Safely composing security protocols via tagging

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LSV, ENS Cachan & CNRS & INRIA project SECSI

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→ joint work with Véronique Cortier, Jérémie Delaitre, Myrto Arapinis and Steve Kremer
Cryptographic protocols

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

The network is unsecure!

Communications take place over a public network like the Internet.
Cryptographic protocols

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Communications take place over a public network like the Internet.
Cryptographic protocols (formal approach)

Messages are abstracted by terms

- pairing $\langle m_1, m_2 \rangle$,
- symmetric $\text{enc}(m, k)$ and public-key encryption $\text{enca}(m, \text{pub}(A))$,
- signature $\text{sign}(m, \text{priv}(A))$. 
Cryptographic protocols (formal approach)

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Presence of an idealized attacker

- may read, intercept and send messages,
- may build new messages following deduction rules (symbolic manipulation on terms).
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Presence of an idealized attacker

- may read, intercept and send messages,
- may build new messages following deduction rules (symbolic manipulation on terms).

Examples:

\[
\begin{align*}
  m & \quad k \\
  \text{enc}(m, k) & \quad \text{enc}(m, k) & \quad k \\
  \text{enca}(m, \text{pub}(a)) & \quad \text{priv}(a) & \quad m
\end{align*}
\]
A simple protocol

\[ \langle \text{Bob, } k \rangle \]

\[ \langle \text{Alice, enc}(s, k) \rangle \]
A simple protocol

\[ \langle \text{Bob, } k \rangle \quad \rightarrow \quad \langle \text{Alice, } \text{enc}(s, k) \rangle \]

Question?
Can the attacker learn the secret \( s \)?
A simple protocol

\[ \langle \text{Bob, k} \rangle \]
\[ \langle \text{Alice, enc}(s, k) \rangle \]

Answer: Of course, Yes!

\[ \langle \text{Alice, enc}(s, k) \rangle \]
\[ \text{enc}(s, k) \]
\[ \langle \text{Bob, k} \rangle \]
\[ k \]
\[ s \]
Composition problem (part 2 of this talk)

sessions coming from the same protocol

\[ A \rightarrow B : \text{enca}(\langle A, K, Na \rangle, \text{pub}(B)), \text{sign}(\text{enca}(\langle A, Na \rangle, \text{pub}(B)), \text{priv}(A)) \]

\[ B \rightarrow A : Na, \text{enc}(s, K) \]

Question?

What about the secrecy of \( s \)?
Composition problem (part 2 of this talk)

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**Attack** with 2 sessions:

\[ A \rightarrow B : \text{enca}(\langle A, K, Na \rangle, \text{pub}(B)), \text{sign}(\text{enca}(\langle A, Na \rangle, \text{pub}(B)), \text{priv}(A)) \]
\[ B \rightarrow A : Na, \text{enc}(s_1, K) \]
\[ l(A) \rightarrow B : \text{enca}(\langle A, Ki, Na \rangle, \text{pub}(B)), \text{sign}(\text{enca}(\langle A, Na \rangle, \text{pub}(B)), \text{priv}(A)) \]
\[ B \rightarrow A : Na, \text{enc}(s_2, Ki) \]

**Question?**

What about the secrecy of \( s \)?
Composition problem (part 1 of this talk)

Protocol 1

\[ P_1 : A \rightarrow B : \text{enca}(s, \text{pub}(B)) \]

Question?

What about the secrecy of \( s \)?
Composition problem (part 1 of this talk)

→ sessions coming from different protocols

Protocol 1

$P_1 : A \rightarrow B : \text{enca}(s, \text{pub}(B))$

Protocol 2

$P_2 : A \rightarrow B : \text{enca}(N_a, \text{pub}(B))$

$B \rightarrow A : N_a$

Question?

What about the secrecy of $s$?
Verification of security protocols

- Existing tools allow us to verify relatively small protocols and sometimes only for a bounded number of sessions.
- Most often, we verify them in isolation. → this is not sufficient.
Motivations

Verification of security protocols

- Existing tools allow us to verify relatively small protocols and sometimes only for a bounded number of sessions.
- Most often, we verify them in isolation → this is not sufficient.

