

`M1A1 | M2A2 | M1M2`

are correct, since the shuffle is unconstrained

Idea

- Shuffle with a synchronization mechanism
- Producer sending action type: α^n must be synchronized with n consumer types ($n \geq 0$)
- Consumer sending action type: α

An unconstrained global type is a particular case of constrained global type where all sending action types have shape α^0

Extended transition rules

- $n_1, \tau_1 \xrightarrow{a} n_2, \tau_2$
- input n_1: sending action types to be consumed
- output n_2: sending action types left to be consumed
- top-level transition: $0, \tau_1 \xrightarrow{a} 0, \tau_2$

New rules:

$$\text{(seq-prod)}\ \frac{}{0, \alpha^n{:}\tau \xrightarrow{a} n, \tau}\ a \in \alpha \qquad \text{(seq-cons1)}\ \frac{}{n, \alpha{:}\tau \xrightarrow{a} n-1, \tau}\ \begin{array}{l} n>0 \\ a\in\alpha \end{array}$$

$$\text{(seq-cons2)}\ \frac{}{n, \alpha{:}\tau \xrightarrow{a} n, \alpha{:}\tau}\ \begin{array}{l} n>0 \\ a\notin\alpha \end{array} \qquad \text{(empty)}\ \frac{}{n, \lambda \xrightarrow{a} n, \lambda}\ n>0$$

$$\text{(fork-sync-l)}\ \frac{n_1, \tau_1 \xrightarrow{a} n_2, \tau_1' \quad n_2, \tau_2 \xrightarrow{a} n_3, \tau_2'}{n_1, \tau_1 | \tau_2 \xrightarrow{a} n_3, \tau_1' | \tau_2'}\ n_2>0$$

$$\text{(fork-sync-r)}\ \frac{n_1, \tau_2 \xrightarrow{a} n_2, \tau_2' \quad n_2, \tau_1 \xrightarrow{a} n_3, \tau_1'}{n_1, \tau_1 | \tau_2 \xrightarrow{a} n_3, \tau_1' | \tau_2'}\ n_2>0$$

Extended transition rules

Generalization of the previous rules:

$$\text{(choice-l)}\ \frac{n_1, \tau_1 \xrightarrow{a} n_2, \tau_1'}{n_1, \tau_1 + \tau_2 \xrightarrow{a} n_2, \tau_1'} \qquad \text{(choice-r)}\ \frac{n_1, \tau_2 \xrightarrow{a} n_2, \tau_2'}{n_1, \tau_1 + \tau_2 \xrightarrow{a} n_2, \tau_2'}$$

$$\text{(fork-l)}\ \frac{n_1, \tau_1 \xrightarrow{a} 0, \tau_1'}{n_1, \tau_1 | \tau_2 \xrightarrow{a} 0, \tau_1' | \tau_2} \qquad \text{(fork-r)}\ \frac{n_1, \tau_2 \xrightarrow{a} 0, \tau_2'}{n_1, \tau_1 | \tau_2 \xrightarrow{a} 0, \tau_1 | \tau_2'}$$

$$\text{(cat-l)}\ \frac{n_1, \tau_1 \xrightarrow{a} n_2, \tau_1'}{n_1, \tau_1 \cdot \tau_2 \xrightarrow{a} n_2, \tau_1' \cdot \tau_2} \qquad \text{(cat-r)}\ \frac{n_1, \tau_2 \xrightarrow{a} n_2, \tau_2'}{n_1, \tau_1 \cdot \tau_2 \xrightarrow{a} n_2, \tau_2'}\ \epsilon(\tau_1)$$

Alternating bit protocol (revisited)

Dimension 2

```
AltBit2 = M1A1 | M2A2 | M1M2
M1A1 = msg1^1:ack1^0:M1A1
M2A2 = msg2^1:ack2^0:M2A2
M1M2 = msg1:msg2:M1M2
```

Dimension 3

```
AltBit3 = M1A1 | M2A2 | M3A3 | M1M2M3
M1A1 = msg1^1:ack1^0:M1A1
M2A2 = msg2^1:ack2^0:M2A2
M3A3 = msg3^1:ack3^0:M3A3
M1M2M3 = msg1:msg2:msg3:M1M2M3
```

Outline

Conclusion

- global types as Prolog regular terms
- dynamic checking of protocol conformance
- formalization
- extension to “constrained shuffle”

Future work

- in depth comparison with other formalisms for protocol specification
- relations with ω-automata
- projecting global types
- from dynamic to static checking of protocol conformance

Thank you for your attention...

...questions?