Verification of security protocols: from confidentiality to privacy

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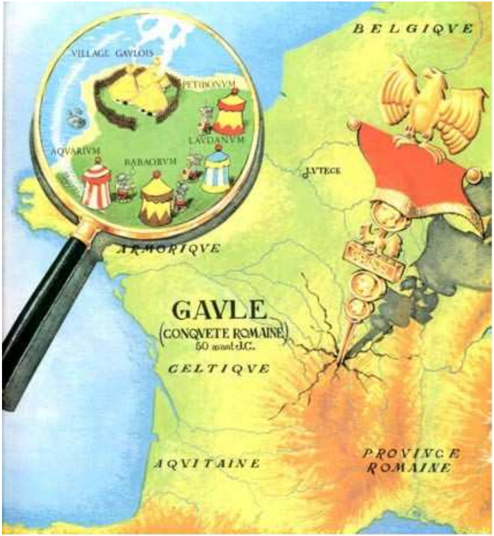
CNRS & IRISA, Rennes, France

Wednesday, May 10th, 2017

Research at IRISA (Rennes)

$\longrightarrow$ 800 members (among which about 400 reasearchers)

Where is it?



Coming soon !

september 2017

Rennes to Paris in 90 min. by train.

EMSEC team

Embedded Security & Cryptography

$\longrightarrow$ 6 permanent researchers, 12 PhD students, and 2 post-docs

P. Derbez, G. Avoine, A. Roux-Langlois, B. Kordy, & P.-A. Fouque.

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 e-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

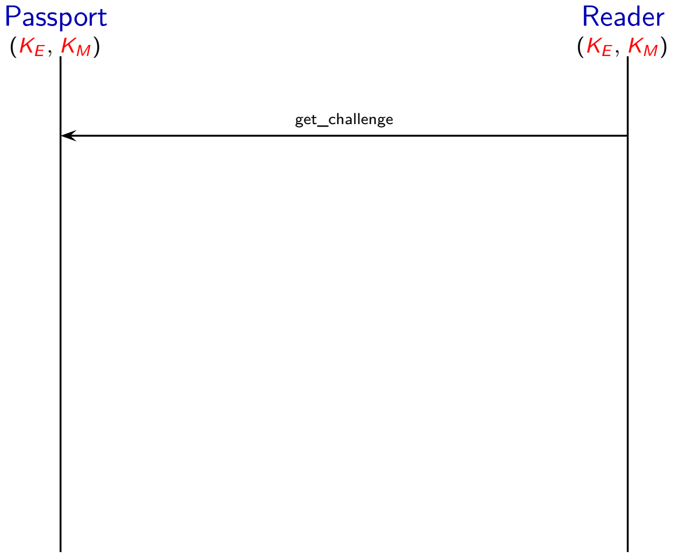
Unlinkability aims to ensure *that a user may make multiple uses of a service or resource without others being able to link these uses together*.

Basic Acccess Control (BAC) protocol

Passport
(K_E, K_M)

Reader
(K_E, K_M)

Basic Acccess Control (BAC) protocol



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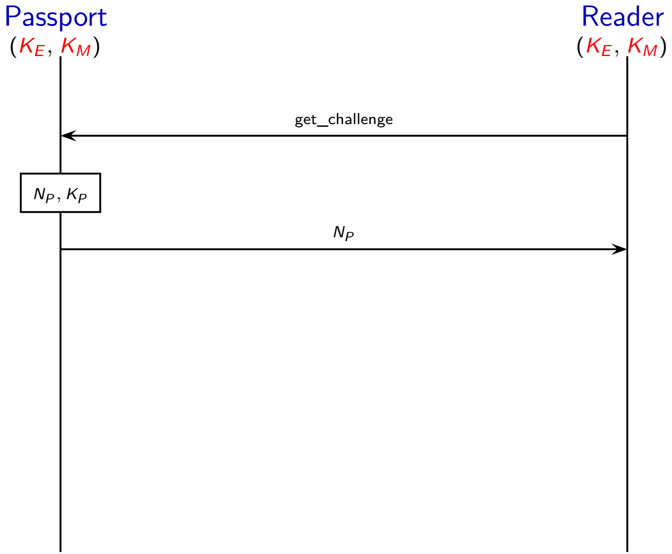

