Abstraction-based Verification of Infinite-state Data-aware Systems

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based on work with Alessio Lomuscio
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Overview

Motivation and Background:

- **Data-aware Systems**: new paradigm in Service-oriented Computing [CH09]
- GSM [HDM+11], KAB [BCM+13], Situation Calculus [DLP16], Reactive Modules [AH99].
- English (ascending bid) auctions as Data-aware Systems
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Main Task: **formal** verification of **infinite-state** Data-aware Systems
- Given a model $M_S$ of system $S$ and a formula $\phi_P$ for property $P$,
  \[
  \text{does } M_S \models \phi_P? 
  \]

  - model checking is appropriate for control-intensive applications...
  - ...but less suited for data-intensive applications (data range over infinite domains) [BK08]
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- ★ ...but less suited for data-intensive applications (data range over infinite domains) [BK08]

3 Key Result:
- Under specific conditions, the verification of DaS is decidable
  \[ \Rightarrow \text{The verification of various types of auction is decidable} \]
Data-aware Systems

Outline

• Recent paradigm in Service-Oriented Computing [CH09, DSV07, DHPV09].
  ▶ aka data-driven/data-centric systems
  ▶ motto: let’s give data and processes the same relevance!
  ▶ key idea behind the UE STREP project ACSI (http://acsi-project.haifa.il.ibm.com/)
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• ACSI: Artifact-Centric Service Interoperation
  ▶ **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.
    ★ several frameworks to formalise Artifact Systems and DaS in general (GSM, KAB, …).
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  ▶ the auctioneer and bidders compare bids
  ▶ the bidders’ behaviour depends on the value of bids
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• Logical Perspective: first-order modal (temporal) Kripke models
Data-aware Systems

Order-to-Cash Scenario

Customer

<table>
<thead>
<tr>
<th>Purchase Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desk</td>
</tr>
<tr>
<td>Chair</td>
</tr>
</tbody>
</table>

Manufacturer

<table>
<thead>
<tr>
<th>Material Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desk Legs</td>
</tr>
<tr>
<td>Chair Legs</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>

Supplier

<table>
<thead>
<tr>
<th>Material Order</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hammer Nails</td>
</tr>
<tr>
<td>Glue</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>

Accept/reject

Accept/reject
a single auctioneer $a$ and a finite number of bidders $b_1, \ldots, b_\ell$
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the auctioneer puts another item on sale . . .
Data-aware Systems
English (ascending bid) Auctions

1. a single auctioneer $a$ and a finite number of bidders $b_1, \ldots, b_\ell$
2. the auctioneer puts on sale an item with a base price (public to all bidders)
3. the bidding process is structured in discrete rounds
4. at each round every bidder can either bid or skip
5. at time out the item is assigned to the bidder with the highest bid.
6. the auctioneer puts another item on sale . . .

Assumptions:
Data-aware Systems

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Assumptions:

- each bidder is rational
- she has an intrinsic value for each item being auctioned
- and she keeps this information private from other bidders and the auctioneer
Data-aware Systems
Auction Data Model

<table>
<thead>
<tr>
<th>Bidding</th>
</tr>
</thead>
<tbody>
<tr>
<td>item</td>
</tr>
</tbody>
</table>

- \text{init}_A(item, \text{base\_price})
- \text{bid}_i(item, \text{bid})
- \text{time\_out}(item)
- \text{skip}_A
- \text{skip}_i
- ...

<table>
<thead>
<tr>
<th>trueValue_i</th>
</tr>
</thead>
<tbody>
<tr>
<td>item</td>
</tr>
</tbody>
</table>

- \text{init}_i(item, \text{true\_value})
- ...

6
Data-aware Systems

Auction Lifecycle

- Agents operate on the data model
  - e.g., the bidder sends a new bid to the auctioneer

- Actions add/remove artifacts or change artifact attributes
  - e.g., the auctioneer puts a new item on auction

- The whole system can be seen as a dynamic *data-aware* system
  - at every step, an action yields a change in the current state
Research questions

1. Which syntax and semantics to specify Data-aware Systems?
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2. Is verification of DaS decidable?
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1. Which syntax and semantics to specify Data-aware Systems?
2. Is verification of DaS decidable?
3. If not, can we identify interesting fragments that are reasonably well-behaved?
Challenges

Distributed (multi-agent) systems, but . . .
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- . . . states have a relational structure,
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Distributed (multi-agent) systems, but . . .