Our Goals

1. propose a general and simple transformation that maps a protocol that is secure for one session into a protocol that is secure for an unbounded number of sessions;
2. investigate sufficient and rather tight conditions for a protocol to be safely used in an environment where other protocols may be executed as well;

→ protocols may share identities and keys (e.g. public keys, long-term symmetric keys)
Outline of the talk

1. Introduction
2. Preliminaries
3. Composition result (1\textsuperscript{st} part)
4. Composition result (2\textsuperscript{nd} part): ongoing work
5. Conclusion
Outline of the talk

1 Introduction

2 Preliminaries

3 Composition result (1st part)

4 Composition result (2nd part): ongoing work

5 Conclusion
Deduction capabilities of the attacker

Composition rules

\[
T \vdash u \quad T \vdash v \\
\quad \quad \frac{}{T \vdash \langle u, v \rangle}
\]

\[
T \vdash u \quad T \vdash v \\
\quad \quad \frac{}{T \vdash f(u, v)} \quad \text{with } f \in \{\text{enc, enca, sign}\}
\]

Decomposition rules

\[
\quad \quad \frac{u \in T}{T \vdash u}
\]

\[
T \vdash \langle u, v \rangle \\
\quad \quad \frac{}{T \vdash u}
\]

\[
T \vdash \langle u, v \rangle \\
\quad \quad \frac{}{T \vdash v}
\]

\[
T \vdash \text{enc}(u, v) \\
\quad \quad \frac{T \vdash v}{T \vdash u}
\]

\[
T \vdash \text{enca}(u, \text{pub}(v)) \\
\quad \quad \frac{}{T \vdash u}
\]

\[
T \vdash \text{priv}(v) \\
\quad \quad \frac{}{T \vdash u}
\]

\[
T \vdash \text{sign}(u, \text{priv}(v)) \\
\quad \quad \frac{}{T \vdash u} \quad \text{(optional)}
\]

Deducibility relation

A term \( u \) is \textbf{deducible} from a set of terms \( T \), denoted by \( T \vdash u \), if there exists a prooftree witnessing this fact.
Needham Schroeder protocol:

\[ A \rightarrow B : \{N_a, A\}_{\text{pub}(B)} \]
\[ B \rightarrow A : \{N_a, N_b\}_{\text{pub}(A)} \]
\[ A \rightarrow B : \{N_b\}_{\text{pub}(B)} \]

A **protocol** is a finite set of roles:

**Exemple:**

role \( \Pi(1) \) corresponding to the 1\(^{st} \) participant played by \( a \) talking to \( b \):

\[ \text{init} \xrightarrow{N} \text{enca}(\langle N, a \rangle, \text{pub}(b)) \]
\[ \text{enca}(\langle N, x \rangle, \text{pub}(a)) \rightarrow \text{enca}(x, \text{pub}(b)). \]
Secrecy via constraint solving

Constraint systems are used to specify secrecy preservation under a particular, finite scenario.

\[
\begin{align*}
\text{Scenario} & \\
\text{Constraint System} & \\
\text{rcv}(u_1) & \xrightarrow{N_1} \text{snd}(v_1) \\
\text{rcv}(u_2) & \xrightarrow{N_2} \text{snd}(v_2) \\
& \ldots \\
\text{rcv}(u_n) & \xrightarrow{N_n} \text{snd}(v_n) \\
\end{align*}
\]
\[
\begin{align*}
C &= \left\{ \begin{array}{l}
T_0 \vdash u_1 \\
T_0, v_1 \vdash u_2 \\
\ldots \\
T_0, v_1, \ldots, v_n \vdash s
\end{array} \right. \\
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**Scenario**

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\text{rcv}(u_1) \xrightarrow{N_1} \text{snd}(v_1) \\
\text{rcv}(u_2) \xrightarrow{N_2} \text{snd}(v_2) \\
\ldots \\
\text{rcv}(u_n) \xrightarrow{N_n} \text{snd}(v_n)
\]

**Constraint System**

\[
C = \begin{cases} 
    T_0 \vdash u_1 \\
    T_0, v_1 \vdash u_2 \\
    \ldots \\
    T_0, v_1, \ldots, v_n \vdash s 
\end{cases}
\]

**Solution of a constraint system**

A substitution \( \sigma \) such that

\[\text{for every } T \vdash u \in C, \ u\sigma \text{ is deducible from } T\sigma.\]
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\end{align*}
\]

Constraint System

\[
C = \left\{ \begin{array}{l}
T_0 \not\models u_1 \\
T_0, v_1 \not\models u_2 \\
& \quad \ldots \\
T_0, v_1, \ldots, v_n \not\models s
\end{array} \right. 
\]

Well-formed constraint system

- **monotonicity**: intruder never forgets information
- **origination**: a variable first appear in a right hand side.