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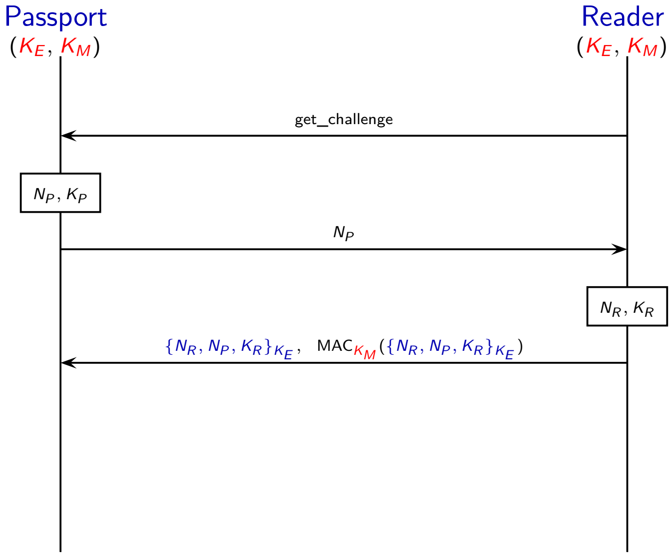

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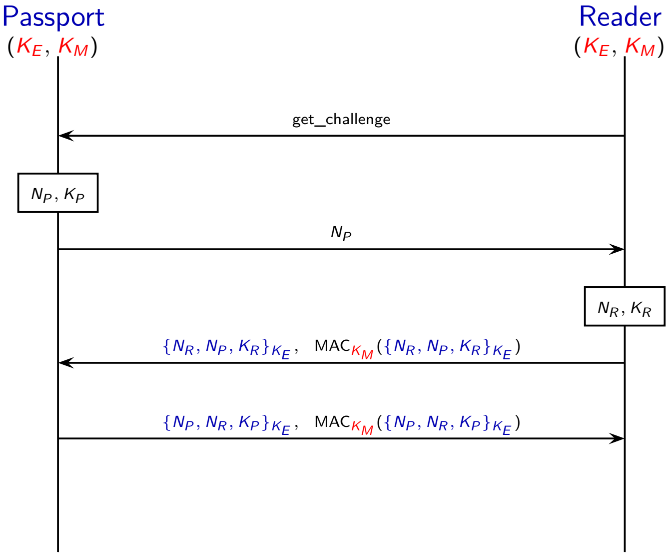

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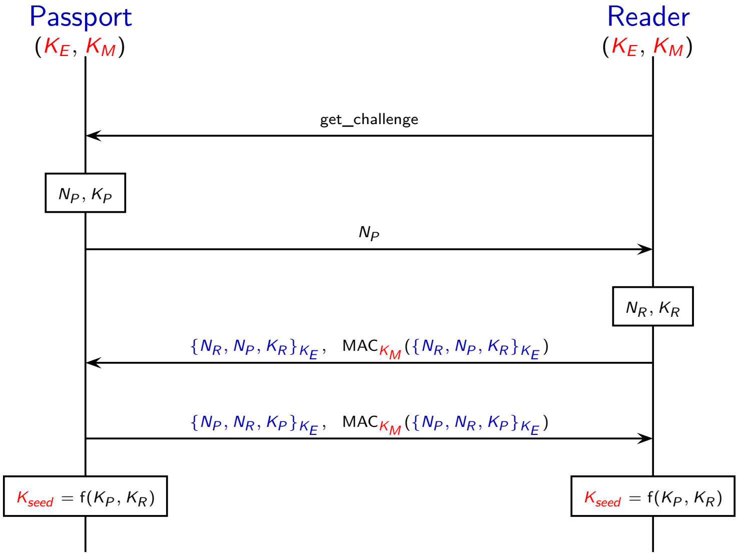

How cryptographic protocols can be attacked?