- . . . states have a relational structure,
- data are potentially infinite,
- the state space is infinite in general.

⇒ the model checking problem cannot be tackled by standard techniques.
Artifact-centric Multi-agent Systems (AC-MAS) as a formal model for DaS.

Intuition: databases that evolve over time and are manipulated by agents.
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**Specification language:** first-order extensions of temporal (strategy) logics

\[
AG \forall it, bd, s(\exists! bp \ Bidding(it, bd, bp, s) \land \exists^{\leq 1} tv \ trueValue_i(it, tv))
\]

*each item has exactly one base price, while bidders associate at most one true value to each item (possibly none).*
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3. **Model theory of FO modal logic:** bisimulations and abstraction to tackle model checking.
   
   **Main result:** under specific conditions MC can be reduced to the finite case.
Artifact-centric Multi-agent Systems (AC-MAS) as a formal model for DaS.

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Model theory of FO modal logic: bisimulations and abstraction to tackle model checking.

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

Case study: modelling and verifying auctions as AC-MAS.
Semantics: Databases

The data model of DaS is given as a database.

- A **database schema** is a finite set $D = \{P_1/a_1, \ldots, P_n/a_n\}$ of (typed) relation symbols $P_i$ with arity $a_i \in \mathbb{N}$
- Consider a (possibly infinite) interpretation domain $U$. A **db instance** on $U$ is a mapping $D$ associating each symbol $P_i$ with a finite $a_i$-ary relation on $U$
- The domain $U$ may be ordered (e.g. reals and rationals with $\leq$)
- The **active domain** $\text{adom}(D)$ is the set of all $u \in U$ appearing in some $D(P_i)$. The active domain is always finite
- The **disjoint union** $D \oplus D'$ is the $(D \cup D')$-interpretation s.t.
  
  (i) $D \oplus D'(P_i) = D(P_i)$
  (ii) $D \oplus D'(P'_i) = D'(P_i)$
Agents have partial observability (*imperfect information*) of the system.

- An **agent** $i = \langle D_i, \text{Act}_i, Pr_i \rangle$ is such that
  - she registers her information in the **local database schema** $D_i$, and
  - performs the **parametric actions** $\alpha(\vec{x})$ in $\text{Act}_i$
  - according to the **local protocol** $Pr_i: D_i(U) \mapsto 2^{\text{Act}_i(U)}$

- the setting is inspired by the **interpreted systems semantics** for MAS [FHMV95],...
- ...but here the local state of each agent is relational.

Agents manipulate data and have (partial) observability of the information contained in the global db schema $\mathcal{D} = \mathcal{D}_1 \cup \cdots \cup \mathcal{D}_\ell$. 

**Artifact-centric Multi-agent Systems**

**Agents**
Example 1: English Auction

- agents: auctioneer, bidder₁, . . . , bidderₗ
- local db schema $D_a$ for auctioneer
  - $Bidding(item, base\_price, bid₁, . . . , bidₗ, status)$
- local db schema $D_i$ for bidders
  - $Bidding(item, base\_price, bid₁, . . . , bidₗ, status)$
  - $TValue_i(item, true\_value)$
- then, $D = \{Bidding, TValue₁, . . . , TValueₗ\}$
- actions introduce values from an infinite domain $U = Items \cup Q \cup \{active, term\}$:
  - $init_a(item, base\_price)$, $time\_out(item)$, $skip_a$ belong to $Act_a$
  - $init_i(item, true\_value)$, $bid_i(item, bid)$, $skip_i$ belong to each $Act_i$
- the protocol function specifies the preconditions for actions:
  - e.g., $bid_i(item, bid) \in Pr_i(D)$ whenever
    - item appears in $D(TValue_i)$
    - for all $j \neq i$, $bid_j < bid \leq true\_value_i$
    - $D(status) = active$ for item
  - the $skip$ actions are always enabled.
Artifact-centric Multi-agent Systems

The Transition System

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

- a **global state** \( s = \langle D_0, \ldots, D_\ell \rangle \) registers information about all agents.

