Symbolic verification of security protocols
Modelling and verifying unlinkability

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GT Méthodes Formelles pour la Sécurité

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⟶ joint work with D. Baelde, A. Debant, L. Hirschi, and S. Moreau

Cryptographic protocols everywhere !

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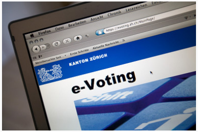
It becomes more and more important to protect our privacy.



Electronic passport

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The Basic Access Control (BAC) protocol is a key establishment protocol that has been designed to protect our personnal data, and to ensure unlinkability.

> 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*. [ISO/IEC standard 15408]

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- can be mounted even assuming perfect cryptography, *e.g.* replay attack, man-in-the middle attack, ...
- subtle and hard to detect by “eyeballing” the protocol

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Example: A traceability attack on the BAC protocol

Security

Defects in e-passports allow real-time tracking

This threat brought to you by RFID

The register - Jan. 2010

How to verify the absence of logical flaws?

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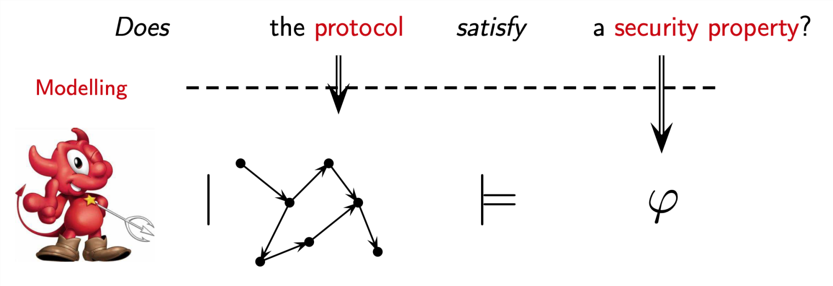
Our approach

formal symbolic verification using automatic/interactive tools

Formal (symbolic) verification in a nutshell



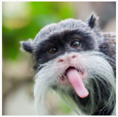
Two main tasks:

1. Modelling: protocols, security properties, and the attacker;
2. Verifying: designing verification algorithms and tools.

$\longrightarrow$ this talk: a focus on unlinkability

Some success stories (mostly related to reachability properties)

ProVerif [Blanchet, 01]



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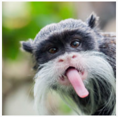

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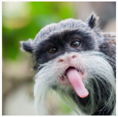

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What about unlinkability (in the symbolic setting)?

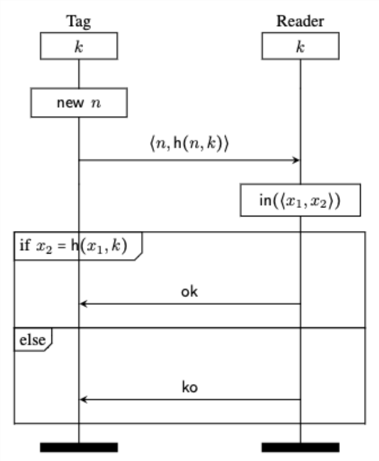
Actually, existing tools like ProVerif and Tamarin are not suitable to analyse unlinkability, and therefore few formal proofs exist in the unbounded setting.

- [Chatzikokolakis *et al.*, 2010]: sufficient conditions checkable using ProVerif that allows one to establish unlinkability for a simple class of protocols (single-step protocols).
  $\longrightarrow$ their notion of unlinkability is rather weak
- [Arapinis *et al.*, 2010]: a formal definition of unlinkability, and a manual proof of unlinkability for a fixed version of the e-passport protocol.
  $\longrightarrow$ this result is wrong
- [Bhargavan *et al.*, 2022]: a symbolic analysis of privacy for TLS 1.3 with Encrypted Client Hello
  $\longrightarrow$ several encodings tricks are used.

Part I

Modelling: protocols, the attacker, and unlinkability

Running example: Basic Hash protocol



- k is a long-term secret key shared between the tag and the reader;
- each tag has its own key k.

