Verification of security protocols
from confidentiality to privacy

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Cryptographic protocols everywhere !

Goal: they aim at securing communications over public/insecure networks

Some security properties

- **Secrecy**: May an intruder learn some secret message between two honest participants?
- Authentication: Is the agent Alice really talking to Bob?
- Anonymity: Is an attacker able to learn something about the identity of the participants who are communicating?
- Non-repudiation: Alice sends a message to Bob. Alice cannot later deny having sent this message. Bob cannot deny having received the message.
- ...

Example: E-voting application

Eligibility: only legitimate voters can vote, and only once

No early results: no early results can be obtained which could influence the remaining voters

Vote-privacy/Receipt-freeness/Coercion-resistance: the fact that a particular voted in a particular way is not revealed to anyone

Individual/Universal verifiability:
a voter can verify that her vote was really counted, and that the published outcome is the sum of all the votes

How does a cryptographic protocol work (or not)? (1/2)

cryptographic primitives = basic building blocks

$\longrightarrow$ symmetric/ asymmetric encryption, signature, hash function, ...

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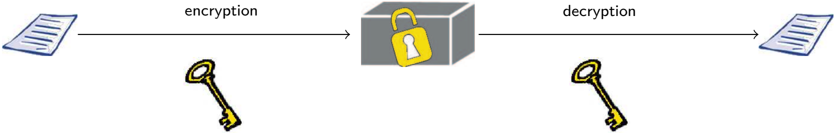
Symmetric encryption



Examples: Caesar cipher, Enigma machine ($\sim$ 1918-1945), or more recently DES (1973) and AES (1997)

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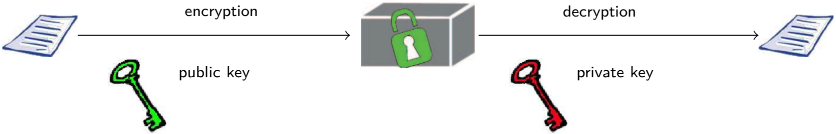

Examples: First system published by Diffie-Hellman (1976), RSA (1977)

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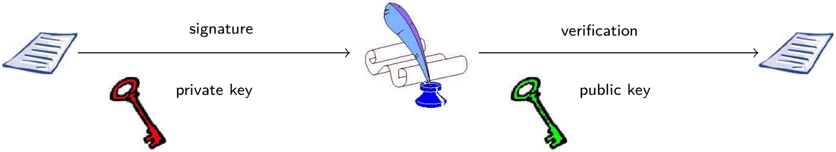
Signature



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$$\begin{array}{lcl} A \rightarrow B & : & \mathsf{aenc}(\mathsf{sign}(k, \mathsf{priv}(A)), \mathsf{pub}(B)) \\ B \rightarrow A & : & \mathsf{senc}(s, k) \end{array}$$

What about secrecy of s ?

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Consider a scenario where A starts a session with C who is dishonest.

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2. $C(A) \to B : \mathrm{aenc}(\mathrm{sign}(k, \mathrm{priv}(A)), \mathrm{pub}(B))$
3. $\quad B \to A : \mathrm{senc}(s, k)$ Attack !

Exercise

We propose to fix the Denning-Sacco protocol as follows:

Version 1

$$\begin{array}{lcl} A \to B & : & \mathrm{aenc}(\langle A, B, \mathrm{sign}(k, \mathrm{priv}(A))\rangle, \mathrm{pub}(B)) \\ B \to A & : & \mathrm{senc}(s, k) \end{array}$$

Version 2

$$\begin{array}{lcl} A \to B & : & \mathrm{aenc}(\mathrm{sign}(\langle A, B, k\rangle, \mathrm{priv}(A))\rangle, \mathrm{pub}(B)) \\ B \to A & : & \mathrm{senc}(s, k) \end{array}$$

Which version would you prefer to use?

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Which version would you prefer to use? Version 2

$\longrightarrow$ Version 1 is still vulnerable to the aforementioned attack.

What about protocols used in real life ?

E-passport

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

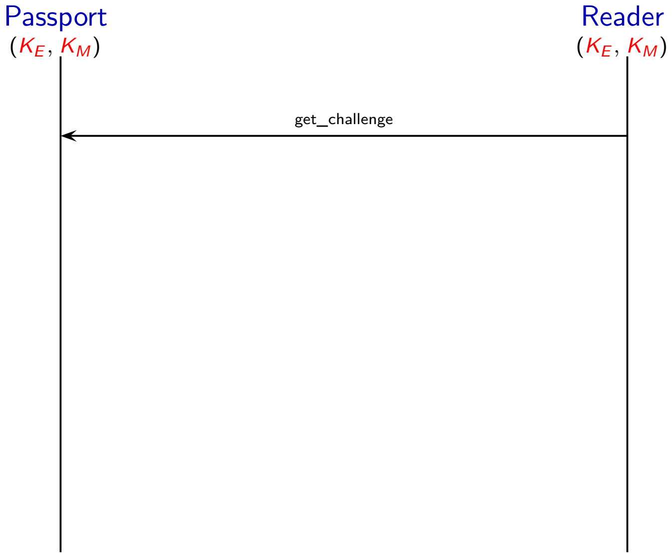
ISO/IEC standard 15408

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.*

BAC protocol

Passport	Reader
(K_E, K_M)	(K_E, K_M)

