Multiagent System-based Verification of Security and Privacy

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Outline

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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 φ encoding one of the system's properties

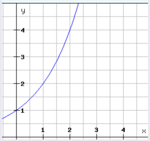
Our Example of Models & Specifications

- M — a **formal** semantics for multiagent systems
- φ — **knowledge**, **joint abilities** beliefs, intentions, . . ., to express fault-tolerance, diagnosability, **security ...**

Model Checking in Practice

Real World Verification

An explicit modelling → 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 in Practice

Pbs & Solutions

- state explosion pb: explicit encodings of state/action in M
  - one solution: efficient/**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

- $S5_n$
- $\varphi = p \mid \neg\varphi \mid \varphi \wedge \varphi \mid K_i\varphi$
- readings:
  - $K_i\varphi$ – “agent *i* knows that φ”

MAS-based Models

Interpreted Systems

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

MAS-based Models

MAS Induced-Models

The *induced model of IS* is a tuple $\mathcal{M}_{\mathcal{IS}} = (S, T, \{\sim_i\}_{i \in \{1 \dots n\}}, V)$ 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;
- $\{\sim_i\}_{i \in Ag \setminus \mathbf{E}} \subseteq S \times S$ 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., $\mathbf{l} \equiv \{\mathbf{m_1}\}_{\mathbf{k_1}}$ and $\mathbf{l'} \equiv \{\mathbf{m_2}\}_{\mathbf{k_2}}$

    (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)
    $\Rightarrow \quad \mathbf{l} \approx_\mathbf{i} \mathbf{l'}$
- $s, s' \in S$ 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
- $(M, s) \models K_i\phi$ iff $\forall s' \in S$ if $s \sim_i s'$ then $(M, s') \models \phi$

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Joint work

Based on:

- previous joint work at Imperial College London
  - I. B., M. Cohen, A. Lomuscio, “Automatic Verification of Temporal-Epistemic Properties of Cryptographic Protocols”, Journal of Applied Non-Classical Logics, 2009
  - I. B., A. Lomuscio, M. Cohen,“Model Checking Detectability of Attacks in Multiagent Systems”, AAMAS 2010
  - I. B,. A. Jones, A. Lomuscio, “Automatic Verification of Temporal-Epistemic Logic under Convergent Equational Theories”, AAMAS 2012
- I. B., “Model checking security protocols: a multi-agent system approach”, PhD Thesis, Imperial College London, 2011
- 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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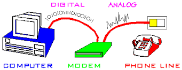

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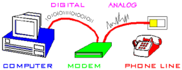

Symbolic Security Attacks

- Example: the Woo-Lam authentication protocol:

$$
\begin{array}{llll}
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}}
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Example: an attack against the Woo-Lam protocol:

$$
\begin{array}{llll}
1'. & I_A \rightarrow B & : & A \\
2'. & B \rightarrow I_A & : & N_b \\
3'. & I_A \rightarrow B & : & N_b \\
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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.)

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/arithmetics-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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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)

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 purposedly

Protocol Executions as (Simple) MAS Models (II)

— some details :

- describe a (honest) instantiated role:
  - **views** – ordered map ⟨ var,value ⟩ ⇒ agents' local states with typed, un-deciphered values, ⊥, à la [Rogaway 2001]
    $(A : alice, B : bob, k_A : pvk_{alice}, k_B : pbk_{bob}, n_A : r_1, \mathbf{n_b} : \bot)$ or,
- describe a DY insider ⇒ local state of the Environment:
  - knowledge-set – ordered multimap ⟨ term,value ⟩
    $X = [\{A, na\}_{k_B} : \{alice, r_1\}_{pbk_{\mathbf{bob}}},$
    $\{A, na\}_{k_B} : \{alice_2, r_2\}_{pbk_{\mathbf{greg}}}, A : alice, A : alice_2, B : bob]$
  - history of actions
    $H = [ag_A.send\,\{alice, r_1\}_{pbk_{\mathbf{bob}}},$
    $ag'_A.send\,\{alice_2, r_2\}_{pbk_{\mathbf{greg}}}, \ldots]$

Protocol Executions as (Simple) MAS Models (III)

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:
    — $out\_match(view_i, M) = true \text{ iff } x = ag.n_a$

    — $in\_match(M, i) =$
    $true$, iff consitstency checks inside M hold; e.g., $n == f(n_a)$

    — $set(view, n_b)$: $n_b := y$ if $in\_match(\ldots) = true$ and $out\_match(\ldots) = true$
  - Env.'s local state update (e.g., DY deductions of the insider):
    $\tilde{a}_E = interceptM$, $\tilde{a}_{ag_A} = sendM$,
    $t_E((X, H), \tilde{a}) = (X \cup M \cup \{t | \{X \cup M\} \vdash t\}, H \cup ag_A.send\ M)$.

