# Asynchronous Multi-Context Systems[1]

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## Outline





## reactive Multi-Context Systems so far ...

### Motivation

- **integration** of heterogeneous KR-formalisms
- **awareness** of continuous flow of knowledge

### Realisation

- Contexts with different KR & Reasoning formalisms
- Bridge-Rules for exchange of beliefs
- Notion of Equilibrium as Semantics
- Run represents the change of knowledge and belief over time



## ... and a slight look to online-applications

- Many different services and sources of knowledge
- Continuous flow of information
- Data collection till sufficient knowledge for their tasks is available
- Communication is often query-based
- Asynchronous communication protocols

## Computer Aided Emergency Team Management

### Example Environment - Emergency Team Management

- Emergency Call
- Classification and Prioritisation of each case
- Overview of available rescue units
- Overview on ETAs for each unit and case
- Suggesting optimal assignments
- Communicate Tasks to rescue units

### Requirements

- Fast response to events
- Consider different sources of data
- Modularity for additional components
- Human as last instance for decisions



## Consequences of Asynchronicity

→ Contexts compute their belief sets independently
→ No agreement on a common Equilibrium
→ No defined basis for Bridge-Rules to fire
→ Need for Output-Rules ($\mathrm{OR}$)
→ Keep track of information provided by $\mathrm{OR}$
→ Input stream for each context
→ Interaction with environment:
- aMCS wide input streams
- aMCS wide output streams



## Other Design-Choices

- Each context decide when to compute
  - realised by computation controller $\mathrm{cc}$
- Dynamic adjustments of context-management
  - computation controller ($\mathrm{cc}$)
  - output rules ($\mathrm{OR}$)
  - context-semantics ($\mathrm{ACC}$)
  - context update function ($\mathrm{cu}$)



## Asynchronous Multi-Context Systems

### Definition

A *data package* is a pair $d = \langle s, I\rangle$, where $s \in \mathcal{N}$ is either a context name or a sensor name, stating the *source* of $d$, and $I \subseteq \mathcal{IL}$ is a set of pieces of information. An *information buffer* is a sequence of data packages.

### Definition

Let $C = \langle \mathsf{n}, \mathcal{LS}\rangle$ be a context. An *output rule* $r$ for $C$ is an expression of the form

$$\langle \mathsf{n}, \mathsf{i}\rangle \leftarrow b_1, \dots, b_j, \mathrm{not}\ b_{j+1}, \dots, \mathrm{not}\ b_m, \quad (1)$$

such that $\mathsf{n} \in \mathcal{N}$ is the name of a context or an output stream, $\mathsf{i} \in \mathcal{IL}$ is a piece of information, and every $b_\ell$ $(1 \leq \ell \leq m)$ is a belief for $C$, i.e., $b_\ell \in S$ for some $S \in \mathcal{BS}_{\mathcal{LS}}$.

# Asynchronous Multi-Context Systems

## Definition

Let $C = \langle \mathsf{n}, \mathcal{LS} \rangle$ be a context, $\mathrm{OR}$ a set of output rules for $C$, $S \in \mathcal{BS}_{\mathcal{LS}}$ a belief set, and $\mathsf{n}' \in \mathcal{N}$ a name. Then, the data package

$$d_C(S, \mathrm{OR}, \mathsf{n}') = \langle \mathsf{n}, \{i \mid r \in \mathrm{OR}, hd(r) = \langle \mathsf{n}', \mathrm{i} \rangle, S \models \mathrm{bd}(r)\} \rangle$$

is the *output* of $C$ with respect to $\mathrm{OR}$ under $S$ relevant for $\mathsf{n}$.