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Logical attacks

- can be mounted even assuming perfect cryptography,
  $\hookrightarrow$ replay attack, man-in-the middle attack, ...
- subtle and hard to detect by "eyeballing" the protocol

This is the so-called **Dolev-Yao attacker** !

as explained on Monday in the talk of Alessandro Armando

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$\longrightarrow$ A traceability attack on the BAC protocol (2010)

Security

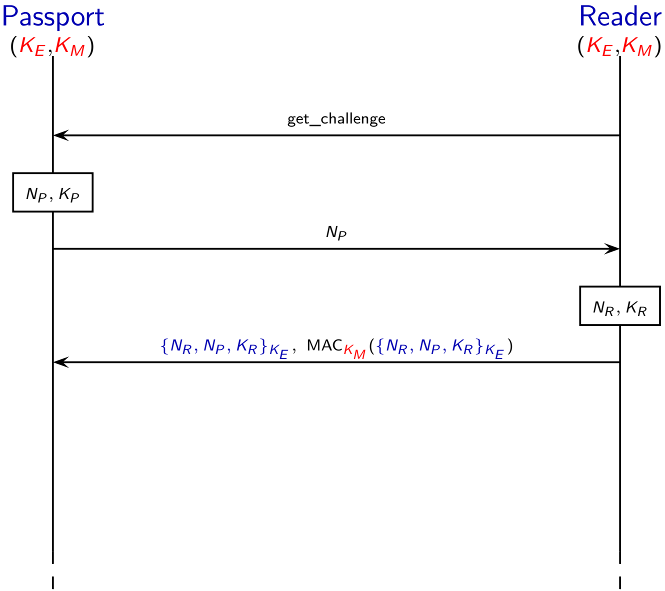
Defects in e-passports allow real-time tracking

This threat brought to you by RFID

The register - Jan. 2010

French electronic passport

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



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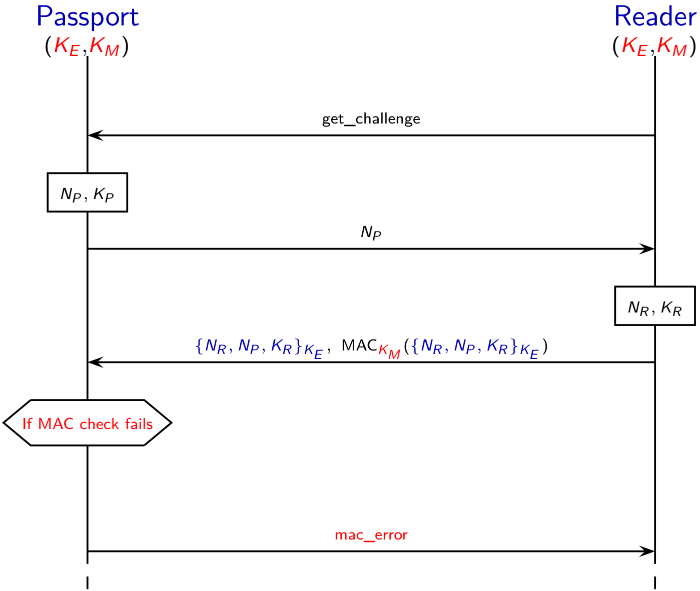