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Security goals to CTLK specification (I)

- atomic goal `agree A : B :` $\overline{\mathtt{VAR}}$

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

i – agents ag_A mappings of *A–role* instance
j – agents ag_B mappings of *B–role* instance

$$agree(i, j, \overline{\mathtt{VAR}}) := \bigwedge_{Var \in \overline{\mathtt{VAR}}} (i.Var = j.Var)$$

- epistemic goal `Knows A :` γ

$$\theta(\mathtt{Knows\ A\ :\ }\gamma) = \bigwedge_{i \in A} AG(end(i) \rightarrow K_i\, \theta^{\mathbf{i}}(\gamma))$$

$\theta^{\mathbf{i}}(\gamma)$ –an appropriate translation of γ from the perspective of agent i:

$$\theta^{\mathbf{i}}(\mathtt{holds\ A\ :\ }\overline{\mathtt{VAR}}) = \bigvee_{j \in A} (i.PartnerA = j.Id \wedge agree(i, j, \overline{\mathtt{VAR}}))$$

Security goals to Specifications — One Example

- Doxastic authentication goal:

$$\texttt{Believes}\, B : \texttt{holds}\, A : \texttt{K}$$

- translation 1:

$$\bigwedge_{i \in B} AG(i.step = 3 \rightarrow K_i\, \theta^{\mathbf{i}}(\texttt{holds A : K}))$$

—$\theta^{\mathbf{i}}(\texttt{holds A : K}) :=$

$$\bigvee_{j \in A} (i.PartnerA = j.Id \wedge i.\texttt{K} = j.\texttt{K})$$

— $\theta^{\mathbf{i}}(\texttt{holds A : K})$ $\Rightarrow$

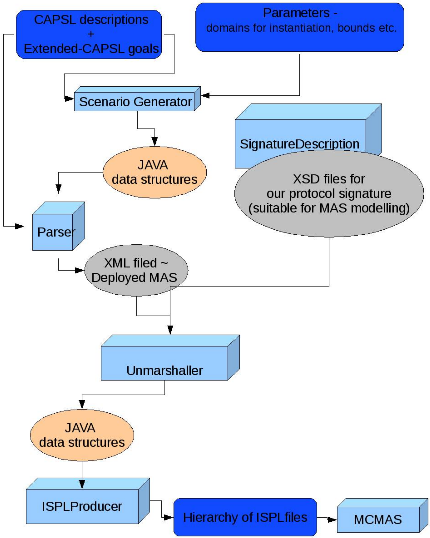
$$\bigwedge_{\mathbf{i} \in \mathbf{B}} \mathbf{AG}(\mathbf{i.step} = \mathbf{3} \rightarrow \mathbf{K_i} \bigvee_{\mathbf{j} \in \mathbf{A}} (\mathbf{i.PartnerA} = \mathbf{j.Id} \wedge \mathbf{i.}\texttt{K} = \mathbf{j.}\texttt{K}))$$

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



(Not So Simple) MAS Models for Security (I)

Intricate Cryptography, MAS and Epistemic

- cryptographic primitives can be complicated (e.g., blind signatures, trapdoor commitments, etc.)
- un-decipharable 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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$$tdcommit(x',f(x,y,z,x'),z) \rightarrow tdcommit(x,y,z)$$
$$f(x',f(x,y,z,x'),z,x'') \rightarrow f(x,y,z,x'')$$

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(Not So Simple) MAS Models for Security (II)

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.

Future Avenues for Security Apps as MAS

- 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.
- new MAS optimisation techniques (abstraction [Lomuscio and Michaliszyn, 2014], cut-off techniques and parametrised MC [Lomuscio and Kouvaros, 2014, 2015] can help improve these MAS-based security specification/verification methodologies
- 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)

Future Avenues for Security Apps as MAS

Thank you!

Future Avenues for Security Apps as MAS