On Global Types and Multi-Party Sessions

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(joint work with Mariangiola Dezani and Luca Padovani)

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DisCoTec 2011 - Reykjavík

1. Relating global descriptions distributed systems with sets of descriptions of their components is the subject of an important and long-standing research.
2. Recently, the community of behavioral types for web services has joined this effort.
3. The aim of this talk is to give an overview of the research done by these newcomers, addressing its goals and specificities.

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For survey and pointers refer to the long version available online. The version in the proceedings focuses on technical content.

Context

Alice, Bob, and Charlie want to collaborate on the net

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There may be deadlocks

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receive ok from Charlie;
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- Communication errors
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Context

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- **Protocol errors**

There may be starvation

Context

```
repeat
  send false to Charlie;
  receive $x from Charlie;
until $x; send ok to Bob
```

```
repeat
  receive $x from Alice;
  send $x to Alice;
until $x;
send ok to Bob
```

```
receive ok from Charlie;
receive ok from Alice
```

Several potential problems

- Communication errors
- **Protocol errors**

There may be starvation

Here Bob starves

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  send false to Charlie;
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  receive $x from Alice;
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receive ok from Charlie;
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These problems may be due to:

Several potential problems

- Communication errors
- Protocol errors

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  receive $x from Alice;
  send $x to Alice;
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receive ok from Charlie;
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These problems may be due to:

- **Programming errors**

Several potential problems

- Communication errors
- Protocol errors

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These problems may be due to:

- **Programming errors**
- **Software evolution**

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- Protocol errors

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- Communication errors
- Protocol errors

These problems may be due to:

- **Programming errors**
- **Software evolution**
- **Rogue participants**

Global vs. Local specifications

Global specification

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Global specification

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- Describe the abstract global behavior of the protocol
- Match against/Extract the behaviors of the participants.

Example of global description

```
Alice sends a Boolean to Charlie;
either Charlie sends ok to Bob; Charlie sends ok to Alice;
    or Charlie sends ok to Alice; Charlie sends ok to Bob;
```

Global vs. Local specifications

The global specification is compact and synthetic

Example of global description

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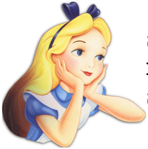
Global vs. Local specifications

