Analysing privacy-type properties in cryptographic protocols

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Cryptographic protocols everywhere !

Cryptographic protocols

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

The network is unsecure!

Communications take place over a public network like the Internet.

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It becomes more and more important to protect our privacy.

Electronic passport

$\longrightarrow$ studied in [Arapinis *et al.*, 10]

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.

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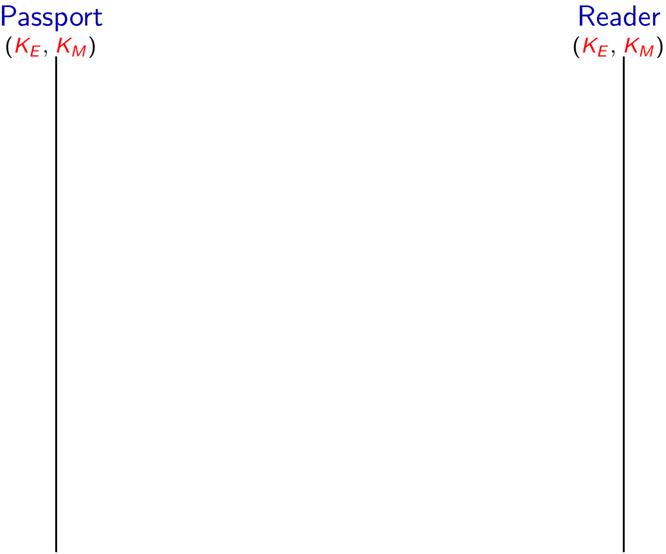
The Basic Access Control (BAC) protocol is a key establishment protocol that has been designed to also ensure unlinkability.

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.*

Basic Acccess Control (BAC) protocol



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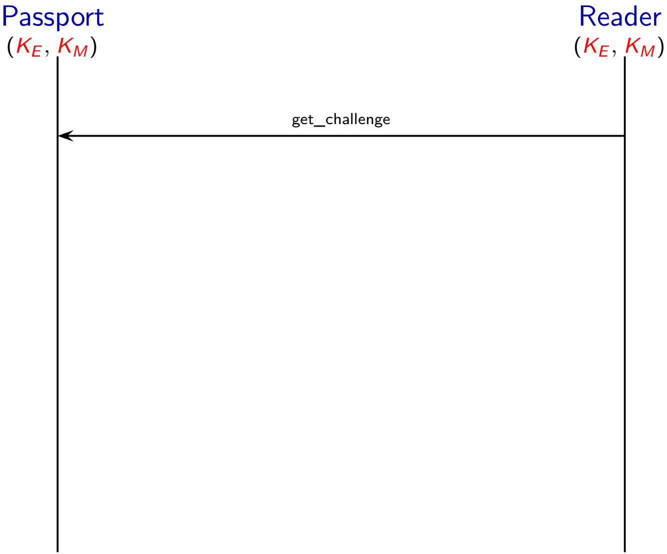

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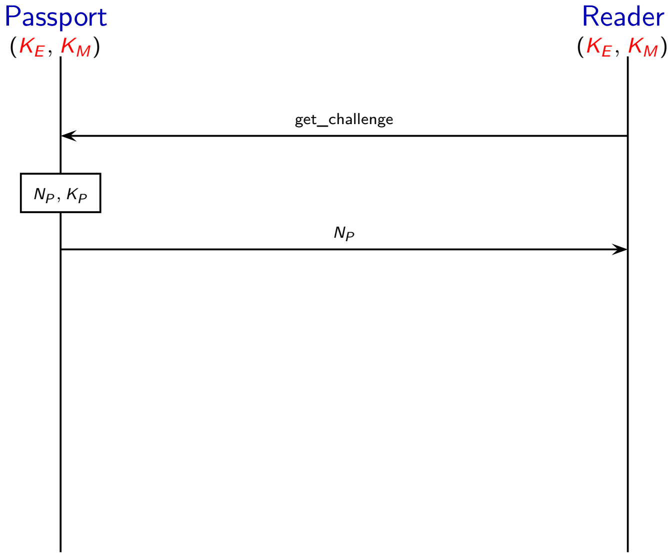

