Verification of Artifact-Centric Multi-Agent Systems via Finite Abstraction: Some Decidability Results

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Model Checking in one slide

Model checking: technique(s) to **automatically** verify that a system design S satisfies a property P **before** deployment.

More formally, given

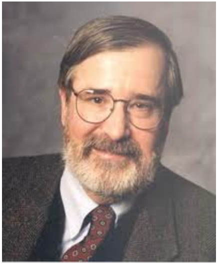
- a model $\mathcal{M}_S$ of a system S
- a formula ϕ_P representing a property P

we check that

$$\mathcal{M}_S \models \phi_P$$

Turing Award 2007

www.acm.org/press-room/news-releases-2008/turing-award-07



(a) E. Clarke (CMU, USA)

(b) A. Emerson (U. Texas, USA)

(c) J. Sifakis (IMAG, F)

- Jury justification

  For their roles in developing model checking into a highly effective verification technology, widely adopted in the hardware and software industries.

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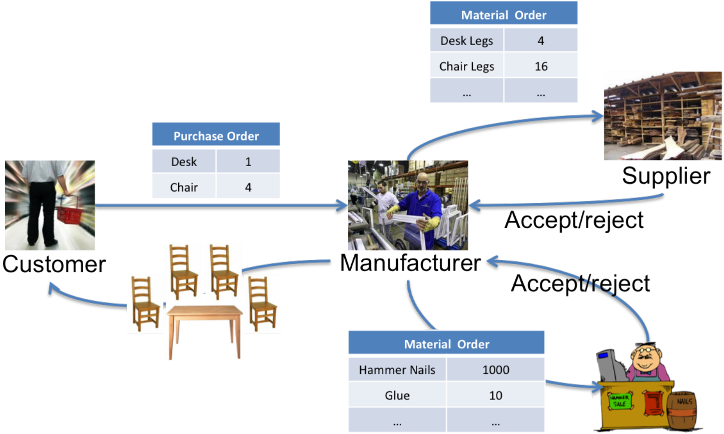
2. Main task: *Formal* verification of *infinite-state* AS
   - model checking is appropriate for control-intensive applications...
   - ...but less suited for data-intensive applications (data typically ranges over infinite domains) [1].
3. Key contribution: Verification of *bounded* and *uniform* AS is decidable

- Recent paradigm for Service-Oriented Computing [2].
- Motto: let's give *data* and *processes* the same relevance!
- *Artifact*: data model + lifecycle
  - (nested) records equipped with actions
  - actions may affect several artifacts
  - evolution stemming from the interaction with other artifacts/external actors
- *Artifact System*: interacting artifacts, representing services, manipulated by agents.

Artifact Systems

Order-to-Cash Scenario



Artifact Systems

Data Model

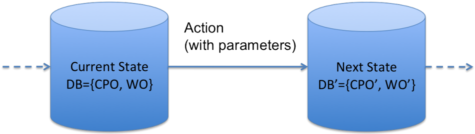
PO			
id	*prod_code*	*offer*	*status*

- *createPO(prod_code, offer)*
- *deletePO(id)*
- *addItemPO(id,itm,qty)*
- ...

MO			
id	*prod_code*	*price*	*status*

- *createMO(id,price)*
- *deleteMO(id)*
- *addLineItemMO(id,mat,qty)*
- ...

- Agents operate on artifacts.
  - e.g., the Customer sends the Purchase Order to the Manufacturer.
- Actions add/remove artifacts or change artifact attributes.
  - e.g., the PO status changes from *created* to *submitted*.
- The whole system can be seen as a *data-aware* dynamic system.
  - at every step, an action yields a change in the current state.



Research questions

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1. Which syntax and semantics to specify AS?
2. Is verification of AS decidable?
3. If not, can we identify *relevant* fragments that are reasonably well-behaved?
4. How can we implement this?

Challenges

Multi-agent systems, but . . .

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$\Rightarrow$ The model checking problem cannot be tackled by standard techniques.

1. *Artifact-centric multi-agent systems* (AC-MAS): formal model for AS.

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2. FO-CTLK as a specification language:

$$AG\ \forall id, pc\ (\exists \vec{x}\ MO(id, pc, \vec{x}) \rightarrow K_M\ \exists \vec{y}\ PO(id, pc, \vec{y}))$$

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   Main result: under specific conditions MC can be reduced to the finite case.

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4. Modelling of declarative GSM systems, developed by IBM, as AC-MAS.