Protocols as processes

$\longrightarrow$ a programming language with constructs for concurrency and communication (applied-pi calculus [Abadi & Fournet, 01])

$$
\begin{array}{rcll}
P, Q & := & 0 & \text{null process} \\
 & | & \mathrm{in}(c, x); P & \text{input} \\
 & | & \mathrm{out}(c, M); P & \text{output} \\
 & | & \mathtt{new}\ n; P & \text{name generation} \\
 & | & \text{if } M = N \text{ then } P \text{ else } Q & \text{conditional} \\
 & | & !P & \text{replication} \\
 & | & (P \mid Q) & \text{parallel composition} \\
 & | & \ldots &
\end{array}
$$

Messages/Computations as terms

Terms are built over a set of names $\mathcal{N}$ (private), and function symbols Σ (public) equipped with an equational theory E.

Example:

$$\Sigma = \{\mathsf{senc}, \mathsf{sdec}\} \text{ with } \mathsf{E} = \{\mathsf{sdec}(\mathsf{senc}(x, y), y) = x\}.$$

Let $\Phi = \{w_1 \mapsto \mathsf{senc}(s, k); \mathsf{w}_2 \mapsto k\}$. $R = \mathsf{sdec}(\mathsf{w}_1, \mathsf{w}_2)$ is a recipe to compute s. Indeed, we have that $R\Phi =_{\mathsf{E}} s$.

Going back to Basic Hash

Mesages/Computations as terms

- $\Sigma = \{\mathsf{h},\ \langle\ \rangle,\ \mathsf{proj}_1,\ \mathsf{proj}_2\}$;
- $\mathsf{E} = \{\mathsf{proj}_1(\langle x_1, x_2\rangle) = x_1,\ \ \mathsf{proj}_2(\langle x_1, x_2\rangle) = x_2\}$.

Protocol as a process

- $\mathsf{T}(k) = \mathtt{new}\ n; \mathtt{out}(c, \langle n, \mathsf{h}(n, k)\rangle)$.
- $\mathsf{R}(k) = \mathtt{in}(c, y); \text{if } \mathsf{h}(\mathsf{proj}_1(y), k) = \mathsf{proj}_2(y)$
  $\text{then } \mathtt{out}(c, \mathsf{ok})$
  $\text{else } \mathtt{out}(c, \mathsf{ko})$.

Then, the whole system can be written as follows:

$$!\ \mathtt{new}\ k;\ (\ !\ \mathsf{R}(k)\ \mid\ !\ \mathsf{T}(k)\ )$$

Semantics (some selected rules)

Labelled transition system over configurations:

$$(\mathcal{P}; \Phi)$$

multiset of processes

frame = knowledge of the attacker

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$$\text{OUT} \quad (\{\text{out}(c, M); P\} \uplus \mathcal{P}; \Phi) \xrightarrow{\text{out}(c, w_i)} (\{P\} \uplus \mathcal{P}; \Phi \cup \{w_i \mapsto M\})$$

with $i = |\Phi|$

$$\text{THEN} \quad (\{\text{if } M_1 = M_2 \text{ then } P \text{ else } Q\} \uplus \mathcal{P}; \Phi) \xrightarrow{\tau} (\{P\} \uplus \mathcal{P}; \Phi)$$

when $M_1 =_{\mathsf{E}} M_2$

$$\text{IN} \quad (\{\text{in}(c, x); P\} \uplus \mathcal{P}; \Phi) \xrightarrow{\text{in}(c, R)} (\{P\{x \mapsto R\Phi\}\} \uplus \mathcal{P}; \Phi)$$

...

Trace equivalence

Trace equivalence between configurations: $K \approx_t K'$.

For any execution trace $K \xrightarrow{\mathsf{tr}} (\mathcal{P}; \Phi)$ there exists an execution $K' \xrightarrow{\mathsf{tr}} (\mathcal{P}'; \Phi')$ such that $\Phi \sim_s \Phi'$ (and conversely)

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Static equivalence between frames: $\Phi \sim_s \Phi'$.