BAC protocol



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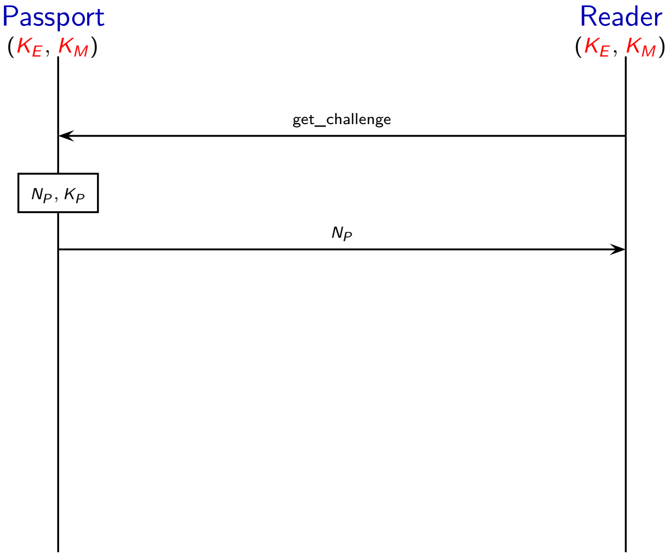

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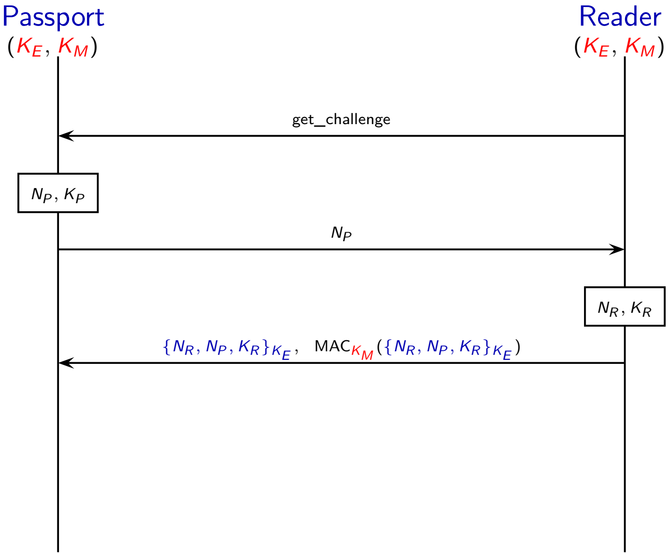

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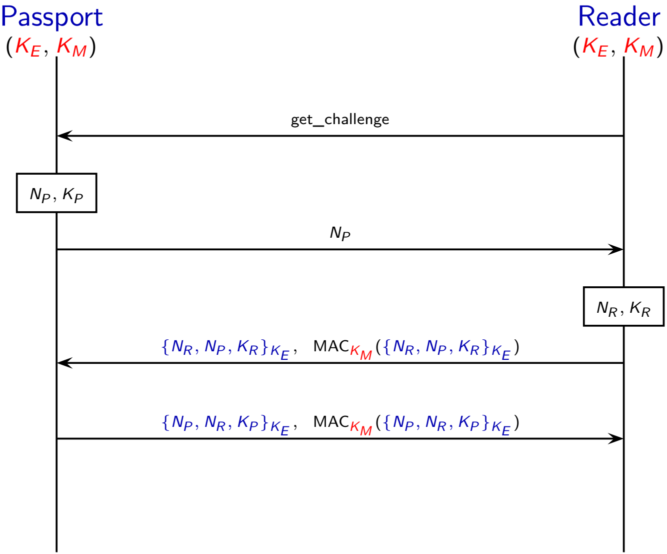

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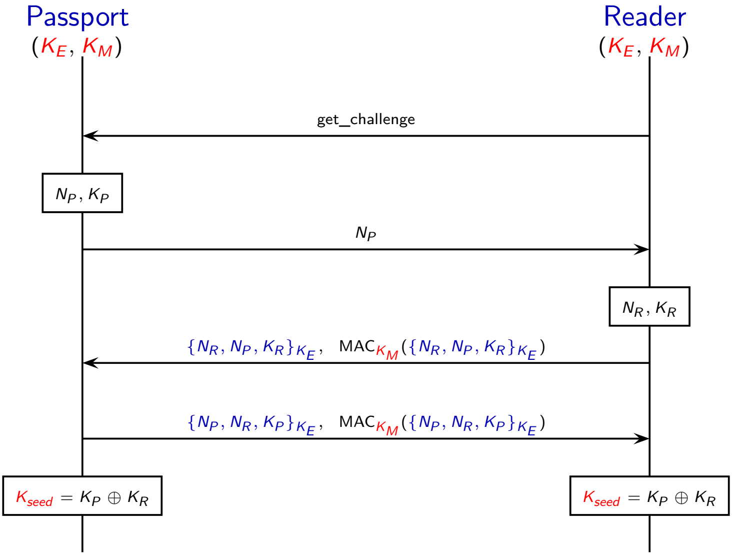
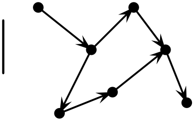


This talk: formal methods for protocol verification

Does the protocol *satisfy* a security property?

Modelling



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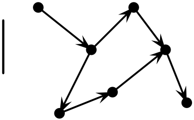

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E-passport application

What about unlinkability of the ePassport holders ?

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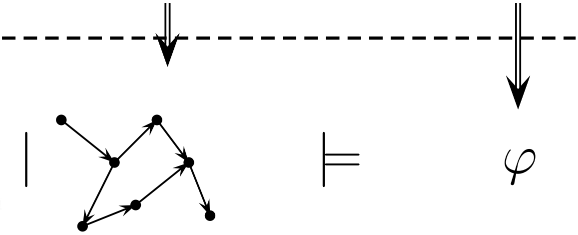

Outline of the this talk

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

Modelling cryptographic protocols and their security properties

Messages as terms

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

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

Example:

- $\mathcal{F} = \{\mathsf{senc}(\cdot,\cdot),\ \mathsf{sdec}(\cdot,\cdot),\ \langle \cdot,\cdot \rangle,\ \mathsf{proj}_1(\cdot),\ \mathsf{proj}_2(\cdot)\}$;
- $\mathcal{N} = \{n, a, k, s, \ldots\}$.