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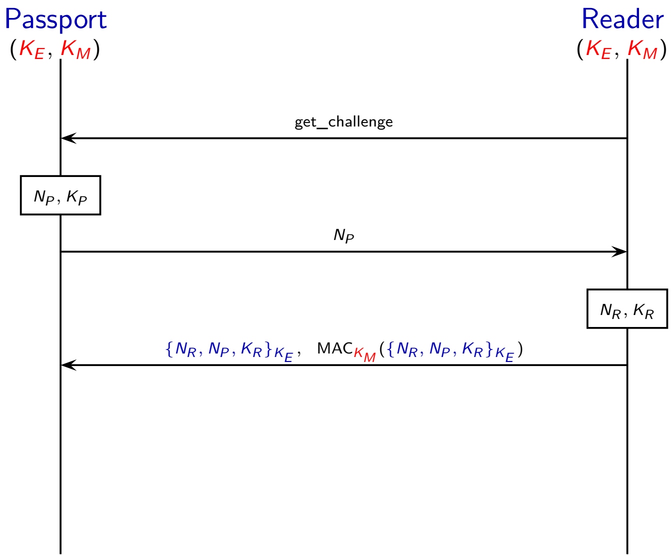

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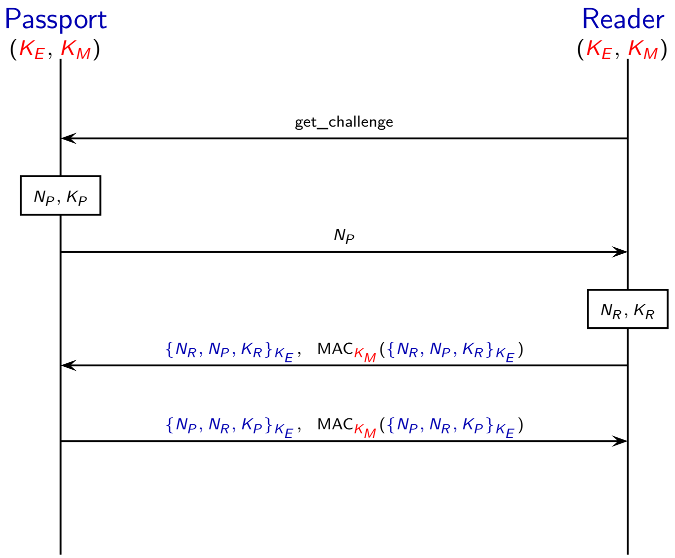

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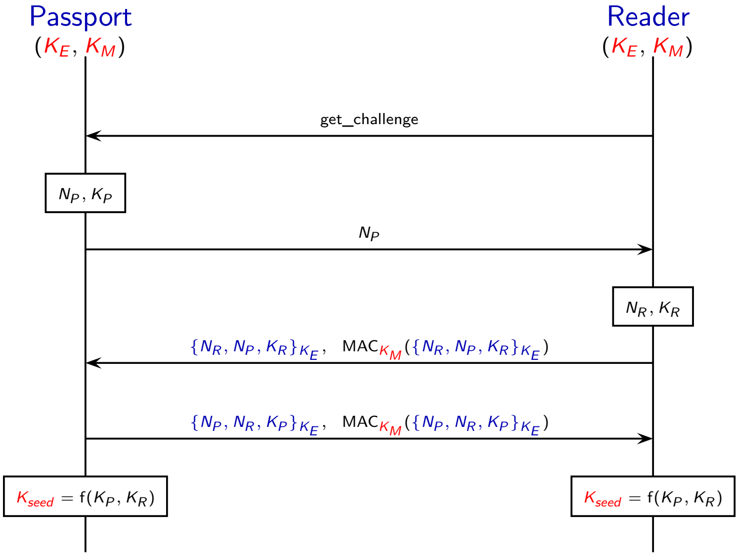

What does unlinkability mean?