An abstract description of this protocol



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```
switch
 | receive ok from Alice -> receive ok from Charlie
 | receive ok from Charlie -> receive ok from Alice
```

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 | receive          lice -> receive ok from Charlie
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It abstracts values

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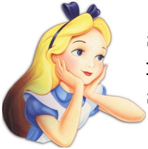

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It abstracts choices

Examp   l descrip   on

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Given a distributed implementation that *"satisfies"* this global specification:

1. Every send of a given type is matched by a reception of the same type;

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We must ensure that *all and only* the expected synchronizations happen.

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... and not with this one!

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We need a theoretical framework for:

- Defining global specifications,
- Defining local specifications,
- Relating them,
- Proving their properties.

A long-standing quest

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- *Verification:* does a given set of components *implement* a global specification?
- *Implementability:* does a set of components that implement the specification *exist* and can it be automatically produced?
- *Analysis:* which properties of the specification can be *checked and transposed* to every implementation that satisfies it?

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Typical approaches:

- *Automata:* software engineering for telecommunications; MSG and SDL-core (*ie*, CFSM); decidability and complexity;
- *Protocols:* cryptographic protocols; MSC, rewriting systems, process algebras; confidentiality, availability;
- *Services:* web services interactions; behavioral types and process algebras; soundness and progress.

A long-standing quest

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These approaches differ by:

- the tackled problems,
- the levels of abstraction,
- the paradigms,
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In the rest of this talk:

1. Present a study typical of the Services approach;
2. Use it to briefly survey the related Services-oriented research;
3. Hint at and compare it with the Automata and Protocols approaches;
4. Draw few conclusions.

A study in the
“services” approach.

From informal descriptions to global types

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- *Control loops:* "*may repeatedly*" becomes "$(\ldots)*$"

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Syntax of Global Types

Global Types

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\begin{array}{llll}
\mathscr{G} & ::= & \mathsf{skip} & \text{(skip)} \\
& \mid & \mathtt{p} \xrightarrow{a} \mathtt{p} & \text{(interaction)} \\
& \mid & \mathscr{G} ; \mathscr{G} & \text{(sequence)} \\
& \mid & \mathscr{G} \wedge \mathscr{G} & \text{(both)} \\
& \mid & \mathscr{G} \vee \mathscr{G} & \text{(either)} \\
& \mid & \mathscr{G}^{*} & \text{(star)}
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 & \mid & \mathscr{G} ; \mathscr{G} & \text{(sequence)} \\
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$$(\mathtt{seller} \xrightarrow{\mathit{price}} \mathtt{buyer1} \wedge \mathtt{bank} \xrightarrow{\mathit{mortgage}} \mathtt{buyer2});$$
$$(\{\mathtt{buyer1},\mathtt{buyer2}\} \xrightarrow{\mathit{accept}} \mathtt{seller} \wedge \{\mathtt{buyer1},\mathtt{buyer2}\} \xrightarrow{\mathit{accept}} \mathtt{bank})$$

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Global Types	$\mathscr{G}$	$::=$	skip	(skip)
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Two observations:

1. Actually instead of just one sender we may specify multiple senders (ranged over by π)

$$(\mathtt{seller} \xrightarrow{\textit{price}} \mathtt{buyer1} \wedge \mathtt{bank} \xrightarrow{\textit{mortgage}} \mathtt{buyer2});$$
$$(\{\mathtt{buyer1},\mathtt{buyer2}\} \xrightarrow{\textit{accept}} \mathtt{seller} \wedge \{\mathtt{buyer1},\mathtt{buyer2}\} \xrightarrow{\textit{accept}} \mathtt{bank})$$

2. Kleene star yields *termination under fairness* for free.

From Global to Local

Back to our example:

$$(\texttt{seller} \xrightarrow{\textit{descr}} \texttt{buyer} \wedge \texttt{seller} \xrightarrow{\textit{price}} \texttt{buyer});$$
$$(\texttt{buyer} \xrightarrow{\textit{offer}} \texttt{seller}; \texttt{seller} \xrightarrow{\textit{price}} \texttt{buyer})*;$$
$$(\texttt{buyer} \xrightarrow{\textit{accept}} \texttt{seller} \vee \texttt{buyer} \xrightarrow{\textit{quit}} \texttt{seller})$$

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A possible implementation:

seller

$\texttt{buyer}!\,descr.$
$\texttt{buyer}!\,price.$
$\mathsf{rec}\ X\ .\ ($
$\quad \texttt{buyer}?\,offer.\texttt{buyer}!\,price.X$
$\ +\texttt{buyer}?\,accept.\mathsf{end}$
$\ +\texttt{buyer}?\,quit.\mathsf{end}\ )$

buyer

$\texttt{seller}?\,descr.$
$\texttt{seller}?\,price.$
$\mathsf{rec}\ X\ .\ ($
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$\ \oplus\texttt{seller}!\,quit.\mathsf{end}\ )$

From Global to Local

Back to our example:

Why is this an implementation?

$$(\mathtt{seller} \xrightarrow{descr} \mathtt{buyer} \wedge \mathtt{seller} \xrightarrow{price} \mathtt{buyer});$$
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Every action corresponds to a pair of communications.

Every communication comes from an action.

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seller

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A possible i on:

output to buyer

seller

$\texttt{buyer}!descr.$
$\texttt{buyer}!price.$
$\mathrm{rec}\ X\ .\ ($
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input from seller

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$\texttt{seller}?descr.$
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Global choices correspond to internal/external choice pairs

A possible implementation:

seller

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A possible implementation:

seller

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bu
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external choice

buyer

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Kleene stars correspond to recursion

A possible implementation:

seller

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The order of sequential compositions is respected

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Actions composed by "$\wedge$" appear in some order.

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But other orders are admitted

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Local Types and Projection

Implementations are specified by:

$$
\begin{array}{rclllcll}
T & ::= & \mathsf{end} & \text{(termination)} & & \mid & X & \text{(variable)} \\
& \mid & \mathtt{p}\,\mathbf{!}a.T & \text{(output)} & & \mid & \boldsymbol{\pi}\mathbf{?}a.T & \text{(input)} \\
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Given a global type we want to automatically produce a mapping from participants to local types that is *sound and complete*, that is:

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Given a global type we want to automatically produce a mapping from participants to local types that is *sound and complete*, **that is**:

1. There is a *1-1* correspondence between actions and communications;
2. Communications of actions in "$;$" respect the order (*sequentiality*);
3. Communications of actions in "$\wedge$" occur in any order (*shuffling*);
4. Communications of actions in "$\vee$" are mutually exclusive (*alternative*)

Soundness and completeness [first technical slide]

1. Define the traces of a global types in the obvious way:

$$tr(\mathsf{skip}) = \{\varepsilon\} \qquad tr(\mathscr{G}_1;\mathscr{G}_2) = tr(\mathscr{G}_1)tr(\mathscr{G}_2)$$
$$tr(\pi \xrightarrow{a} \mathtt{p}) = \{\pi \xrightarrow{a} \mathtt{p}\} \qquad tr(\mathscr{G}_1 \vee \mathscr{G}_2) = tr(\mathscr{G}_1) \cup tr(\mathscr{G}_2)$$
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$$\left[\begin{array}{c}\mathbb{B}::(\mathtt{p}_i\xrightarrow{a}\mathtt{p})_{i\in I}\\ \{\dots,\mathtt{p}:\sum_{j\in J}\pi_j?a_j.T_j,\dots\}\end{array}\right] \xrightarrow{\pi_k\xrightarrow{a}\mathtt{p}} \left[\begin{array}{c}\mathbb{B}\\ \{\dots,\mathtt{p}:T_k,\dots\}\end{array}\right] \quad (\pi_k=\{\mathtt{p}_i\}_{i\in I})$$

3. **Soundness:** $tr(\{\mathtt{p}_i:T_i\}_{i\in I}) \subseteq tr(\mathscr{G})$
every trace of $\{\mathtt{p}_i:T_i\}_{i\in I}$ is a trace of $\mathscr{G}$

Soundness and completeness [first technical slide]

1. Define the traces of a global types in the obvious way:

$$tr(\text{skip}) = \{\varepsilon\} \qquad tr(\mathcal{G}_1;\mathcal{G}_2) = tr(\mathcal{G}_1)tr(\mathcal{G}_2)$$
$$tr(\pi \xrightarrow{a} \mathrm{p}) = \{\pi \xrightarrow{a} \mathrm{p}\} \qquad tr(\mathcal{G}_1 \vee \mathcal{G}_2) = tr(\mathcal{G}_1) \cup tr(\mathcal{G}_2)$$
$$tr(\mathcal{G}^*) = (tr(\mathcal{G}))^\star \qquad tr(\mathcal{G}_1 \wedge \mathcal{G}_2) = tr(\mathcal{G}_1) \sqcup\!\sqcup\, tr(\mathcal{G}_2)$$

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4. **Completeness:** $tr(\mathcal{G}) \subseteq tr(\{\mathrm{p}_i{:}T_i\}_{i\in I})^\circ$:
every trace of $\mathcal{G}$ is the *permutation* of a trace of $\{\mathrm{p}_i{:}T_i\}_{i\in I}$.

$L^\circ \stackrel{def}{=} \{\alpha_1\cdots\alpha_n \mid \exists$ a permutation σ s.t. $\alpha_{\sigma(1)}\cdots\alpha_{\sigma(n)} \in L\}$

Flawed global types

Some global types cannot be implemented by a sound and complete set of components

1. *No sequentiality:* Actions cannot synch without covert channels:

$$(\mathtt{p} \xrightarrow{a} \mathtt{q}; \mathtt{r} \xrightarrow{b} \mathtt{s})$$

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$$\begin{array}{c}(\mathtt{p} \xrightarrow{a} \mathtt{q}; \mathtt{q} \xrightarrow{a} \mathtt{r}; \mathtt{r} \xrightarrow{a} \mathtt{p})\\ \vee \\ (\mathtt{p} \xrightarrow{b} \mathtt{q}; \mathtt{q} \xrightarrow{a} \mathtt{r}; \mathtt{r} \xrightarrow{b} \mathtt{p})\end{array}$$

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See proceedings for a formal characterization of the various kinds of flaw

Examples

This still leaves a lot of flexibility (*cf.* state of the art):

- same message different receivers in a choice

$$\begin{array}{ll}(& \texttt{seller} \xrightarrow{\textit{price}} \texttt{buyer1}; \texttt{buyer1} \xrightarrow{\textit{price}} \texttt{buyer2} \\ \vee & \texttt{seller} \xrightarrow{\textit{price}} \texttt{buyer2}; \texttt{buyer2} \xrightarrow{\textit{price}} \texttt{buyer1})\end{array}$$

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- different receivers to break a loop

$$\begin{array}{l}\texttt{seller} \xrightarrow{\textit{agency}} \texttt{broker}; \\ (\texttt{broker} \xrightarrow{\textit{offer}} \texttt{buyer}; \texttt{buyer} \xrightarrow{\textit{counteroffer}} \texttt{broker})*; \\ (\texttt{broker} \xrightarrow{\textit{result}} \texttt{seller} \wedge \texttt{broker} \xrightarrow{\textit{result}} \texttt{buyer})\end{array}$$

Projection [last technical slide]

Global types not inherently flawed are associated to sound and complete sets of components compositionally by a deduction system

Global types not inherently flawed are associated to sound and complete sets of components compositionally by a deduction system

(SP-SKIP)

$$\Delta \vdash \mathsf{skip} \triangleright \Delta$$

(SP-ACTION)

$$\{\mathrm{p} : S, \mathrm{q} : T, \dots\} \vdash \mathrm{p} \xrightarrow{a} \mathrm{q} \triangleright \{\mathrm{p} : \mathrm{q}!a.S, \mathrm{q} : \mathrm{p}?a.T, \dots\}$$

(SP-SEQUENCE)

$$\frac{\Delta \vdash \mathscr{G}_2 \triangleright \Delta' \qquad \Delta' \vdash \mathscr{G}_1 \triangleright \Delta''}{\Delta \vdash \mathscr{G}_1; \mathscr{G}_2 \triangleright \Delta''}$$

(SP-ITERATION)

$$\frac{\{\mathrm{p} : T_1 \oplus T_2, \dots\} \vdash \mathscr{G} \triangleright \{\mathrm{p} : T_1, \dots\}}{\{\mathrm{p} : T_2, \dots\} \vdash \mathscr{G}^* \triangleright \{\mathrm{p} : T_1 \oplus T_2, \dots\}}$$

(SP-ALTERNATIVE)

$$\frac{\Delta \vdash \mathscr{G}_1 \triangleright \{\mathrm{p} : T_1, \dots\} \qquad \Delta \vdash \mathscr{G}_2 \triangleright \{\mathrm{p} : T_2, \dots\}}{\Delta \vdash \mathscr{G}_1 \vee \mathscr{G}_2 \triangleright \{\mathrm{p} : T_1 \oplus T_2, \dots\}}$$

(SP-SUBSUMPTION)

$$\frac{\Delta \vdash \mathscr{G}' \triangleright \Delta' \qquad \mathscr{G}' \leqslant \mathscr{G} \qquad \Delta'' \leqslant \Delta'}{\Delta \vdash \mathscr{G} \triangleright \Delta''}$$

$$(X \leqslant Y \stackrel{def}{=} tr(L) \subseteq tr(M) \subseteq tr(L)^\circ)$$

Global types not inherently flawed are associated to sound and complete sets of components compositionally by a deduction system

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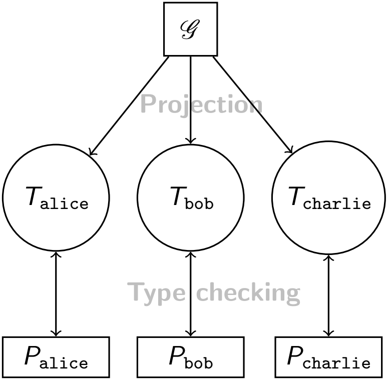
Makes projection algorithm very hard (see proceedings)

A three-layered structure



Global Type $\mathscr{G} = \texttt{alice} \xrightarrow{\mathit{nat}} \texttt{bob};\ \texttt{bob} \xrightarrow{\mathit{nat}} \texttt{charlie}$

Local Types $T_{\texttt{bob}} = \texttt{alice?}\mathit{nat}.\ \texttt{charlie!}\mathit{nat}.\ \mathsf{end}$

Processes $P_{\texttt{bob}} =$