$\longrightarrow$ some terms: $\mathsf{senc}(\langle s, a \rangle, k)$, $\mathsf{sdec}(\mathsf{enc}(s, k), k)$, and s.

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Term algebra is equipped with an equational theory E.

Example: $\mathrm{dec}(\mathrm{enc}(x, y), y) = x$, $\mathrm{proj}_1(\langle x, y\rangle) = x$, $\mathrm{proj}_2(\langle x, y\rangle) = y$.

We have that $\mathrm{sdec}(\mathrm{senc}(s, k), k) =_{\mathsf{E}} s$.

Going back to the Denning Sacco protocol

$$\begin{array}{lcl} A \rightarrow B & : & \mathsf{aenc}(\mathsf{sign}(k, \mathsf{priv}(A)), \mathsf{pub}(B)) \\ B \rightarrow A & : & \mathsf{senc}(s, k) \end{array}$$

What function symbols and equations do we need to model this protocol?

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The two terms involved in a normal execution are:

$$\mathsf{aenc}(\mathsf{sign}(k, ska), \mathsf{pk}(skb)), \text{ and } \mathsf{senc}(s, k)$$

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], and in some ways similar to the spi-calculus [Abadi & Gordon, 98]

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Some advantages:

- allows us to model cryptographic primitives
- both reachability and equivalence-based specification of properties
- powerful proof techniques for hand proofs
- some tool support, e.g. ProVerif (2001) [Blanchet]

  $\longrightarrow$ `http://proverif.rocq.inria.fr/`

Protocols as processes - syntax and semantics

$$
\text{Syntax :}\quad P, Q \quad := \quad
\begin{array}{ll}
0 & \text{null process} \\
\mathsf{in}(c, x).P & \text{input} \\
\mathsf{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}
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Semantics $\rightarrow$:

Comm	$\mathsf{out}(c, M).P \mid \mathsf{in}(c, x).Q \rightarrow P \mid Q\{M/x\}$
Then	if $M = N$ then P else $Q \rightarrow P$ when $M =_{\mathsf{E}} N$
Else	if $M = N$ then P else $Q \rightarrow Q$ when $M \neq_{\mathsf{E}} N$

closed by structural equivalence ($\equiv$) and application of evaluation contexts.

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Alice and Bob as processes:

$$\begin{array}{lll} P_A(sk_a, pk_b) & = & \mathsf{new}\ k.\ \mathsf{out}(c, \mathsf{aenc}(\mathsf{sign}(k, sk_a), pk_b)). \\ & & \qquad \mathsf{in}(c, x_a).\ \mathsf{let}\ y_a = \mathsf{sdec}(x_a, k)\ \mathsf{in}\ldots \end{array}$$

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One possible scenario:

$$P_{\mathrm{DS}} \;=\; \text{new } sk_a, sk_b.(P_A(sk_a, \mathrm{pk}(sk_b)) \mid P_B(sk_b, \mathrm{pk}(sk_a)))$$

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$\longrightarrow$ this simply models a normal execution between two honest participants

Security properties - confidentiality

Confidentiality for process P w.r.t. secret s

For all processes A such that $A \mid P \rightarrow^* Q$, we have that Q is not of the form $C[\mathrm{out}(c, s).Q']$ with c public.

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Some difficulties:

- we have to consider all the possible executions in presence of an arbitrary adversary (modelled as a process)
- we have to consider realistic initial configurations
  $\longrightarrow$ replications to model an unbounded number of sessions,
  $\longrightarrow$ reveal public keys and private keys to model dishonest agents,
  $\longrightarrow$ P_A/P_B may play with other (and perhaps) dishonest agents, ...

Going back to the Denning Sacco protocol

$$\begin{array}{rcl} A \to B & : & \mathsf{aenc}(\mathsf{sign}(k, \mathsf{priv}(A)), \mathsf{pub}(B)) \\ B \to A & : & \mathsf{senc}(s, k) \end{array}$$

The aforementioned attack

$$1.\ A \to C : \ \mathsf{aenc}(\mathsf{sign}(k, \mathsf{priv}(A)), \mathsf{pub}(C))$$

$$\begin{array}{ll} 2. & C(A) \to B : \mathsf{aenc}(\mathsf{sign}(k, \mathsf{priv}(A)), \mathsf{pub}(B)) \\ 3. & \qquad B \to A : \mathsf{senc}(s, k) \end{array}$$

The "minimal" initial configuration to retrieve the attack is:

$$\mathsf{new}\ sk_a.\mathsf{new}\ sk_b.(P_A(sk_a, \mathsf{pk}(sk_c)) \mid P_B(sk_b, \mathsf{pk}(sk_a)))$$

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Exercise: Exhibit the process A (the behaviour of the attacker) that witnesses the aforementioned attack.

Security properties - privacy

Privacy-type properties are modelled as equivalence-based properties

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

for all processes A, we have that:

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

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

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

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

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Example 2:

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

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

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Exercise: Are the two following processes in testing equivalence?

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

Going back to the e-passport protocol

What does unlinkability mean?