Informally, an observer/attacker can not observe the difference between the two following situations:

1. a situation where the same passport may be used twice (or even more);
2. a situation where each passport is used at most once.

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More formally,

$$!\text{new } ke.\text{new } km.(!P_{\text{BAC}} \mid !R_{\text{BAC}}) \overset{?}{\approx} !\text{new } ke.\text{new } km.(P_{\text{BAC}} \mid !R_{\text{BAC}})$$

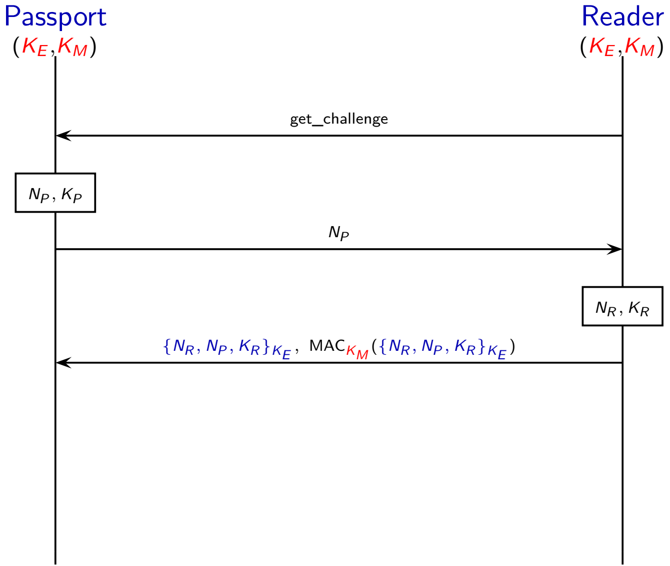
↑ many sessions for each passport

↑ only one session for each passport

(we still have to formalize the processes and the notion of equivalence)

French electronic passport

$\longrightarrow$ the passport must reply to all received messages.



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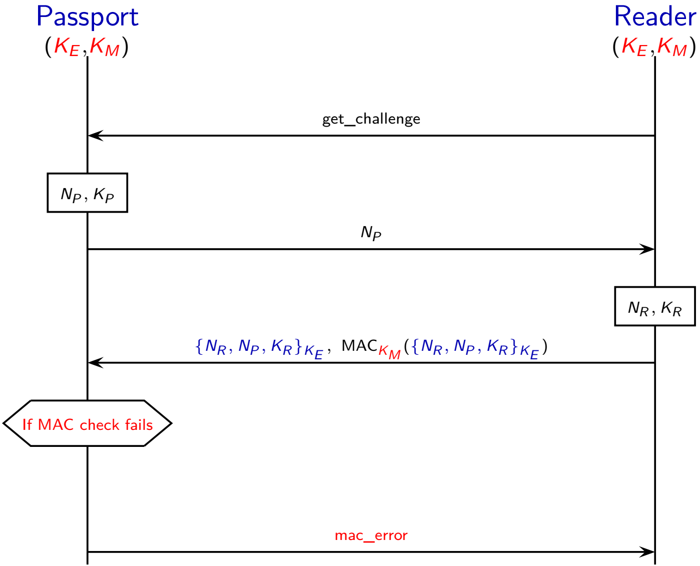

