Multiagent System-based Verification of Security and Privacy

Ioana Boureanu

Imperial College London
Department of Computing

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Outline

1. Model Checking Multiagent Systems

2. MAS for Security
   - Introduction
   - (Simple) MAS Modelling for Security
   - (Not So Simple) MAS Models for Security – A Glance
   - Future Avenues for Security Apps as MAS
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Model Checking MAS

1. Model Checking in Theory
2. Model Checking MAS in Practice
3. Logic-based Languages
4. MAS-based Models
Model Checking In Theory

- **Model checking** [Clarke et al., 1999] is a verification technique
- \( M \models \varphi \), given a model \( M \) for a system and a specification \( \varphi \) encoding one of the system’s properties

Our Example of Models & Specifications

- \( M \) — a **formal** semantics for multiagent systems
- \( \varphi \) — **knowledge, joint abilities** beliefs, intentions, . . . , to express fault-tolerance, diagnosability, **security** ...
Model Checking Multiagent Systems

Model Checking in Practice

Real World Verification

An explicit modelling $\rightarrow$ state-space exponential in the size of the input

An optimised, much simplified model for onion routing has $3.03439e+58$ reachable states!

We need efficient methods and tools!
Model Checking Multiagent Systems

Model Checking in Practice

Pbs & Solutions
- state explosion pb: explicit encodings of state/action in $M$
  - one solution: efficient \textbf{symbolic} encodings, e.g., via binary decision diagrams (BDDs)

(More) Pbs & Solutions
- MC algorithms over BDD-encoded specifications & tools
  - solution: MAS symbolic model-checking techniques [Lomuscio and Raimondi, 2006]

(More) Pbs & Solutions
- there’s always a need for optimisations
  - solutions: cut-offs, abstractions [Lomuscio and Kouvaros, 2015], etc.
  - and/in a robust tool MCMAS [Lomuscio et al., 2015]
Model Checking MAS in Practice

MCMAS [Lomuscio et al., 2015]

- Support for epistemic specifications, ATL (uniformity and fairness), CTL, deontic modalities
- Dedicated modelling language (ISPL)
- BDD-based (via CUDD). Sequential and parallel MC
- Eclipse GUI
- Support for witnesses, counterexamples, etc
- Open source
- Used for robotic swarms, web-services, security...
Logic-based Languages

A Stop At Epistemic Specifications

- $S5_n$
- $\varphi = p | \neg \varphi | \varphi \land \varphi | Ki\varphi$
- readings:
  - $Ki\varphi$ – “agent $i$ knows that $\varphi$”
MAS-based Models

Interpreted Systems

- Multiagent-based models
  [Lodaya et al., 1995, Fagin et al., 1995]
  - $A = \{1, \ldots, n\}$ agents and Environment agent;
  - $\forall i \in A \cup E: L_i$ – possible local states, $\text{Act}_i$ – local actions,
    $P_i : L_i \rightarrow 2^{\text{Act}_i}$ – protocol function (actions enabled at $l_i$);
  - $t_i(l_i, a_1, \ldots, a_n, a_E) = l'_i$ – local evolution function;
  - $G$ – global states, $\overline{P}$ – joint protocol,
    $\text{Act}$ – joint actions, $T$ global evolution function — by composition;
  - $IS = \left< G, \overline{P}, T, I, V \right>$ – interpreted system,
    where $I \subset G$ – initial global states and
    $V : G \rightarrow 2^{\overline{AP}}$ – valuation function;
MAS-based Models

MAS Induced-Models

The induced model of IS is a tuple

\[ \mathcal{M}_{\text{IS}} = (S, T, \{\sim_i\}_{i \in \{1\ldots n\}}, V) \]

where:

- \( S \subseteq L_0 \times \cdots \times L_n \) is the set of global states reachable from I via T
- \( T \) encodes the temporal evolution;
- \( \{\sim_i\}_{i \in A_g \setminus E} \subseteq S \times S \) is a set of equivalence relations encoding epistemic accessibility
## MAS-based Models