Any test that holds in Φ also holds in Φ' (and conversely).

Example:

$\{\mathsf{w}_1 \mapsto k; \mathsf{w}_2 \mapsto \langle n, \mathsf{h}(n, k)\rangle\} \not\sim_s \{\mathsf{w}_1 \mapsto k; \mathsf{w}_2 \mapsto \langle n', \mathsf{h}(n', k')\rangle\}$

$\longrightarrow$ with the test $\mathsf{h}(\mathsf{proj}_1(w_2), w_1) \stackrel{?}{=} \mathsf{proj}_2(w_2)$.

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$$\{\mathsf{w}_1 \mapsto \langle n_1, \mathsf{h}(n_1, k)\rangle;\ \mathsf{w}_2 \mapsto \langle n_2, \mathsf{h}(n_2, k)\rangle\}$$
$$\sim_s$$
$$\{\mathsf{w}_1 \mapsto \langle n_1', \mathsf{h}(n_1', k)\rangle;\ \mathsf{w}_2 \mapsto \langle n_2', \mathsf{h}(n_2', k')\rangle\}$$

Modelling unlinkability using trace equivalence

> 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*. [ISO/IEC standard 15408]

$\longrightarrow$ the real system should be equivalent to the ideal one (from the point of view of the attacker).

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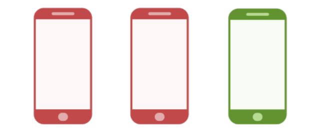 ... $\overset{?}{\approx}_t$  ...

many sessions
for each identity

only one session
for each identity

Modelling unlinkability (1^{th} attempt)

For single-step protocols, we may consider the following equivalence:

$$! \, \texttt{new} \, k; \; ! \; T(k) \;\approx_t\; ! \, \texttt{new} \, k; \; T(k)$$

$\longrightarrow$ This approach was used in [Chatzikokolakis *et al.*, 2010] to establish unlinkability for BH and OSK protocols.

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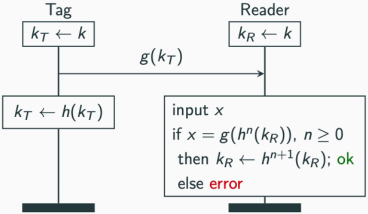
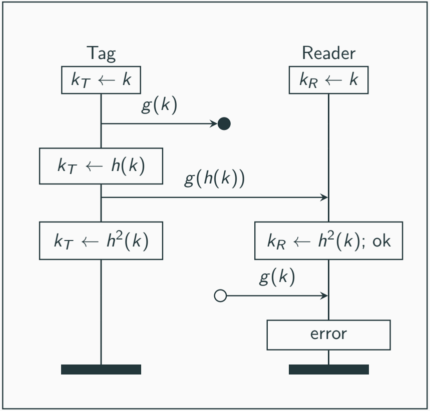
Example: OSK protocol



- h and g are two hash functions;
- k is updated - with $h(k)$ - after a successful execution on both sides.

Attack on the OSK protocol

Tags are proved unlinkable in [Chatzikokolakis *et al.*, 2010] but there is an attack !



Keypoint #1: modelling the reader is important.

Modelling unlinkability (2th attempt)

$\longrightarrow$ definition first proposed by [Arapinis *et al.*, CSF'10] (but for another notion of equivalence)