```
receive x from alice;
send x+42 to charlie;
end
```

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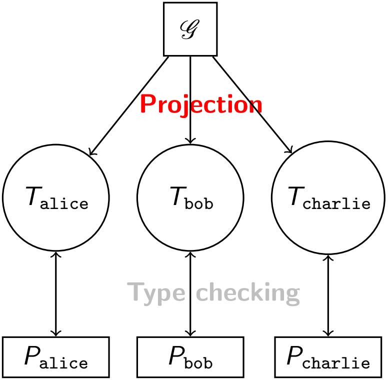

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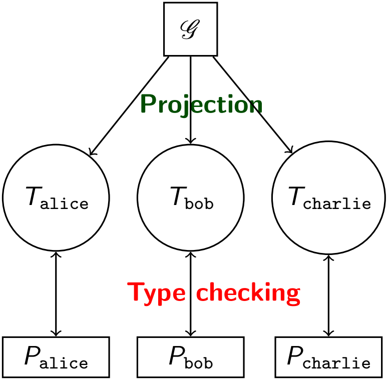

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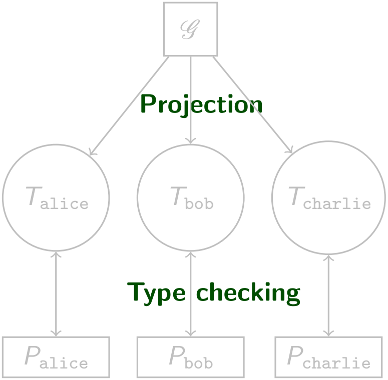

Global Type $\mathscr{G} =$ alice $\xrightarrow{nat}$ bob; bob $\xrightarrow{nat}$ charlie

soundness
completeness

Local Types $T_{\texttt{bob}} =$ alice?*nat*. charlie!*nat*. end

subject reduction
progress, fairness

Processes $P_{\texttt{bob}} =$ `receive x from alice; send x+42 to charlie; end`

Sought properties (second-third layers):

1. Subject reduction: No communication errors;
2. Progress: No stuck processes (safety);
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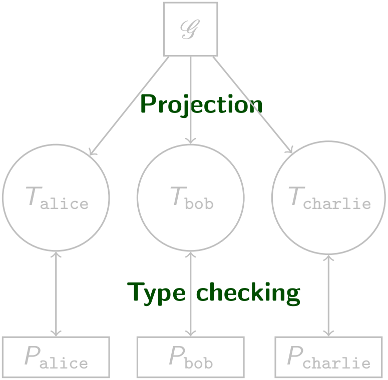
A three-layered structure



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Checked on Local Types

Other approaches

Automata approach: global specifications

Seller sends buyer a price and a description of the product; then buyer may repeatedly send seller an offer then wait for a new price; then buyer sends seller acceptance or quits the conversation.

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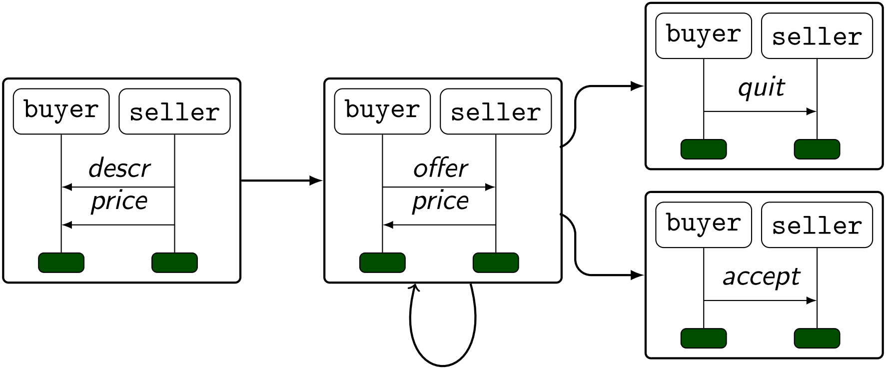
Message Sequence Graphs:



Automata approach: global specifications

$$(\texttt{seller} \xrightarrow{\textit{descr}} \texttt{buyer} \wedge \texttt{seller} \xrightarrow{\textit{price}} \texttt{buyer});$$
