Analysing privacy-type properties using formal methods

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Cryptographic protocols

- small programs designed to secure communication (e.g. confidentiality, authentication, ...)
- use cryptographic primitives (e.g. encryption, signature, .......)

The network is unsecure!

Communications take place over a public network like the Internet.
Cryptographic protocols

- small programs designed to secure communication (*e.g.* confidentiality, authentication, . . .)
- use cryptographic primitives (*e.g.* encryption, signature, . . . . . .)
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- use cryptographic primitives (e.g. encryption, signature, .......)

It becomes more and more important to protect our privacy.
An electronic passport is a passport with an RFID tag embedded in it.

The RFID tag stores:
- the information printed on your passport,
- a JPEG copy of your picture.

Example: electronic passport

→ studied in [Arapinis et al., 10]
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The Basic Access Control (BAC) protocol is a key establishment protocol that has been designed to also ensure unlinkability.

ISO/IEC standard 15408

Unlinkability aims to ensure that a user may make multiple uses of a service or resource without others being able to link these uses together.
The electronic passport protocol

Passport
$(K_E, K_M)$

Reader
$(K_E, K_M)$
The electronic passport protocol

Passport
$(K_E, K_M)$

Reader
$(K_E, K_M)$

get_challenge
The electronic passport protocol

Passport \((K_E, K_M)\)

Reader \((K_E, K_M)\)

\[ N_P, K_P \]

\[ N_P \]

get\_challenge
The electronic passport protocol

Passport
\((K_E, K_M)\)

Reader
\((K_E, K_M)\)

\(N_P, K_P\)

\(N_P\)

\(N_R, K_R\)

get\(_\text{challenge}\)

The electronic passport protocol

Passport $(K_E, K_M)$

$N_P, K_P$

Reader $(K_E, K_M)$

$N_P$


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get_challenge

\(N_P, K_P\)

\(N_P\)


\(K_{seed} = K_P \oplus K_R\)

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How cryptographic protocols can be attacked?
Some famous examples

The Serge Humpich case (1997)

He factorizes the number (320 bits) used to protect credit cards and he builds a false credit card. (the « YesCard »).

→ this makes it possible to withdraw a bank account that does not exist!
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Attack on the Belgian e-passport (2006)

→ this makes it possible to obtain the personal data of the user (e.g. the signature)
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Logical attacks

- can be mounted even assuming perfect cryptography,
  - replay attack, man-in-the-middle attack, ...
- are numerous,
  - a flaw discovered in 2010 in Single Sign On Protocols used in Google App (Avantssar european project)
- subtle and hard to detect by “eyeballing” the protocol
French electronic passport

→ the passport must reply to all received messages.

Passport

$(K_E, K_M)$

Reader

$(K_E, K_M)$

get_challenge

$N_P, K_P$

$N_P$


$N_R, K_R$
French electronic passport

→ the passport must reply to all received messages.

Passport \((K_E, K_M)\)

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\(N_R, K_R\)


If MAC check fails

mac\_error
the passport must reply to all received messages.

Passport $(K_E, K_M)$

Reader $(K_E, K_M)$

get_challenge

$N_P, K_P$

$N_P$


If MAC check succeeds

If nonce check fails

nonce_error
An attack on the French passport [Chothia & Smirnov, 10]

Attack against unlinkability

An attacker can track a French passport, provided he has once witnessed a successful authentication.
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An attacker can track a French passport, provided he has once witnessed a successful authentication.

Part 1 of the attack. The attacker eavesdrops on Alice using her passport and records message $M$.

Alice’s Passport

$(K_E, K_M)$

Reader

$(K_E, K_M)$

get_challenge

$N_P, K_P$


$N_P$

$N_R, K_R$
An attack on the French passport [Chothia & Smirnov, 10]

Part 2 of the attack.

The attacker replays the message $M$ and checks the error code he receives.

**????’s Passport**

$(K'_E, K'_M)$

**Attacker**


$N'_P$

get_challenge

$N'_P, K'_P$
An attack on the French passport [Chothia & Smirnov, 10]

Part 2 of the attack.
The attacker replays the message $M$ and checks the error code he receives.

???'s Passport \[(K'_E, K'_M)\]

Attacker

get_challenge

$N'_P, K'_P$

$N'_P$


mac_error

$\Rightarrow$ MAC check failed $\Rightarrow$ $K'_M \neq K_M$ $\Rightarrow$ ???' is not Alice
An attack on the French passport [Chothia & Smirnov, 10]

Part 2 of the attack.
The attacker replays the message $M$ and checks the error code he receives.

???'s Passport

$(K_E', K_M')$

Attacker

get_challenge

$\Rightarrow$


nonce_error

$\Rightarrow$ MAC check succeeded

$\Rightarrow K_M' = K_M$

$\Rightarrow$ ???? is Alice
**DEMO**

(thanks to Myrto Arapinis, Tom Chothia, and Vincent Cheval... and to those who lend me their e-passport.)