Semantics: Databases

The data model of Artifact Systems is given as a database.

- a *database schema* is a *finite* set $\mathcal{D} = \{P_1/a_1, \ldots, P_n/a_n\}$ of predicate symbols P_i with arity $a_i \in \mathbb{N}$.
- an *instance* on a domain U is a mapping D associating each predicate symbol P_i with a *finite* a_i-ary relation on U.
- *Disjoint union*: $D \oplus D'$ is the $(\mathcal{D} \cup \mathcal{D}')$-interpretation s.t.
  (i) $D \oplus D'(P_i) = D(P_i)$
  (ii) $D \oplus D'(P_i') = D'(P_i)$

Agents have partial access (*views*) to the artifact system.

- An *agent* is a tuple $i = \langle \mathcal{D}_i, Act_i, Pr_i \rangle$ where
  - $\mathcal{D}_i$ is the *local database schema*
  - Act_i is the set of *local actions* $\alpha(\vec{x})$ with parameters $\vec{x}$
  - $Pr_i : \mathcal{D}_i(U) \mapsto 2^{Act_i(U)}$ is the *local protocol function*
- the setting is reminiscent of the *interpreted systems semantics* for MAS [3],...
- ...but here the local state of each agent is relational.

Intuitively, agents manipulate artifacts and have (partial) access to the information contained in the global db schema $\mathcal{D} = \mathcal{D}_1 \cup \cdots \cup \mathcal{D}_n$.

Example 1: the Order-to-Cash Scenario

- Agents: Customer, Manifacturer, Supplier.
- Local db schema $\mathcal{D}_C$
  - *Products(prod_code, budget)*
  - *PO(id, prod_code, offer, status)*
- Local db schema $\mathcal{D}_M$
  - *PO(id, prod_code, offer, status)*
  - *MO(id, prod_code, price, status)*
- Local db schema $\mathcal{D}_S$
  - *Materials(mat_code, cost)*
  - *MO(id, prod_code, price, status)*
- Then, $\mathcal{D} = \{Materials, Products, PO, MO\}$.
- Parametric actions can introduce values from an infinite domain U.
  - *createPO(prod_code, offer)* belongs to Act_C.
  - *createMO(prod_code, price)* belongs to Act_M.

Artifact-centric Multi-agent Systems

Agents are modules that can be composed together to obtain AC-MAS.

- *Global states* are tuples $s = \langle D_0, \ldots, D_n \rangle \in \mathcal{D}(U)$.
- An *AC-MAS* is a tuple $\mathcal{P} = \langle Ag, s_0, \tau \rangle$ where:
  - $Ag = \{0, \ldots, n\}$ is a *finite set of agents*
  - $s_0 \in \mathcal{D}(U)$ is the *initial global state*
  - $\tau : \mathcal{D}(U) \times Act(U) \mapsto 2^{\mathcal{D}(U)}$ is the *transition function*
- *Temporal transition*: $s \rightarrow s'$ iff there is $\alpha(\vec{u})$ s.t. $s' \in \tau(s, \alpha(\vec{u}))$.
- *Epistemic relation*: $s \sim_i s'$ iff $D_i = D'_i$.
- AC-MAS are infinite-state systems in general.

AC-MAS are first-order temporal epistemic structures.
Hence, FO-CTLK can be used as a specification language.

Syntax: FO-CTLK

- Data call for First-order Logic.
- Evolution calls for Temporal Logic.
- Agents (operating on artifacts) call for Epistemic Logic.

The specification language FO-CTLK:

$$\varphi ::= P(\vec{t}) \mid t = t' \mid \neg\varphi \mid \varphi \rightarrow \varphi \mid \forall x \varphi \mid AX\varphi \mid A\varphi U\varphi \mid E\varphi U\varphi \mid K_i\varphi$$

Alternation of free variables and modal operators is enabled.