$$(\texttt{buyer} \xrightarrow{\textit{offer}} \texttt{seller}; \texttt{seller} \xrightarrow{\textit{price}} \texttt{buyer})*;$$
$$(\texttt{buyer} \xrightarrow{\textit{accept}} \texttt{seller} \vee \texttt{buyer} \xrightarrow{\textit{quit}} \texttt{seller})$$

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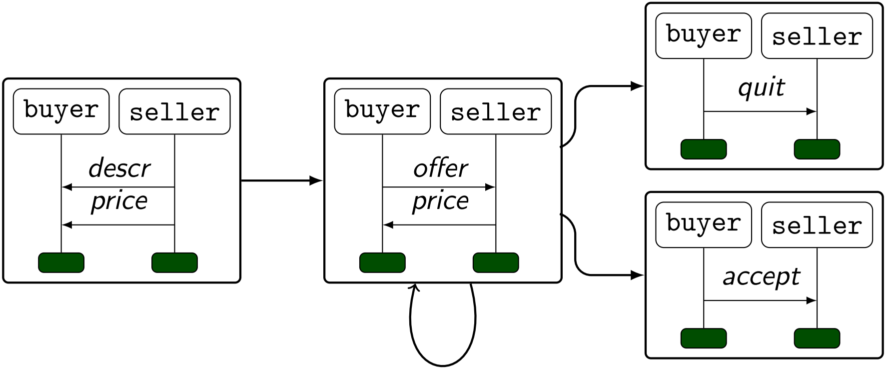
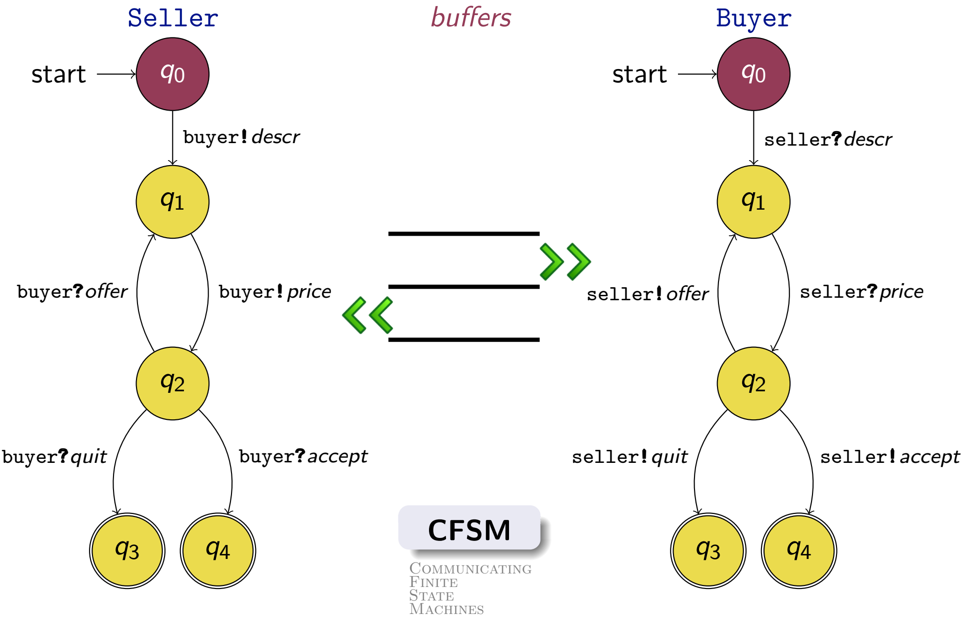


Automata approach: local specifications



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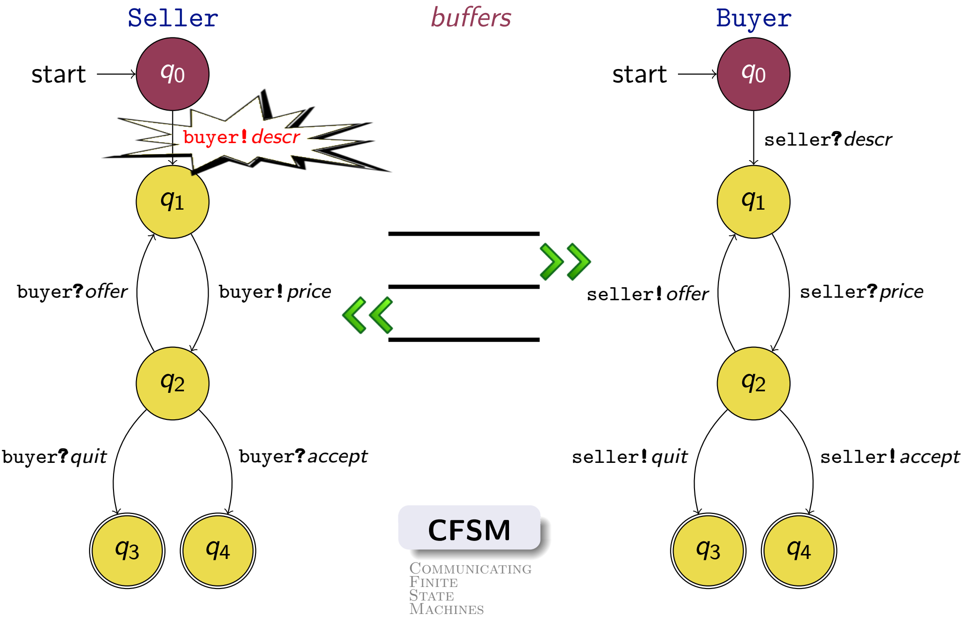

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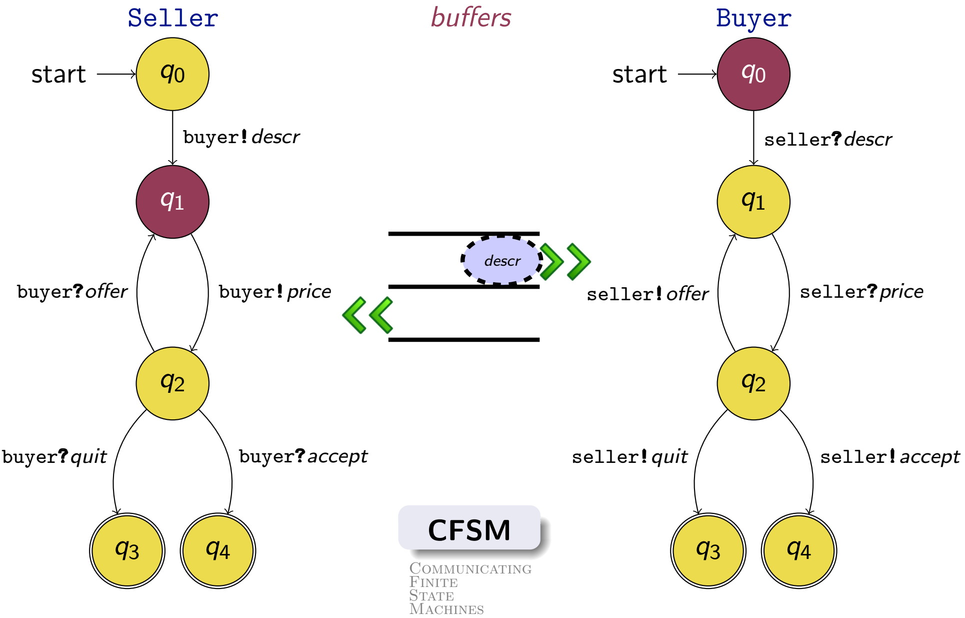

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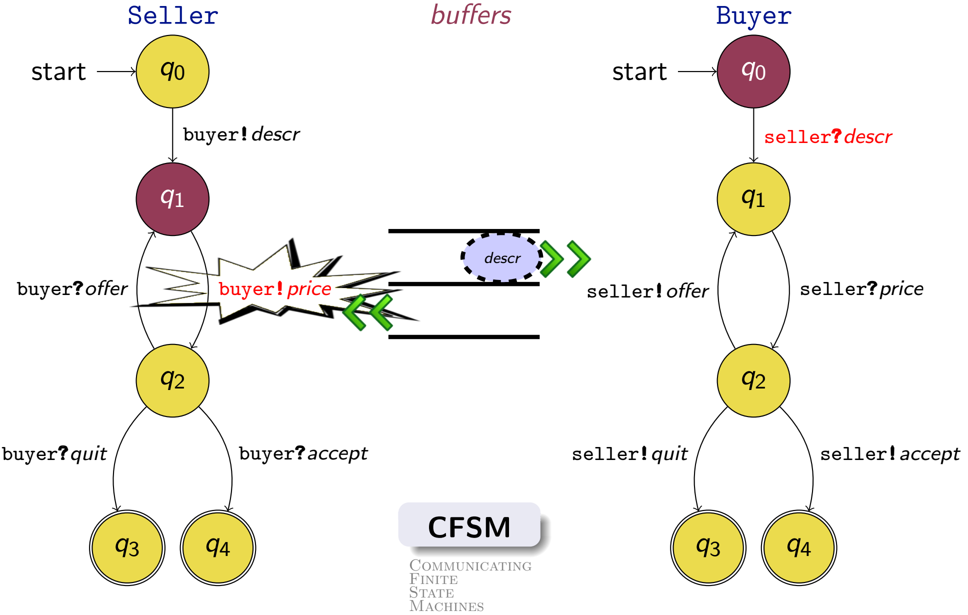

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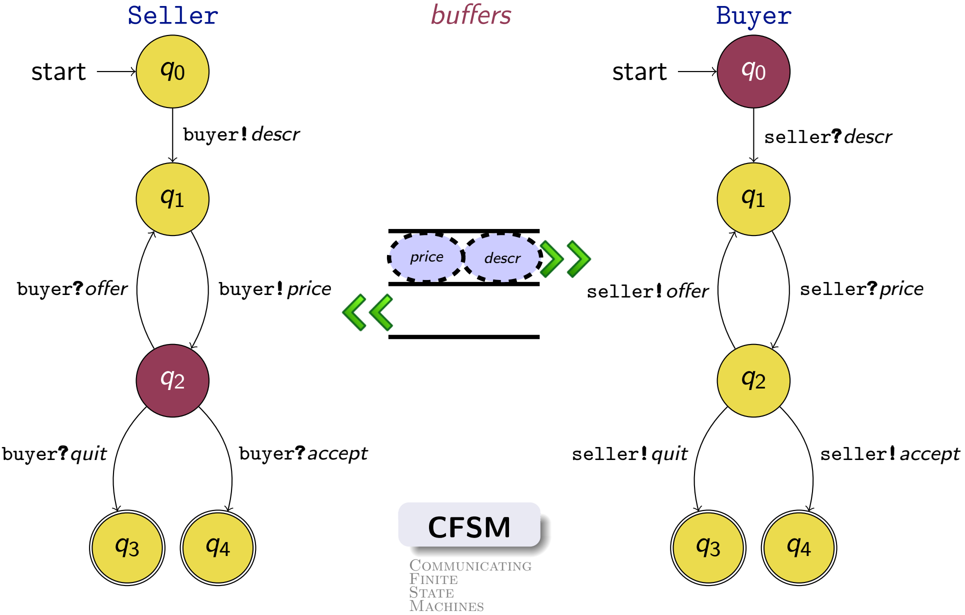

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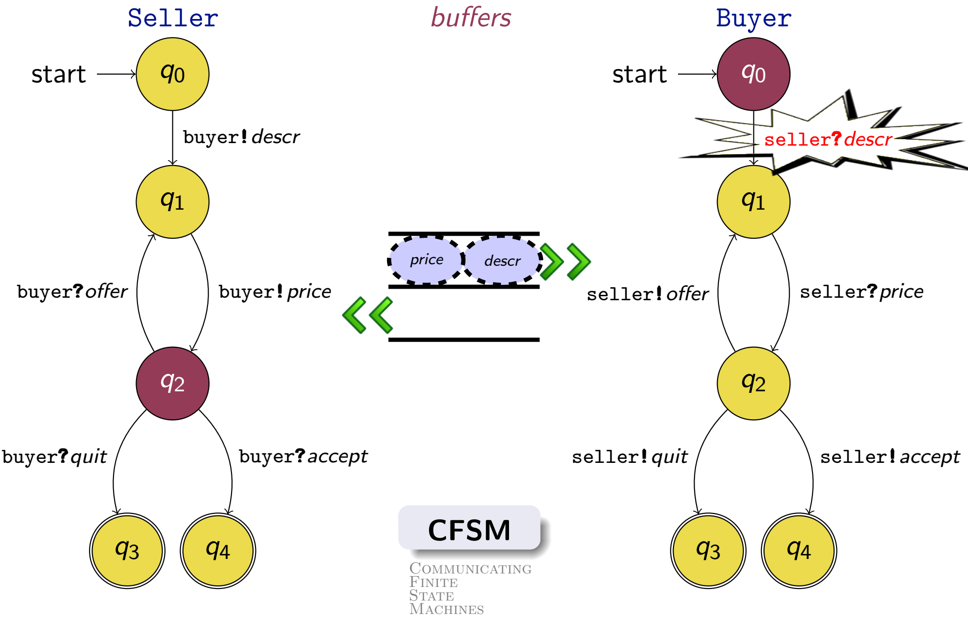

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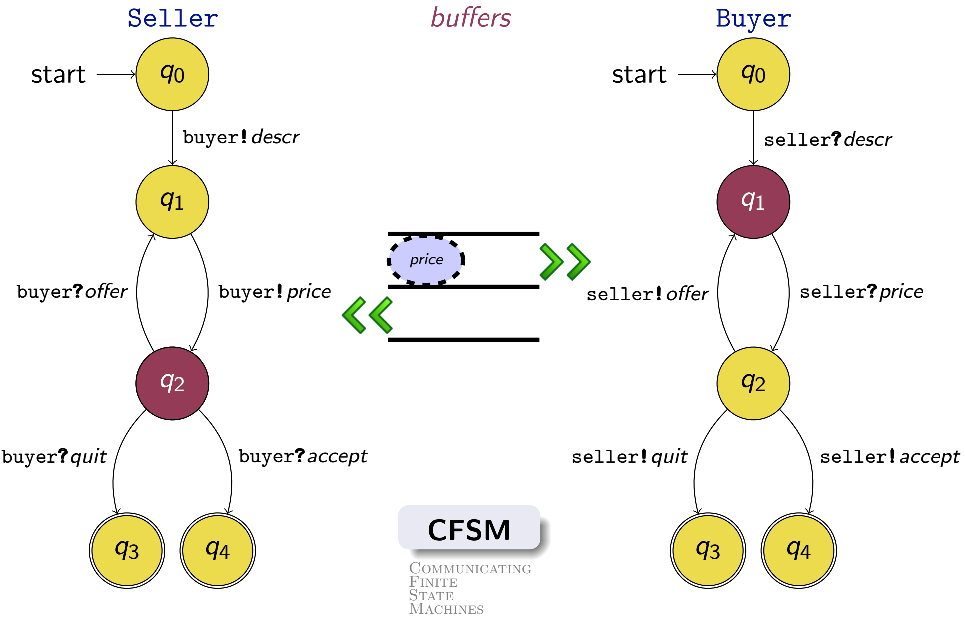

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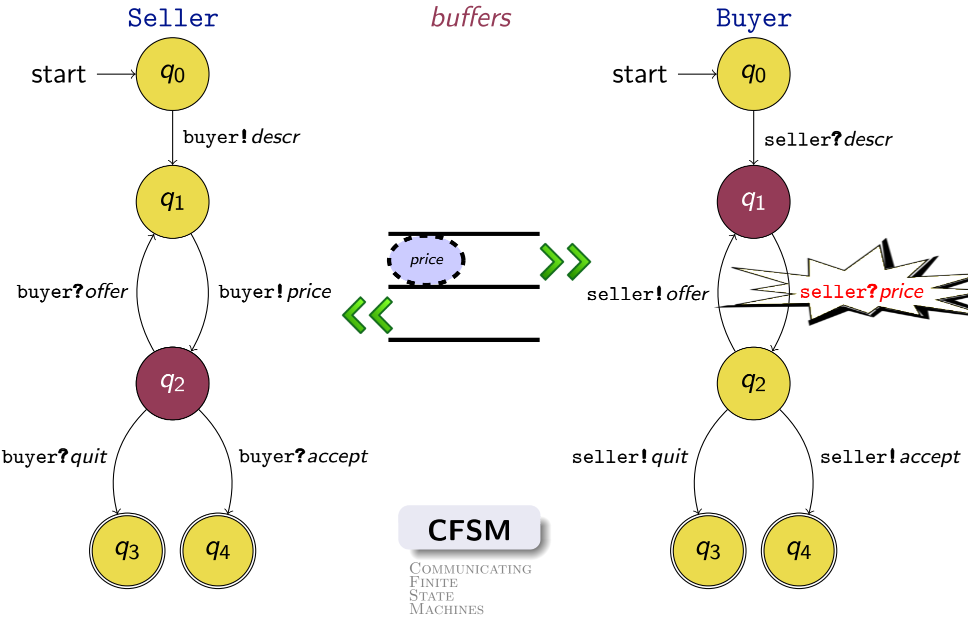

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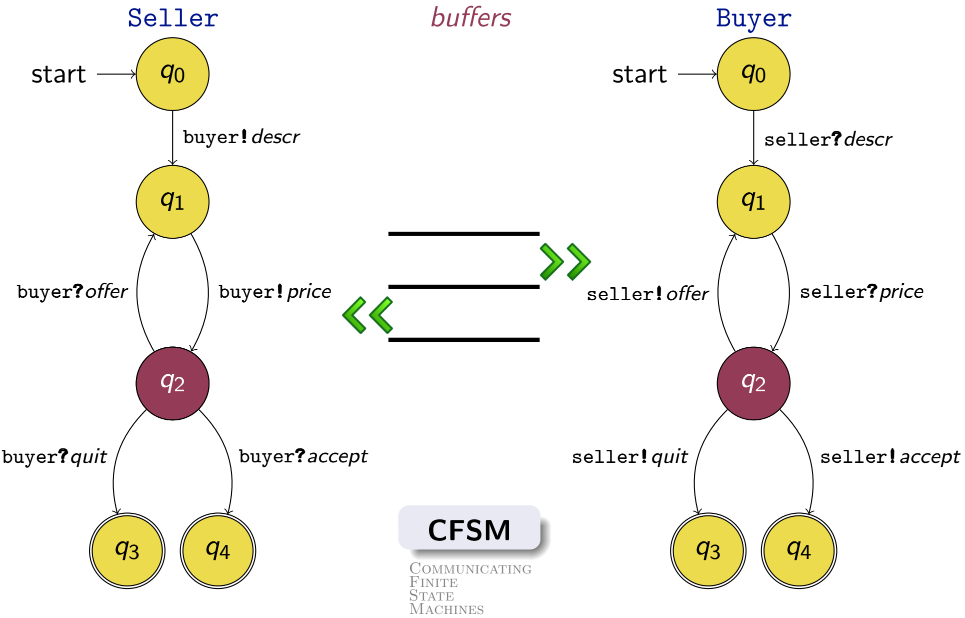

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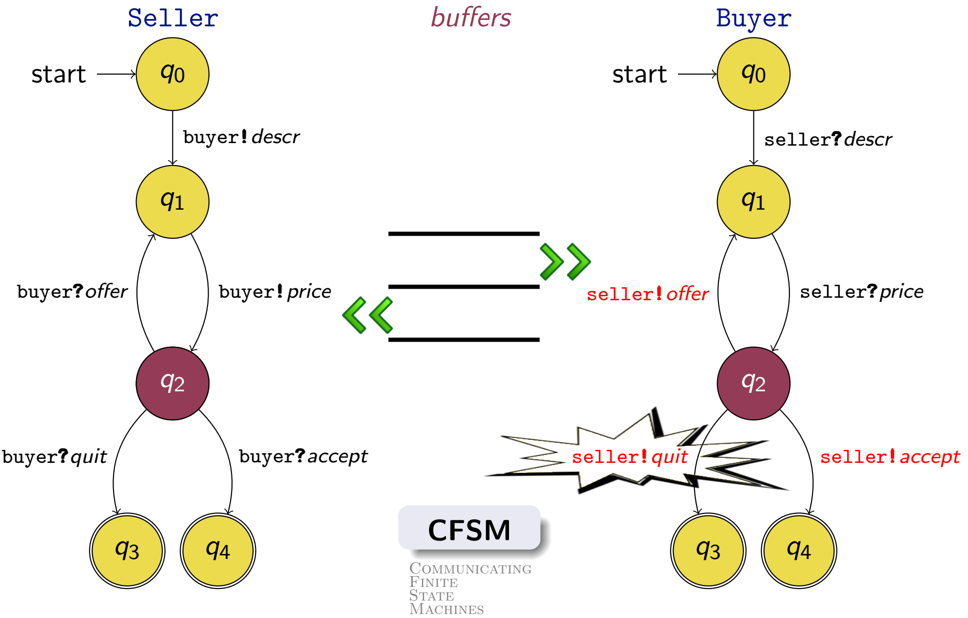

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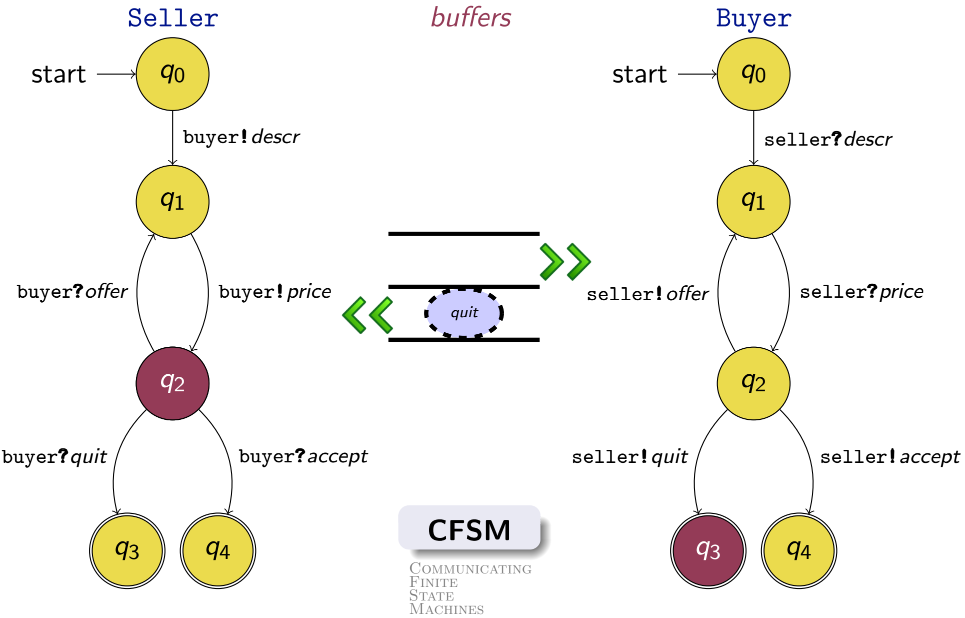