# Asynchronous Multi-Context Systems

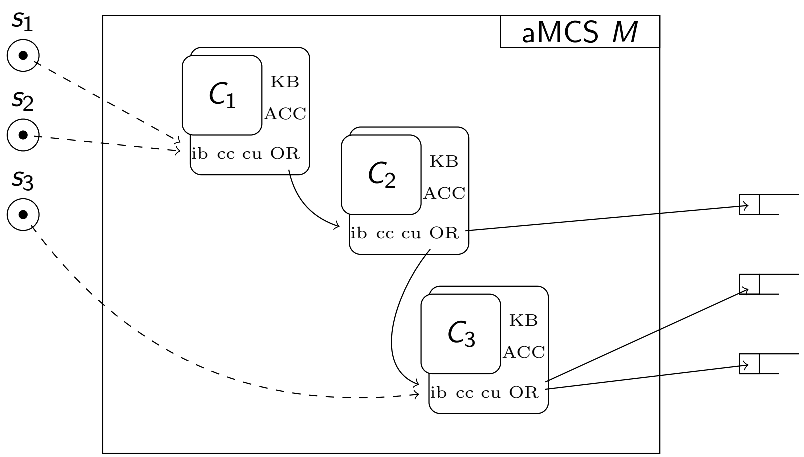
## Definition

Let $C = \langle \mathsf{n}, \mathcal{LS} \rangle$ be a context. A *configuration* of $C$ is a tuple $cf = \langle \mathrm{KB}, \mathrm{ACC}, \mathrm{ib}, cm \rangle$, where $\mathrm{KB} \in \mathcal{KB}_{\mathcal{LS}}$, $\mathrm{ACC} \in \mathcal{ACC}_{\mathcal{LS}}$, $\mathrm{ib}$ is a finite information buffer, and $cm$ is a *context management* for $C$ which is a triple $cm = \langle \mathrm{cc}, \mathrm{cu}, \mathrm{OR} \rangle$, where

- $\mathrm{cc}$ is a computation controller for $C$,
- $\mathrm{OR}$ is a set of output rules for $C$, and
- $\mathrm{cu}$ is a *context update function* for $C$ which is a function that maps an information buffer $\mathrm{ib} = d_1, \dots, d_m$ and an admissible knowledge base of $\mathcal{LS}$ to a configuration $cf' = \langle \mathrm{KB}', \mathrm{ACC}', \mathrm{ib}', cm' \rangle$ of $C$ with $\mathrm{ib}' = d_k, \dots, d_m$ for some $k \geq 1$.



# Asynchronous Multi-Context Systems






# Run of an aMCS

## Configuration of an aMCS

- Configuration for each Context
- Content of each output stream (output buffer)

## Definition (Run structure)

Let $M = \langle \langle C_1, \dots, C_n \rangle, \langle \mathsf{o}_1, \dots, \mathsf{o}_m \rangle \rangle$ be an aMCS. A run structure for $M$ is a sequence

$$R = \dots, Cf^t, Cf^{t+1}, Cf^{t+2}, \dots \quad ,$$

where $t \in \mathbb{Z}$ is a point in time, and every $Cf^{t'}$ in $R$ ($t' \in \mathbb{Z}$) is a configuration of $M$.

## Run of an aMCS

### Time-awareness

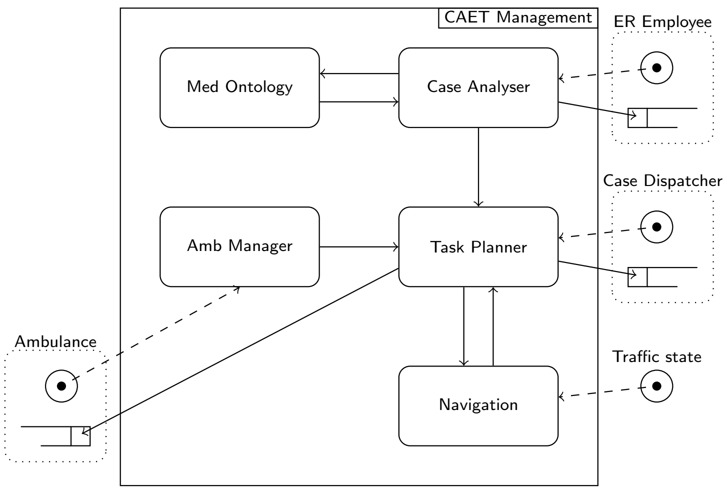
- Computation of belief sets takes time
- Enumeration of belief sets takes time
- Verification of non-existence of (further) belief sets takes time

### Run execution

- If a Context finds a belief set, $\mathrm{OR}$ are applied
- Information is distributed to input-buffers of contexts or output streams
- If a Context has finished its computation, $\mathrm{EOC}$ is sent to all stakeholders



## Example of an aMCS






## Differences to rMCS

- rMCSs use equilibria
  - strong semantics
  - tight integration approach where context semantics are interdependent
  - every context need to agree $\rightarrow$ each context needs to wait $\rightarrow$ synchronous approach
- rMCSs have equilibria as source of non-determinism
- aMCSs have computation time as source of non-determinism



## Simulation of rMCS

- For each Context $C_i$ of the rMCS, introduce three aMCS Contexts:
  - $C_i^{kb}$ stores its current knowledge base
  - $C_i^{kb'}$ stores update of the knowledge base and compute its semantics
  - $C_i^m$ implements the bridge rules and the management function
- Three contexts for the rMCS, where
  - $C^{obs}$ receives sensor data and distributes the information,
  - $C^{guess}$ guesses equilibrium candidates and propagates them to $C_i^m$, and
  - $C^{check}$ compares all results of the contexts and informs other contexts if an equilibrium has been found

## Future Work

- Study modelling patterns and best practices for aMCS
- Analysis how other approaches (e.g., `clingo` [Gebser et al., 2012]) are capable for prototypical implementations
- Analysis how features of other approaches (e.g., online queries, iterative computing, ...) relate to aMCS concepts (e.g., $\mathrm{ib}$, $\mathrm{OR}$,$\mathrm{cc}$, ...)