→ to discard some weird protocols, we also require plaintext origination
Procedure due to H. Comon-Lundh

Input: A (well-formed) constraint system
Output: Either ⊥ or a constraint system in solved form

→ systems in solved form always have a solution

$\mathcal{R}_5 : \; C \land T \models f(u, v) \rightarrow C \land T \models u \land T \models v$

for $f \in \{\langle \rangle, \text{enc, enca, sign}\}$

$\mathcal{R}_4 : \; C \land T \models u \rightarrow \bot$

if $\text{vars}(T, u) = \emptyset$ and $T \not\models u$

$\mathcal{R}_1 : \; C \land T \models u \rightarrow C$

if $T \cup \{x \mid T' \models x \in C, T' \subset T\} \models u$

$\mathcal{R}_2 : \; C \land T \models u \rightarrow_{\sigma} C\sigma \land T\sigma \models u\sigma$

$u' \in \text{st}(T)$

$\mathcal{R}_3 : \; C \land T \models v \rightarrow_{\sigma} C\sigma \land T\sigma \models v\sigma$

if $\sigma = \text{mgu}(u, u'), u, u' \notin \mathcal{X}, u \neq u'$

These simplification rules give us an algorithm to decide satisfiability of a well-formed constraint system.
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for \( f \in \{\langle\rangle, \text{enc}, \text{enca}, \text{sign}\} \)

\[ R_4 : \quad C \land T \vdash u \quad \leadsto \quad \bot \quad \text{if} \quad \text{vars}(T, u) = \emptyset \quad \text{and} \quad T \not\vdash u \]

\[ R_1 : \quad C \land T \vdash u \quad \leadsto \quad C \quad \text{if} \quad T \cup \{x \mid T' \vdash x \in C, T' \subsetneq T\} \vdash u \]

\[ R_2 : \quad C \land T \vdash u \quad \leadsto_{\sigma} \quad C\sigma \land T\sigma \vdash u\sigma \quad u' \in \text{st}(T) \]

\[ R_3 : \quad C \land T \vdash v \quad \leadsto_{\sigma} \quad C\sigma \land T\sigma \vdash v\sigma \quad u, u' \in \text{st}(T) \]

if \( \sigma = \text{mgu}(u, u') \), \( u, u' \not\in X \), \( u \neq u' \)

These simplification rules give us an algorithm to decide satisfiability of a well-formed constraint system.
Procedure due to H. Comon-Lundh

**Input:** A (well-formed) constraint system

**Output:** Either $\bot$ or a constraint system in solved form

$\rightarrow$ systems in solved form always have a solution

$R_5 : \quad C \land T \not\models f(u, v) \leadsto C \land T \not\models u \land T \not\models v$

for $f \in \{\langle\rangle, \text{enc}, \text{enca}, \text{sign}\}$

$R_4 : \quad C \land T \models u \leadsto \bot$ if $\text{vars}(T, u) = \emptyset$ and $T \not\models u$

$R_1 : \quad C \land T \models u \leadsto C$ if $T \cup \{x \mid T' \models x \in C, T' \subsetneq T\} \not\models u$

$R_2 : \quad C \land T \models u \leadsto_{\sigma} C\sigma \land T\sigma \models u\sigma$

$u' \in \text{st}(T)$

$R_3 : \quad C \land T \models v \leadsto_{\sigma} C\sigma \land T\sigma \models v\sigma$

$u, u' \in \text{st}(T)$

if $\sigma = \text{mgu}(u, u')$, $u, u' \notin X$, $u \neq u'$

These simplification rules give us an algorithm to decide satisfiability of a well-formed constraint system.
Refinement of the procedure

\[ R'_2 : \ C \land T \vdash u \xrightarrow{\sigma} C\sigma \land T\sigma \vdash u\sigma \quad u' \in st(T) \]
\[ R'_3 : \ C \land T \vdash v \xrightarrow{\sigma} C\sigma \land T\sigma \vdash v\sigma \]
\[ \text{if } \sigma = \text{mgu}(u, u'), u, u' \notin \mathcal{X}, u \neq u' \]
\[ u, u' \text{ are not pairs} \]

Proposition - Cortier et al., FSTTCS’07

These simplification rules, i.e. \( R_1, R_4, R_5, R'_2 \) and \( R'_3 \), still forms a complete decision procedure.