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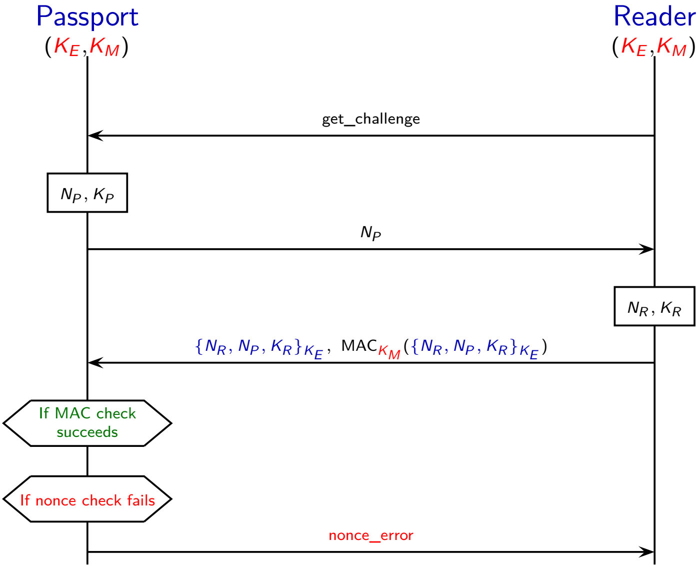

An attack on the French passport [Chothia & Smirnov, 10]

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

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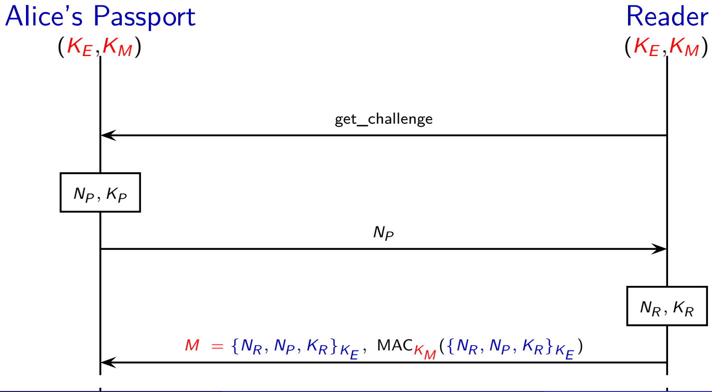
Part 1 of the attack. The attacker eavesdropes on Alice using her passport and records message M.



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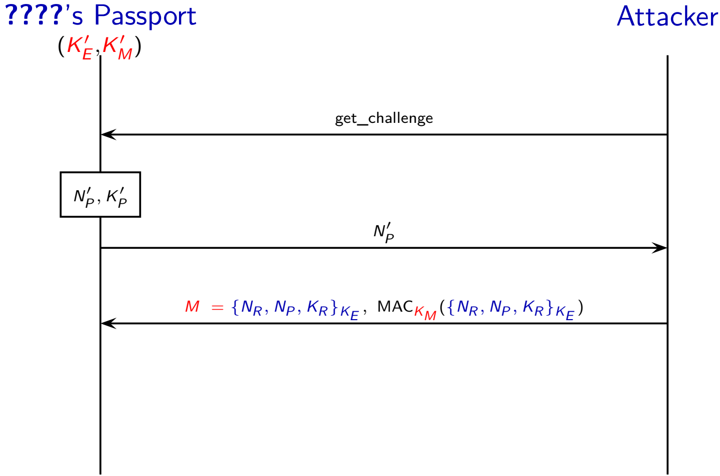
Part 2 of the attack.

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



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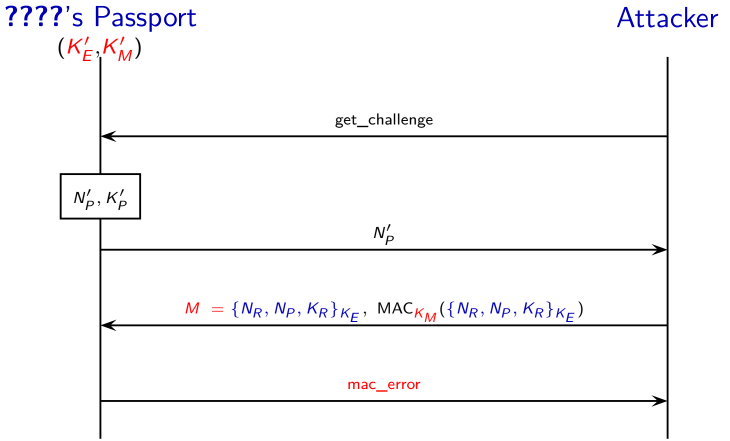