## Related Work

- aMCS are motivated by rMCS [Brewka et al., 2014] and are based on MCS [Brewka et al., 2011a, Brewka et al., 2011b]
- Evolving Mulit-Context Systems [Gonçalves et al., 2014] follow a similar approach to rMCS
- A concept similar for output rules in reactive Multi-Context Systems has been presented as reactive bridge rules [Ellmauthaler, 2013]



# Thank you for your interest!



## References I

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[Gonçalves et al., 2014] Gonçalves, R., Knorr, M., and Leite, J. (2014).
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To appear.




**Definition**

A context is a pair $C = \langle \mathrm{n}, \mathcal{LS} \rangle$ where $\mathrm{n} \in \mathcal{N}$ is the name of the context and $\mathcal{LS}$ is a logic suite.



**Definition**

An aMCS (of length $n$ with $m$ output streams) is a pair $M = \langle \mathrm{C}, \mathrm{O} \rangle$, where $\mathrm{C} = \langle C_1, \ldots, C_n \rangle$ is an $n$-tuple of contexts and $\mathrm{O} = \langle \mathrm{o}_1, \ldots, \mathrm{o}_m \rangle$ with $\mathrm{o}_j \in \mathcal{N}$ for each $1 \leq j \leq m$ is a tuple containing the names of the output streams of $M$.



**Definition**

A *data package* is a pair $d = \langle s, I \rangle$, where $s \in \mathcal{N}$ is either a context name or a sensor name, stating the *source* of $d$, and $I \subseteq \mathcal{IL}$ is a set of pieces of information. An *information buffer* is a sequence of data packages.

## Definition

Let $C = \langle \mathsf{n}, \mathcal{LS} \rangle$ be a context. A *computation controller* for $C$ is a relation $\mathrm{cc}$ between a KB $\mathrm{KB} \in \mathcal{KB}_{\mathcal{LS}}$ and a finite information buffer.



## Definition

Let $C = \langle \mathsf{n}, \mathcal{LS} \rangle$ be a context. An *output rule* $r$ for $C$ is an expression of the form

$$\langle \mathsf{n}, \mathsf{i} \rangle \leftarrow b_1, \dots, b_j, \mathrm{not}\ b_{j+1}, \dots, \mathrm{not}\ b_m, \tag{2}$$

such that $\mathsf{n} \in \mathcal{N}$ is the name of a context or an output stream, $\mathsf{i} \in \mathcal{IL}$ is a piece of information, and every $b_\ell$ ($1 \leq \ell \leq m$) is a belief for $C$, i.e., $b_\ell \in S$ for some $S \in \mathcal{BS}_{\mathcal{LS}}$.



## Definition

Let $C = \langle \mathsf{n}, \mathcal{LS} \rangle$ be a context, $\mathrm{OR}$ a set of output rules for $C$, $S \in \mathcal{BS}_{\mathcal{LS}}$ a belief set, and $\mathsf{n}' \in \mathcal{N}$ a name. Then, the data package

$$d_C(S, \mathrm{OR}, \mathsf{n}') = \langle \mathsf{n}, \{ i \mid r \in \mathrm{OR}, hd(r) = \langle \mathsf{n}', \mathsf{i} \rangle, S \models \mathrm{bd}(r) \} \rangle$$

is the *output* of $C$ with respect to $\mathrm{OR}$ under $S$ relevant for $\mathsf{n}$.



## Definition

Let $C = \langle \mathsf{n}, \mathcal{LS} \rangle$ be a context. A *configuration* of $C$ is a tuple $cf = \langle \mathrm{KB}, \mathrm{ACC}, \mathrm{ib}, cm \rangle$, where $\mathrm{KB} \in \mathcal{KB}_{\mathcal{LS}}$, $\mathrm{ACC} \in \mathcal{ACC}_{\mathcal{LS}}$, $\mathrm{ib}$ is a finite information buffer, and $cm$ is a *context management* for $C$ which is a triple $cm = \langle \mathrm{cc}, \mathrm{cu}, \mathrm{OR} \rangle$, where

- $\mathrm{cc}$ is a computation controller for $C$,
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## Definition