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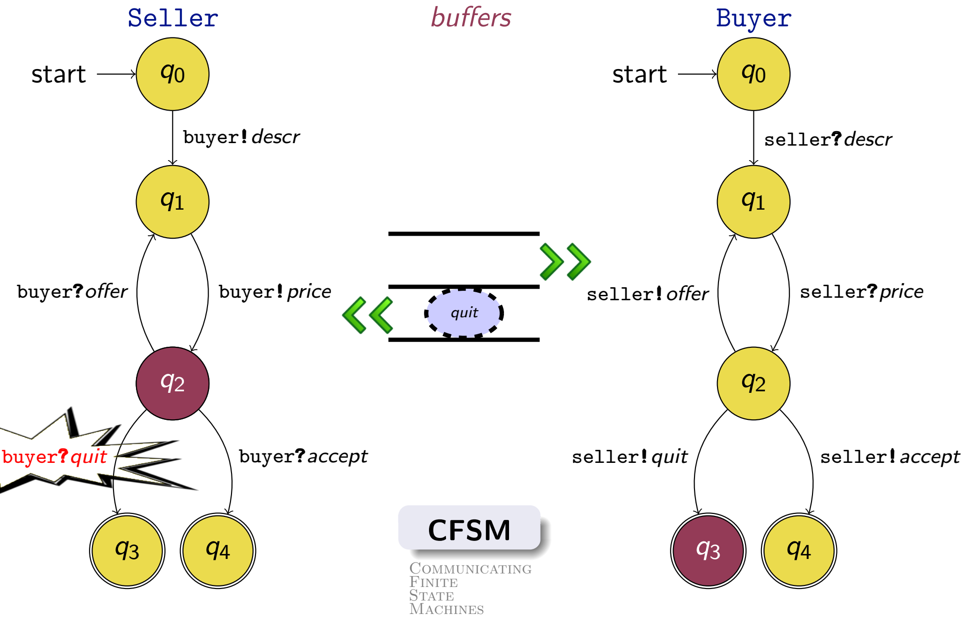

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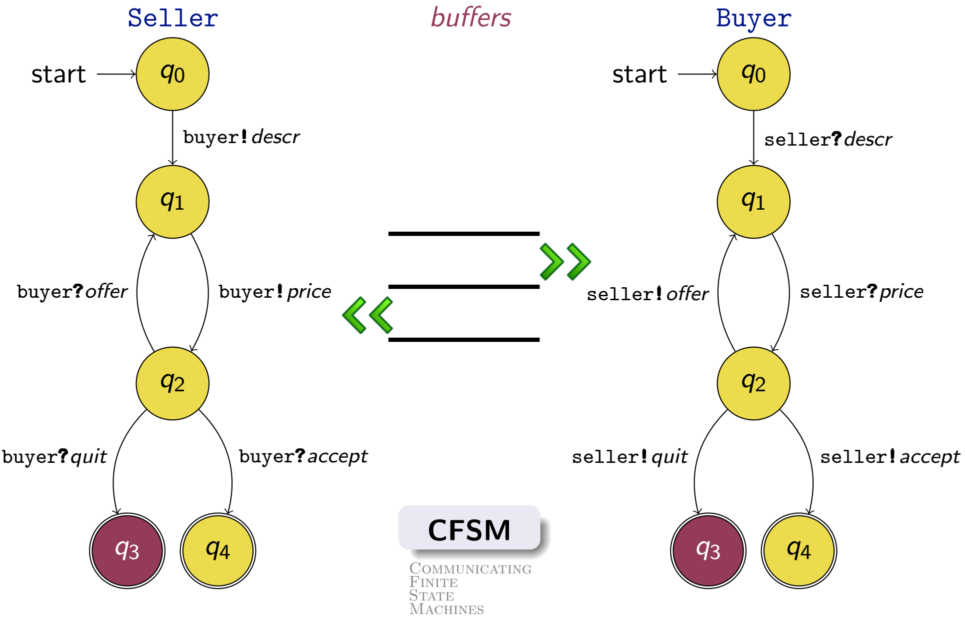

Automata approach: problems and results

Research focused on *decidability*, *expressivity*, and *complexity*.

1. *CFSM are Turing complete.*
   - *Typical problems*: termination, reachability, deadlock freedom, boundedness (in general undecidable).
   - *Study of restrictions* to make them decidable (*eg*, lossy channels, half-duplex, bounded buffers,...).
2. *MSG are finitely generated.*
   - *Typical problems*: model checking, implementability.
   - *Study of variants*: to have good closure properties, to make projection (into CFSM) effectively and efficiently implementable,
3. *Implementability* (generally meaning the *same* traces).
   - *Study of different notions of implementability* (*eg*, unsound implementations, implementations with a controlled use of covert channels, implementation admitting deadlocks) to obtain decidability and/or polynomial complexity.

The protocol approach: global specifications

MSC (as for automata, but much more detailed):

RFC 2945 (SRP Authentication and Key Exchange System)

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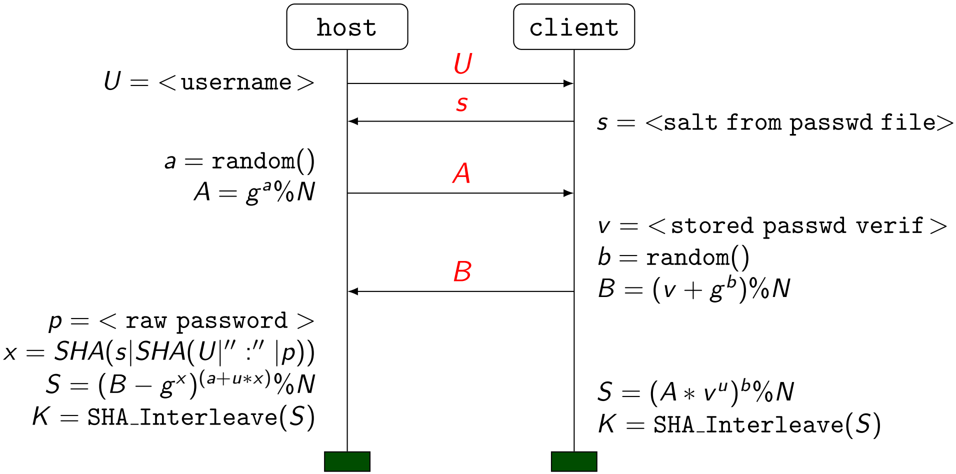

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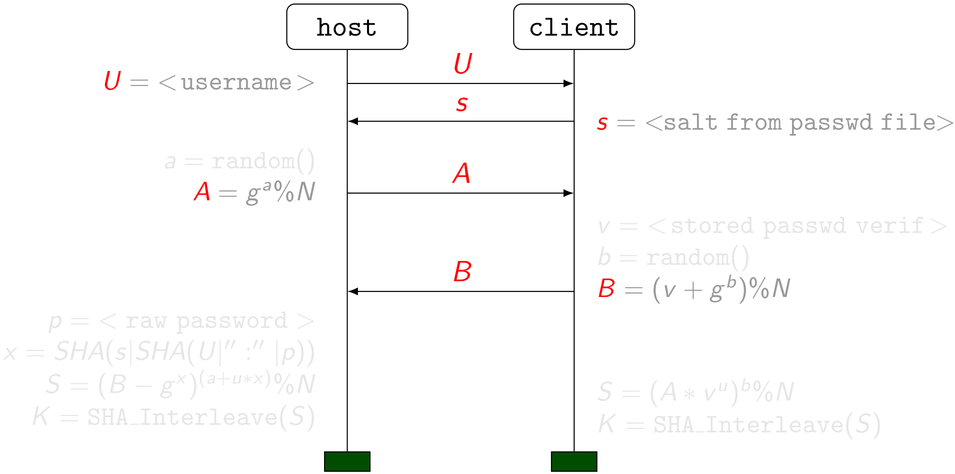


Says how messages are generated

RFC 2945 (SRP Authentication and Key Exchange System)

