Organising LTL Monitors over Systems with a Global Clock

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Outline

1. Background
2. Motivations
3. Decentralised Monitoring of LTL formulae
4. Implementation and Evaluation
5. Conclusions
Outline – Background

1 Background
   • Monitoring
   • Linear-time Temporal Logic (for monitoring)

2 Motivations

3 Decentralised Monitoring of LTL formulae

4 Implementation and Evaluation

5 Conclusions
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“Classical” runtime validation method: monitoring

Runtime Verification [Klaus Havelund, Grigore Rosu]

- A lightweight verification technique “bridging the gap” between testing and verification
- **Checking** whether a run of the system under scrutiny satisfies a given correctness specification
Classical” runtime validation method: monitoring

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Get a **program/system**
“Classical” runtime validation method: monitoring

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Get a program/system
Synthesize a monitor: a decision procedure for the specification
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Instrument the underlying program to observe relevant events: $e_i \in \Sigma$
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Get a program/system

Synthesize a monitor: a decision procedure for the specification

Instrument the underlying program to observe relevant events: $e_i \in \Sigma$

A monitor acts at runtime as an oracle for the specification (validation/violation)
"Classical" runtime validation method: **monitoring**

Determine a set of atomic propositions $AP$ of the system e.g., for a car $AP = \{\text{speed}\_\text{low}, \text{seat}\_\text{belt}\_1\_\text{on}, \ldots\}$

Several existing tools (e.g., Java-MOP [Rosu et al.], RuleR [Barringer et al.], \ldots)

Applied to several domains: Java/C programs, Web services, Space flight software, system biology \ldots
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One of the most widely used specification formalism

Consider a set of atomic propositions AP

Syntax:

$$\varphi ::= p \in AP \mid (\varphi) \mid \neg \varphi \mid \varphi \lor \varphi \mid X\varphi \mid \varphi U \varphi$$

where:

- $\neg$, $\lor$ are operators from propositional logic
- $X$ is the “next” operator
- $U$ is the until operator

Additional operators:

- $F$ is the “eventually” operator: $F\varphi = \text{true} U \varphi$
- $G$ is the “globally” operator: $G\varphi = \neg (F(\neg \varphi))$
Given $w \in \Sigma^\infty$ and $i \geq 0$ the (inductive) semantics is:

\[
\begin{align*}
w^i \models p & \iff p \in w(i), \text{ for any } p \in AP \\
w^i \models \neg \varphi & \iff w^i \not\models \varphi \\
w^i \models \varphi_1 \lor \varphi_2 & \iff w^i \models \varphi_1 \lor w^i \models \varphi_2 \\
w^i \models X\varphi & \iff w^{i+1} \models \varphi \\
w^i \models \varphi_1 U \varphi_2 & \iff \exists k \in [i, \infty[. \ w^k \models \varphi_2 \land \forall l \in [i, k[. \ w^l \models \varphi_1
\end{align*}
\]
LTL for monitoring: LTL\textsubscript{3} - Bauer et al.

LTL has mostly been used in validation techniques such as model-checking.
LTL for monitoring: LTL$_3$ - Bauer et al.

LTL has mostly been used in validation techniques such as model-checking. The semantics needs to be adapted for monitoring.

2 issues with a semantics over infinite sequences:

- liveness properties
- we do not “know” the future
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\[
\begin{align*}
F_{\varphi} & \quad \neg \varphi \quad \neg \varphi \quad \neg \varphi \quad \neg \varphi \quad \ldots \text{unknown} \quad \ldots \text{false?} \\
G_{\varphi} & \quad \varphi \quad \varphi \quad \varphi \quad \varphi \quad \ldots \text{unknown} \quad \ldots \text{true?}
\end{align*}
\]
LTL for monitoring: $\text{LTL}_3$ - Bauer et al.

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\begin{align*}
F\varphi & \quad \varphi \quad \varphi \quad \varphi \quad \varphi \quad \varphi \quad \text{true (} \top \text{)} \\
G\varphi & \quad \varphi \quad \varphi \quad \varphi \quad \varphi \quad \varphi \quad \text{false (} \bot \text{)}
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\]
LTL for monitoring: LTL₃ - Bauer et al.

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2 issues with a semantics over infinite sequences:

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\[
\begin{align*}
F \varphi & \quad \neg \varphi \rightarrow \neg \varphi \rightarrow \neg \varphi \rightarrow \neg \varphi \rightarrow \varphi \\
G \varphi & \quad \varphi \rightarrow \varphi \rightarrow \varphi \rightarrow \varphi \rightarrow \neg \varphi 
\end{align*}
\]

true (\(\top\))

false (\(\bot\))

**Definition (LTL₃ semantics for a formula \(\varphi\))**

- \(\text{good}(\varphi) = \{ u \in \Sigma^* \mid u \cdot \Sigma^\omega \subseteq \mathcal{L}(\varphi) \}\)
- \(\text{bad}(\varphi) = \{ u \in \Sigma^* \mid u \cdot \Sigma^\omega \subseteq \Sigma^\omega \setminus \mathcal{L}(\varphi) \}\)
- Given \(u \in \Sigma^*\):

\[
\begin{align*}
u \models_3 \varphi \begin{cases} 
\top & \text{if } u \in \text{good}(\varphi) \\
\bot & \text{if } u \in \text{bad}(\varphi) \\
? & \text{otherwise}
\end{cases}
\end{align*}
\]
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An introductory example

Most modern cars realise the following abstract requirement:

“Issue warning if one of the passengers is not wearing a seat belt (when the car has reached a certain speed).”
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Could be formalised using LTL:

$$\varphi := G(speed\_low \lor (\text{pressure\_sensor\_1\_high} \Rightarrow \text{seat\_belt\_1\_on}) \land \ldots \land (\text{pressure\_sensor\_n\_high} \Rightarrow \text{seat\_belt\_n\_on})))$$

and then monitored as usual...
An introductory example

However, cars are nowadays highly distributed systems ($\geq 130$ CPUs):

Legend:

3. Occupant sensing system (only one shown)
7. Seat-belt buckle sensors
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Legend:

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You can’t easily monitor $\varphi$ without central observation point!
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   • Our setting and the intuitive idea
   • Organising Decentralised LTL Monitors (overview)
   • Migration-based Monitoring

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Decentralised monitoring – Our setting

Distributed system operating under a global clock:

\[ \Sigma = \Sigma_1 \cup \ldots \cup \Sigma_n \]

No central observation point but monitors \( M_1, \ldots, M_n \) are attached to components.
Decentralised monitoring – Our setting

Distributed system operating under a global clock:

- A set of “components” $C_1, \ldots, C_n$

\[ \Sigma = \Sigma_1 \cup \ldots \cup \Sigma_n : \text{all system events (where } \forall i, j : i \neq j \Rightarrow \Sigma_i \cap \Sigma_j = \emptyset) \]
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- No central observation point
- but monitors $M_1, \ldots, M_n$ are attached to components

\[
\begin{array}{cccc}
C_1 & \ldots & C_i & \ldots \\
\Sigma_1 & \ldots & \Sigma_i & \ldots \\
M_1 & \ldots & M_i & \ldots \\
\end{array}
\]
Decentralised monitoring – Our setting

Distributed system operating under a global clock:

- A set of “components” $C_1, \ldots, C_n$
- $\Sigma = \Sigma_1 \cup \ldots \cup \Sigma_n$: all system events (where $\forall i, j: i \neq j \Rightarrow \Sigma_i \cap \Sigma_j = \emptyset$)
- No central observation point
- but monitors $M_1, \ldots, M_n$ are attached to components
- **Synchronous** bus: at time $t$ a monitor may send/receive a message:
  - At $t + 1$ this message is received by the recipient.
  - That is, computation takes no time.
Decentralised monitoring – the idea

Monitoring $\phi(\Sigma)$?

SYNCHRONOUS BUS

$C_1 \ldots C_i \ldots C_n$

$M_1 \ldots M_i \ldots M_n$
Decentralised monitoring – the idea

Distribute $\varphi$’s evaluation & exchange obligations

Proposed Solution:

$C_1 \ldots C_i \ldots C_n$

$M_1 \varphi^t_1 \ldots M_i \varphi^t_i \ldots M_n \varphi^t_n$

SYNCHRONOUS BUS
Decentralised monitoring – the idea

Distribute $\varphi$’s evaluation & exchange obligations

Proposed Solution:

Three organizations of monitors: orchestration, migration, and choreography
(borrowing terminology from Francalanza et al.)
A note on the global clock and synchrony

– “Is a global clock realistic?”
A note on the global clock and synchrony

– “Is a global clock realistic?”
– “Not always, but many safety critical systems use it.”
A note on the global clock and synchrony

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Automotive domain uses FlexRay data bus, which has (among others) a synchronous transfer mode:

Examples: Steer-by-wire, brake-by-wire, engine management, etc.

Flight-control systems mostly synchronous (fly-by-wire):

Examples for implementation/verification systems used in this domain: SIGNAL, Lustre, Astrée verifier, etc.
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Central point monitoring the global formula.
Several communication “protocols” can be used to forward local observations.
Central point monitoring the global formula.

Several communication “protocols” can be used to forward local observations.

At the central site, at each time step, when globally monitoring $\varphi$:

1. Wait for all observations to arrive from the remote components.
2. Merge all observations to form an event.
3. Progress $\varphi$ with the event and simplify the progressed formula.
4. If a verdict is reached, stop monitoring and report result.
Migration (simplified)

- Monitor state encoded by a formula traversing the network.
- Formula to be satisfied given the local observations of traversed components.
- Formula may contain references to past time instants.
Migration (ctd)

At each component with a formula $\varphi$ to process, at each time step:

1. Use the current local observations to resolve relevant propositions.
2. Use the local history to resolve any past references to local observations.
3. Progress $\varphi$ using “obligations” to earlier observations when not locally available.
4. If a verdict is reached, stop monitoring and report result.
5. Otherwise, select the component which can resolve the “oldest” obligation and send the formula to this component.
Breaking down the formula across the network (following its syntax tree).

Tree structure where results from subformulae flow up to the parent formula.
Breaking down the formula across the network (following its syntax tree).

*Tree structure* where results from subformulae flow up to the parent formula.

At each time instant, on each component:

1. If a verdict from a child is received:
   1. Substitute the verdict for the corresponding place holder in the local formula;
   2. Apply simplification rules to the local formula.

