A decision procedure for proving trace equivalence (Work in progress)

V. Cheval, H. Comon-Lundh, S. Delaune

LSV, Project SECSI

10 December 2010

Context

Automatic procedure for proving security properties on protocol

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Trace properties

- Examples : simple secret, authentication, . . .
- All traces of a protocol has to satisfy a certain property.
- Lot of previous works on those security properties.
- Tools already exists (example : ProVerif, Maude-NPA,. . .)

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Automatic procedure for proving security properties on protocol

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- Tools already exists (example : ProVerif, Maude-NPA,...)

Equivalence properties

- Examples : strong secret, dictionnary attacks, anonymity, ...
- Express the indistinguishability of two protocols
- Theoretical results (Baudet, Chevalier, Rusinowitch, ...)
- No general tool implemented

Related works

Huttel (2002)

- Only spi-calculus (fixed primitives)
- Untractable implementation (multi-exponential complexity)
- Doesn't handle trace properties.

Cortier, Delaune (2009) + Baudet (2005) or Chevalier,Rusinowitch (2009)

- Bounded number of sessions
- Infinitely many traces are represented by constraint systems
- Observational equivalence of processes $\Leftrightarrow$ symbolic equivalence of constraint systems
- Algorithm for the symbolic equivalence of positive constraint systems when the equational theory is given by a subterm convergent rewriting system.

Related works : ProVerif

Blanchet, Abadi, Fournet (2008)

- Unbounded number of sessions
- Diff-equivalence : Observational equivalence between two process with the same structure but different messages.
- Very efficient
- Possibility of false attacks. Doesn't always terminate

ProVerif extension

ProSwapper (see the talk of Ben Smyth)

Examples

Minimum benchmark

Two examples we want our algorithm to prove :

- Privacy for the Private authentication protocol (Abadi and Fournet, 2004)
- Unlinkability for the E-Passport protocol (Arapinis, Chothia, Ritter and Ryan, CSF 2010)

We'll explain why the existing tools cannot handle them.

Private authentication protocol

Informal representation

$$\begin{array}{lll} 0. & A \longrightarrow B : & \mathsf{aenc}(\langle N_a, \mathsf{p}(A)\rangle, \mathsf{p}(B)) \\ 1. & B \longrightarrow A : & \mathsf{aenc}(\langle N_a, N_b, \mathsf{p}(B)\rangle, \mathsf{p}(A)) \end{array}$$

Role A : $P_A(a, b)$

$\nu N_a.\ \overline{c}\langle \mathsf{aenc}(\langle N_a, \mathsf{p}(a)\rangle, \mathsf{p}(b))\rangle.\ c(x)$

Role B : $P_B(b, a)$

$c(x)$. let $desc = \mathsf{adec}(x, b)$ in
let $n_a = \mathsf{proj}_1(desc)$ and $pub_a = \mathsf{proj}_2(desc)$ in
if $pub_a = \mathsf{p}(a)$
then $\nu N_b.\ \overline{c}\langle \mathsf{aenc}(\langle n_a, N_b, \mathsf{p}(b)\rangle, \mathsf{p}(a))\rangle$
else $\nu K.\ \overline{c}\langle \mathsf{aenc}(K, \mathsf{p}(a))\rangle$

Private authentication protocol

$$\overline{c}\langle \mathsf{p}(a)\rangle.\overline{c}\langle \mathsf{p}(a')\rangle.\overline{c}\langle \mathsf{p}(b)\rangle \mid P_A(a,b) \mid P_B(b,a)$$
$$\approx$$
$$\overline{c}\langle \mathsf{p}(a)\rangle.\overline{c}\langle \mathsf{p}(a')\rangle.\overline{c}\langle \mathsf{p}(b)\rangle \mid P_A(a',b) \mid P_B(b,a')$$

Role A (a,b)	Intruder	Role B (b,a)

Private authentication protocol

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Role A (a,b)

Intruder

$M_1 = \mathsf{p}(a)$
$M_2 = \mathsf{p}(a')$
$M_3 = \mathsf{p}(b)$

Role B (b,a)

Private authentication protocol

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Role A (a,b)	Intruder	Role B (b,a)
	$M_1 = \mathsf{p}(a)$ $M_2 = \mathsf{p}(a')$ $M_3 = \mathsf{p}(b)$	
$\xrightarrow{\{\langle N_a, \mathsf{p}(a)\rangle\}_{\mathsf{p}(b)}}$		