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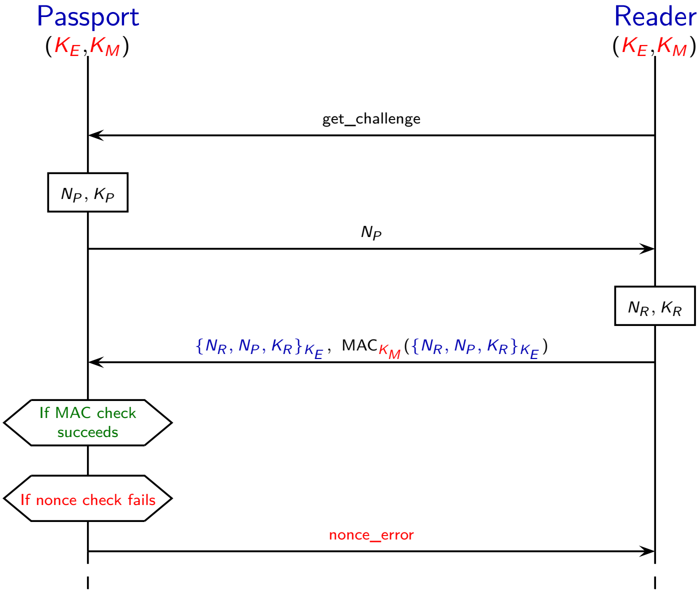

An attack on the French passport [Chothia & Smirnov, 10]

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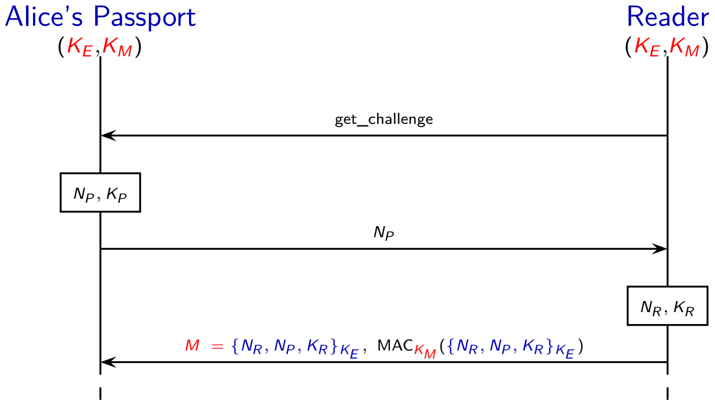
Part 1 of the attack. The attacker eavesdropes on Alice using her passport and records message M.



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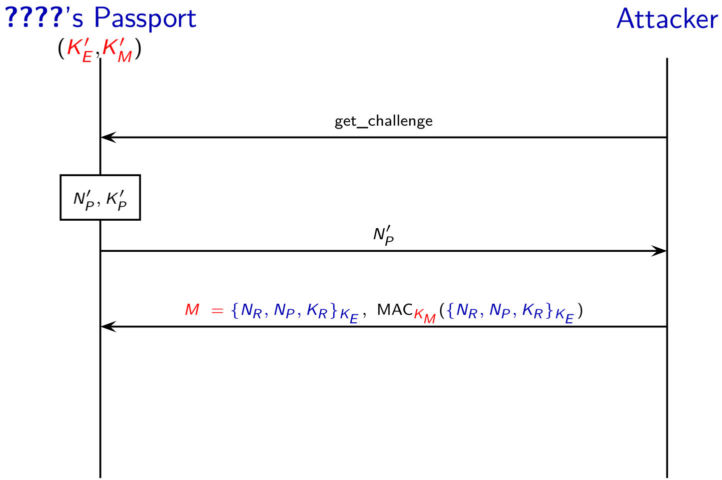
Part 2 of the attack.