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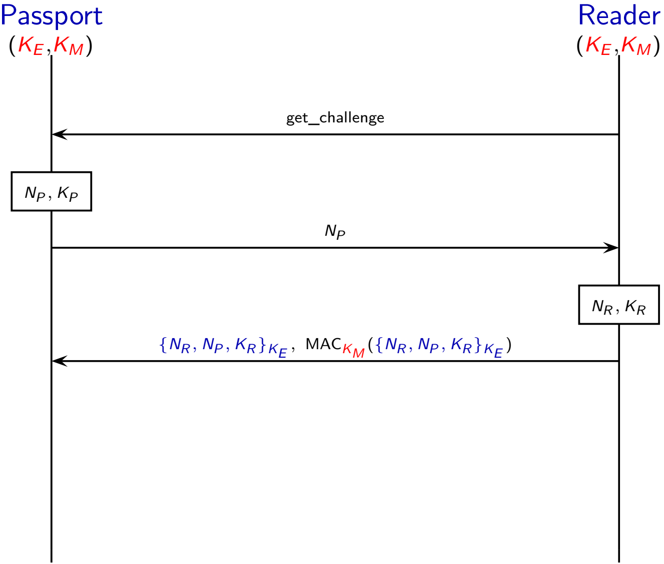
1. a situation where the same passport may be used twice (or even more);
2. a situation where each passport is used at most once.

More precisely, we have that:

$$!\mathrm{new}\ ke.\mathrm{new}\ km.(!P_{\mathrm{Pass}} \mid !P_{\mathrm{Reader}}) \overset{?}{\approx} !\mathrm{new}\ ke.\mathrm{new}\ km.(\ P_{\mathrm{Pass}} \mid !P_{\mathrm{Reader}})$$

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



French electronic passport

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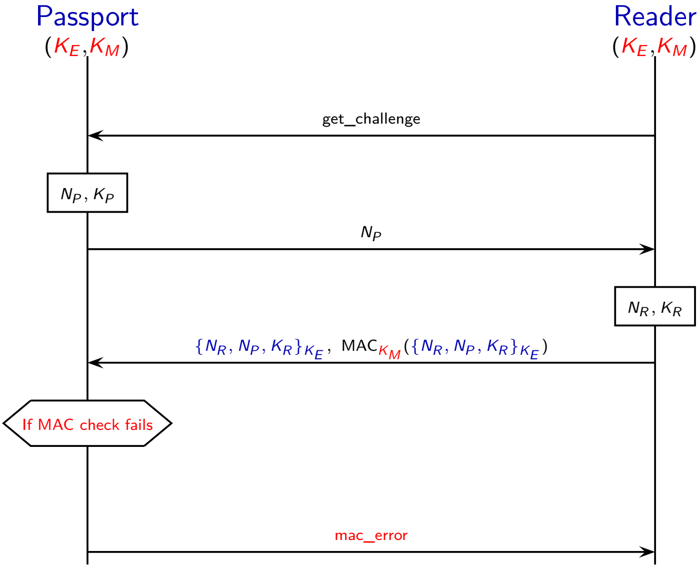

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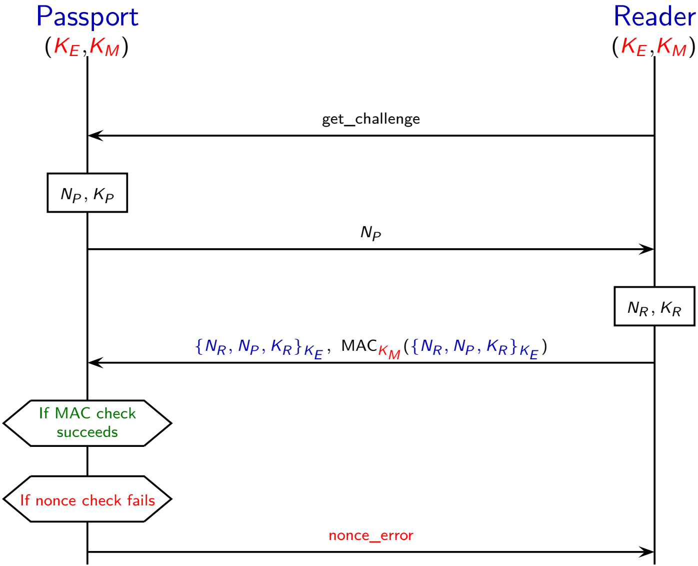

An attack on the French passport

Attack against unlinkability [Chothia & Smirnov, 10]

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

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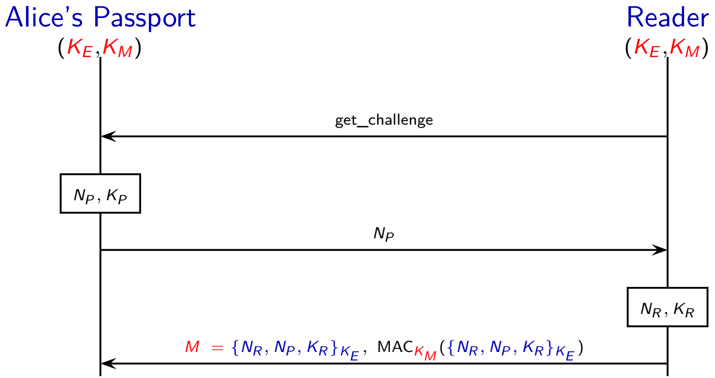
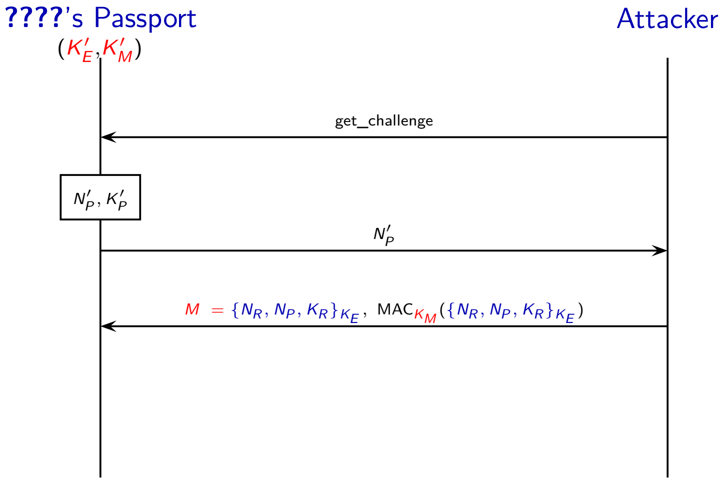
Part 1 of the attack. The attacker eavesdropes on Alice using her passport and records message M.