Semantics of FO-CTLK

Formal definition

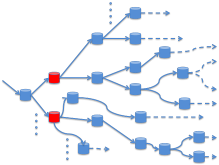
An AC-MAS $\mathcal{P}$ satisfies an FO-CTLK-formula φ in a state s for an assignment σ, iff

$$
\begin{array}{lll}
(\mathcal{P}, s, \sigma) \models P_i(\vec{t}) & \text{iff} & \langle \sigma(t_1), \ldots, \sigma(t_{a_i}) \rangle \in D_s(P_i) \\
(\mathcal{P}, s, \sigma) \models t = t' & \text{iff} & \sigma(t) = \sigma(t') \\
(\mathcal{P}, s, \sigma) \models \neg\varphi & \text{iff} & (\mathcal{P}, s, \sigma) \not\models \varphi \\
(\mathcal{P}, s, \sigma) \models \varphi \rightarrow \psi & \text{iff} & (\mathcal{P}, s, \sigma) \not\models \varphi \text{ or } (\mathcal{P}, s, \sigma) \models \psi \\
(\mathcal{P}, s, \sigma) \models \forall x \varphi & \text{iff} & \text{for all } u \in adom(s),\ (\mathcal{P}, s, \sigma^x_u) \models \varphi \\
(\mathcal{P}, s, \sigma) \models AX\varphi & \text{iff} & \text{for all runs } r,\ r^0 = s \text{ implies } (\mathcal{P}, r^1, \sigma) \models \varphi \\
(\mathcal{P}, s, \sigma) \models A\varphi U\varphi' & \text{iff} & \text{for all runs } r,\ r^0 = s \text{ implies } (\mathcal{P}, r^k, \sigma) \models \varphi' \text{ for some } k \geq 0, \\
 & & \text{and } (\mathcal{P}, r^{k'}, \sigma) \models \varphi \text{ for all } 0 \leq k' < k \\
(\mathcal{P}, s, \sigma) \models E\varphi U\varphi' & \text{iff} & \text{there exists } r \text{ s.t. } r^0 = s,\ (\mathcal{P}, r^k, \sigma) \models \varphi' \text{ for some } k \geq 0, \\
 & & \text{and } (\mathcal{P}, r^{k'}, \sigma) \models \varphi \text{ for all } 0 \leq k' < k \\
(\mathcal{P}, s, \sigma) \models K_i\varphi & \text{iff} & \text{for all states } s',\ s \sim_i s' \text{ implies } (\mathcal{P}, s', \sigma) \models \varphi
\end{array}
$$

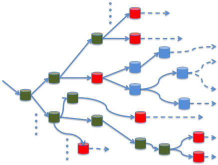
- Active-domain semantics: $adom(D)$ is the set of all $u \in U$ appearing in D

Semantics of FO-CTLK

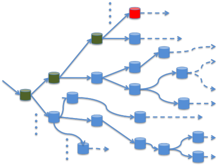
Intuition



(d) $AX\varphi$



(e) $A\varphi U\psi$



(f) $E\varphi U\psi$

Verification of AC-MAS

How do we verify FO-CTLK specifications on AC-MAS?

- the manufacturer M knows that each MO has to match a corresponding PO:

$$AG\ \forall id, pc\ (\exists pr, s\ MO(id, pc, pr, s) \rightarrow K_M\ \exists o, s'\ PO(id, pc, o, s'))$$

- the client C knows that every PO will eventually be discharged (by M):

$$AG\ \forall id, pc\ (\exists pr, s\ MO(id, pc, pr, s) \rightarrow EF\ K_C\ \exists o\ PO(id, ps, o, \text{shipped}))$$

Problem: the infinite domain U may generate infinitely many states!

Investigated solution: can we *simulate* the concrete values from U with a finite set of *abstract* symbols?

Abstraction: Isomorphism and Bisimulation

- Two states s, s' are *isomorphic*, or $s \simeq s'$, if there is a bijection

$$\iota : adom(s) \cup C \mapsto adom(s') \cup C$$

such that

  - ι is the identity on C
  - for every $\vec{u} \in adom(s)^{a_i}$, $i \in Ag$, $\vec{u} \in D_i(P_j) \Leftrightarrow \iota(\vec{u}) \in D'_i(P_j)$

D	
a	b
b	c
d	e

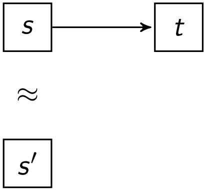
$\simeq$

D'	
1	2
2	c
4	5

  - $\iota : a \mapsto 1$
    $b \mapsto 2$
    $c \mapsto$ c
    $d \mapsto 4$
    $e \mapsto 5$

Abstraction: Isomorphism and Bisimulation

- Two states s, s' are *bisimilar*, or $s \approx s'$, if
  - $s \simeq s'$
  - if $s \longrightarrow t$ then there is t' s.t. $s' \longrightarrow t'$, $s \oplus t \simeq s' \oplus t'$, and $t \approx t'$