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



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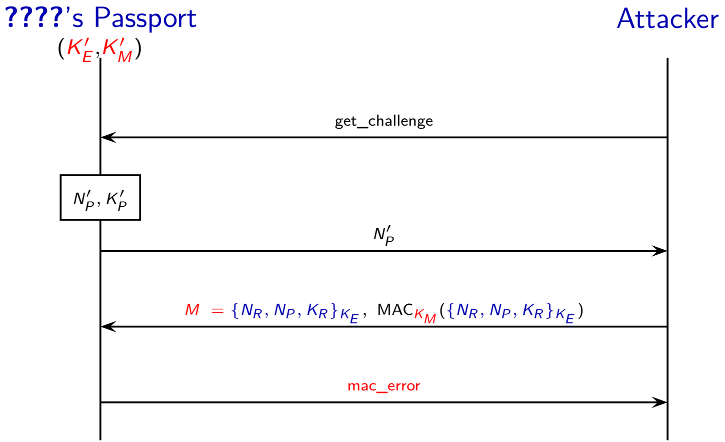

MAC check failed $\implies$ $K'_M \neq K_M$ $\implies$ **????** is not Alice

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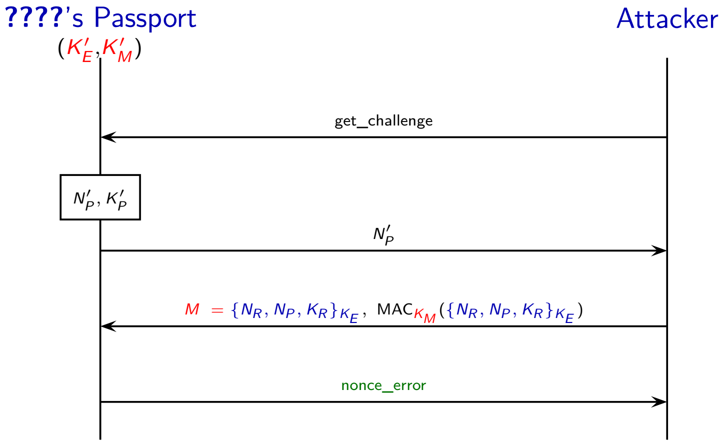
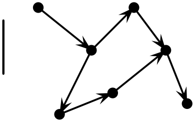


MAC check succeeded $\Longrightarrow$ $K'_M = K_M$ $\Longrightarrow$ **????** is Alice

Outline

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

Two major families of models ...

... with some advantages and some drawbacks.

Computational model

- + messages are bitstring, a general and powerful adversary
- – manual proofs, tedious and error-prone

Symbolic model

- – abstract model, e.g. messages are terms
- + automatic proofs

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Symbolic model

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- + automatic proofs

Some results allowed to make a link between these two very different models.
$\longrightarrow$ Abadi & Rogaway 2000

Messages as terms

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

$$
\begin{array}{lcll}
\mathrm{t} & ::= & n & \text{name } n \\
 & | & f(t_1, \ldots, t_k) & \text{application of symbol } f \in \mathcal{F}
\end{array}
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Example: representation of $\{a, n\}_k$

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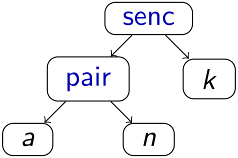
- constructors: senc, pair,



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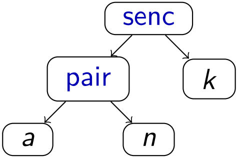

The term algebra is equipped with an equational theory E.

$$\mathsf{sdec}(\mathsf{senc}(x, y), y) = x \qquad \begin{array}{rcl} \mathsf{proj}_1(\mathsf{pair}(x, y)) & = & x \\ \mathsf{proj}_2(\mathsf{pair}(x, y)) & = & y \end{array}$$

Example: $\mathsf{sdec}(\mathsf{senc}(s, k), k) =_{\mathsf{E}} s$.

Protocols as processes

The Applied pi calculus is a basic programming language with constructs for concurrency and communication

[Abadi & Fournet, 01]

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

Back to the BAC protocol

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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

$\longrightarrow$ $\mathsf{sdec}(\mathsf{senc}(x, y), y) = x$, $\mathsf{proj}_1(\langle x, y\rangle) = x$, $\mathsf{proj}_2(\langle x, y\rangle) = y$.