Private authentication protocol

$$\overline{c}\langle \mathsf{p}(a)\rangle.\overline{c}\langle \mathsf{p}(a')\rangle.\overline{c}\langle \mathsf{p}(b)\rangle \mid P_A(a,b) \mid P_B(b,a)$$
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Role A (a,b)

Intruder

Role B (b,a)

$M_1 = \mathsf{p}(a)$
$M_2 = \mathsf{p}(a')$
$M_3 = \mathsf{p}(b)$

$\xrightarrow{\{\langle N_a, \mathsf{p}(a)\rangle\}_{\mathsf{p}(b)}}$

$\xrightarrow{\{\langle N_i, M_1\rangle\}_{M_3}}$

Private authentication protocol

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Role A (a,b)

Intruder

Role B (b,a)

$M_1 = \mathsf{p}(a)$
$M_2 = \mathsf{p}(a')$
$M_3 = \mathsf{p}(b)$

$\xrightarrow{\{\langle N_a, \mathsf{p}(a)\rangle\}_{\mathsf{p}(b)}}$

$\xrightarrow{\{\langle N_i, M_1\rangle\}_{M_3}}$

$x = \{\langle N_i, \mathsf{p}(a)\rangle\}_{\mathsf{p}(b)}$

Private authentication protocol

$$\overline{c}\langle \mathrm{p}(a)\rangle.\overline{c}\langle \mathrm{p}(a')\rangle.\overline{c}\langle \mathrm{p}(b)\rangle \mid P_A(a,b) \mid P_B(b,a)$$
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Role A (a,b)

Intruder

Role B (b,a)

$M_1 = \mathrm{p}(a)$
$M_2 = \mathrm{p}(a')$
$M_3 = \mathrm{p}(b)$

$\xrightarrow{\{\langle N_a, \mathrm{p}(a)\rangle\}_{\mathrm{p}(b)}}$

$\xrightarrow{\{\langle N_i, M_1\rangle\}_{M_3}}$

$x = \{\langle N_i, \mathrm{p}(a)\rangle\}_{\mathrm{p}(b)}$
Verify key succeeds
$\mathrm{p}(a) = \mathrm{p}(a)$

Private authentication protocol

$$\overline{c}\langle \mathsf{p}(a)\rangle.\overline{c}\langle \mathsf{p}(a')\rangle.\overline{c}\langle \mathsf{p}(b)\rangle \mid P_A(a,b) \mid P_B(b,a)$$
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Role A (a,b)

Intruder

Role B (b,a)

$M_1 = \mathsf{p}(a)$
$M_2 = \mathsf{p}(a')$
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$\xrightarrow{\{\langle N_a, \mathsf{p}(a)\rangle\}_{\mathsf{p}(b)}}$

$\xrightarrow{\{\langle N_i, M_1\rangle\}_{M_3}}$

$x = \{\langle N_i, \mathsf{p}(a)\rangle\}_{\mathsf{p}(b)}$
Verify key succeeds
$\mathsf{p}(a) = \mathsf{p}(a)$

$\xleftarrow{\{\langle N_i, N_b, \mathsf{p}(b)\rangle\}_{\mathsf{p}(a)}}$

Private authentication protocol

$$\overline{c}\langle \mathrm{p}(a)\rangle.\overline{c}\langle \mathrm{p}(a')\rangle.\overline{c}\langle \mathrm{p}(b)\rangle \mid P_A(a,b) \mid P_B(b,a)$$
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$$\overline{c}\langle \mathrm{p}(a)\rangle.\overline{c}\langle \mathrm{p}(a')\rangle.\overline{c}\langle \mathrm{p}(b)\rangle \mid P_A(a',b) \mid P_B(b,a')$$

Role A (a,b)		Intruder		Role B (b,a)
		$M_1 = \mathrm{p}(a)$ $M_2 = \mathrm{p}(a')$ $M_3 = \mathrm{p}(b)$		
	$\xrightarrow{\{\langle N_a, \mathrm{p}(a)\rangle\}_{\mathrm{p}(b)}}$			
			$\xrightarrow{\{\langle N_i, M_1\rangle\}_{M_3}}$	
				$x = \{\langle N_i, \mathrm{p}(a)\rangle\}_{\mathrm{p}(b)}$ Verify key succeeds $\mathrm{p}(a) = \mathrm{p}(a)$
			$\xleftarrow{\{\langle N_i, N_b, \mathrm{p}(b)\rangle\}_{\mathrm{p}(a)}}$	
		$M_4 = \{\langle N_i, N_b, \mathrm{p}(b)\rangle\}_{\mathrm{p}(a)}$		