$\Longrightarrow$ MAC check failed $\Longrightarrow$ $K'_M \neq K_M$ $\Longrightarrow$ **????** is not Alice

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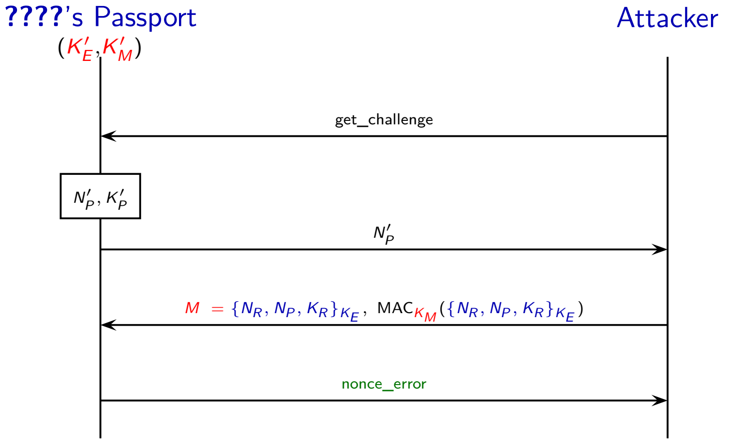
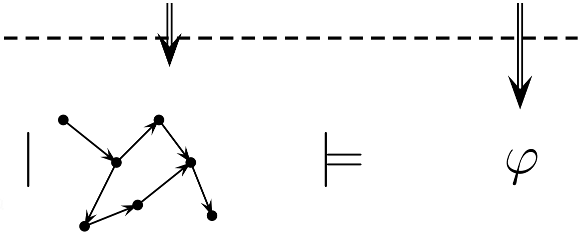


$\Longrightarrow$ MAC check succeeded $\Longrightarrow$ $K'_M = K_M$ $\Longrightarrow$ **????** is Alice

Does the protocol *satisfy* a security property?

Modelling



$\models \quad \varphi$

Outline of the remaining of this talk

1. Modelling cryptographic protocols and their security properties
2. Designing verification algorithms

$\longrightarrow$ we focus here on privacy-type security properties

Part I

Modelling cryptographic protocols
and their security properties

Protocols as processes

Applied pi calculus [Abadi & Fournet, 01]

basic programming language with constructs for concurrency and communication

$\longrightarrow$ based on the π-calculus [Milner *et al.*, 92] ...

P, Q	$:=$	0	null process
		$\mathsf{in}(c, x).P$	input
		$\mathsf{out}(c, u).P$	output
		$\mathsf{if}\ u = v\ \mathsf{then}\ P\ \mathsf{else}\ Q$	conditional
		$P \mid Q$	parallel composition
		$!P$	replication
		$\mathsf{new}\ n.P$	fresh name generation

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... but messages that are exchanged are not necessarily atomic !

Messages as terms

Messages are abstracted by (ground) terms

Ground terms are built over a set of names $\mathcal{N}$, and a signature $\mathcal{F}$.

t	::=	n	name n
	$\mid$	$f(t_1, \ldots, t_k)$	application of symbol $f \in \mathcal{F}$

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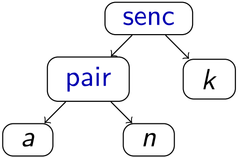
Example: representation of $\{a, n\}_k$

- Names: n, k, a
- constructors: senc, pair,



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$\longrightarrow$ The term algebra is equipped with an equational theory E.

Example: representation of $\{a, n\}_k$

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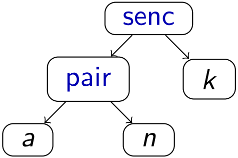
- destructors: sdec, proj_1, proj_2.