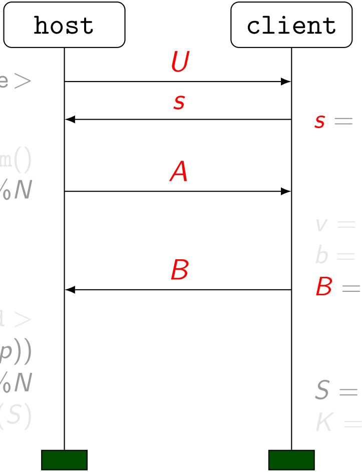
The protocol approach: global specifications

MSC (as for automata, but much more detailed):

$U = <\texttt{username}>$

$a = \texttt{random}()$
$A = g^{a}\% N$

$p = <\texttt{raw password}>$
$x = SHA(s|SHA(U|'':''|p))$
$S = (B - g^{x})^{(a+u*x)}\% N$
$K = \texttt{SHA\_Interleave}(S)$



$s = <\texttt{salt from passwd file}>$

$v = <\texttt{stored passwd verif}>$
$b = \texttt{random}()$
$B = (v + g^{b})\% N$

$S = (A * v^{u})^{b}\% N$
$K = \texttt{SHA\_Interleave}(S)$

Says how messages are generated

Says how messages are used

RFC 2945 (SRP Authentication and Key Exchange System)

Differences with automata and service approaches

Simpler and lower-level paradigms:

- *Interaction patterns are simpler*
  (protocols are finite: MSCs instead of MSGs)
- *Content of interactions is richer and more detailed*
  (in automata a finite set of message is often used).
- *The details of internal execution are exposed* both in global and local specifications (a small overlook may yield dramatic flaws)

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A larger variety of specification languages (induced by the points above):

- Global: Carlsen, Casper, CAPSL, CASRUL, ...
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Dynamicity (accounted for both by projection and by analysis)

- Protocols are specified for *roles*, implemented by several participants.
- Systems may include intruders and non specified participants that may alter the topology of interactions