Private authentication protocol

$$\overline{c}\langle \mathrm{p}(a)\rangle.\overline{c}\langle \mathrm{p}(a')\rangle.\overline{c}\langle \mathrm{p}(b)\rangle \mid P_A(a,b) \mid P_B(b,a)$$
$$\approx$$
$$\overline{c}\langle \mathrm{p}(a)\rangle.\overline{c}\langle \mathrm{p}(a')\rangle.\overline{c}\langle \mathrm{p}(b)\rangle \mid P_A(a',b) \mid P_B(b,a')$$

Role A (a',b)	Intruder	Role B (b,a')

Private authentication protocol

$$\overline{c}\langle \mathsf{p}(a)\rangle.\overline{c}\langle \mathsf{p}(a')\rangle.\overline{c}\langle \mathsf{p}(b)\rangle \mid P_A(a,b) \mid P_B(b,a)$$
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$$\overline{c}\langle \mathsf{p}(a)\rangle.\overline{c}\langle \mathsf{p}(a')\rangle.\overline{c}\langle \mathsf{p}(b)\rangle \mid P_A(a',b) \mid P_B(b,a')$$

Role A	Intruder	Role B
(a',b)		(b,a')
	$M_1 = \mathsf{p}(a)$	
	$M_2 = \mathsf{p}(a')$	
	$M_3 = \mathsf{p}(b)$	

Private authentication protocol

$$\overline{c}\langle \mathsf{p}(a)\rangle.\overline{c}\langle \mathsf{p}(a')\rangle.\overline{c}\langle \mathsf{p}(b)\rangle \mid P_A(a,b) \mid P_B(b,a)$$
$$\approx$$
$$\overline{c}\langle \mathsf{p}(a)\rangle.\overline{c}\langle \mathsf{p}(a')\rangle.\overline{c}\langle \mathsf{p}(b)\rangle \mid P_A(a',b) \mid P_B(b,a')$$

Role A (a',b)

Intruder

Role B (b,a')

$M_1 = \mathsf{p}(a)$
$M_2 = \mathsf{p}(a')$
$M_3 = \mathsf{p}(b)$

$\xrightarrow{\{\langle N_a, \mathsf{p}(a')\rangle\}_{\mathsf{p}(b)}}$

Private authentication protocol

$$\overline{c}\langle \mathsf{p}(a)\rangle.\overline{c}\langle \mathsf{p}(a')\rangle.\overline{c}\langle \mathsf{p}(b)\rangle \mid P_A(a,b) \mid P_B(b,a)$$
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Role A (a',b)	Intruder	Role B (b,a')
	$M_1 = \mathsf{p}(a)$ $M_2 = \mathsf{p}(a')$ $M_3 = \mathsf{p}(b)$	

$\xrightarrow{\{\langle N_a, \mathsf{p}(a')\rangle\}_{\mathsf{p}(b)}}$

$\xrightarrow{\{\langle N_i, M_1\rangle\}_{M_3}}$

Private authentication protocol

$$\overline{c}\langle \mathrm{p}(a)\rangle.\overline{c}\langle \mathrm{p}(a')\rangle.\overline{c}\langle \mathrm{p}(b)\rangle \mid P_A(a,b) \mid P_B(b,a)$$
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Role A (a',b) | Intruder | Role B (b,a')

$$M_1 = \mathrm{p}(a)$$
$$M_2 = \mathrm{p}(a')$$
$$M_3 = \mathrm{p}(b)$$

$\xrightarrow{\{\langle N_a, \mathrm{p}(a')\rangle\}_{\mathrm{p}(b)}}$

$\xrightarrow{\{\langle N_i, M_1\rangle\}_{M_3}}$

$$x = \{\langle N_i, \mathrm{p}(a)\rangle\}_{\mathrm{p}(b)}$$

Private authentication protocol

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Role A (a',b)	Intruder	Role B (b,a')
	$M_1 = \mathsf{p}(a)$ $M_2 = \mathsf{p}(a')$ $M_3 = \mathsf{p}(b)$	
$\xrightarrow{\{\langle N_a, \mathsf{p}(a')\rangle\}_{\mathsf{p}(b)}}$		
	$\xrightarrow{\{\langle N_i, M_1\rangle\}_{M_3}}$	
		$x = \{\langle N_i, \mathsf{p}(a)\rangle\}_{\mathsf{p}(b)}$ Verify key fails $\mathsf{p}(a) \neq \mathsf{p}(a')$