2. Progress the local formula using the local observation.

3. If the local formula reaches a verdict, send the verdict to the parent (if any).

4. If the formula at the root of the tree reaches a verdict, stop monitoring and report result.
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Monitoring by progression

Definition (Progression function $P: \text{LTL} \times \Sigma \rightarrow \text{LTL}$)

Let $\varphi, \varphi_1, \varphi_2 \in \text{LTL}$, and $\sigma \in \Sigma$ be an event.

\[
\begin{align*}
P(p \in AP, \sigma) &= \top, \text{ if } p \in \sigma, \bot \text{ otherwise} \\
P(\varphi_1 \lor \varphi_2, \sigma) &= P(\varphi_1, \sigma) \lor P(\varphi_2, \sigma) \\
P(\varphi_1 U \varphi_2, \sigma) &= P(\varphi_2, \sigma) \lor P(\varphi_1, \sigma) \land \varphi_1 U \varphi_2 \\
P(G \varphi, \sigma) &= P(\varphi, \sigma) \land G(\varphi) \\
P(F \varphi, \sigma) &= P(\varphi, \sigma) \lor F(\varphi) \\
P(\top, \sigma) &= \top \\
P(\bot, \sigma) &= \bot \\
P(\neg \varphi, \sigma) &= \neg P(\varphi, \sigma) \\
P(X \varphi, \sigma) &= \varphi
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Example (Progression)

- Let $\varphi = G(a \land b \lor c)$
- At time $t = 0$, let $u = \{a\}$
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P(\varphi, u) = P(a \land b \lor c, u) \land G(a \land b \lor c) \\
= (P(a, u) \land P(b, u) \lor P(c, u)) \land G(a \land b \lor c) \\
= \bot \land G(a \land b \lor c) \\
= \bot
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= (P(a, u) \land P(b, u) \lor P(c, u)) \land G(a \land b \lor c) \\
= \top \lor G(a \land b \lor c) \\
= G(a \land b \lor c)
\]
Monitoring by progression

Progression provides a monitoring algorithm

\[ P(P(\ldots P(\varphi, u(0)) \ldots, u(n-1)), u(n)) = \top \implies u \in \text{good}(\varphi) \]
\[ P(P(\ldots P(\varphi, u(0)) \ldots, u(n-1)), u(n)) = \bot \implies u \in \text{bad}(\varphi) \]
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\end{align*}
\]

Observe:

- Efficiency does not depend on length of trace, but
- Potential “formula explosion” problem
  \(\iff\) continuous syntactic simplification
Is (classical) progression adequate for migration?

Example (Non-adequacy of (classical) progression)

- Architecture with components $A, B, C$, resp. observing propositions $a, b, c$
- At time $t = 0$, $u = \{a, c\}$ and $\varphi = G(a \land b \lor c)$
Is (classical) progression adequate for migration?

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- Architecture with components $A, B, C$, resp. observing propositions $a, b, c$
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- Let’s take a look at what happens on $M_A$:

\[
\text{“} P_A(\varphi, u) \text{”} = P_A(\varphi, \{a\}) \\
= P_A(a \land b \lor c, \{a\}) \land G(a \land b \lor c) \\
= (\top \land \bot \lor \bot) \land G(a \land b \lor c) \\
= \bot
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  = (\top \land \bot \lor \bot) \land G(a \land b \lor c) \\
  = \bot
  \]

- However, $u$ is not a bad prefix!
Decentralising progression on some component $C_i$

Not much changes except for atomic propositions…

**Definition (Decentralised progression for atomic propositions)**

On some component $C_i$ with atomic propositions $\text{AP}_i$

\[
P(p, \sigma, \text{AP}_i) = \begin{cases} 
\top & \text{if } p \in \sigma \\
\bot & \text{if } p \notin \sigma \land p \in \text{AP}_i \\
\text{X}_p & \text{otherwise}
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$$P(p, \sigma, AP_i) = \begin{cases} \top & \text{if } p \in \sigma \\ \bot & \text{if } p \notin \sigma \land p \in AP_i \\ \overline{X}p & \text{otherwise} \end{cases}$$

**Definition (Decentralised progression for past goals)**

On some component $C_i$ with atomic propositions $AP_i$

$$P(\overline{X}^m p, \sigma, AP_i) = \begin{cases} \top & \text{if } p \in AP_i \cap \Pi_i(\sigma(-m)) \\ \bot & \text{if } p \in AP_i \setminus \Pi_i(\sigma(-m)) \\ \overline{X}^{m+1}p & \text{otherwise} \end{cases}$$

where $\Pi_i(\sigma(-m))$ is the event observed $m$ times ago on $C_i$
Example (Adequacy of decentralised progression)

- Architecture with components $A, B, C$, resp. observing propositions $a, b, c$
- At time $t = 0$, $u = \{a, c\}$ and $\varphi = G(a \land b \lor c)$
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\text{"}P_A(\varphi, u)\text{"} = P_A(\varphi, \{a\}) \\
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= P_A(a \land b \lor c, \{a\}, \{a\}) \land P_A(a \land b \lor c, \{b\}, \{a\}) \\
\quad \land P_A(a \land b \lor c, \{c\}, \{a\}) \land G(a \land b \lor c) \\
= (\top \land \overline{X}b \lor \overline{X}c) \land G(a \land b \lor c) \\
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\begin{align*}
"P_A(\varphi, u)" & = P_A(\varphi, \{a\}) \\
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& = P_A(a \land b \lor c, \{a\}, \{a\}) \land P_A(a \land b \lor c, \{b\}, \{a\}) \land P_A(a \land b \lor c, \{c\}, \{a\}) \land G(a \land b \lor c) \\
& = (\top \land \overline{X}b \lor \overline{X}c) \land G(a \land b \lor c) \\
& = (\overline{X}b \lor \overline{X}c) \land G(a \land b \lor c) \\
\end{align*}
\]

- Monitoring can continue :-)}
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     - Migration-based Monitoring
       - Decentralised Monitoring