This result is of independent interest:

- we provide a more efficient procedure for solving constraint systems

\[ \rightarrow \text{ of course, the theoretical complexity remains the same, i.e. NP} \]
Refinement of the procedure

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4. Composition result (2\textsuperscript{nd} part): ongoing work
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Condition 1 - Tagging

Condition 1 (well-tagged protocol)

Each protocol is given an identifier (e.g. the protocol’s name). This identifier has to appear in any encrypted and signed message.

→ this tagging policy will avoid interaction between two different protocols.

Example: $P_1$ is 1-tagged whereas $P_2$ is 2-tagged

Protocol $P_1$

$A \rightarrow B : \text{enca}(\langle 1, s \rangle, \text{pub}(B))$

Protocol $P_2$

$A \rightarrow B : \text{enca}(\langle 2, N_a \rangle, \text{pub}(B))$

$B \rightarrow A : N_a$
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$B \rightarrow A : N_a$
Condition 2 - No critical key in plaintext

Protocol $P_1$

$A \rightarrow B : \text{enca}(\langle 1, s \rangle, \text{pub}(B))$

Protocol $P_2$

$B \rightarrow A : \text{priv}(B)$

Condition 2 (no critical key in plaintext)

Let $KC$ be the set of critical keys, i.e. constants and long-term keys used in $P_1$ or $P_2$ and not publicly known.

$$KC \cap (\text{plaintext}(P_1) \cup \text{plaintext}(P_2)) = \emptyset.$$ 

Example: We have that $KC = \{\text{priv}(B)\}$.

$\rightarrow$ Condition 2 (no critical key in plaintext) is not satisfied by $P_2$. 

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Condition 2 - No critical key in plaintext

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Main result - Composition theorem

Let $P_1$ and $P_2$ be two well-tagged protocols such that

1. $P_1$ is $\alpha$-tagged and $P_2$ is $\beta$-tagged with $\alpha \neq \beta$,
2. critical keys do not appear in plaintext position, i.e.

$$KC \cap (plaintext(P_1) \cup plaintext(P_2)) = \emptyset$$

where $KC = (\text{ExtNames}(P_1) \cup \text{ExtNames}(P_2)) \setminus T_0$

Let $s$ be a $\alpha$-tagged term such that $\text{vars}(s) \subseteq \text{vars}(P_1)$.

Then $P_1$ preserves the secrecy of $s$ for the initial knowledge $T_0$ if and only if $P_1 \mid P_2$ preserves the secrecy of $s$ for $T_0$. 
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Main steps of the proof

**Proposition**

Let $sc$ be a scenario of $\Pi_1 \mid \Pi_2$, $T_0$ the intruder’s knowledge, $s$ the secret. Let

- $C$ be the constraint system associated to $sc$, $T_0$ and $s$,
- $C'$ be the constraint system associated to $sc\mid \Pi_1$, $T_0$ and $s$.

We have that $C$ satisfiable implies $C'$ satisfiable.

1. If $C$ satisfiable, there exists a solution $\theta$ without any mixing, i.e. terms in $C'\theta$ will be either $\alpha$-tagged or $\beta$-tagged.  

   → refinement of the constraint solving procedure due to H. Comon-Lundh

2. Removing $\beta$-tagged terms from a left hand side of a constraint is safe.

   \[ T_0, T_\alpha\theta, T_\beta\theta \vdash u_\alpha\theta \quad \Rightarrow \quad T_0, T_\alpha\theta \vdash u_\alpha\theta \]

   → proved by induction on the proof tree witnessing $T_0, T_\alpha\theta, T_\beta\theta \vdash u_\alpha\theta$
Main steps of the proof

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- \( C \) be the constraint system associated to \( sc \), \( T_0 \) and \( s \),
- \( C' \) be the constraint system associated to \( sc|_{\Pi_1} \), \( T_0 \) and \( s \).