Private authentication protocol

$$\overline{c}\langle \mathrm{p}(a)\rangle.\overline{c}\langle \mathrm{p}(a')\rangle.\overline{c}\langle \mathrm{p}(b)\rangle \mid P_A(a,b) \mid P_B(b,a)$$
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Role A (a',b)	Intruder	Role B (b,a')
	$M_1 = \mathrm{p}(a)$ $M_2 = \mathrm{p}(a')$ $M_3 = \mathrm{p}(b)$	
$\xrightarrow{\{\langle N_a, \mathrm{p}(a')\rangle\}_{\mathrm{p}(b)}}$		
	$\xrightarrow{\{\langle N_i, M_1\rangle\}_{M_3}}$	
		$x = \{\langle N_i, \mathrm{p}(a)\rangle\}_{\mathrm{p}(b)}$ Verify key fails $\mathrm{p}(a) \neq \mathrm{p}(a')$
	$\xleftarrow{\{K\}_{\mathrm{p}(a)}}$	

Private authentication protocol

$$\overline{c}\langle \mathsf{p}(a)\rangle.\overline{c}\langle \mathsf{p}(a')\rangle.\overline{c}\langle \mathsf{p}(b)\rangle \mid P_A(a,b) \mid P_B(b,a)$$
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Role A (a',b)		Intruder		Role B (b,a')
		$M_1 = \mathsf{p}(a)$ $M_2 = \mathsf{p}(a')$ $M_3 = \mathsf{p}(b)$		
	$\xrightarrow{\{\langle N_a, \mathsf{p}(a')\rangle\}_{\mathsf{p}(b)}}$			
			$\xrightarrow{\{\langle N_i, M_1\rangle\}_{M_3}}$	
				$x = \{\langle N_i, \mathsf{p}(a)\rangle\}_{\mathsf{p}(b)}$ Verify key fails $\mathsf{p}(a) \neq \mathsf{p}(a')$
			$\xleftarrow{\{K\}_{\mathsf{p}(a)}}$	
		$M_4 = \{K\}_{\mathsf{p}(a)}$		

Private authentication protocol : related works

Theoretical works

- Cannot be applied since there is some else branches.
- If the else branches are removed, there is an attack (Cortier, Delaune (2009))

ProVerif

- ProVerif accepts else branch;
- but this example doesn't satisfy the diff-equivalence.

E-Passport protocol : description

Passport (ke, km)		Reader
	$\xrightarrow{ke, km}_{\text{priv}}$	
	$\xleftarrow{Get\_C}$	
N_T		
	$\xrightarrow{N_T}$	
		N_R, K_R $E_1 = \{N_R, N_T, K_R\}_{ke}$ $M_1 = MAC_{km}(E_1)$
	$\xleftarrow{E_1, M_1}$	
Verify Mac (Error 6300) Verify N_T (Error 6A80) K_T $E_2 = \{N_T, N_R, K_T\}_{ke}$ $M_2 = MAC_{km}(E_2)$		
	$\xrightarrow{E_2, M_2}$	
		Verify Mac, Verify N_R

Unlinkability

An attacker cannot identify particular sessions which involved the same principal

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An attacker cannot identify particular sessions which involved the same principal

Formally (Arapinis, Chothia, Ritter and Ryan, CSF 2010)

$$!Reader \mid !\nu ke.\ \nu km.!Pass(ke, km)$$
$$\approx$$
$$!Reader \mid !\nu ke.\ \nu km.Pass(ke, km)$$

$!Reader \mid !\nu ke.\ \nu km.!Pass(ke, km) \approx !Reader \mid !\nu ke.\ \nu km.Pass(ke, km)$