4. Implementation and Evaluation

5. Conclusions
Decentralised Monitoring: local algorithm at time $t$

$C_1 \quad \cdots \quad C_i \quad \cdots \quad C_n$

$M_1 \quad \cdots \quad M_i \quad \cdots \quad M_n$

SYNCHRONOUS BUS
L1. [Next goal.] Let $\varphi^t_i$ be the monitor’s current local obligation ($\varphi^0_i := \varphi$)
Decentralised Monitoring: local algorithm at time $t$

1. [Next goal.] Let $\varphi_i^t$ be the monitor’s current local obligation ($\varphi_i^0 := \varphi$)

2. [Receive messages.] ($\{\varphi_j\}_{j \in [1,m], j \neq i}$: received obligations)
   Set $\varphi_i^t := \varphi_i^t \land \bigwedge_{j \in [1,m], j \neq i} \varphi_j$
Decentralised Monitoring: local algorithm at time $t$

L1. [Next goal.] Let $\varphi^t_i$ be the monitor’s current local obligation ($\varphi^0_i := \varphi$)

L2. [Receive messages.] ($\{\varphi_j\}_{j \in [1,m], j \neq i}$: received obligations)
   Set $\varphi^t_i := \varphi^t_i \land \bigwedge_{j \in [1,m], j \neq i} \varphi_j$

L3. [Receive event.] Read next $\sigma$
Decentralised Monitoring: local algorithm at time $t$

**L1.** [Next goal.] Let $\varphi_i^t$ be the monitor’s current local obligation ($\varphi_i^0 := \varphi$)

**L2.** [Receive messages.] ($\{\varphi_j\}_{j \in [1,m], j \neq i}$: received obligations)
Set $\varphi_i^t := \varphi_i^t \land \bigwedge_{j \in [1,m], j \neq i} \varphi_j$

**L3.** [Receive event.] Read next $\sigma$

**L4.** [Progress.] Let the rewriting engine determine $\varphi_i^{t+1} := P(\varphi_i^t, \sigma, AP_i)$
Decentralised Monitoring: local algorithm at time $t$

L1. [Next goal.] Let $\varphi^t_i$ be the monitor’s current local obligation ($\varphi^0_i := \varphi$)

L2. [Receive messages.] ($\{\varphi_j\}_{j \in [1,m], j \neq i}$: received obligations)
Set $\varphi^t_i := \varphi^t_i \land \bigwedge_{j \in [1,m], j \neq i} \varphi_j$

L3. [Receive event.] Read next $\sigma$

L4. [Progress.] Let the rewriting engine determine $\varphi^{t+1}_i := P(\varphi^t_i, \sigma, AP_i)$

L5. [Evaluate and return.] If $\varphi^{t+1}_i = \top$ return $\top$, if $\varphi^{t+1}_i = \bot$ return $\bot$
Decentralised Monitoring: local algorithm at time $t$

L1. [Next goal.] Let $\varphi_i^t$ be the monitor's current local obligation ($\varphi_i^0 := \varphi$)

L2. [Receive messages.] ($\{\varphi_j\}_{j \in [1,m], j \neq i}$: received obligations)
   Set $\varphi_i^t := \varphi_i^t \land \bigwedge_{j \in [1,m], j \neq i} \varphi_j$

L3. [Receive event.] Read next $\sigma$

L4. [Progress.] Let the rewriting engine determine $\varphi_i^{t+1} := P(\varphi_i^t, \sigma, AP_i)$

L5. [Evaluate and return.] If $\varphi_i^{t+1} = \top$ return $\top$, if $\varphi_i^{t+1} = \bot$ return $\bot$

L6. [Communicate.] If $\varphi_i^{t+1}$ is urgent send it to the most “relevant” monitor
Decent progress of $\varphi = F(a \land b \land c)$, 3 components

Monitoring $\varphi = F(a \land b \land c)$

- over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$

- with
  $$\text{AP}_A = \{a\}, \text{AP}_B = \{b\}, \text{AP}_C = \{c\}$$
Decent progress of $\varphi = F(a \land b \land c)$, 3 components

Monitoring $\varphi = F(a \land b \land c)$

- over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$
- with
  $AP_A = \{a\}$, $AP_B = \{b\}$, $AP_C = \{c\}$

\[\begin{array}{ccc}
A & & B \\
\Sigma_A & \downarrow & \Sigma_B \\
M_A & & M_B \\
\end{array} \quad \begin{array}{cc}
B & C \\
\Sigma_B & \downarrow \\
M_B & M_C \\
\end{array}\]
Decent. progress. of $\varphi = F(a \land b \land c)$, 3 components

Monitoring $\varphi = F(a \land b \land c)$

- over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$
- with
  $\text{AP}_A = \{a\}, \text{AP}_B = \{b\}, \text{AP}_C = \{c\}$

\[ t = 0 \]

\begin{tikzpicture}
  \node [circle, draw] (A) at (0,0) {$A$};
  \node [rectangle, draw] (MA) at (-1,-1) {$M_A$};
  \node [circle, draw] (B) at (1,0) {$B$};
  \node [rectangle, draw] (MB) at (1,-1) {$M_B$};
  \node [circle, draw] (C) at (2,0) {$C$};
  \node [rectangle, draw] (MC) at (2,-1) {$M_C$};

  \draw [->] (A) -- (MA);
  \draw [->] (B) -- (MB);
  \draw [->] (C) -- (MC);

  \node [cloud, draw] at (MA) {$\varphi$};
  \node [cloud, draw] at (MB) {$\varphi$};
  \node [cloud, draw] at (MC) {$\varphi$};
\end{tikzpicture}