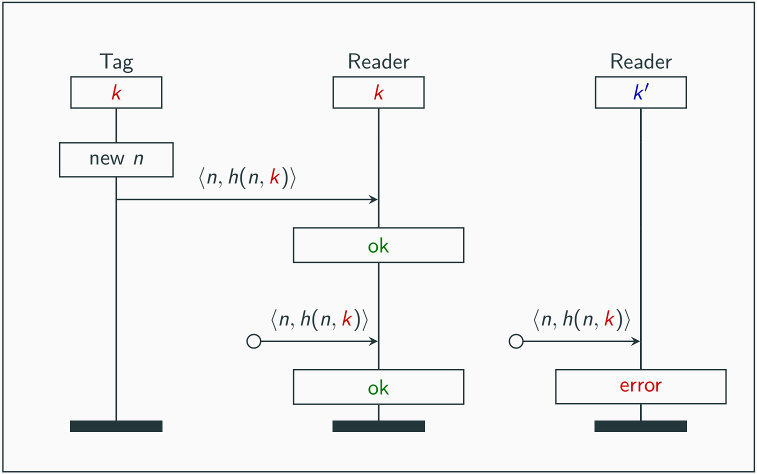
$$! \, \mathtt{new}\ k; \ (\, ! \, \mathsf{R}(k) \ | \ \ ! \, \mathsf{T}(k)) \ \approx_t \ ! \, \mathtt{new}\ k; \ (\, \mathsf{R}(k) \ | \ \mathsf{T}(k) \,)$$

This definition is:

- suitable to analyse e.g. e-passport protocols, and many other stateless protocols;
- the one we used in our work [Hirschi, Baelde & D., SP'16 & JCS'19].

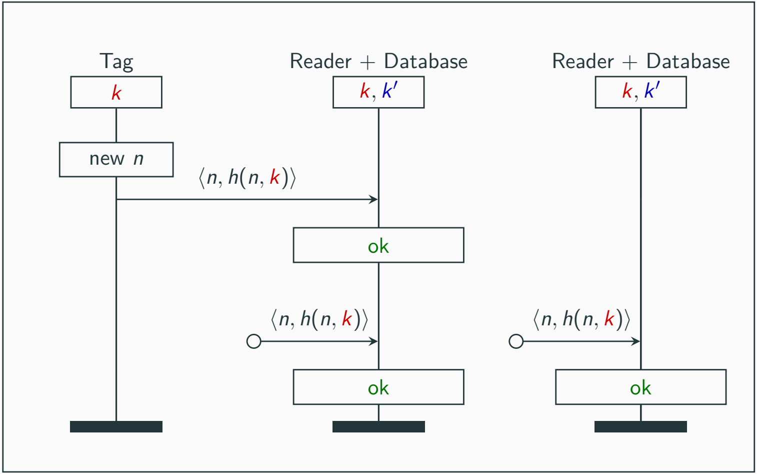
Going back to Basic Hash protocol (a stateful protocol)

$\longrightarrow$ linkable according to our previous definition (specific readers).



Basic Hash protocol

$\longrightarrow$ with a generic reader, no linkability attack.



Keypoint #2: The way the reader is modelled is important.

Modelling unlinkability for stateful protocols (3rd attempt)

$\longrightarrow$ definition proposed in [Baelde, D., Moreau, CSF'20]

We consider a generic reader having an access to a database DB

$$! \mathsf{R} \mid (\, !\, \mathtt{new}\ k; \mathtt{insert}\ \mathsf{DB}(k); !\, \mathsf{T}(k))$$
$$\approx_t$$
$$! \mathsf{R} \mid (\, !\, \mathtt{new}\ k; \mathtt{insert}\ \mathsf{DB}(k);\ \mathsf{T}(k))$$

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Basic Hash Example

- $\mathsf{R} = \mathtt{in}(c, y); \mathsf{get}\ z_k \in \mathsf{DB}\ \mathsf{suchthat}\ \mathsf{h}(\mathsf{proj}_1(y), z_k) = \mathsf{proj}_2(y)$
  $\mathsf{in}\ \mathtt{out}(c, \mathsf{ok})$
  $\mathsf{else}\ \mathtt{out}(c, \mathsf{ko})$.

$\longrightarrow$ Modelling tables in ProVerif (or Tamarin) is not an issue.

Part II

How can we establish unlinkability?