An attack on the French passport

Part 2 of the attack.

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



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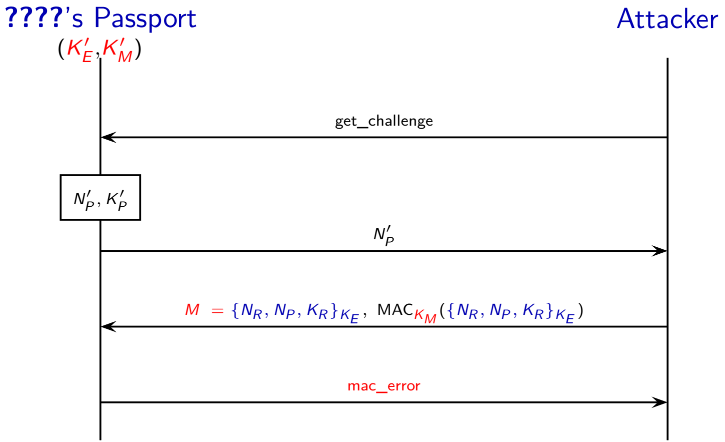

$\Longrightarrow$ MAC check failed $\Longrightarrow$ $K'_M \neq K_M$ $\Longrightarrow$ **????** is not Alice

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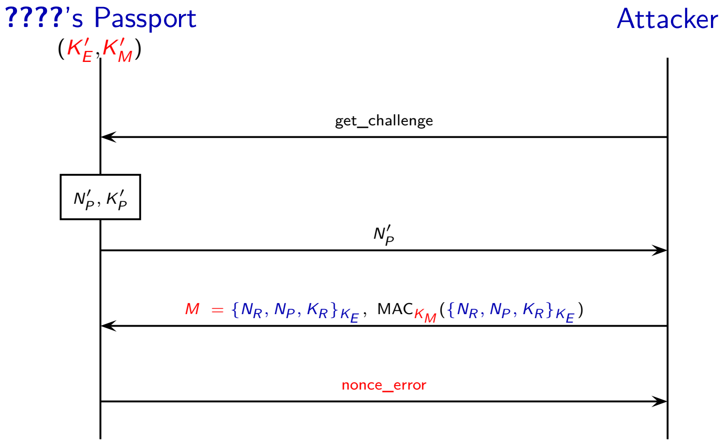

$\Longrightarrow$ MAC check succeeded $\Longrightarrow$ $K'_M = K_M$ $\Longrightarrow$ **????** is Alice

An attack on the French passport

Attack !

The equivalence does not hold: $P_{\text{same}} \not\approx P_{\text{diff}}$.

More formally,

$$P_{\text{same}} \stackrel{\text{def}}{=} !\text{new } ke.\text{new } km.(!P_{\text{Pass}} \mid !P_{\text{Reader}})$$
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Exercise: Exhibit the process A that witnesses the attack.

Part II

Designing verification algorithms

1. From confidentiality ...

   $\longrightarrow$ *i.e.* trace-based security properties

2. ... to privacy

   $\longrightarrow$ *i.e.* equivalence-based security properties

Designing verification algorithms

1. **From confidentiality ...**

   $\longrightarrow$ ***i.e.* trace-based security properties**

2. ... to privacy

   $\longrightarrow$ *i.e.* equivalence-based security properties

State of the art in a nutshell

for analysing trace-based security properties

Unbounded number of sessions

- undecidable in general [Even & Goldreich, 83; Durgin *et al*, 99]

$\longrightarrow$ ProVerif: A tool that does not correspond to any decidability result but works well in practice. [Blanchet, 01]

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Bounded number of sessions

- a decidability result (NP-complete) [Rusinowitch & Turuani, 01; Millen & Shmatikov, 01]
- result extended to deal with various cryptographic primitives.

$\longrightarrow$ various automatic tools, e.g. AVISPA platform [Armando *et al.*, 05]

Skip

The deduction problem: is u deducible from T?

We consider a signature $\mathcal{F}$ and an equational theory E.

The deduction problem

input A sequence ϕ of ground terms (*i.e.* messages) and a term s (the secret) $\phi = \{w_1 \triangleright v_1, \ldots, w_n \triangleright v_n\}$

output Can the attacker learn s from ϕ, *i.e.* does there exist a term (called recipe) R built using public symbols and $w_1, \ldots, w_n$ such that $R\phi =_{\mathsf{E}} s$.

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Example: Let $\phi = \{w_1 \triangleright \mathsf{pk}(ska);\ w_2 \triangleright \mathsf{pk}(skb);\ w_3 \triangleright skc;$
$w_4 \triangleright \mathsf{aenc}(\mathsf{sign}(k, ska), \mathsf{pk}(skc));\ w_5 \triangleright \mathsf{senc}(s, k)\}$.

We have that:

- k is deducible from ϕ using $R_1 = \mathsf{check}(\mathsf{adec}(w_4, w_3), w_1)$,
- s is deducible from ϕ using $R_2 = \mathsf{sdec}(w_5, R_1)$.