[L1.] [Next goal.] Let $\varphi^t_i$ be the monitor’s current local obligation ($\varphi^0_i := \varphi$)
Decent. progress. of $\varphi = F(a \wedge b \wedge c)$, 3 components

Monitoring $\varphi = F(a \wedge b \wedge c)$
- over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$
- with
  $AP_A = \{a\}, \ AP_B = \{b\}, \ AP_C = \{c\}$

\[ t = 0 \]

[L2.] [Receive messages.] ($\{\varphi_j\}_{j \in [1,m], j \neq i}$: received obligations)
Set $\varphi^t_i := \varphi_i^t \wedge \bigwedge_{j \in [1,m], j \neq i} \varphi_j$
Decent progress of $\varphi = F(a \land b \land c)$, 3 components

Monitoring $\varphi = F(a \land b \land c)$
- over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$
- with
  $\text{AP}_A = \{a\}$, $\text{AP}_B = \{b\}$, $\text{AP}_C = \{c\}$

$L3.$ [Receive event.] Read next $\sigma$

```
\begin{array}{c}
\text{A} \\
\{a\} \\
M_A \varphi \\
B \\
\{b\} \\
M_B \varphi \\
C \\
\emptyset \\
M_C \varphi
\end{array}
```
Decent. progress. of $\varphi = \mathbf{F}(a \land b \land c)$, 3 components

Monitoring $\varphi = \mathbf{F}(a \land b \land c)$
- over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$
- with
  $\text{AP}_A = \{a\}$, $\text{AP}_B = \{b\}$, $\text{AP}_C = \{c\}$

[L4.] [Progress.] Let the rewriting engine determine $\varphi_i^{t+1} := P(\varphi_i^t, \sigma, \text{AP}_i)$
- $\varphi_1^A := P(\varphi, \{a\}, \text{AP}_A) = P(a \land b \land c, \{a\}, \text{AP}_A) \lor \varphi = \overline{X}b \land \overline{X}c \lor \varphi$
Decent progress of $\varphi = F(a \land b \land c)$, 3 components

Monitoring $\varphi = F(a \land b \land c)$

- over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$
- with $AP_A = \{a\}, AP_B = \{b\}, AP_C = \{c\}$

\[ t = 0 \]

[L4.] [Progress.] Let the rewriting engine determine $\varphi_i^{t+1} := P(\varphi_i^t, \sigma, AP_i)$

- $\varphi_A^1 := P(\varphi, \{a\}, AP_A) = P(a \land b \land c, \{a\}, AP_A) \lor \varphi = \overline{X}b \land \overline{X}c \lor \varphi$
- $\varphi_B^1 := P(\varphi, \{b\}, AP_B) = P(a \land b \land c, \{b\}, AP_B) \lor \varphi = \overline{X}a \land \overline{X}c \lor \varphi$
Decent progress of $\varphi = F(a \land b \land c)$, 3 components

Monitoring $\varphi = F(a \land b \land c)$
- over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$
- with
  $$\text{AP}_A = \{a\}, \text{AP}_B = \{b\}, \text{AP}_C = \{c\}$$

\[ t = 0 \]

[L4.] [Progress.] Let the rewriting engine determine $\varphi_i^{t+1} := P(\varphi_i^t, \sigma, \text{AP}_i)$
- $\varphi_A^1 := P(\varphi, \{a\}, \text{AP}_A) = P(a \land b \land c, \{a\}, \text{AP}_A) \lor \varphi = \overline{X}b \land \overline{X}c \lor \varphi$
- $\varphi_B^1 := P(\varphi, \{b\}, \text{AP}_B) = P(a \land b \land c, \{b\}, \text{AP}_B) \lor \varphi = \overline{X}a \land \overline{X}c \lor \varphi$
- $\varphi_C^1 := P(\varphi, \emptyset, \text{AP}_C) = P(a \land b \land c, \emptyset, \text{AP}_C) \lor \varphi = \varphi$
Decent progress of $\varphi = F(a \land b \land c)$, 3 components

Monitoring $\varphi = F(a \land b \land c)$
- over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$
- with $AP_A = \{a\}, AP_B = \{b\}, AP_C = \{c\}$

$L5.$ [Evaluate and return.] If $\varphi_i^{t+1} = \top$ return $\top$, if $\varphi_i^{t+1} = \bot$ return $\bot$
Decent progress of $\varphi = F(a \land b \land c)$, 3 components

Monitoring $\varphi = F(a \land b \land c)$

- over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$
- with $\text{AP}_A = \{a\}$, $\text{AP}_B = \{b\}$, $\text{AP}_C = \{c\}$

\[ t = 0 \]

[Communicate.] If $\varphi_i^{t+1}$ is urgent send it to the most “relevant” monitor

- $\text{urgency}(\varphi_1^A) = \text{urgency}(\overline{X}b \land \overline{X}c \lor \varphi) = 1 \leadsto M_B$
- $\text{urgency}(\varphi_1^B) = \text{urgency}(\overline{X}a \land \overline{X}c \lor \varphi) = 1 \leadsto M_A$
- $\text{urgency}(\varphi_1^C) = \text{urgency}(\varphi) = 0$
Decent. progress. of $\varphi = F(a \land b \land c)$, 3 components

Monitoring $\varphi = F(a \land b \land c)$
- over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$
- with
  $\text{AP}_A = \{a\}, \text{AP}_B = \{b\}, \text{AP}_C = \{c\}$

$L1.$ [Next goal.] Let $\varphi_i^t$ be the monitor’s current local obligation ($\varphi_i^0 := \varphi$)
Decent progress of $\varphi = F(a \land b \land c)$, 3 components