Exsiting tools able to establish trace equivalence

The problem is undecidable in general.

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Approach 1: Limiting the number of sessions

- the problem becomes decidable (under some assumptions);
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Approach 2: Trying to solve the general case

- ProVerif: over-approximations are performed, termination is not guaranteed [Blanchet *et al.*, 2005]
- Tamarin: an interactive tool [Basin *et al.*, 2015]

$\longrightarrow$ they are based on diff-equivalence (too strong)

Diff-equivalence

How does it work (or not)?

- form a bi-process B using the operator $\mathsf{diff}[M_\mathsf{L}, M_\mathsf{R}]$;
- both sides of the bi-process B have to evolve simulatenously (+ static equivalence) to be declared in diff-equivalence

$\longrightarrow$ In such a case, we have that $\mathsf{fst}(B) \approx_t \mathsf{snd}(B)$.

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Formally, the semantics is given by a labelled transition system over bi-configurations $(\mathcal{P}; \Phi)$ where messages and computations may contain the diff operator.

Example 1: $\mathsf{out}(a) \mid \mathsf{out}(b) \stackrel{?}{\approx} \mathsf{out}(b) \mid \mathsf{out}(a)$

$\longrightarrow B = \mathsf{out}(\mathsf{diff}[a, b]) \mid \mathsf{out}(\mathsf{diff}[b, a])$ (* not in diff-equivalence *)

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Example 2

$$B = \texttt{insert}\ DB(\mathsf{diff}[a, b]); \texttt{insert}\ DB(\mathsf{diff}[b, a]);$$
$$\text{get } x \text{ suchthat } x = a \text{ then } \mathsf{out}(c, ok) \text{ else } \mathsf{out}(c, ko)$$

(* not in diff-equivalence *)

Diff-equivalence does not hold on Basic Hash

$$B \; = !R \;|\; (!\,\texttt{new}\; k;\; !\texttt{new}\; kk; \texttt{insert}\; \mathrm{DB}(\mathrm{diff}[k, kk]); \mathrm{T}(\mathrm{diff}[k, kk])$$

Let's consider a scenario with:

- 1 reader;
- 2 tags: $T(\mathrm{diff}[k, kk_1])$, and $T(\mathrm{diff}[k, kk_2])$.

DB	left	right
line 1	k	kk_1
line 2	k	kk_2

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1. The tag outputs $w_1 = \langle n_1, \mathrm{h}(n_1, \mathrm{diff}[k, kk_1])\rangle$;
2. The reader R will diverge on this input:

$\mathrm{R} = \texttt{in}(c, y);$
$\texttt{get}\ DB(z_k)\ \texttt{st.}\ \mathrm{eq}(\mathrm{h}(\mathrm{proj}_1(y), z_k), \mathrm{proj}_2(y))\ \texttt{in}\ \texttt{out}(c, \mathrm{ok})\ \texttt{else}\ \texttt{out}(c, \mathrm{ko})$

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$\longrightarrow$ Proverif returns `cannot be proved`.

Our result for stateless 2-party protocols

[Hirschi, Baelde, D.; S&P, 2016, JCS'19]

Theorem

If a protocol ensures both well-authentication and frame opacity then it ensures unlinkability, i.e.:

$$! \, \mathtt{new}\ k; \left(\,! \, \mathrm{R}(k) \;\mid\; ! \, \mathrm{T}(k) \right) \approx_t \; ! \, \mathtt{new}\ k; \left(\mathrm{R}(k) \;\mid\; \mathrm{T}(k) \right)$$

$\longrightarrow$ These 2 conditions are easier to check by existing tools

Intuition behind the sufficient conditions

Well-Authentication

- Goal = avoid leaks through outcomes of conditionals.
- "Whenever a conditional is positively evaluated, the agents involved are having so far an honest interaction."

$\longrightarrow$ This is a reachability property.

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Frame Opacity

- Goal = avoid leaks through relations over messages.
- "Any reachable frame must be statically equivalent to an idealised frame that only depends on data already observed during the execution."