The ground case

Proposition

The deduction problem is decidable in PTIME for the equational theory modelling the DS protocol (and for many others)

Proof (sketch)

1. saturation of ϕ with its deducible subterm ϕ^+
2. does there exist R such that $R\phi^+ = s$ (syntaxic equality)

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  $w_4 \rhd \mathrm{aenc}(\mathrm{sign}(k, ska), \mathrm{pk}(skc));\ w_5 \rhd \mathrm{senc}(s, k)\}.$
- $\phi^+ = \phi \uplus \{w_6 \rhd \mathrm{sign}(k, ska);\ w_7 \rhd k;\ w_8 \rhd s\}.$

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- $\phi^+ = \phi \uplus \{w_6 \triangleright \mathsf{sign}(k, ska);\ w_7 \triangleright k;\ w_8 \triangleright s\}.$

$\longrightarrow$ The deduction problem is actually decidable for many interesting equational theories.

Confidentiality using the constraint solving approach

$\longrightarrow$ for a bounded number of sessions

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 constraint systems
   $\longrightarrow$ this set can be huge (exponential on the number of sessions) ... but some optimizations are used to reduce this number

2. A decision procedure for deciding whether a constraint system has a solution or not.

   $\longrightarrow$ this algorithm works quite well

Confidentiality via constraint solving

Constraint systems are used to specify confidentiality (or more generally any trace-based property) under a particular scenario.

Protocol rules

- a particular interleaving -

$\mathrm{in}(u_1);$

$\mathrm{out}(v_1); \mathrm{in}(u_2);$

$\ldots$

$\mathrm{out}(v_n)$

Constraint System

$$\mathcal{C} = \begin{cases} T_0 \overset{?}{\vdash} u_1 \\ T_0, v_1 \overset{?}{\vdash} u_2 \\ \quad ... \\ T_0, v_1, .., v_n \overset{?}{\vdash} s \end{cases}$$

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Solution of a constraint system $\mathcal{C}$

A substitution σ such that

for every $T \overset{?}{\vdash} u \in \mathcal{C}$, $u\sigma$ *is deducible from* $T\sigma$.

for every $u = v \in \mathcal{C}$ *(resp.* $u \neq v$*),* $u\sigma =_{\mathsf{E}} v\sigma$ *(resp.* $u\sigma \neq_{\mathsf{E}} v\sigma$*)*

Going back to the Denning Sacco protocol

$$\begin{array}{lcl} A \to B & : & \mathsf{aenc}(\mathsf{sign}(k, \mathsf{priv}(A)), \mathsf{pub}(B)) \\ B \to A & : & \mathsf{senc}(s, k) \end{array}$$

One possible interleaving:

$$\mathsf{out}(\mathsf{aenc}(\mathsf{sign}(k, ska), \mathsf{pk}(skc)))$$
$$\mathsf{in}(\mathsf{aenc}(\mathsf{sign}(x, ska), \mathsf{pk}(skb))); \mathsf{out}(\mathsf{senc}(s, x))$$

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The associated constraint system is:

$$\begin{array}{rcl} T_0;\ \mathsf{aenc}(\mathsf{sign}(k, ska), \mathsf{pk}(skc)) & \stackrel{?}{\vdash} & \mathsf{aenc}(\mathsf{sign}(x, ska), \mathsf{pk}(skb)) \\ T_0;\ \mathsf{aenc}(\mathsf{sign}(k, ska), \mathsf{pk}(skc));\ \mathsf{senc}(s, x) & \stackrel{?}{\vdash} & s \end{array}$$

with $T_0 = \{\mathsf{pk}(ska),\ \mathsf{pk}(skb);\ skc\}$.

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Question: Does $\mathcal{C}$ admit a solution?

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with $T_0 = \{\mathsf{pk}(ska),\ \mathsf{pk}(skb);\ skc\}$.

Question: Does $\mathcal{C}$ admit a solution? Yes: $x \to k$.

The general case: is the constraint system $\mathcal{C}$ satisfiable?

Main idea: simplify them until reaching $\perp$ or solved forms

Constraint system in solved form

$$\mathcal{C} = \begin{cases} T_0 \overset{?}{\vdash} x_0 \\ T_0 \cup T_1 \overset{?}{\vdash} x_1 \\ \quad \ldots \\ T_0 \cup T_1 \ldots \cup T_n \overset{?}{\vdash} x_n \end{cases}$$

Question

Is there a solution to such a system ?

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Question

Is there a solution to such a system ?

Of course, yes ! Choose $u_0 \in T_0$, and consider the substitution:

$$\sigma = \{x_0 \mapsto u_0, \ldots, x_n \mapsto u_0\}$$

Skip

Simplification rules

$\longrightarrow$ these rules deal with pairs and symmetric encryption only

$$\mathsf{R}_{\mathsf{ax}}: \quad \mathcal{C} \wedge T \overset{?}{\vdash} u \quad \rightsquigarrow \quad \mathcal{C} \quad \text{if } T \cup \{x \mid T' \overset{?}{\vdash} x \in \mathcal{C}, T' \subsetneq T\} \vdash u$$

$$\mathsf{R}_{\mathsf{unif}}: \quad \mathcal{C} \wedge T \overset{?}{\vdash} u \quad \rightsquigarrow_\sigma \quad \mathcal{C}\sigma \wedge T\sigma \overset{?}{\vdash} u\sigma$$

$$\text{if } \sigma = \mathrm{mgu}(t_1, t_2) \text{ where } t_1, t_2 \in st(T) \cup \{u\}$$

$$\mathsf{R}_{\mathsf{fail}}: \quad \mathcal{C} \wedge T \overset{?}{\vdash} u \quad \rightsquigarrow \quad \perp \quad \text{if } vars(T \cup \{u\}) = \emptyset \text{ and } T \not\vdash u$$

$$\mathsf{R}_{\mathsf{f}}: \quad \mathcal{C} \wedge T \overset{?}{\vdash} f(u_1, u_2) \rightsquigarrow \mathcal{C} \wedge T \overset{?}{\vdash} u_1 \wedge T \overset{?}{\vdash} u_2 \quad f \in \{\langle\rangle, \mathrm{senc}\}$$