### State Indistinguishability

- $l \in L_i$ and $l' \in L_i$ are $i$-indistinguishable, $l \approx_i l'$ if -in general- $\approx_i \subseteq L_i \times L_i$ is an equivalence relation over $L_i$
  
  - **standard:**
    - $\approx_i$ is the equality relation: $l_i(g) \approx_i l_i(g')$ iff $l_i(g) = l_i(g')$}
  
  - **non-standard:**
    - $\approx_i$ is a bespoke equiv. relation

  e.g., $l \equiv \{m_1\}_{k_1}$ and $l' \equiv \{m_2\}_{k_2}$

  (assuming $l$ containing just the encryption of a term with a key and $l'$ containing yet just the encryption of another term with another key)

  $\Rightarrow$ $l \approx_i l'$

- $s, s' \in S$ are $i$-indistinguishable, $s \sim_i s'$, if $l_i(s) \approx_i l_i(s)$
MAS-based Models

Satisfaction of Formulae on MAS Models

- CTL and ATL fragments as usual
- \((M, s) \models K \phi \iff \forall s' \in S \text{ if } s \sim i s' \text{ then } (M, s') \models \phi\)
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Joint work

Based on:

- previous joint work at Imperial College London


- ongoing joint work with A. Lomuscio and the VAS group at Imperial College London

- H2020 “Logic-based Verification of Privacy-Preservation in Europe’s 2020 ICT”
Motivation...

- “Protocols ... are prone to extremely subtle errors that are unlikely to be detected in normal operation.”
  (Needham and Schroeder, 1978)

- VeriSign spent > $10^8 in 2009–2010 to upgrade the .com DNS servers

- more interconnected devices, more conversative apps, more security threats
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Example: the **Woo-Lam** authentication protocol:

1. $A \rightarrow B : A$
2. $B \rightarrow A : N_b$
3. $A \rightarrow B : \{A, B, N_b\}_{K_{AS}}$
4. $B \rightarrow S : \{A, B, \{A, B, N_b\}_{K_{AS}}\}_{K_{BS}}$
5. $S \rightarrow B : \{A, B, N_b\}_{K_{BS}}$
Symbolic Security Attacks

Example: the **Woo-Lam** authentication protocol:

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5. \( S \rightarrow B : \{ A, B, N_b \}_{K_{BS}} \)

Example: an attack against the **Woo-Lam** protocol:

1’. \( I_A \rightarrow B : A \)
2’. \( B \rightarrow I_A : N_b \)
3’. \( I_A \rightarrow B : N_b \)
4’. \( B \rightarrow I_S : \{ A, B, N_b \}_{K_{BS}} \)
5’. \( I_S \rightarrow B : \{ A, B, N_b \}_{K_{BS}} \)
Introduction

Security Goals

‘Well-established’ Requirements
- flavours of: secrecy, authentication, key-agreement, etc.

Application-Level Privacy Requirements
- privacy of application-data
- vote-privacy, receipt-freeness, coercion-resistance

Data-transport privacy
- origin anonymity, destination anonymity, unlinkability within routing

Fault-Diagnosability Requirements
- attack (un)detectability
Symbolic Verification of Cryptographic Protocols

SYMBOLIC = cryptographic messages are algebraic terms; cryptography is perfect/un-tamperable
NO ppt. capabilities on protocol parties

- logic-based formalisms (BAN logics, Horn clauses);
  inductive methods;
  rewriting-based formalisms process-algebra formalisms
  (CSP, spi-calculus, pi-calculus);
  ...