$\longrightarrow$ $\text{sdec}(\text{senc}(x, y), y) = x, \quad \text{proj}_1(\text{pair}(x, y)) = x, \quad \text{proj}_2(\text{pair}(x, y)) = y.$

Going back to the e-passport

Cryptographic primitives are modelled using function symbols

- encryption/decryption: senc/2, sdec/2
- concatenation/projections: $\langle\,,\,\rangle/2$, $\mathsf{proj}_1/1$, $\mathsf{proj}_2/1$
- mac construction: mac/2

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Nonces n_r, n_p, and keys k_r, k_p, k_e, k_m are modelled using names

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Modelling Passport's role

$$
\begin{array}{l}
P_{\mathsf{BAC}}(k_E, k_M) \;=\; \mathsf{new}\ n_P.\mathsf{new}\ k_P.\mathsf{in}(\langle z_E, z_M\rangle). \\
\quad \mathtt{if}\ z_M = \mathsf{mac}(z_E, k_M)\ \mathtt{then}\ \mathtt{if}\ n_P = \mathsf{proj}_1(\mathsf{proj}_2(\mathsf{sdec}(z_E, k_E))) \\
\qquad\qquad\qquad\qquad\qquad\qquad \mathtt{then}\ \mathsf{out}(\langle m, \mathsf{mac}(m, k_M)\rangle) \\
\qquad\qquad\qquad\qquad\qquad\qquad \mathtt{else}\ \mathsf{out}(nonce\_error) \\
\qquad\qquad\qquad\qquad \mathtt{else}\ \mathsf{out}(mac\_error)
\end{array}
$$

where $m = \mathsf{senc}(\langle n_P, \langle \mathsf{proj}_1(z_E), k_P\rangle\rangle, k_E)$.

Semantics

Semantics $\to$:

COMM	$\mathsf{out}(c,u).P \mid \mathsf{in}(c,x).Q \to P \mid Q\{u/x\}$
THEN	$\mathsf{if}\ u = v\ \mathsf{then}\ P\ \mathsf{else}\ Q \to P\ \mathsf{when}\ u =_{\mathsf{E}} v$
ELSE	$\mathsf{if}\ u = v\ \mathsf{then}\ P\ \mathsf{else}\ Q \to Q\quad \mathsf{when}\ u \neq_{\mathsf{E}} v$

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ELSE	if $u = v$ then P else $Q \rightarrow Q$ when $u \neq_{\mathsf{E}} v$

closed by

- structural equivalence ($\equiv$):

$$P \mid Q \equiv Q \mid P, \qquad P \mid 0 \equiv P, \qquad \ldots$$

- application of evaluation contexts:

$$\frac{P \rightarrow P'}{\mathsf{new}\, n.\ P \rightarrow \mathsf{new}\, n.\ P'} \qquad \frac{P \rightarrow P'}{P \mid Q \rightarrow P' \mid Q}$$

Security properties - privacy

Privacy-type properties are modelled as equivalence-based properties

testing equivalence between P and Q, $P \approx_t Q$

for all processes A, we have that:

$$(A \mid P) \Downarrow_c \text{ if, and only if, } (A \mid Q) \Downarrow_c$$

where $P \Downarrow_c$ means that P can evolve and emits on public channel c.

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Example 1: $\mathsf{out}(a, s) \not\approx_t \mathsf{out}(a, s')$

$$\longrightarrow \quad A = \mathsf{in}(a, x).\mathsf{if}\ x = s\ \mathsf{then}\ \mathsf{out}(c, ok)$$

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Example 2:

$$\text{new } s.\mathsf{out}(a, \mathsf{senc}(s, k)).\mathsf{out}(a, \mathsf{senc}(s, k')) \overset{?}{\approx}_t \text{new } s, s'.\mathsf{out}(a, \mathsf{senc}(s, k)).\mathsf{out}(a, \mathsf{senc}(s', k'))$$