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Example: $T_0;\ \mathrm{aenc}(\mathrm{sign}(k, ska), \mathrm{pk}(skc)) \overset{?}{\vdash} \mathrm{aenc}(\mathrm{sign}(x, ska), \mathrm{pk}(skb))$

$$\rightsquigarrow (\text{with } \mathsf{R}_{\mathsf{f}}) \begin{cases} T_0;\ \mathrm{aenc}(\mathrm{sign}(k, ska), \mathrm{pk}(skc)) \overset{?}{\vdash} \mathrm{sign}(x, ska) \\ T_0;\ \mathrm{aenc}(\mathrm{sign}(k, ska), \mathrm{pk}(skc)) \overset{?}{\vdash} \mathrm{pk}(skb) \end{cases}$$

Exercice - still about the Denning Sacco protocol

Exercise

Reach a solved form starting with the constraint system:

$$
\begin{array}{rcl}
T_0;\ \mathrm{aenc}(\mathrm{sign}(k, ska), \mathrm{pk}(skc)) & \overset{?}{\vdash} & \mathrm{aenc}(\mathrm{sign}(x, ska), \mathrm{pk}(skb)) \\
T_0;\ \mathrm{aenc}(\mathrm{sign}(k, ska), \mathrm{pk}(skc));\ \mathrm{senc}(s, x) & \overset{?}{\vdash} & s
\end{array}
$$

You should be able to reach a constraint system in solved form (actually the empty one) in 3 steps.

Hint: $\mathsf{R}_{\mathrm{unif}}$ and R_{ax} twice.

Results on the simplification rules

Given a (well-formed) constraint system $\mathcal{C}$:

Soundness:
If $\mathcal{C} \rightsquigarrow^*_\sigma \mathcal{C}'$ and θ solution of $\mathcal{C}'$ then $\sigma\theta$ is a solution of $\mathcal{C}$.

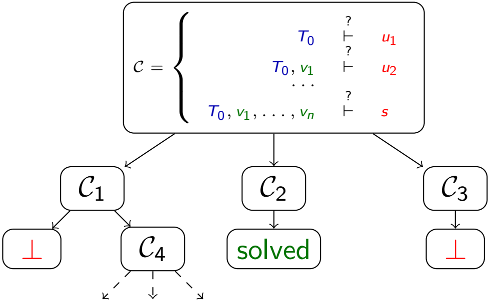
$\longrightarrow$ easy to show

Completeness:
If θ is a solution of $\mathcal{C}$ then there exists $\mathcal{C}'$ and θ' such that $\mathcal{C} \rightsquigarrow^*_\sigma \mathcal{C}'$, θ' is a solution of $\mathcal{C}'$, and $\theta = \sigma\theta'$.

$\longrightarrow$ more involved to show

Termination: There is no infinite chain $\mathcal{C} \rightsquigarrow_{\sigma_1} \mathcal{C}_1 \ldots \rightsquigarrow_{\sigma_n} \mathcal{C}_n$.
$\longrightarrow$ using the lexicographic order (number of var, size of rhs)

Main idea of the procedure:

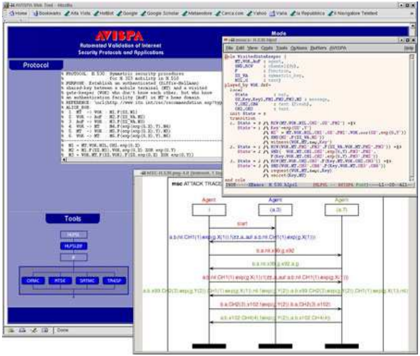


$\longrightarrow$ this gives us a symbolic representation of all the solutions.

Results and tools

Theorem

Deciding confidentiality for a bounded number of sessions is decidable for classical primitives (actually in co-NP).



$\longrightarrow$ This approach has been implemented in the AVISPA Platform

http://www.avispa-project.org/

Part II

Designing verification algorithms

1. From confidentiality ...

   $\longrightarrow$ *i.e.* trace-based security properties

2. **... to privacy**

   $\longrightarrow$ ***i.e.* equivalence-based security properties**

State of the art in a nutshell

for analysing equivalence-based security properties

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for analysing equivalence-based security properties

Unbounded number of sessions [Blanchet, Abadi & Fournet, 05]

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

- + various cryptographic primitives;
- − termination is not guaranteed; diff-equivalence (too strong)

$\longrightarrow$ some extensions to go beyond diff-equivalence

Bounded number of sessions

e.g. [Baudet, 05], [Dawson & Tiu, 10], [Chevalier & Rusinowitch, 10], ...

$\longrightarrow$ this allows one to decide testing equivalence between "simple" processes without else branch.

None of these results is able to analyse the e-passport protocol.

A recent contribution

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

Main result

A procedure for deciding testing equivalence for a large class of processes for a bounded number of sessions.

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Main result

A procedure for deciding testing equivalence for a large class of processes for a bounded number of sessions.

Our class of processes:

- + non-trivial else branches, private channels, and non-deterministic choice;
- – a fixed set of cryptographic primitives (signature, encryption, hash function, mac).