- agent-based formalism
  - sound knowledge of participants;
  - natural expression of state-based properties (anonymity, non-repudiation etc.)
Introduction

**Challenges in (MAS) Security Specification/Verification**

- even secrecy in the unbounded setting is undecidable; need to design good/sound bounded security formalisms [Tiplea et al., 2009]
- mechanise cryptographic operations in MAS formalisms, i.e., no inherent intermediate, algebra/arithmetic-based language
- encapsulate standard threat models (e.g., at least Dolev-Yao [D.Dolev and A.Yao, 1983]) in MAS formalisms
- get sound cryptography-driven indistinguishability relations & cryptography-aware epistemic modalities
- do any/all of the above in a systematic/automatable way
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**Challenges in (MAS) Security**

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(Simple) MAS Modelling for Security

Protocol Executions as MAS Models

Security Protocols

the Needham-Schroeder Public Key (NSPK) protocol

an actual A is alice: e.g., a customer

an actual B is bob, e.g., a bank-server

1. \( A \rightarrow B : \{A, N_A\}_{pub(B)} \)

2. \( B \rightarrow A : \{N_A, N_B\}_{pub(A)} \)

3. \( A \rightarrow B : \{N_B\}_{pub(B)} \)

- alice could have, in the same time, a session from her mobile device and another session from her PC
- there could be other servers, but bob, that alice could connect to
- if this was, e.g., a contract-signing protocol, alice could have two, simultaneous running sessions: in one she could be auctioning (A-role) and in the other she could be a buyer (B-role)
(Simple) MAS Modelling for Security

Protocol Executions as (Simple) MAS Models (I)

MAS Mapping

- each role instance \((A, alice)^1, (A, alice)^2 or (A, bob)^3 \) etc. \(\rightarrow\) an agent (of the IS)
- a (Dolev-Yao) intruder \(\rightarrow\) the Environment agent, modelled purposely
— some details:

- describe a (honest) instantiated role:
  - views — ordered map \( \langle \text{var, value} \rangle \Rightarrow \text{agents' local states} \) with typed, un-deciphered values, \( \bot \), à la [Rogaway 2001]
    \[
    (A : alice, B : bob, k_A : pvk_{alice}, k_B : pbk_{bob}, n_A : r_1, n_B : \bot) \]
    or,

- describe a DY insider \( \Rightarrow \text{local state of the Environment:} \)
  - knowledge-set — ordered multimap \( \langle \text{term, value} \rangle \)
    \[
    X = \{ \{A, na\}_{k_B} : \{alice, r_1\}_{pbk_{bob}}, \\
    \{A, na\}_{k_B} : \{alice_2, r_2\}_{pbk_{greg}}, A : alice, A : alice_2, B : bob \}
    \]
  - history of actions
    \[
    H = [ag_A.\text{send} \{alice, r_1\}_{pbk_{bob}}, \\
    ag'_A.\text{send} \{alice_2, r_2\}_{pbk_{greg}}, \ldots ]
    \]
protocol role instantiated under $\rho \rightarrow$

- **evolution function**

- **simple agents’ local state update**
  e.g., “matching receive” of message $M = \{x, f(x), y\}_{K_{alice}}$ for the symbolic $\{n_a, n, n_b\}_{K_a}$ & agent $i$ has previously set $n_a$:
  - $\text{out\_match}(\text{view}_i, M) = \text{true}$ iff $x = \text{ag}\cdot n_a$
  
  - $\text{in\_match}(M, i) = \text{true}$, iff consistency checks inside $M$ hold; e.g., $n == f(n_a)$

  - $\text{set(view, n_b)}$: $n_b := y$ if $\text{in\_match}(\ldots) = \text{true}$ and $\text{out\_match}(\ldots) = \text{true}$

- Env.’s local state update (e.g., DY deductions of the insider):
  $\tilde{a}_E = \text{intercept}M, \tilde{a}_{\text{ag}_A} = \text{send}M,$
  $t_E((X, H), \tilde{a}) = (X \cup M \cup \{t\} \vdash X \cup M \vdash t) \cup H \cup \text{ag}_A.\text{send} M)$. 