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

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

Modelling Passport's role

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

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

Semantics

Semantics $\rightarrow$:

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

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\textsc{Else} & \text{if } u = v \text{ then } P \text{ else } Q \rightarrow Q \quad \text{ when } u \neq_{\mathsf{E}} v
\end{array}
$$

closed by

- structural equivalence ($\equiv$):

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

- application of evaluation contexts:

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

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,

$$!\mathrm{new}\ ke.\mathrm{new}\ km.(\underset{\substack{\uparrow\\ \boxed{\text{many sessions for each passport}}}}{!P_{\mathrm{BAC}}} \mid !R_{\mathrm{BAC}}) \overset{?}{\approx} !\mathrm{new}\ ke.\mathrm{new}\ km.(\underset{\substack{\uparrow\\ \boxed{\text{only one session for each passport}}}}{P_{\mathrm{BAC}}} \mid R_{\mathrm{BAC}})$$

(we still have to formalize the notion of equivalence)

Testing equivalence

Definition - Testing equivalence - $P \approx Q$

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 channel c.

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Example 1: $\mathrm{out}(a, yes) \stackrel{?}{\approx} \mathrm{out}(a, no)$

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Example 1: $\mathrm{out}(a, \mathit{yes}) \not\approx \mathrm{out}(a, \mathit{no})$

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

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Example 2:

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

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

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Exercise: Are the two following processes in testing equivalence?

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

Some other equivalence-based security properties

The notion of testing equivalence can be used to express:

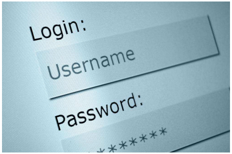
Vote privacy

the fact that a particular voted in a particular way is not revealed to anyone

Strong secrecy

the fact that an adversary cannot see any difference when the value of the secret changes

$\longrightarrow$ stronger than the notion of secrecy as non-deducibility.



Guessing attack

the fact that an adversary can not learn the value of passwords even if he knows that they have been choosen in a particular dictionary.

Part II

Designing verification algorithms for privacy-type properties

How can we check testing equivalence?

The problem is undecidable in general

$\longrightarrow$ even under quite severe restrictions [Chrétien PhD thesis, 2016]

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Several procedures and automatic tools already exist !

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Several procedures and automatic tools already exist !

Two main categories of tools have been developed:

- bounded number of sessions: Spec [Dawson & Tiu, 2010], Apte [Cheval et al, 2011], and Akiss [Chadha et al, 2012].
- unbounded number of sessions: ProVerif [Blanchet et al, 2005], Tamarin [Basin et al, 2015], and Maude-NPA [Yang et al, 2016].

Part II.A

Designing verification algorithms for privacy-type properties

for a bounded number of sessions

Testing equivalence for a bounded number of sessions

$\longrightarrow$ decidable when considering classical primitives

- A decision procedure implemented in the tool Apte:
  non-trivial else branches, private channels, and
  non-deterministic choice, a fixed set of primitives
  [Cheval, Comon & D., 11]
- A procedure implemented in the tool Akiss:
  no else branches, but a larger class of primitives
  [Chadha et al, 12]

$\longrightarrow$ Work in progress: a procedure that takes advantage of both !

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$\longrightarrow$ Work in progress: a procedure that takes advantage of both !