$\longrightarrow$ this allows us in particular to deal with the e-passport example

▸ Skip

The ground case: are ϕ and ψ in static equivalence?

The static equivalence problem

input Two frames ϕ and ψ

$$\phi = \{w_1 \triangleright u_1, \ldots, w_\ell \triangleright u_\ell\} \qquad \psi = \{w_1 \triangleright v_1, \ldots, w_\ell \triangleright v_\ell\}$$

ouput Can the attacker distinguish the two frames, *i.e.* does there exist a test $R_1 \stackrel{?}{=} R_2$ such that:

$$R_1\phi =_E R_2\phi \text{ but } R_1\psi \neq_E R_2\psi \text{ (or the converse).}$$

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Example: Consider the frames:

- $\phi = \{w_1 \rhd \mathrm{aenc}(\langle yes, r_1\rangle, \mathrm{pk}(sks));\ w_2 \rhd sks\}$; and
- $\psi = \{w_1 \rhd \mathrm{aenc}(\langle no, r_2\rangle, \mathrm{pk}(sks));\ w_2 \rhd sks\}$.

They are not in static equivalence: $\mathrm{proj}_1(adec(w_1, w_2)) \stackrel{?}{=} yes$.

The ground case

Proposition

The static equivalence problem is decidable in PTIME for the theory modelling the DS protocol (and for many others)

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Proof (sketch)

1. saturation of ϕ/ψ with their deducible subterms ϕ^+/ψ^+
2. does there exist a test $R_1 \stackrel{?}{=} R_2$ such that $R_1\phi^+ = R_2\phi^+$ whereas $R_1\psi^+ \neq R_2\psi^+$ (again syntaxic equality) ?
   $\longrightarrow$ Actually, we only need to consider small tests

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Going back to the previous example:

- $\phi^+ = \phi \uplus \{w_3 \triangleright \langle yes, r_1\rangle;\ w_4 \triangleright yes;\ w_5 \triangleright r_1\}$, and
- $\psi^+ = \psi \uplus \{w_3 \triangleright \langle no, r_2\rangle;\ w_4 \triangleright no;\ w_5 \triangleright r_2\}$.

$\longrightarrow$ ϕ^+ and ψ^+ are not in static equivalence: $w_4 \stackrel{?}{=} yes$.

Privacy using the constraint solving approach

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 constraint systems

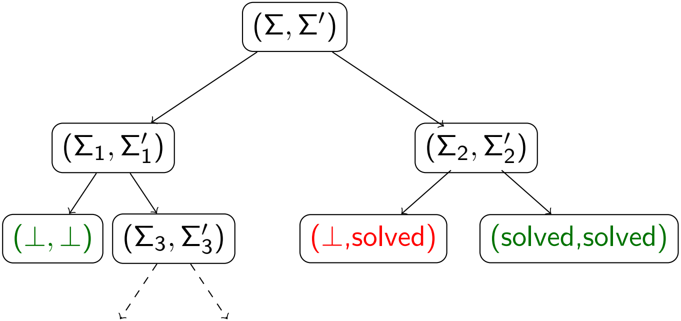
   $\longrightarrow$ this set can be huge (exponential on the number of sessions) !

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

   $\longrightarrow$ this algorithm works quite well

Deciding symbolic equivalence

Main idea: We rewrite pairs (Σ, Σ') of sets of constraint systems (extended to keep track of some information) until a trivial failure or a trivial success is found.



Results on the simplification rules

Termination

Applying blindly the simplification rules does not terminate but there is a particular strategy $\mathcal{S}$ that allows us to ensure termination.

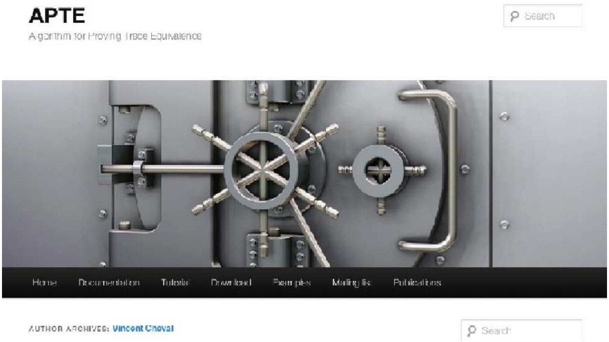
Soundness/Completeness

Let (Σ_0, Σ_0') be pair of sets of constraint systems, and consider a binary tree obtained by applying our simplification rule following a strategy $\mathcal{S}$.

1. soundness: If all leaves of the tree are labeled with $(\perp, \perp)$ or $(\mathit{solved}, \mathit{solved})$, then $\Sigma_0 \approx_s \Sigma_0'$.
2. completeness: if $\Sigma_0 \approx_s \Sigma_0'$, then all leaves of the tree are labeled with $(\perp, \perp)$ or $(\mathit{solved}, \mathit{solved})$.

Theorem

Deciding testing equivalence between processes without replication for classical primitives is decidable.



$\longrightarrow$ This approach has been implemented in APTE by Vincent CHEVAL

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

Limitations of these approaches

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. not all scenario are checked
$\longrightarrow$ no guarantee if the protocol is used one more time !

Conclusion

A need of formal methods in verification of security protocols.
Regarding confidentiality (or authentication), powerful tool support that are nowdays used by industrials and security agencies.

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

- formal definitions of some sublte security properties
- algorithms (and tools!) for checking automatically trace equivalence for various cryptographic primitives;
- more composition results.

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- more composition results.

VIP - Verification of Indistinguishability Properties

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

$\longrightarrow$ A post-doc position (for 1 year) is available on this project.