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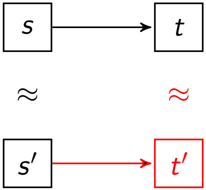
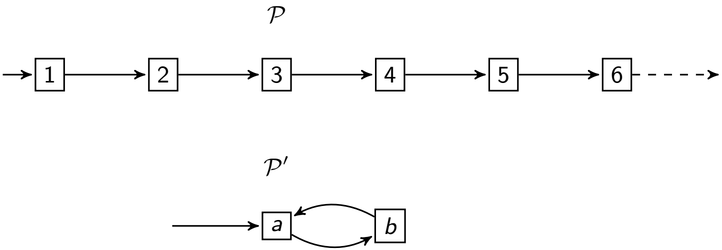


  - the other direction holds as well
  - similarly for the epistemic relation $\sim_i$

Abstraction: Isomorphism and Bisimulation

However, bisimulation is not sufficient to preserve FO-CTLK formulas:



$$\phi \quad = \quad AG\ \forall x\ (P(x) \rightarrow AX\ AG\ \neg P(x))$$

Uniformity

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- More formally, an AC-MAS $\mathcal{P}$ is *uniform* iff for $s, t, s' \in \mathcal{S}$ and $t' \in \mathcal{D}(U)$:
  - $s \rightarrow t$ and $s \oplus t \simeq s' \oplus t'$ imply $s' \rightarrow t'$

s	
a	b
b	c
d	e

$\longrightarrow$

t	
a	f
f	c

s'	
1	2
2	c
4	5

t'	
1	6
6	c

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- Uniform AC-MAS cover a vast number of interesting cases [2, 4].

Bisimulation and Equivalence w.r.t. FO-CTLK

Theorem

Consider

- bisimilar *and* uniform *AC-MAS* $\mathcal{P}_1$ *and* $\mathcal{P}_2$
- *an FO-CTLK formula* φ

If

1. $|U_2| \geq 2 \cdot \sup_{s \in \mathcal{P}_1} |adom(s)| + |C| + |vars(\varphi)|$
2. $|U_1| \geq 2 \cdot \sup_{s' \in \mathcal{P}_2} |adom(s')| + |C| + |vars(\varphi)|$

then

$$\mathcal{P}_1 \models \varphi \quad \textit{iff} \quad \mathcal{P}_2 \models \varphi$$

Can we apply this result to finite abstraction?

Abstractions

- Abstractions are defined in an agent-based, modular way.
- Let $A = \langle \mathcal{D}, Act, Pr \rangle$ be an agent defined on the domain U. Given a domain U', the *abstract agent* $A' = \langle \mathcal{D}', Act', Pr' \rangle$ on U' is s.t.
  - $\mathcal{D}' = \mathcal{D}$
  - $Act' = Act$
  - Pr' is the smallest function s.t. if $\alpha(\vec{u}) \in Pr(D)$, $D' \in \mathcal{D}'(U')$ and $D' \simeq D$ for some witness ι, then $\alpha(\vec{u}') \in Pr'(D')$ where $\vec{u}' = \iota'(\vec{u})$ for some constant-preserving bijection ι' extending ι to $\vec{u}$.
- Let Ag' be the set of abstract agents on U'.
- Let $\mathcal{P} = \langle Ag, s_0, \tau \rangle$ be an AC-MAS. The AC-MAS $\mathcal{P}' = \langle Ag', s_0', \tau' \rangle$ is an *abstraction* of $\mathcal{P}$ iff
  - $s_0' \simeq s_0$;
  - τ' is the smallest function s.t. if $t \in \tau(s, \alpha(\vec{u}))$, $s', t' \in D'(U')$ and $s \oplus t \simeq s' \oplus t'$ for some witness ι, then $t' \in \tau'(s', \alpha(\vec{u}'))$ where $\vec{u}' = \iota'(\vec{u})$ for some constant-preserving bijection ι' extending ι to $\vec{u}$.

Bounded Models and Finite Abstractions

- An AC-MAS $\mathcal{P}$ is *b-bounded* iff for all $s \in \mathcal{P}$, $|adom(s)| \leq b$.
- Bounded systems can still be infinite!