- Different executions of the protocol may not be independent
  (*cf.* store and replay attacks)

Related work in the "services" approach.

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The "services" approach explores different variants of global specifications, ... as the "automata" approach does.

The focus is on *how to model some use-cases* rather than how to satisfy some properties.

Two examples:

1. How to model a dynamically changing topology: *channels*.
2. How to model a dynamically changing set of participants: *roles*.

See the long version of the article for an extensive review of related work

Higher-order sessions [Honda, Yoshida, Carbone 2008]

Specify channels and pass them around

Specify channels and pass them around

Two channels: b shared by Alice and Bob, and c by Alice and Charlie.

$\texttt{Alice} \xrightarrow{c\langle \mathsf{Int}\rangle} \texttt{Charlie};$	*send an integer on channel c*
$\texttt{Alice} \xrightarrow{b\langle c{:}!\mathsf{Int}\rangle} \texttt{Bob};$	*delegate the sending of an int on c*
$\texttt{Bob} \xrightarrow{c\langle \mathsf{Int}\rangle} \texttt{Charlie};$	*send an integer on channel c*
$\texttt{Alice} \xrightarrow{c\langle \mathsf{Int}\rangle} \texttt{Charlie};$	*send an integer on channel c*

Higher order sessions [Honda, Yoshida, Carbone 2008]

Channels names are specified

Sp… s and pass them around

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Alice