$\longrightarrow$ This can be verified with (an extension of) diff-equivalence.

Summary of our case studies using ProVerif

Protocol	WA	FO	unlinkability
Feldhofer	✓	✓	**safe**
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**

Our result for stateful 2-party protocols

[Baelde, D., Moreau, CSF'20]

Theorem

If a protocol ensures well-authentication, frame opacity and no desynchronisation then it ensures unlinkability, i.e.:

$$\begin{aligned} & !\,\mathsf{R} \mid (\,!\,\mathtt{new}\ k; \mathtt{insert}\ \mathsf{DB}(k); !\,\mathsf{T}(k)) \\ \approx_t\ & !\,\mathsf{R} \mid (\,!\,\mathtt{new}\ k; \mathtt{insert}\ \mathsf{DB}(k);\ \mathsf{T}(k)) \end{aligned}$$

No desynchronisation

- Goal = avoid leaks through desynchronisations between agents.
- "An honest interaction between a tag and a reader cannot fail."

$\longrightarrow$ This is also a reachability property! (But a little more tricky...)

Summary of our case studies using Tamarin

Protocol	WA	FO	ND	unlinkability
Basic Hash	✓	✓	✓	**safe**
Hash Lock	✓	✓	✓	**safe**
Feldhofer	✓	✓	✓	**safe**
OSK v1	✓		✗	attack
OSK v2	✓	✓	✓	**safe**
LAK (pairs)	✓		✗	attack
LAK (pairs, fixed)	✓	✓	✓	**safe**
LAK (pairs, no update)	✓	✓	✓	**safe**
5G-AKA (simplified)	✓	✓	✓	**safe**

$\longrightarrow$ simple conditions in the theory but not so easily checkable in practice

A recent result for stateful 2-party protocols

[Baelde, Debant, D., CSF'23]

Main Goal

Transform a ProVerif model $\mathcal{M}$ into another model $\mathcal{M}'$ such that:

- diff-equivalence on $\mathcal{M}' \Rightarrow$ trace equivalence on $\mathcal{M}$; and
- diff-equivalence is verified with ProVerif on $\mathcal{M}'$.

Our transformation:

1. duplicate the get instructions in $\mathcal{M}$ to dissociate the two parts of the bi-process; (possible using the `allowDiffPatterns` option)
2. add some axioms (proved correct manually) to help ProVerif to reason on our new model.

Basic Hash example

```
let T(k) = new nT; out(c,(nT,h(nT,k))).

let R = in(c,y);
 get db(k) suchthat snd(y) = h(fst(y),k) in out(c,ok)
             else out(c,ko).

process
   (! new k; ! new kk; insert db(diff[k,kk]);
           phase 1; T(diff[k,kk]))
        | (phase 1; ! R)
```

Step 1: Basic Hash example

$\longrightarrow$ duplicate the get instructions to dissociate the two parts of the bi-process.

```
let R =
  in(c,diff[y1L,y1R]);
  get db(diff[kL,wR]) suchthat snd(y1L) = h(fst(y1L),kL) in
    (get db(diff[wL,kR]) suchthat snd(y1R) = h(fst(y1R),kR) in
      out(c,diff[ok,ok])
    else
      out(c,diff[ok,ko]))
  else
    (get db(diff[wL,kR]) suchthat snd(y1R) = h(fst(y1R),kR) in
      out(c,diff[ko,ok])
    else
      out(cR,diff[ko,ko])).
```

Step 2: Refining the analysis in the failure branches

We illustrate this on a very simple example.

Before, ...

$$\begin{aligned} B = \ & \texttt{insert}\ \mathit{tbl}(\mathsf{ok}); \\ & \mathsf{get}\ \mathit{tbl}(x)\ \mathsf{st.\ true\ in}\ \texttt{out}(c, \mathsf{ok}) \\ & \qquad\qquad \mathsf{else}\ \texttt{out}(c, \mathsf{diff}[\mathsf{ok}_\mathsf{L}, \mathsf{ok}_\mathsf{R}]) \end{aligned}$$

... and ProVerif can not proved equivalence (whereas it holds).