Monitoring $\varphi = F(a \land b \land c)$
- over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$
- with
  $\mathsf{AP}_A = \{a\}, \mathsf{AP}_B = \{b\}, \mathsf{AP}_C = \{c\}$

$L2.$ [Receive messages.] $(\{\varphi_j\}_{j \in [1,m], j \neq i}$: received obligations)
Set $\varphi^t_i := \varphi^t_i \land \bigwedge_{j \in [1,m], j \neq i} \varphi_j$
Decent. progress. of $\varphi = F(a \land b \land c)$, 3 components

Monitoring $\varphi = F(a \land b \land c)$
- over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$
- with
  $\text{AP}_A = \{a\}$, $\text{AP}_B = \{b\}$, $\text{AP}_C = \{c\}$

$L3.$ [Receive event.] Read next $\sigma$

$t = 1$
Decent progress. of $\varphi = F(a \land b \land c)$, 3 components

Monitoring $\varphi = F(a \land b \land c)$
- over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$
- with $AP_A = \{a\}, AP_B = \{b\}, AP_C = \{c\}$

$[L4.]$ [Progress.] Let the rewriting engine determine $\varphi_{i+1}^t := P(\varphi_i^t, \sigma, AP_i)$
- $\varphi_A^2 := P(\overline{X}a \land \overline{X}c \lor \varphi \land \# \land \{a\}, AP_A) = \overline{X}^2 c \lor (\overline{X}b \land \overline{X}c \lor \varphi)$
Decent. progress. of $\varphi = F(a \land b \land c)$, 3 components

Monitoring $\varphi = F(a \land b \land c)$
- over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$
- with
  \[ AP_A = \{a\}, \ AP_B = \{b\}, \ AP_C = \{c\} \]

\[ t = 1 \]

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{diagram.png}
\end{figure}

[L4.] [Progress.] Let the rewriting engine determine $\varphi_i^{t+1} := P(\varphi_i^t, \sigma, AP_i)$
- $\varphi_A^2 := P(\overline{X}a \land \overline{X}c \lor \varphi \land \#, \{a\}, AP_A) = \overline{X}^2 c \lor (\overline{X}b \land \overline{X}c \lor \varphi)$
- $\varphi_B^2 := P(\overline{X}b \land \overline{X}c \lor \varphi \land \#, \{b\}, AP_B) = \overline{X}^2 c \lor (\overline{X}a \land \overline{X}c \lor \varphi)$
Decent. progress. of $\varphi = F(a \land b \land c)$, 3 components

Monitoring $\varphi = F(a \land b \land c)$
- over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$
- with
  $$\text{AP}_A = \{a\}, \text{AP}_B = \{b\}, \text{AP}_C = \{c\}$$

\[ t = 1 \]

[L4.] [Progress.] Let the rewriting engine determine $\varphi_i^{t+1} := P(\varphi_i^t, \sigma, \text{AP}_i)$
- $\varphi_A^2 := P(\overline{X}a \land \overline{X}c \lor \varphi \land \# , \{a\}, \text{AP}_A) = \overline{X}^2 c \lor (\overline{X}b \land \overline{X}c \lor \varphi)$
- $\varphi_B^2 := P(\overline{X}b \land \overline{X}c \lor \varphi \land \# , \{b\}, \text{AP}_B) = \overline{X}^2 c \lor (\overline{X}a \land \overline{X}c \lor \varphi)$
- $\varphi_C^2 := P(\varphi, \{c\}, \text{AP}_C) = \overline{X}a \land \overline{X}b \lor \varphi$
Decent progress of \( \varphi = \mathsf{F}(a \land b \land c) \), 3 components

**Monitoring** \( \varphi = \mathsf{F}(a \land b \land c) \)
- over \( \{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset \)
- with
  \[
  \text{AP}_A = \{a\}, \text{AP}_B = \{b\}, \text{AP}_C = \{c\}
  \]

\[
\begin{array}{llll}
A & & B & \text{C}\\
M_A & \overline{X}^2c \lor (\overline{X}b \land \overline{X}c \lor \varphi) & M_B & \overline{X}^2c \lor (\overline{X}b \land \overline{X}c \lor \varphi) & M_C & \overline{X}a \land \overline{X}b \lor \varphi
\end{array}
\]

[L5.] [Evaluate and return.] If \( \varphi^t_{i+1} = \top \) return \( \top \), if \( \varphi^t_{i+1} = \bot \) return \( \bot \)
Decent progress of \( \varphi = F(a \land b \land c) \), 3 components

Monitoring \( \varphi = F(a \land b \land c) \)
- over \( \{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset \)
- with
  \[
  AP_A = \{a\}, AP_B = \{b\}, AP_C = \{c\}
  \]

\[
\begin{align*}
A & : M_A \quad \overline{X}^2 c \lor (\overline{X}b \land \overline{X}c \lor \varphi) \\
B & : M_B \quad \overline{X}^2 c \lor (\overline{X}b \land \overline{X}c \lor \varphi) \\
C & : M_C \quad \overline{X}a \land \overline{X}b \lor \varphi
\end{align*}
\]

\[t = 1\]

[L6.] [Communicate.] If \( \varphi_i^{t+1} \) is urgent send it to the most “relevant” monitor
- \( \text{urgency}(\overline{X}^2 c \lor (\overline{X}a \land \overline{X}c \lor \varphi)) = 2 \leadsto M_C \)
- \( \text{urgency}(\overline{X}^2 c \lor (\overline{X}a \land \overline{X}c \lor \varphi)) = 2 \leadsto M_C \)
- \( \text{urgency}(\overline{X}a \land \overline{X}b \lor \varphi) = 1 \leadsto M_A \)
Decent. progress. of $\varphi = F(a \land b \land c)$, 3 components