```
send 1 on c in
send c on b in
send 3 on c in
()
```

Bob

```
receive $k on b in
send 2 on $k in ()
```

Charlie

```
receive $x on c in
receive $y on c in
receive $z on c in
$x+$y+$z
```

Specify channels and pass them around

Two channels: *b* shared by Alice and Bob, and *c* by Alice and Charlie.

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$\texttt{Alice} \xrightarrow{b\langle c{:}!\mathsf{Int}\rangle} \texttt{Bob};$	*delegate the sending of an int on c*
$\texttt{Bob} \xrightarrow{c\langle \mathsf{Int}\rangle} \texttt{Charlie};$	*send an integer on channel c*
$\texttt{Alice} \xrightarrow{c\langle \mathsf{Int}\rangle} \texttt{Charlie};$	*integer on channel c*

Charlie is not aware that this communication is with Bob

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Dynamic multirole sessions [Deniélou & Yoshida 2011]

A seller that deal with just one or two buyers is unrealistic:

$$\forall x : \texttt{buyer}. \quad (\texttt{seller} \xrightarrow{descr} x \wedge \texttt{seller} \xrightarrow{price} x);$$
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In this and the previous work roles and dynamicity are respectively internalized (in the "protocols" approach they usually are at the meta-level)

Conclusion

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Automata and Services:

- The *automata approach* has a wealth of results in decidability and complexity that the *services* approach can use in studying its own framework and as guidelines for the definition of new ones.
- The automata community can find in the service framework new applications for their results and a new playground.

Protocol and Services:

- Protocols and Services approaches have a lot of common and they can mutually influence much more.
- Typing techniques are used to prove security properties while security protocols research spurs new research in type theory.
- Mutual influence is already happening:
  - WPPL [McCarthy & Krishnamurthi 2008] is a work in the verification of protocols directly inspired to multiparty section types
  - Dynamic multirole session types [Deniélou & Yoshida 2011] endow sessions with *roles* that protocols have been studying for many years.

A conclusion that Jacques II de Chabannes, seigneur de Lapalisse would have been proud of:

There are huge potential benefits for these communities to put their research efforts together.

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