We have that \( C \) satisfiable implies \( C' \) satisfiable

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   \[
   T_0, T_{\alpha}\theta, T_{\beta}\theta \vdash u_{\alpha}\theta \Rightarrow T_0, T_{\alpha}\theta \vdash u_{\alpha}\theta
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   → proved by induction on the prooftree witnessing \( T_0, T_{\alpha}\theta, T_{\beta}\theta \vdash u_{\alpha}\theta \)
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   $$T_0, T_{\alpha} \theta, T_{\beta} \theta \vdash u_{\alpha} \theta \Rightarrow T_0, T_{\alpha} \theta \vdash u_{\alpha} \theta$$

   → proved by induction on the prooftree witnessing $T_0, T_{\alpha} \theta, T_{\beta} \theta \vdash u_{\alpha} \theta$
In the journal version of the paper (currently under submission)

- we add a new primitive: hash function $h(m)$,
- we relax the condition “well-tagged” to non-unifiability,
- we deal with a class of security properties
  $\rightarrow$ we introduce a logic for which the composition result holds
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  \[ \psi := \text{true} | P(t_1, \ldots, t_n) | \neg \psi | \psi_1 \land \psi_2 | \psi_1 \lor \psi_2 | Y\psi | \psi_1 S \psi_2 \]
  \[ | \exists x. \psi | \forall x. \psi \]
- we introduce a logic for which the composition result holds

This logic allows us to express:

- secrecy of a nonce: $\forall x. (\Box \text{nonce}(x)) \Rightarrow \neg \text{learn}(x)$
- several notions of authentication, e.g. aliveness:
  \[ \text{end}(a, b) \Rightarrow \Box \text{start}(b) \land (\text{end}(b, a) \Rightarrow \Box \text{start}(a)) \]
The idea of adding an identifier is not novel:

- Principle 10 in the prudent engineering paper, [Abadi & Needham, 1995]
- ...

There are also some formal results about this composition problem:

- Protocol independence through disjoint encryption [Guttman & Thayer, 00]  
  → asymmetric condition allowing one to deal with protocols with ticket (e.g. Neuman-Strubblebine protocol)  
  → their condition has to hold on any valid execution of the protocol

- Sufficient conditions for composing security protocols [Andova et al., 07]  
  → different kinds of composition (parallel, sequential)  
  → they have to assume typing hypothesis, they can not deal with protocols with ciphertext forwarding
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Outline of the talk

1. Introduction
2. Preliminaries
3. Composition result (1\textsuperscript{st} part)
4. Composition result (2\textsuperscript{nd} part): ongoing work
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Our Goal

We propose a transformation which maps a protocol $P$ that is secure for a single session to a protocol $\overline{P}$ that is secure for an unbounded number of sessions.

$\rightarrow$ side-effect: we also characterize a class of protocols for which secrecy for an unbounded number of sessions is decidable

Main Difficulty

We can not assume that a (static) tag is already shared between the different participants of one session.

$\rightarrow$ we will use dynamic tags
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Our transformation

Let $P$ be a protocol with $\ell$ participants as given below:

\[
\begin{align*}
A_{i_1} & \rightarrow A_{j_1} : \ m_1 \\
A_{i_2} & \rightarrow A_{j_2} : \ m_2 \\
& \vdots \\
A_{i_k} & \rightarrow A_{j_k} : \ m_k
\end{align*}
\]
Our transformation

The protocol $\overline{P}$ (with $\ell$ participants) is described below:

**Initialisation phase:** broadcast of fresh nonces

\[
\begin{align*}
A_1 & \rightarrow All : A_1, N_1 \\
A_2 & \rightarrow All : A_2, N_2 \\
& \vdots \\
A_\ell & \rightarrow All : A_\ell, N_\ell
\end{align*}
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**Initialisation phase**: broadcast of fresh nonces

- $A_1 \rightarrow All : A_1, N_1$
- $A_2 \rightarrow All : A_2, N_2$
  
  ...
  