Monitoring $\varphi = F(a \land b \land c)$ over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$

with $\Sigma_A = \{a\}, \Sigma_B = \{b\}, \Sigma_C = \{c\}$

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<td>$\sigma$</td>
<td>${a, b}$</td>
<td>${a, b, c}$</td>
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<tr>
<td>$M_A$: $\varphi_A^1$</td>
<td>$P(\varphi, {a}, AP_A) = P(a \land b \land c, {a}, AP_A) \lor \varphi$</td>
<td>$P(\varphi_B^1 \land #, {a}, AP_A)$</td>
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<td></td>
<td>$= \overline{X}b \land \overline{X}c \lor \varphi$</td>
<td>$= \overline{X}c \lor (\overline{X}b \land \overline{X}c \lor \varphi)$</td>
</tr>
<tr>
<td>$M_B$: $\varphi_B^1$</td>
<td>$P(\varphi, {b}, AP_B) = P(a \land b \land c, {b}, AP_B) \lor \varphi$</td>
<td>$P(\varphi_A^1 \land #, {b}, AP_B)$</td>
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<tr>
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<td>$= \overline{X}a \land \overline{X}c \lor \varphi$</td>
<td>$= \overline{X}c \lor (\overline{X}a \land \overline{X}c \lor \varphi)$</td>
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<td>$M_C$: $\varphi_C^1$</td>
<td>$P(\varphi, {c}, AP_C) = P(a \land b \land c, \emptyset, AP_C) \lor \varphi$</td>
<td>$P(\varphi, {c}, AP_C)$</td>
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Decent. progress. of $\varphi = F(a \land b \land c)$, 3 components

Monitoring $\varphi = F(a \land b \land c)$ over $\{a, b\} \cdot \{a, b, c\} \cdot \emptyset \cdot \emptyset$

with $\Sigma_A = \{a\}, \Sigma_B = \{b\}, \Sigma_C = \{c\}$

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<td>${a, b}$</td>
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<td>$M_A$:</td>
<td>$\varphi_A^1 := P(\varphi, {a}, AP_A) = P(a \land b \land c, {a}, AP_A) \lor \varphi$</td>
<td>$\varphi_A^2 := P(\varphi_A^1 \land #, {a}, AP_A)$</td>
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<td>$= \overline{X} b \land \overline{X} c \lor \varphi$</td>
<td>$= \overline{X}^2 c \lor (\overline{X} b \land \overline{X} c \lor \varphi)$</td>
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<td>$M_B$:</td>
<td>$\varphi_B^1 := P(\varphi, {b}, AP_B) = P(a \land b \land c, {b}, AP_B) \lor \varphi$</td>
<td>$\varphi_B^2 := P(\varphi_B^1 \land #, {b}, AP_B)$</td>
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<td>$M_C$:</td>
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<td>$\varphi_C^2 := P(\varphi, {c}, AP_C)$</td>
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<td>$\emptyset$</td>
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<td>$M_A$:</td>
<td>$\varphi_A^3 := P(\varphi_C^2 \land #, \emptyset, AP_A)$</td>
<td>$\varphi_A^4 := P(\varphi_C^3 \land #, \emptyset, AP_A)$</td>
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<td>$= \overline{X}^2 b \lor (\overline{X} b \land \overline{X} c \lor \varphi)$</td>
<td>$= \overline{X}^3 b \lor (\overline{X} b \land \overline{X} c \lor \varphi)$</td>
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<td>$M_B$:</td>
<td>$\varphi_B^3 := P(#, \emptyset, AP_B)$</td>
<td>$\varphi_B^4 := P(\varphi_A^3 \land #, \emptyset, AP_B)$</td>
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<tr>
<td></td>
<td>$= #$</td>
<td>$= \top$</td>
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<tr>
<td>$M_C$:</td>
<td>$\varphi_C^3 := P(\varphi_A^3 \land \varphi_B^3 \land #, \emptyset, AP_C)$</td>
<td>$\varphi_C^4 := P(# , \emptyset, AP_C)$</td>
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<tr>
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<td>$= \overline{X}^2 a \land \overline{X}^2 b \lor \varphi$</td>
<td>$= #$</td>
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</table>
Some properties of the algorithm

Let $\varphi \in \text{LTL}$ and $u \in \Sigma^*$

What is the link between:
- $\models_3$: centralised $LTL_3$ semantics
- $\models_D$: decentralised $LTL_3$ semantics

Theorem (Soundness)

$u \models_3 \varphi = \top / \bot \Rightarrow u \models_3 \varphi = ?$

Theorem (Completeness)

$u \models_3 \varphi = \top / \bot \Rightarrow \exists u' \in \Sigma^*, |u'| \leq |M| \land u \cdot u' = D \varphi = \top / \bot$
Some properties of the algorithm

Let $\varphi \in \text{LTL}$ and $u \in \Sigma^*$

What is the link between:

- $\models_3$: centralised $\text{LTL}_3$ semantics
- $\models_D$: decentralised $\text{LTL}_3$ semantics

**Theorem (Soundness)**

$u \models_D \varphi = T/\bot \Rightarrow u \models_3 \varphi = T/\bot$

$u \models_3 \varphi = ? \Rightarrow u \models_D \varphi = ?$
Some properties of the algorithm

Let $\varphi \in \text{LTL}$ and $u \in \Sigma^*$

What is the link between:

- $\models_3$: centralised $LTL_3$ semantics
- $\models_D$: decentralised $LTL_3$ semantics

**Theorem (Soundness)**

\[
\begin{align*}
    u \models_D \varphi = \top / \bot \Rightarrow u \models_3 \varphi = \top / \bot \\
    u \models_3 \varphi = ? \Rightarrow u \models_D \varphi = ?
\end{align*}
\]

**Theorem (Completeness)**

\[
\begin{align*}
    u \models_3 \varphi = \top / \bot \Rightarrow \exists u' \in \Sigma^*. \|u'| \leq |\mathcal{M}| \land u \cdot u' \models_D \varphi = \top / \bot
\end{align*}
\]
How much a monitor has to remember?