Step 2: Refining the analysis in the failure branches

We illustrate this on a very simple example.

After, ...

$$B = \mathtt{event}(\mathsf{Inserted}(\mathsf{ok})); \ \mathtt{insert}\ tbl(\mathsf{ok});$$
$$\quad \mathsf{get}\ tbl(x)\ \mathsf{st.\ true\ in}\ \mathtt{out}(c, \mathsf{ok})$$
$$\qquad \mathsf{else}\ \mathtt{event}(\mathsf{Fail}()); \mathtt{out}(c, \mathsf{diff}[\mathsf{ok}_{\mathsf{L}}, \mathsf{ok}_{\mathsf{R}}])$$

... together with the following axiom:

$$\mathtt{event}(\mathsf{Fail}()) \wedge \mathtt{event}(\mathsf{Inserted}(\mathtt{diff}[y^{\mathsf{L}}, y^{\mathsf{R}}])) \Rightarrow \mathsf{false}.$$

$\longrightarrow$ Now, Proverif is able to conclude that equivalence holds.

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Going back to the Basic Hash protocol

$$\mathtt{event}(\mathsf{FailL}(x^{\mathsf{L}})) \wedge \mathtt{event}(\mathsf{Inserted}(\mathtt{diff}[y^{\mathsf{L}}, y^{\mathsf{R}}])) \Rightarrow \mathsf{proj}_2(x^{\mathsf{L}}) \neq \mathsf{h}(\mathsf{proj}_1(x^{\mathsf{L}}), y^{\mathsf{L}})$$
$$\mathtt{event}(\mathsf{FailR}(x^{\mathsf{R}})) \wedge \mathtt{event}(\mathsf{Inserted}(\mathtt{diff}[y^{\mathsf{L}}, y^{\mathsf{R}}])) \Rightarrow \mathsf{proj}_2(x^{\mathsf{R}}) \neq \mathsf{h}(\mathsf{proj}_1(x^{\mathsf{R}}), y^{\mathsf{R}})$$

Case studies

Implementation

The two steps of the transformation have been implemented ($\approx$ 2k Ocaml LoC).

Case studies

Basic Hash, Hash-Lock, Feldhofer, a variant of LAK, OSK.

$\longrightarrow$ ProVerif is able to conclude on all these examples !

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(during a break if someone is interested)

Conclusion

Summary

- modelling unlinkability is rather subtle:
  $\longrightarrow$ importance of modelling the reader, and how it is modelled;
  $\longrightarrow$ states can introduce observables, especially in the case of a desynchronisation.
- verifying unlinkability properties is not an easy task but a lot of progress has been done.

Summary

- modelling unlinkability is rather subtle:
  $\longrightarrow$ importance of modelling the reader, and how it is modelled;
  $\longrightarrow$ states can introduce observables, especially in the case of a desynchronisation.
- verifying unlinkability properties is not an easy task but a lot of progress has been done.

Going a step further:

- stateful protocols (with updates) using ProVerif/GSVerif;
- from diff-equivalence to session equivalence;
- A nice way to encore unlinkability in Tamarin is to rely on (asymmetric) restrictions but currently the tool does not support them.

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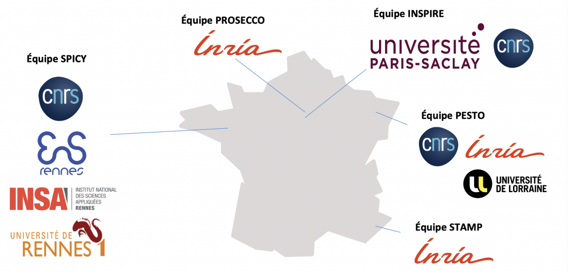

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