Main limitation: a limited practical impact because these tools scale badly, e.g. unlinkability of a fixed version of BAC (2 sessions)

$\longrightarrow$ **more than 2 days !**

Partial order reduction for security protocols

[Hirschi PhD thesis, 2017]

Main objective

to develop POR techniques that are suitable for analysing security protocols (especially testing equivalence)

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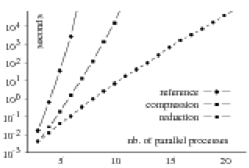
Example: $\mathsf{in}(c_1, x_1).\mathsf{out}(c_1, \mathsf{ok}) \mid \mathsf{in}(c_2, x_2).\mathsf{out}(c_2, \mathsf{ok})$

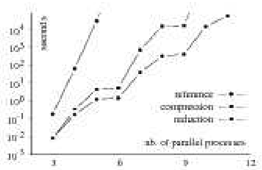
We propose two optimizations:

1. compression: we impose a simple strategy on the exploration of the available actions (roughly outputs are performed first and using a fixed arbitrary order)
2. reduction: we avoid exploring some redundant traces taking into account the data that are exchanged

Practical impact of our optimizations (in APTE)



Toy example



Denning Sacco protocol

$\longrightarrow$ Each optimisation brings an exponential speedup.

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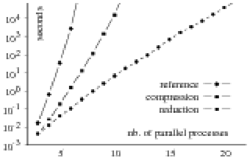

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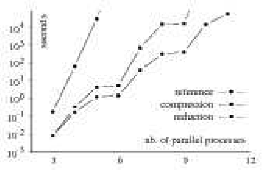

Denning Sacco protocol

⟶ Each optimisation brings an exponential speedup.

Protocol	reference	with POR
Yahalom (3-party)	4	5
Needham Schroeder (3-party)	4	7
Private Authentication (2-party)	4	7
E-Passport PA (2-party)	4	9
Denning-Sacco (3-party)	5	10
Wide Mouthed Frog (3-party)	6	13

Maximum number of parallel processes verifiable in 20 hours.

⟶ Our optimisations make Apte much more useful in practice for investigating interesting scenarios.

SAT-Equiv: a new tool for checking testing equivalence

[CSF, 2017]

SAT-Equiv in a nutshell:

- inspired from SATMC [Armando et al, 2014];
- bounded verification (messages of bounded size)
  $\longrightarrow$ this is possible without missing any attacks when protocols are type-compliant. [Chretien PhD thesis, 2016]
- a successful combination of techniques developed for planning, and the use of SAT solvers;
- less sensitive to the number of concurrent sessions analysed.

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Work in progress:

- more cryptographic primitives: asymmetric encryption, signature, . . .
- a larger class of processes: else branches, beyond simple processes, . . .

Some encouraging results with SAT-Equiv

Denning-Sacco protocol:

$$\begin{array}{ll} 1. & A \to S : \ A, B \\ 2. & S \to A : \ \{B, K_{ab}, \{K_{ab}, A\}_{K_{bs}}\}_{K_{as}} \\ 3. & A \to B : \ \{K_{ab}, A\}_{K_{bs}} \end{array}$$

Comparison of the different tools:

# roles	Spec	Akiss	Apte	Apte-por	**Sat-Eq**
3	12s	0.10s	0.3s	0.03s	0.25s
6	MO	15s	TO	8s	1s
7		101s		13s	2s
10		SO		39m	4s
12				TO	7s
14					10s

$\longrightarrow$ similar results when considering other protocols, e.g. Needham-Schroeder, Wide-Mouth-Frog, Yahalom, Otway Rees, ...

Part II.B

Designing verification algorithms
for privacy-type properties

for an unbounded number of sessions

Testing equivalence for an unbounded number of sessions

Some recent theoretical results [Chrétien PhD thesis, 2016]

- undecidable in general (and even under quite severe restriction)
- a first decidability result through a characterization of equivalence of protocols in terms of equality of languages of deterministic pushdown automata. [Icalp'13, TOCL'15]
- decidable for a subclass of tagged protocols [CSF'15]

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Main limitations:

- a restricted set of primitives: symmetric encryption, and concatenation only;
- not really practical (no verification tool).

A more pragmatic approach

[Blanchet *et al.*, LICS'05]

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

- various cryptographic primitives modeled using equations;
- various security properties: secrecy, authentication, and equivalence-based properties (namely diff-equivalence);

The tool may not terminate or give false attacks.