Intruder		Passport (ke, km)		Reader (ke, km)
			$\xleftarrow{Get\_C}$	
		N_T		
			$\xrightarrow{N_T}$	
				N_R, K_R $E_1 = \{N_R, N_T, K_R\}_{ke}$ $M_1 = MAC_{km}(E_1)$
			$\xleftarrow{E_1, M_1}$	
		$\vdots$		
	$\xrightarrow{Get\_C}$			
		N'_T		
	$\xleftarrow{N'_T}$			
Reply third msg	$\xrightarrow{E_1, M_1}$			
		Verify Mac succeeds Verify N'_T fails		
	$\xleftarrow{6A80}$			

E-Passport protocol : the attack

$!Reader \mid !\nu ke.\ \nu km.!Pass(ke, km) \approx !Reader \mid !\nu ke.\ \nu km.Pass(ke, km)$

Intruder		Passport (ke, km)		Reader (ke, km)
			$\xleftarrow{Get\_C}$	
		N_T		
			$\xrightarrow{N_T}$	
				N_R, K_R $E_1 = \{N_R, N_T, K_R\}_{ke}$ $M_1 = MAC_{km}(E_1)$
			$\xleftarrow{E_1, M_1}$	
		⋮		
		Passport (ke', km')		
	$\xrightarrow{Get\_C}$			
		N'_T		
	$\xleftarrow{N'_T}$			
Reply third msg	$\xrightarrow{E_1, M_1}$			
		Verify Mac fails		
	$\xleftarrow{6300}$			

E-Passport protocol : related works

Theoretical works

Cannot be applied since there is some else branches.

ProVerif

The example doesn't satisfy the diff-equivalence

Algorithm

Algorithm

Previous work : IJCAR '10

- Algorithm for proving the symbolic equivalence of couples of constraint systems
- Implemented and efficient
- Can be used for proving the trace equivalence of simple processes without else-branch : Cortier, Delaune (2009)

Work in progress

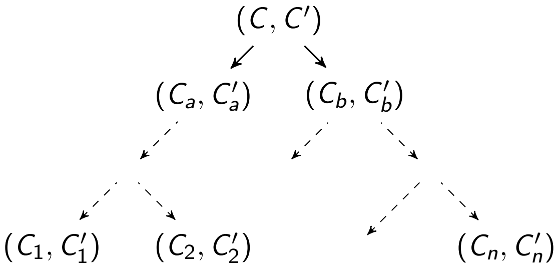
- Algorithm for proving the symbolic equivalence of constraint systems sets with disequation
- Extension to trace equivalence for a class of protocol including E-Passport and Private authentication protocol

- Set of rules.
- Each rule takes a couple of constraint system as input
- Each rule creates two couples of constraint system as output

$$
\begin{array}{ccc}
 & (C, C') & \\
\swarrow & & \searrow \\
(C_a, C'_a) & & (C_b, C'_b)
\end{array}
$$

IJCAR '10

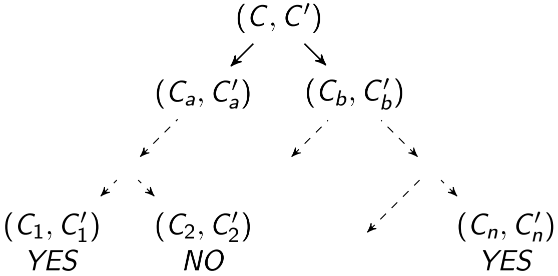
- Set of rules.
- Each rule takes a couple of constraint system as input
- Each rule creates two couples of constraint system as output



The application of the rules creates a binary tree where each node is a couple of constraint systems.

IJCAR '10

- Set of rules.
- Each rule takes a couple of constraint system as input
- Each rule creates two couples of constraint system as output



The application of the rules creates a binary tree where each node is a couple of constraint systems.

Symbolic equivalence of constraint systems sets

- We modified the rules such that they take a couple of constraint systems sets as input and output.
- We added some rules to deal with disequations.

The application of the rules creates a binary tree where each node is a couple of constraint systems sets.

The algorithm is implemented and is efficient but the proof isn't done yet

Trace equivalence of protocols

- Reduce the problem of trace equivalence of protocols to the problem of symbolic equivalence of constraint systems sets
- An algorithm is implemented and works with the Private authentication and E-Passport protocols;
- but it's not efficient : optimizations are needed
- No proof yet

Conclusion

- An algorithm for deciding trace equivalence has been implemented using the rules described in IJCAR '10
- First tool to work on both Private authentication protocol and E-Passport protocol
- Not efficient enough
- Lot of proofs are missing