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$$\longrightarrow A = \text{in}(a, x).\text{in}(a, y).\text{if } (\text{sdec}(x, k) = \text{sdec}(y, k')) \text{ then out}(c, ok)$$

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Question: Are the two following processes in testing equivalence?

$$\text{new } s.\text{out}(a, s) \ \stackrel{?}{\approx}_t \ \text{new } s.\text{new } k.\text{out}(a, \text{senc}(s, k))$$

Some privacy-type properties

Unlinkability [Arapinis et al, 2010]

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↑ many sessions for each passport

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Vote privacy [Kremer and Ryan, 2005]

$$V_A(yes) \approx_t V_A(no)$$

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↑ A votes yes, B votes no

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$\longrightarrow$ often requires some assumptions $S[\_]$

Designing verification algorithms for privacy-type properties

How can we check testing equivalence?

testing equivalence is undecidable in general

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Some decidability results [Chrétien, Cortier & D., ICALP'13 & CONCUR'14]

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A more pragmatic approach [Blanchet *et al.*, 2005]

ProVerif `http://www.proverif.ens.fr`

- \+ various cryptographic primitives
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$\longrightarrow$ These results are not suitable to analyse vote-privacy, or unlinkability of the BAC protocol.

Testing equivalence (for processes without replication)

For processes without replication
testing equivalence is decidable
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Some difficulties

- We still have to consider any possible behavior for the attacker (for all quantification over processes).
  $\longrightarrow$ no hope to test each possible behavior of the attacker in turn
- Once the behavior of the attacker is fixed, we still have to decide whether the two sequences of messages that are outputted are indistinguishable or not.
  $\longrightarrow$ the so-called static equivalence problem.

A recent result

Cheval, Comon-Lundh & D. CCS 2011

A procedure for deciding testing equivalence for a large class of processes implemented in a tool called APTE

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, symmetric and asymmetric encryptions, hash function, mac, pairs).

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Similar results for restricted class of processes have been obtained in [Baudet, 05], [Dawson & Tiu, 10], [Chevalier & Rusinowitch, 10], [Chadha *et al.*, 12], . . .

Our procedure in a nutshell

Two main steps:

1. A symbolic exploration of all the possible traces

   The infinite number of possible traces (*i.e.* experiment) are represented by a finite set of symbolic traces.

   $\longrightarrow$ this set is still huge (exponential) !

2. A decision procedure for deciding (symbolic) equivalence between sets of symbolic traces.

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Some applications

- unlinkability in RFID protocols (*e.g.* e-passport protocol)
- anonymity (*e.g.* private authentication protocol)

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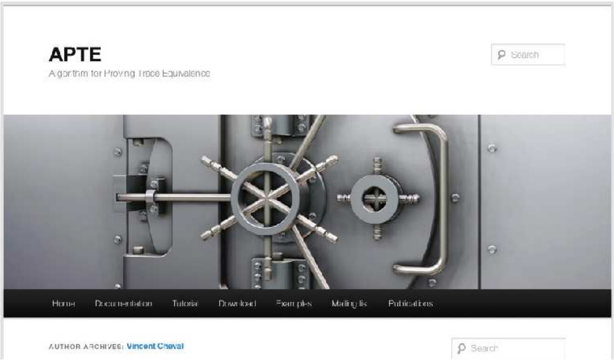
Main limitations

- e-voting protocols are still out of reach
- we can only handle very few sessions (state space explosion problem)

APTE- Algorithm for Proving Trace Equivalence

`http://projects.lsv.ens-cachan.fr/APTE`

$\longrightarrow$ developed by Vincent Cheval



$\longrightarrow$ written in Ocaml, around 12 KLocs

Conclusion - What remains to do?

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

- formal definitions of some sublte security properties (receipt-freeness, coercion-resistance, . . .)
- algorithms (and tools!) for checking (automatically or not) testing equivalence for various cryptographic primitives;
- result to allow a modular analysis

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

$\longrightarrow$ a postdoc position is available on this project.