Works very well in many situations, e.g. strong secrecy

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Main issue: diff-equivalence is too strong in many situations.
$\longrightarrow$ ProVerif is not suitable to analyse unlinkability properties.

The Tamarin and Maude-NPA tools are also based on diff-equivalence and they suffer from the same problem.

Our approach is pragmatic too [S&P, 2016]

Provide a method to analyse unlinkability for a large class of 2 party protocols, and tool support for that.

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> Provide a method to analyse unlinkability for a large class of 2 party protocols, and tool support for that.

On the theoretical side

2 reasonable conditions implying anonymity and unlinkability for a large class of 2 party protocols

On the practical side

- our conditions can be checked automatically using existing tools, and we provide tool support for that.
- new proofs and attacks on several RFID protocols.

$\longrightarrow$ first results published at Security & Privacy in 2016 extended since to deal with a larger class of processes

Tool support

Our two conditions can be automatically verified using ProVerif:

- well-authentication: this is a pure reachability property
  $\longrightarrow$ ProVerif (and other existing tools) works well
- frame opacity: equivalence between sequences of messages
  $\longrightarrow$ checkable with good precision via diff-equivalence

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Tool UKANO

A tool built on top of ProVerif that automatically checks our two conditions.

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

Summary of our case studies using UKANO

Protocol	FO	WA	unlinkability
Feldhofer	✓	✓	**safe**
Feldhofer variant (with !)	✓	✗	attack
Hash-Lock	✓	✓	**safe**
LAK (stateless)	–	✗	attack
Fixed LAK	✓	✓	**safe**
BAC	✓	✓	**safe**
BAC/PA/AA	✓	✓	**safe**
PACE (faillible dec)	–	✗	attack
PACE (as in [Bender et al, 09])	–	✗	attack
PACE	–	✗	attack
PACE with tags	✓	✓	**safe**
DAA sign	✓	✓	**safe**
DAA join	✓	✓	**safe**
abcdh (irma)	✓	✓	**safe**

Conclusion

To sum up

Cryptographic protocols are:

- difficult to design and analyse;
- particularly vulnerable to logical attacks.

Strong primitives are necessary . . .

. . . **but this is not sufficient !**

To sum up

Cryptographic protocols are:

- difficult to design and analyse;
- particularly vulnerable to logical attacks.

It is important to ensure that
the protocols we are using every day work properly.

We now have automatic and powerful verification tools to analyse:

- classical security goals, *e.g.* secrecy and authentication;
- relatively small protocols;
- protocols that rely on standard cryptographic primitives.

Limitations of the symbolic approach

1. the algebraic properties of the primitives are abstracted away
   $\longrightarrow$ no guarantee if the protocol relies on an encryption that satisfies some additional properties (*e.g.* RSA, ElGamal)

2. only the specification is analysed and not the implementation
   $\longrightarrow$ most of the passports are actually linkable by a carefull analysis of time or message length.

   http://www.loria.fr/~glondu/epassport/attaque-tailles.html

3. when considering a bounded number of sessions, not all scenario are checked
   $\longrightarrow$ no guarantee if the protocol is used one more time !

Regarding privacy-type security properties

It remains a lot to do

- formal definitions of some sublte security properties
  $\longrightarrow$ receipt-freeness, coercion-resistance in e-voting
- algorithms (and tools!) for checking automatically trace equivalence for various cryptographic primitives;
  $\longrightarrow$ homomorphic encryption used in e-voting, exclusive-or used in RFID protocols [CSF, 2017]
- more composition results
  $\longrightarrow$ Could we derive some security guarantees of the whole e-passport application from the analysis performed on each subprotocol?
- develop more fine-grained models (and tools) to take into account side channel attacks
  $\longrightarrow$ e.g. timing attacks

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$\longrightarrow$ contact me: `stephanie.delaune@irisa.fr`

Questions ?