- an **AC-MAS** \( \mathcal{P} = \langle Ag, s_0, \rightarrow \rangle \) describes the interactions of . . .
  - a **finite set** \( Ag = \{a_0, \ldots, a_\ell\} \) of agents
  - from some **initial global state** \( s_0 \)
  - according to the **transition relation** \( s \xrightarrow{\alpha(\overline{u})} s' \)

- **AC-MAS** are infinite-state systems in general

AC-MAS are first-order temporal structures.

⇒ **FO temporal logics can be used as specification languages.**
Example 2: the Auction AC-MAS

The **Auction AC-MAS** $A = \langle Ag, s_0, \rightarrow \rangle$ is given as

- $Ag = \{a, b_1, \ldots, b_\ell\}$
- $s_0$ is the **empty interpretation** of $D = \{Bidding, TValue_1, \ldots, TValue_\ell\}$
- $\rightarrow$ is the **transition relation** s.t. $s \xrightarrow{\alpha(u)} s'$ whenever
  - $\alpha_i = bid_i(item, bid')$ and $s'$ modifies $s$ by replacing any tuple $(item, \ldots, bid_i, \ldots, status)$ in $D_s(Bidding)$ with $(item, \ldots, bid'_i, \ldots, status)$
  - $\alpha_A = timeout(item)$ and the value of $status$ in $D_{s'}(Bidding)$ for $item$ is **term**
  - ...

...
Syntax: First-order CTL

- Data call for First-order Logic
- Evolution calls for Temporal Logic

The specification language **FO-CTL**:

$$\varphi ::= P(t_1, \ldots, t_a) \mid t = t' \mid t \leq t' \mid \neg \varphi \mid \varphi \rightarrow \varphi \mid \forall x \varphi \mid AX \varphi \mid A\varphi U \varphi \mid E\varphi U \varphi$$

where $P$ is any relation symbol in $D$.

Alternation of free variables and modal operators is enabled.

- We can also deal with FO extensions of ATL, as well as epistemic modalities [BLP14, BL16].
An **assignment** is a function $\sigma : \text{Var} \rightarrow U$.

An AC-MAS $\mathcal{P}$ **satisfies** an FO-CTL formula $\varphi$ in a state $s$ for an assignment $\sigma$, iff

\[
\begin{align*}
  \langle \mathcal{P}, s, \sigma \rangle = P(\bar{t}) & \quad \text{iff} \quad \langle \sigma(t_1), \ldots, \sigma(t_a) \rangle \in D_s(\mathcal{P}) \\
  \langle \mathcal{P}, s, \sigma \rangle = t = t' & \quad \text{iff} \quad \sigma(t) = \sigma(t') \\
  \langle \mathcal{P}, s, \sigma \rangle = t \leq t' & \quad \text{iff} \quad \sigma(t) \leq \sigma(t') \\
  \langle \mathcal{P}, s, \sigma \rangle = \neg \varphi & \quad \text{iff} \quad (\mathcal{P}, s, \sigma) \not\models \varphi \\
  \langle \mathcal{P}, s, \sigma \rangle = \varphi \rightarrow \psi & \quad \text{iff} \quad (\mathcal{P}, s, \sigma) \not\models \varphi \text{ or } (\mathcal{P}, s, \sigma) \models \psi \\
  \langle \mathcal{P}, s, \sigma \rangle = \forall x \varphi & \quad \text{iff} \quad \text{for every } u \in \text{adom}(s), (\mathcal{P}, s, \sigma^u_x) \models \varphi \\
  \langle \mathcal{P}, s, \sigma \rangle = AX \varphi & \quad \text{iff} \quad \text{for every run } r, r(0) = s \text{ implies } (\mathcal{P}, r(1), \sigma) \models \varphi \\
  \langle \mathcal{P}, s, \sigma \rangle = A \varphi U \varphi' & \quad \text{iff} \quad \text{for every run } r, r(0) = s \text{ implies } (\mathcal{P}, r(k), \sigma) \models \varphi' \text{ for some } k \geq 0, \\
  & \quad \text{and } (\mathcal{P}, r(k'), \sigma) \models \varphi \text{ for every } 0 \leq k' < k \\
  \langle \mathcal{P}, s, \sigma \rangle = E \varphi U \varphi' & \quad \text{iff} \quad \text{for some run } r, r(0) = s, (\mathcal{P}, r(k), \sigma) \models \varphi' \text{ for some } k \geq 0, \\
  & \quad \text{and } (\mathcal{P}, r(k'), \sigma) \models \varphi \text{ for all } 0 \leq k' < k
\end{align*}
\]