- $A_\ell \rightarrow All : A_\ell, N_\ell$

Every participant obtain a tag $= \langle A_1, N_1, A_2, N_2, \ldots, A_\ell, N_\ell \rangle$
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Every participant obtain a $\text{tag} = \langle A_1, N_1, A_2, N_2, \ldots, A_\ell, N_\ell \rangle$

**Main phase:**

where the function $\overline{m}$ is defined by:

\[
\begin{align*}
A_{i_1} \rightarrow A_{j_1} : & \quad \overline{m_1} \\
A_{i_2} \rightarrow A_{j_2} : & \quad \overline{m_2} \\
\vdots & \quad \vdots \\
A_{i_k} \rightarrow A_{j_k} : & \quad \overline{m_k} \\
\end{align*}
\]

\[
\begin{align*}
\langle u_1, u_2 \rangle & \rightarrow \langle \overline{u_1}, \overline{u_2} \rangle \\
f(u_1, u_2) & \rightarrow f(\langle \text{tag}, \overline{u_1} \rangle, \overline{u_2}) & \text{when } f \in \{\text{enc, enca, sign}\} \\
\overline{u} & \rightarrow u & \text{otherwise}
\end{align*}
\]
Example

Consider again the protocol $\overline{P}$ between $A$ and $B$

\[
A \rightarrow B : \text{ enca}(\langle A, K, Na \rangle, \text{pub}(B)), \\
\text{sign}(\text{enca}(\langle A, Na \rangle, \text{pub}(B)), \text{priv}(A))
\]

\[
B \rightarrow A : \text{Na}, \text{enc}(s, K)
\]

there is an attack involving 2 sessions between $A$ and $B$.

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Conjecture (almost established)

Under the same kind of hypothesis than the previous composition result (i.e. no critical key in plaintext, plaintext origination property), we have that

\[ \text{If } P \text{ preserves the secrecy of } s \text{ for a single honest session then } \overline{P} \text{ preserves the secrecy of } s \text{ for an unbounded number of sessions.} \]

\[ \rightarrow \] we prove this result by contradiction and we rely on the refinement of the procedure due to H. Comon-Lundh.

Remark: In each constraint system obtained after several simplification steps of the procedure, the terms are always uniquely tagged (even if there are not necessarily tagged as expected by a normal execution (i.e. no intervention of the attacker)).
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Related Works

Another compiler

- *Synthesizing secure protocols* [Cortier et al., 07]
  - their notion of security for $P$ is very weak (essentially with no adversary)
  - their transformation is heavier than ours

Some other decidability classes for an unbounded number of sessions

- *On the security of ping-pong protocols* [Dolev et al., 83]
  - PTIME decision procedure
  - the class of protocols they consider is very restrictive

- *Towards a completeness result ... of security protocols* [Lowe, 98]

- *Tagging makes secrecy decidable for unbounded nonces as well* [Rammanujam et al., 03]
  - notion of secrecy that disallow temporary secrets
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How to combine both results?

→ by using tags of the form $\text{tag} = \langle id_\alpha, A_1, N_1, \ldots, A_\ell, N_\ell \rangle$.

Remark: dynamic tagging is not sufficient to compose different protocols.

Protocol 1

$A \to B : A, N_1$

$B \to A : B, N_2$

$A \to B : \text{enca}(\langle A, N_1, B, N_2, s \rangle, \text{pub}(B))$

There is an attack on $s$:

- role $B$ of $P_2$ with the tag $\langle A, N_1, B, N'_2 \rangle$.
- role $A$ of $P_1$ with the tag $\langle A, N_1, B, N'_2 \rangle$. 
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**Protocol 2**

\[
\begin{align*}
A \to B & : A, N'_1 \\
B \to A & : B, N'_2 \\
A \to B & : \text{enca}(\langle A, N'_1, B, N'_2, N_a \rangle, \\
& \quad \text{pub}(B)) \\
B \to A & : N_a
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\[
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A & \rightarrow B : \quad \text{enca}(\langle A, N'_1, B, N'_2, N_a \rangle, \\
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Conclusion: Two composition results

- one that can be used to compose protocols that satisfy disjoint encryption
  -→ this can be obtained with static tags
- one that is useful to compose sessions of the same protocol (general class of protocols)
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Both results are based on a refinement of the procedure due to H. Comon

Yet another composition result: with S. Kremer and M. Ryan

- another class of protocols: password based protocols
- another notion of security: resistance against guessing attacks
  -→ we use another notion of tagging
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