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(Simple) MAS Modelling for Security

Security goals to CTLK specification (I)

- **atomic goal** \(\text{agree } A : B : \overline{\text{VAR}}\)

\[
\theta(\text{agree } A : B : \overline{\text{VAR}}) = \bigwedge_{i \in A} AG(\text{end}(i) \rightarrow \bigvee_{j \in B} \text{agree}(i, j, \overline{\text{VAR}}))
\]

- \(i\) – agents \(ag_A\) mappings of \(A\)-role instance
- \(j\) – agents \(ag_B\) mappings of \(B\)-role instance

\[
\text{agree}(i, j, \overline{\text{VAR}}) := \bigwedge_{\text{Var} \in \overline{\text{VAR}}} (i.\text{Var} = j.\text{Var})
\]

- **epistemic goal** \(\text{Knows } A : \gamma\)

\[
\theta(\text{Knows } A : \gamma) = \bigwedge_{i \in A} AG(\text{end}(i) \rightarrow K_i \theta^i(\gamma))
\]

\(\theta^i(\gamma)\) – an appropriate translation of \(\gamma\) from the perspective of agent \(i\):

\[
\theta^i(\text{holds } A : \overline{\text{VAR}}) = \bigvee_{j \in A} (i.\text{PartnerA} = j.\text{Id} \land \text{agree}(i, j, \overline{\text{VAR}}))
\]
Doxastic authentication goal:

\[\text{Believes } B : \text{holds } A : K\]

Translation 1:

\[
\bigwedge_{i \in B} AG(i.\text{step} = 3 \rightarrow K_i \theta^i(\text{holds } A : K))
\]

\[\neg \theta^i(\text{holds } A : K) := \bigvee_{j \in A} (i.\text{Partner}A = j.\text{Id} \land i.K = j.K)\]

\[\neg \theta^i(\text{holds } A : K) \Rightarrow \bigwedge_{i \in B} AG(i.\text{step} = 3 \rightarrow K_i \bigvee_{j \in A} (i.\text{Partner}A = j.\text{Id} \land i.K = j.K))\]
Security Protocols to MAS and CTLK

- translate different types of authentication, secrecy, key-exchange and their goals into CTLK formulas
- undetectability of attacks $\rightarrow$ new MAS formalism and hierarchy of CTLK formulas
- MAS formalisms proven correct w.r.t. trace properties, i.e., aligned with established security specification formalisms (MSR)
- done automatically from library of protocols in CAPSL to ISPL, into MCMAS
(Simple) MAS Modelling for Security

Security Protocols to MAS and CTLK – PD2IS

[Diagram and text content as per the given bounding box]
Intricate Cryptography, MAS and Epistemic

- cryptographic primitives can be complicated (e.g., blind signatures, trapdoor commitments, etc.)
- un-deciphurable yet typed data requires attentive modelling (e.g., values in local states)
- local evolutions (e.g., checks to be made) become convoluted
- systematisation/automation possible per classes of primitives only
- need for sound epistemic modalities to be interpreted over these
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\begin{align*}
\text{open}(\text{tdcommit}(x, y, z), y) & \rightarrow x \\
\text{open}(\text{tdcommit}(x, y, z), f(x, y, z, x')) & \rightarrow x' \\
\text{tdcommit}(x', f(x, y, z, x'), z) & \rightarrow \text{tdcommit}(x, y, z) \\
f(x', f(x, y, z, x'), z, x'') & \rightarrow f(x, y, z, x'')
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Intricate Cryptography, MAS and Epistemics

- for cryptographic primitives expressed as subterm convergent rewriting, we give a MAS modelling
- we augment agents with logical predicates to encode the cryptographic data they hold
- we soundly approximate cryptographic indistinguishability/knowledge $\sim_i$ via indistinguishability/knowledge modulo these predicates
- we implement this in MCMAS and extend PD2IS to automatically verify e-voting modelled as MAS, against CTLK formulae for vote-privacy, receipt-freeness, etc.
soundness of such MAS methodologies w.r.t. state-based properties (e.g., privacy) remains to be proven

many properties not captured by these models, e.g., data-origin, origin-privacy, etc.


newer applied logics (ATL, strategy logics [Cermak et al., 2013]) can be used to verify tighter requirements and more properties (e.g., privacy in e-auctioning protocols, shared resources in IoT, multi-party computations)
Thank you!
Future Avenues for Security Apps as MAS