**Active-domain semantics, but...**

- ...we can refer to individuals that no longer exist
- the number of states is infinite in general
Semantics of FO-CTL

Intuition

(a) $AX \varphi$

(b) $A \varphi U \psi$

(c) $E \varphi U \psi$
Verification of AC-MAS

How do we check FO-CTL specifications on auctions?

- for each bidder, each bid is less than or equal to her true value:
  \[ \forall it, \vec{x}, bd_i, \vec{y}, tv((Bidding(it, \vec{x}, bd_i, \vec{y})) \land TValue_i(it, tv) \rightarrow bd_i \leq tv) \]

- each bidder can raise her bid unless she has already hit her true value:
  \[ \forall it, \vec{x}, bd_i, \vec{y}(Bidding(it, \vec{x}, bd_i, \vec{y}) \rightarrow (TValue_i(it, bd_i) \lor EF \exists \vec{x}', bd'_i, \vec{y}'(bd'_i > bd_i \land Bidding(it, \vec{x}', bd'_i, \vec{y}')))) \]

- define
  \[ Win_i(it) = Status(it, term) \land \exists \vec{x}, bd_i, \vec{y}(Bidding(it, \vec{x}, bd_i, \vec{y}) \land \bigwedge_{j \neq i} \forall \vec{x}', bd_j, \vec{y}'(Bidding(it, \vec{x}', bd_j, \vec{y}') \rightarrow bd_j < bd_i)) \]

**Manipulability**: bidder \( b_i \) will necessarily win the auction for item \( it \) eventually

\[ AF Win_i(it) \]

**Problem**: the infinite domain \( U \) may generate infinitely many states!

**Investigated solution**: can we **simulate** the **concrete** values in \( U \) with a finite set of **abstract** symbols?
Bisimulation: Isomorphism

- two states \(s, s'\) are **isomorphic**, or \(s \simeq s'\), if there is a bijection
  \[ \iota : \text{adom}(s) \leftrightarrow \text{adom}(s') \]
  such that for every \(\vec{u}\) in \(\text{adom}(s)\), \(i \in Ag, \vec{u} \in D_i(P) \leftrightarrow \iota(\vec{u}) \in D_i'(P)\)

\[
\begin{array}{|c|c|}
\hline
P_1 & a & b \\
\hline
P_2 & b & c \\
\hline
P_3 & d & e \\
\hline
\end{array}
\sim

\[
\begin{array}{|c|c|}
\hline
P_1 & 1 & 2 \\
\hline
P_2 & 2 & 3 \\
\hline
P_3 & 4 & 5 \\
\hline
\end{array}
\]

- \(\iota : a \mapsto 1\)
  \(b \mapsto 2\)
  \(c \mapsto 3\)
  \(d \mapsto 4\)
  \(e \mapsto 5\)
Bisimulation

- two states $s, s'$ are **bisimilar**, or $s \approx s'$, if
  1. $s \approx s'$
  2. if $s \rightarrow t$ then for some $t'$, $s' \rightarrow t'$, $s \oplus t \approx s' \oplus t'$, and $t \approx t'$

\[
\begin{array}{c}
\text{\includegraphics[width=0.3\textwidth]{diagram}}
\end{array}
\]
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the other direction holds as well
However, bisimulations are not sufficient to preserve FO-CTL formulas:

\[ \phi = AG \forall x (P(x) \rightarrow AX AG \neg P(x)) \]
Uniformity

- The behaviour of uniform AC-MAS is independent from data not explicitly mentioned in the system description.
- related to the notion of genericity in databases.
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- related to the notion of **genericity** in databases.
- more formally, an AC-MAS $\mathcal{P}$ is **uniform** iff for states $s, t, s' \in S$ and $t' \in D(U)$,
  - $s \rightarrow t$ and $s \oplus t \simeq s' \oplus t'$ imply $s' \rightarrow t'$

$$
\begin{array}{|c|c|}
\hline
s  \\
\hline
a & b  \\
\hline
b & c  \\
\hline
d & e  \\
\hline
\end{array}
\quad
\begin{array}{|c|c|}
\hline
t  \\
\hline
a & f  \\
\hline
f & c  \\
\hline
\end{array}
$$

$$
\begin{array}{|c|c|}
\hline
s'  \\
\hline
1 & 2  \\
\hline
2 & 3  \\
\hline
4 & 5  \\
\hline
\end{array}
\quad
\begin{array}{|c|c|}
\hline
t'  \\
\hline
1 & 6  \\
\hline
6 & 3  \\
\hline
\end{array}
$$
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\begin{align*}
\begin{array}{|c|c|}
\hline
s & \hline
a & b \\
\hline
b & c \\
\hline
d & e \\
\hline
\end{array}
\end{align*}

\begin{align*}
\begin{array}{|c|c|}
\hline
\hline
\end{array}
\end{align*}

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\begin{array}{|c|c|}
\hline
s' & \hline
1 & 2 \\
\hline
2 & 3 \\
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\hline
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\begin{array}{|c|c|}
\hline
t & \hline
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\hline
\end{array}
\end{align*}

\begin{align*}
\begin{array}{|c|c|}
\hline
\hline
\end{array}
\end{align*}

\begin{align*}
\begin{array}{|c|c|}
\hline
t' & \hline
1 & 6 \\
\hline
6 & 3 \\
\hline
\end{array}
\end{align*}

\begin{align*}
\begin{array}{|c|c|}
\hline
\hline
\end{array}
\end{align*}
Uniformity

- The behaviour of uniform AC-MAS is independent from data not explicitly mentioned in the system description.
- related to the notion of genericity in databases.
- more formally, an AC-MAS $\mathcal{P}$ is uniform iff for states $s, t, s' \in S$ and $t' \in \mathcal{D}(U),$
  
  $s \rightarrow t$ and $s \oplus t \simeq s' \oplus t'$ imply $s' \rightarrow t'$

- Uniform AC-MAS cover most cases of interest
  - GSM [HDM+11], KAB [BCM+13], Situation Calculus [DLP16], Reactive Modules [BL16]
  - by assuming suitable restrictions on the language (e.g., no function symbols)
Bisimulation and Equivalence w.r.t. FO-CTL

Theorem (Preservation Result)

Consider

- bisimilar and uniform AC-MAS $\mathcal{P}$ and $\mathcal{P}'$
- an FO-CTLK formula $\varphi$

If

1. $|U'| \geq 2 \cdot \sup_{s \in \mathcal{P}} \{|\text{adom}(s)|\} + |\text{vars}(\varphi)|$
2. $|U| \geq 2 \cdot \sup_{s' \in \mathcal{P}'} \{|\text{adom}(s')|\} + |\text{vars}(\varphi)|$

then

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

The condition on domains allows us to mimic the transitions in each system.

Can we apply this result to obtain finite abstractions?
Abstraction

Abstractions are defined in an agent-based, modular way.

- Let $i = \langle D, \text{Act}, Pr \rangle$ be an agent defined on domain $U$.
  Given domain $U'$, the abstract agent $i' = \langle D, \text{Act}, Pr' \rangle$ on $U'$ is s.t.
  - $Pr'$ is the smallest function s.t. for every $D' \in D'(U')$, if
    1. $D' \simeq D$ for some witness $\iota$
    2. $\alpha(\vec{u}) \in Pr(D)$
    then $\alpha(\iota(\vec{u})) \in Pr'(D')$.