Theorem

Consider

- *a* b-bounded *and* uniform *AC-MAS* $\mathcal{P}$ *on an infinite domain* U
- *an FO-CTLK formula* φ

Given $U' \supseteq C$ *s.t.*

$$|U'| \geq 2b + |C| + \max\{|vars(\varphi)|, N_{Ag}\}$$

there exists a finite abstraction $\mathcal{P}'$ *of* $\mathcal{P}$ *s.t.*

- $\mathcal{P}'$ *is uniform and bisimilar to* $\mathcal{P}$

In particular,

$$\mathcal{P} \models \varphi \quad \textit{iff} \quad \mathcal{P}' \models \varphi$$

How can we define finite abstractions constructively?

Compact descriptions: AS Programs

Example of uniform AC-MAS written in a FO language.

- for each agent i, Act_i is the set of of *local (parametric) actions* of the form $\omega(\vec{x}) = \langle \pi(\vec{y}), \psi(\vec{z}) \rangle$ s.t.
  - $\omega(\vec{x})$ is the *operation signature* and $\vec{x} = \vec{y} \cup \vec{z}$ is the set of *operation parameters*
  - $\pi(\vec{y})$ is the *operation precondition*, i.e., an FO-formula over $\mathcal{D}_i$
  - $\psi(\vec{z})$ is the *operation postcondition*, i.e., an FO-formula over $\mathcal{D} \cup \mathcal{D}'$

We call the AC-MAS specified in this way *Artifact System Programs*.

Example 2: the Order-to-Cash Scenario

Specification of actions affecting the MO in the order-to-cash scenario:

- $createMO(po\_id, price) = \langle \pi(po\_id, price), \psi(po\_id, price) \rangle$, where:
  - $\pi(po\_id, price) \equiv$
    $\exists p, o\ (PO(po\_id, p, o, \text{prepared}) \wedge \exists cost\ Materials(p, cost) \wedge \phi_{b-1}$
  - $\psi(po\_id, price) \equiv$
    $\exists id\ (MO'(id, po\_id, price, \text{preparation}) \wedge$

    $\forall id', c, p, s\ (MO(id', c, p, s) \rightarrow id \neq id')) \wedge \phi_b$

where ϕ_k is the FO-formula saying that there are at most k objects in the active domain.

The specification of *createMO* guarantees that the bound b is not violated by action execution.

Verification of Artifact System Programs

Lemma

AS programs generate uniform AC-MAS.

Theorem

Consider

- *a* b-bounded *AS program* $\mathcal{P}_{Act,U}$ *on an infinite domain* U
- *an FO-CTLK formula* φ.

Given $U' \supseteq C$ *s.t.*

$$|U_2| \geq 2b + |C| + \max\{N_{AS}, |vars(\varphi)|\}$$

then $\mathcal{P}_{Act,U'}$ *is a finite abstraction of* $\mathcal{P}_{Act,U}$ *s.t.*

- $\mathcal{P}_{Act,U'}$ *is uniform and bisimilar to* $\mathcal{P}_{Act,U}$

In particular,

$$\mathcal{P}_{Act,U} \models \varphi \quad \textit{iff} \quad \mathcal{P}_{Act,U'} \models \varphi$$

- The abstraction is finite and the procedure is *constructive*.
- Thus, we can apply standard techniques in model checking.

Extensions

1. Non-uniform AC-MAS: for *sentence-atomic* FO-CTL the results above still hold.

$$AG\ \forall c\ (shippedPO(c) \rightarrow \forall m(related(c, m) \rightarrow shippedMO(m))) \qquad ✔$$

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2. Non-uniform AC-MAS: one-way preservation result for FO-ACTL.

Theorem

If an AC-MAS $\mathcal{P}$ is bounded, *and $\varphi \in$ FO-ACTL, then there exists a finite abstraction $\mathcal{P}'$ such that if $\mathcal{P}' \models \varphi$ then $\mathcal{P} \models \varphi$.*

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The model checking problem for finite AC-MAS w.r.t. FO-CTLK is EXPSPACE-complete in the size of the formula and data.

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5. The finite abstraction result can be extended to typed FO-CTLK including predicates with an infinite interpretation ($<$ on rationals)

Results

and main limitations

- We are able to model check AC-MAS w.r.t. full FO-CTLK...
- ...however, our results hold only for *uniform* and *bounded* systems.
- This class includes many interesting systems (AS programs, [2, 4]).
- The model checking problem is EXPSPACE-complete.

Next Steps

- Techniques for finite abstraction.
- Model checking techniques for finite-state systems are effective on the abstract system?
- How to perfom the boundedness check.

Merci!

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