Let $M = \langle\langle C_1, \ldots, C_n\rangle, \langle o_1, \ldots, o_m\rangle\rangle$ be an aMCS. A *configuration* of $M$ is a pair

$$Cf = \langle\langle cf_1, \ldots, cf_n\rangle, \langle \mathrm{ob}_1, \ldots, \mathrm{ob}_m\rangle\rangle,$$

where

- for all $1 \leq i \leq n$ $cf_i = \langle \mathrm{KB}, \mathrm{ACC}, \mathrm{ib}, cm\rangle$ is a configuration for $C_i$ and for every output rule $r \in \mathrm{OR}_{cm}$ we have $\mathrm{n} \in \mathcal{N}(M)$ for $\langle \mathrm{n}, \mathrm{i}\rangle = hd(r)$, and
- $\mathrm{ob}_j = \ldots, d_{l-1}, d_l$ is an information buffer with a final element $d_l$ that corresponds to the data on the output stream named $o_j$ for each $1 \leq j \leq m$ such that for each $h \leq l$ with $d_h = \langle \mathrm{n}, \mathrm{i}\rangle$ we have $\mathrm{n} = \mathrm{n}_{C_i}$ for some $1 \leq i \leq n$.



## Definition

Let $M = \langle\langle C_1, \ldots, C_n\rangle, \langle o_1, \ldots, o_m\rangle\rangle$ be an aMCS. A run structure for $M$ is a sequence

$$R = \ldots, Cf^{t}, Cf^{t+1}, Cf^{t+2}, \ldots \quad ,$$

where $t \in \mathbb{Z}$ is a point in time, and every $Cf^{t'}$ in $R$ ($t' \in \mathbb{Z}$) is a configuration of $M$.



## Definition

Let $M$ be an aMCS of length $n$ with $m$ output streams and $R$ a run structure for $M$. $R$ is a *run* for $M$ if the following conditions hold for every $1 \leq i \leq n$ and every $1 \leq j \leq m$:

(i) if $cf_i^t$ and $cf_i^{t+1}$ are defined, $C_i$ is neither busy nor waiting at time $t$, then
- $C_i$ is busy at time $t+1$,
- $cf_i^{t+1} = \mathrm{cu}_{cm_i^t}(\mathrm{ib}_i^t, \mathrm{KB}_i^t)$

We say that $C_i$ *started a computation* for $\mathrm{KB}_i^{t+1}$ at time $t+1$.

(ii) if $C_i$ *started a computation* for KB at time $t$ then
- we say that this computation ended at time $t'$, if $t'$ is the earliest time point with $t' \geq t$ such that $\langle \mathrm{n}_{C_i}, \mathrm{EOC}\rangle$ is added to every stakeholder buffer $\mathrm{b}$ of $C_i$ at $t'$; the addition of $d_{C_i}(S, \mathrm{OR}_{cm_i^{t''}}, \mathrm{n})$ to $\mathrm{b}$ is called an *end of computation notification*.
- for all $t' > t$ such that $cf_i^{t'}$ is defined, $C_i$ is busy at $t'$ unless the computation ended at some time $t''$ with $t < t'' < t'$.
- if the computation ended at time $t'$ and $cf_i^{t'+1}$ is defined then $C_i$ is not busy at $t'+1$.



## Definition

(iii) if $C_i$ *started a computation* for KB at time $t$ that ended at time $t'$ then for every belief set $S \in \mathrm{ACC}_i^t$ there is some time $t''$ with $t \leq t'' \leq t'$ such that
- $d_{C_i}(S, \mathrm{OR}_{cm_i^{t''}}, \mathrm{n})$ is added to every stakeholder buffer $\mathrm{b}$ of $C_i$ for n at $t''$.

We say that $C_i$ *computed* $S$ at time $t''$. The addition of $d_{C_i}(S, \mathrm{OR}_{cm_i^{t''}}, \mathrm{n})$ to $\mathrm{b}$ is called a *belief set notification*.

(iv) if $\mathrm{ob}_j^t$ and $\mathrm{ob}_j^{t+1}$ are defined and $\mathrm{ob}_j^t = \ldots, d_{l-1}, d_l$ then $\mathrm{ob}_j^{t+1} = \ldots, d_{l-1}, d_l, \ldots, d_{l'}$ for some $l' \geq l$. Moreover, every data package $d_{l''}$ with $l < l'' \leq l'$ that was added at time $t+1$ results from an end of computation notification or a belief set notification.

(v) if $cf_i^t$ and $cf_i^{t+1}$ are defined, $C_i$ is busy or waiting at time $t$, and $\mathrm{ib}_i^t = d_1, \ldots, d_l$ then we have $\mathrm{ib}_i^{t+1} = d_1, \ldots, d_l, \ldots, d_{l'}$ for some $l' \geq l$. Moreover, every data package $d_{l''}$ with $l < l'' \leq l'$ that was added at time $t+1$ either results from an end of computation notification or a belief set notification or $\mathrm{n} \notin \mathcal{N}(M)$ (i.e., n is a sensor name) for $d_{l''} = \langle \mathrm{n}, \mathrm{i}\rangle$.