- Let $P = \langle Ag, s_0, \rightarrow \rangle$ be an AC-MAS.
  The abstraction $P' = \langle Ag', s'_0, \rightarrow' \rangle$ of $P$ is an AC-MAS s.t.
  - $Ag'$ be the set of abstract agents on $U'$
  - $s'_0 \simeq s_0$
  - $\rightarrow'$ is the smallest function s.t. if
    1. $s \xrightarrow{\alpha(\vec{u})} t$
    2. $s \oplus t \simeq s' \oplus t'$ for some witness $\iota$
    then $s' \xrightarrow{\alpha(\iota(\vec{u}))} t'$. 
Abstraction

- Let $N_{Ag} = \sum_{i \in Ag} \max_{\{\alpha(\vec{x}) \in Act_i\}} |\vec{x}|$ be the sum of the maximum numbers of parameters contained in the action types of each agent.

**Lemma (Abstraction Existence)**

Consider

- a **uniform** AC-MAS $\mathcal{P}$
- a set $U'$ s.t. $|U'| \geq 2 \sup_{s \in \mathcal{P}} |adom(s)| + N_{Ag}$

Then, there exists an abstraction $\mathcal{P}'$ of $\mathcal{P}$ that is **uniform** and **bisimilar** to $\mathcal{P}$.

How can we obtain **finite** abstractions?
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!
- Bounded systems arise naturally
  ▶ e.g., in reactive modules each agent controls a finite number of variables

Theorem (Finite Abstraction)

Consider
- a $b$-bounded and uniform AC-MAS $\mathcal{P}$ on an infinite domain $U$
- an FO-CTL formula $\varphi$

Given a finite domain $U'$ s.t.

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

there exists a finite abstraction $\mathcal{P}'$ of $\mathcal{P}$ s.t.
- $\mathcal{P}'$ is uniform and bisimilar to $\mathcal{P}$

In particular,

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

⇒ Under specific conditions, we can model check an infinite-state system by verifying its finite abstraction.
Finite Abstract Auction I

- Suppose that at most $n$ items are put on sale simultaneously
  - the auction AC-MAS $A$ is bounded by $b = (2|Ag| - 1)n + 2$

- Consider a finite $U'$ such that $|U'| \geq 2b + |\text{vars}(\phi)|$

- Define abstract agents _auctioneer_ $a'$ and _bidders_ $b'_i$ s.t.
  - the local db schemas $D'_a$ and $D'_i$ are the same as for $a$ and $b_i$
  - the sets of actions $Act'_a$ and $Act'_i$ are the same as for $a$ and $b_i$
  - the protocol function $Pr'_a$ is the same as for $a$
  - as to $Pr'_i$, $\text{bid}_i(\text{item}, \text{bid}) \in Pr'_i(D')$ whenever
    - $\text{bid}$ is an abstract value that does not represent any bid in $D'$
    - ...
The abstract auction AC-MAS $A' = \langle A', s'_0, \tau' \rangle$ is defined as

- $A' = \{a', b'_1, \ldots, b'_\ell\}$
- $s'_0$ is the empty interpretation of $D$
- $\rightarrow'$ mimics $\rightarrow$
  - e.g., if $\alpha_i = bid_i(item, bid)$, then $s \xrightarrow{\alpha_i'} t$ whenever $t$ modifies $s$ by replacing any tuple $(item, \ldots, bid_i, \ldots, status)$ in $D_s(Bidding)$ with $(item, \ldots, bid'_i, \ldots, status)$, where the value $bid' \in U'$ has been found as above. In particular, $bid < bid' \leq \text{true\_value}$ in $t$.

- By assuming that $|U'| \geq 2b + |\text{vars}(\phi)|$ and Theorem 3 we have that $A'$ is a finite abstraction of $A$.
- In particular, $A'$ is uniform and bisimilar to $A$ and

$$A \models \varphi \iff A' \models \varphi$$
Extensions

First-order extension of ATL: alternating bisimulations [BL16]

Epistemic operators for individual and group knowledge [BLP14]

∀it ¬∃tv ⋁ j̸=i ∨ j=a Kj TValue i (it, tv)

the true value of items for each bidder \(i\) is secret to all other bidders and the auctioneer

Non-uniform and bounded AC-MAS: one-way preservation result for FO-ACTL [Bel14]:

Theorem For every AC-MAS \(P\) and \(ϕ\) ∈ FO-ACTL, there exists a finite abstraction \(P′\) s.t. \(P′|= ϕ \Rightarrow P|= ϕ\)

Model checking bounded AC-MAS w.r.t. FO-CTL is undecidable [BL13, LM14]

Complexity result [BLP14]:

Theorem The model checking problem for finite AC-MAS w.r.t. FO-CTL is EXPSPACE-complete.
Extensions

1. First-order extension of ATL: alternating bisimulations [BL16]

2. Epistemic operators for individual and group knowledge [BLP14]

\[ AG \forall it \neg \exists tv \bigvee_{j \neq i \lor j = a} K_j TValue_i(it, tv) \]

_The true value of items for each bidder b_i is secret to all other bidders and the auctioneer_
Extensions

1. First-order extension of ATL: alternating bisimulations [BL16]
2. Epistemic operators for individual and group knowledge [BLP14]
3. Non-uniform and bounded AC-MAS: one-way preservation result for FO-ACTL [Bel14]:

\[
AG \forall it \neg \exists tv \bigvee_{j \neq i \land j = a} K_j TValue_i(it, tv)
\]

the true value of items for each bidder $b_i$ is secret to all other bidders and the auctioneer

Theorem

For every AC-MAS $\mathcal{P}$ and $\varphi \in \text{FO-ACTL}$, there exists a finite abstraction $\mathcal{P}'$ s.t.

$\mathcal{P}' \models \varphi \Rightarrow \mathcal{P} \models \varphi$
Extensions

1. First-order extension of ATL: alternating bisimulations [BL16]
2. Epistemic operators for individual and group knowledge [BLP14]

\[ AG \ \forall it \ \neg \exists tv \ \bigvee_{j \neq i \ \land j = a} K_j TValue_i(it, tv) \]

the true value of items for each bidder \( b_i \) is secret to all other bidders and the auctioneer

3. Non-uniform and bounded AC-MAS: one-way preservation result for FO-ACTL [Bel14]:

**Theorem**

For every AC-MAS \( \mathcal{P} \) and \( \varphi \in \text{FO-ACTL} \), there exists a finite abstraction \( \mathcal{P}' \) s.t.

\[ \mathcal{P}' \models \varphi \ \Rightarrow \ \mathcal{P} \models \varphi \]

4. Model checking **bounded** AC-MAS w.r.t. FO-CTL is undecidable [BL13, LM14]
Extensions

1. First-order extension of ATL: alternating bisimulations [BL16]
2. Epistemic operators for individual and group knowledge [BLP14]

\[ AG \forall it \neg \exists tv \bigvee_{j \neq i \land j = a} K_j \text{TValue}_i(it, tv) \]

*the true value of items for each bidder \( b_i \) is secret to all other bidders and the auctioneer*

3. Non-uniform and bounded AC-MAS: one-way preservation result for FO-ACTL [Bel14]:

**Theorem**

*For every AC-MAS \( \mathcal{P} \) and \( \varphi \in \text{FO-ACTL} \), there exists a finite abstraction \( \mathcal{P}' \) s.t.*

\[ \mathcal{P}' \models \varphi \Rightarrow \mathcal{P} \models \varphi \]

4. Model checking **bounded** AC-MAS w.r.t. FO-CTL is undecidable [BL13, LM14]

5. Complexity result [BLP14]:

**Theorem**

*The model checking problem for finite AC-MAS w.r.t. FO-CTL is EXPSPACE-complete.*
Results and main limitations

- Bisimulation and finite abstraction for first-order Kripke models.
- We are able to model check AC-MAS w.r.t. full FO-CTL...
- ...however, our abstraction results hold only for uniform and bounded systems.
- This class includes many interesting systems
  - GSM [HDDM+11], KAB [BCM+13], Situation Calculus [DLP16], Reactive Modules [BL16])
- including English auctions.
Next Steps

- Constructive techniques for finite abstractions.
- Model checking techniques for finite-state systems are effective on DaS?
- How to perform the boundedness check?
- What if the system is unbounded/not uniform?
  - can we include some (limited form of) arithmetic?
Thank you!
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