**Theorem (Maximum delay)**

Let $\neg X^m p \in \text{LTL}$ be a local obligation on some monitor $M_i \in \mathcal{M}$.

In the worst case, $m \leq \min(|\mathcal{M}|, t + 1)$ at any time $t \in \mathbb{N}^{\geq 0}$. This, at the same time, reflects the communication delay by which a decentralised monitor may come to a verdict!

However, unless, there could be a (possibly infinite) delay not due to communication: $XX \text{true}$ and $G(\text{true} U (Gb \lor F \neg b))$.

**Corollary**

Given a "clean input": communication delay = memory requirements = verdict delay. (Otherwise, we can't say much at all.)
How much a monitor has to remember?

Theorem (Maximum delay)

Let $\overline{X}^m p \in \text{LTL}$ be a local obligation on some monitor $M_i \in \mathcal{M}$

In the worst case, $m \leq \min(|\mathcal{M}|, t + 1)$ at any time $t \in \mathbb{N}^\geq 0$

This, at the same time, reflects the communication delay by which a decentralised monitor may come to a verdict!
How much a monitor has to remember?

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Unless, there could be a (possibly infinite) delay not due to communication:

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**However**

Unless, there could be a (possibly infinite) delay not due to communication:

- $XXtrue$ and $G(trueU(Gb \lor F\neg b))$

**Corollary**

Given a “clean input”: communication delay $=$ memory requirements $=$ verdict delay. (Otherwise, we can’t say much at all.)
Outline – Decentralised Monitoring of LTL formulae

1 Background

2 Motivations

3 Decentralised Monitoring of LTL formulae

4 Implementation and Evaluation

5 Conclusions
DecentMon: an OCaml benchmark simulating the decentralised algorithm

http://decentmon.forge.imag.fr/

Occurrences of atomic propositions can be parameterised according to several probability distributions
What we wanted to compare

Two monitoring modes:

- **decentralised** mode (i.e., each trace is read by a separate monitor)
- **centralised** mode by merging the traces and using a “central monitor”

Four metrics:

- **length of the trace** needed to reach a verdict
- **number and size of messages** exchanged between monitors
- **number of progressions** performed by local monitors
Experimental Results - number of messages

**random formula generation**

- orchestration
- migration
- choreography

**biased formula generation**

- orchestration
- migration
- choreography
Experimental Results - size of messages

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Experimental Results - number of progressions

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Outline – Conclusions

1. Background
2. Motivations
3. Decentralised Monitoring of LTL formulae
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Conclusions

Summary [FM12, RV14, FMSD16a, FMSD16b]

- Monitoring of (off the shelf) LTL specifications in a decentralised fashion
- No central observation point
- Keeping the communication at a minimum with negligible delay
- Validated by experimental results

Future Work

- Operational description of specifications (e.g. automata).
- Heuristics based on syntactic criteria to determine the organisation of monitor.
- Rigorous analysis of the cost of decentralised monitoring.
Please consider submitting to RV 2016 :-)!

The 16th International Conference on Runtime Verification,
September 23-30 2016, Madrid, Spain


- Abstract deadline: May 20, 2016
- Paper and tutorial deadline: May 27, 2016
- COST ARVI Summer school on Runtime Verification: September 23-25, 2016
- Workshops and tutorials: September 26-27, 2016
Andreas Klaus Bauer and Yliès Falcone.
Decentralised LTL monitoring.

Andreas Bauer and Yliès Falcone.
Decentralised LTL monitoring.
To appear. Online version at Springer.

Christian Colombo and Yliès Falcone.
Organising LTL monitors over distributed systems with a global clock.
To appear. Online version at Springer.

Christian Colombo and Yliès Falcone.
Organising LTL monitors over distributed systems with a global clock.
Related Work

**Diagnosis of DES**

- detect the occurrence of a fault after a finite number of discrete steps
- *diagnosability*: a system model is *diagnosable* if it is always the case that the occurrence of a fault can be detected after a finite number of discrete steps
- Uses the model of a system (usually contains faulty + nominal behaviours)

**Decentralised observability**

- Various degrees of observability depending on available memory of local observers
- Combine the local observers’ states after reading some trace to a truthful verdict w.r.t. the monitored property
- Comparison with our approach:
  - No central-observation point
  - Observability is taken for granted
  - Minimisation of communication overhead
Related Work (ctd)

Monitoring

- MtTL monitoring properties of *asynchronous systems* [Sen et al.]
  - systems operating concurrently
  - partially ordered traces
  - LTL + modalities about the distributed nature of the system
  - Comparison with our approach:
    - synchronous systems
    - not restricted to safety properties
    - no collection of global behavior

- Monitoring distributed controllers [Genon et al.]
  - partially ordered traces (asynchronous systems)
  - exploration of execution interleavings
  - restricted to bad prefixes