Attack found in 2010 by T. Chothia and V. Smirnov
Objectives

Formal and automatic analysis of new applications

*Target applications:* electronic voting protocols, RFID protocols, routing protocols, vehicular ad hoc networks, electronic auction protocols, ...
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Challenges:

1. Formal definitions of the expected security properties
   → privacy-type security properties

2. Designing appropriate verification algorithms

3. Modularity issues
Some basic features (symbolic models)

→ Various models (e.g. [Dolev & Yao, 81]) having some common features
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Messages

They are abstracted by terms together with an equational theory.
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Messages

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Examples:

→ symmetric encryption/decryption: \( \text{dec}(\text{enc}(x, y), y) = x \)

→ exclusive or operator:

\[
\begin{align*}
(x \oplus y) \oplus z &= x \oplus (y \oplus z) \\
x \oplus y &= y \oplus x \\
x \oplus 0 &= x \\
x \oplus x &= 0
\end{align*}
\]
Some basic features (symbolic models)

→ Various models (e.g. [Dolev & Yao, 81]) having some common features

Messages
They are abstracted by terms together with an equational theory.

The attacker
- may read every message sent on the network,
- may intercept and send new messages according to its deduction capabilities.
→ only symbolic manipulations on terms.
Formal definition of privacy-type properties

Equivalence based properties

“An observer cannot observe any difference between P and Q”

→ unlinkability, anonymity, privacy related properties in e-voting, ...
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**Equivalence based properties**

“An observer cannot observe any difference between P and Q”

→ unlinkability, anonymity, privacy related properties in e-voting, . . .

Recently, some formal definitions have been proposed:

- vote-privacy [Delaune et al., 2008],
- unlinkability in RFID systems [Arapinis et al., 2010], [Bruso et al., 2010],

... but some definitions are still missing for many applications (e.g. anonymous routing protocols)
trace equivalence is undecidable in general
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Bounded number of sessions
e.g. [Baudet, 05], [Dawson & Tiu, 10], [Chevalier & Rusinowitch, 10], ... → this allows us to decide trace equivalence between simple processes with trivial else branches. [Cortier & Delaune, 09]
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Unbounded number of sessions
[Blanchet, Abadi & Fournet, 05]


- unbounded number of sessions; various cryptographic primitives;
- termination is not guaranteed; diff-equivalence (too strong)

→ ProSwapper extension [Smyth, 10]
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+ unbounded number of sessions; various cryptographic primitives;

− termination is not guaranteed; diff-equivalence (too strong)

→ ProSwapper extension [Smyth, 10]

→ None of these results is able to analyse the e-passport protocol.
A recent contribution

V. Cheval, H. Comon-Lundh, and S. Delaune  CCS 2011

Main result

A procedure for deciding testing equivalence for a large class of processes.
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Our class of processes:

- non-trivial else branches, private channels, and non-deterministic choice;
- but no replication, and a fixed set of cryptographic primitives (signature, encryption, hash function, mac).
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Our class of processes:

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this allows us in particular to deal with the e-passport example
Some motivations:

- Existing tools allow us to verify relatively small protocols and sometimes only for a bounded number of sessions.
- Most often, we verify them in isolation → this is not sufficient.
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Example:

\[ P_1 : A \rightarrow B : \{ s \}_{\text{pub}(B)} \]

Question: What about the secrecy of \( s \)?
Modularity issues (1/2)

Some motivations:

- Existing tools allow us to verify relatively small protocols and sometimes only for a bounded number of sessions.
- Most often, we verify them in isolation → this is not sufficient.

Example:

\[ P_1 : A \rightarrow B : \{s\}_{pub(B)} \quad P_2 : A \rightarrow B : \{N_a\}_{pub(B)} \]

\[ B \rightarrow A : N_a \]

Question: What about the secrecy of \( s \)?
Our goals

investigate sufficient conditions to ensure that protocols (that may share some keys) can be safely used in an environment where:

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Several results have been proposed for sequential/parallel composition, e.g.:

- parallel composition using tagging
  \[\rightarrow \text{[Guttman & Thayer, 2000], [Cortier et al., 2007]}\]
- sequential composition for arbitrary primitives
  \[\rightarrow \text{[Ciobaca & Cortier, 2010]}\]

... but none of them are well-suited for analysing privacy-type properties
Conclusion

- need of formal methods in verification of security protocols
- state-of-the-art is quite satisfactory to analyze classical security properties (secrecy, authentication, ...)
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- state-of-the-art is quite satisfactory to analyse classical security properties (secrecy, authentication, ...)

It remains a lot to do for analysing privacy-type properties:

- formal definitions of some subtle security properties (receipt-freeness, coercion-resistance, ...)
- algorithms (and tools!) for checking automatically trace equivalence for various cryptographic primitives;
- more composition results.

Main topics of the ANR JCJC - VIP project
(Jan. 2012 - Dec 2015)
http://www.lsv.ens-cachan.fr/Projects/anr-vip/
Research Theme 2 (RT2)

More precisely in “privacy analysis using logical approach” (RT 2.1)

Some expectations

1. new collaborations
   → in particular with the COMÈTE team
   - on privacy analysis using logical approach
     Mayla Brusò, Konstantinos Chatzikokolakis, Jerry den Hartog, *Formal Verification of Privacy for RFID Systems*. CSF 2010: 75-88
   - on privacy analysis using probabilistic approach

2. new case studies
   → Examples: protocols used to protect online social networks and/or electronic health record systems