Safely composing security protocols via tagging

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⟶ joint work with Véronique Cortier, Jérémie Delaitre, Myrto Arapinis and Steve Kremer

Context: cryptographic protocols

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.

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Cryptographic protocols (formal approach)

Messages are abstracted by terms

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

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Presence of an idealized attacker

- may read, intercept and send messages,
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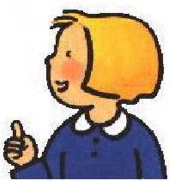
Examples:

$$\frac{m \quad k}{\mathsf{enc}(m,k)} \qquad \frac{\mathsf{enc}(m,k) \quad k}{m} \qquad \frac{\mathsf{enca}(m,\mathsf{pub}(a)) \quad \mathsf{priv}(a)}{m}$$

A simple protocol

$$\xrightarrow{\langle \mathsf{Bob}, \mathsf{k} \rangle}$$

$$\xleftarrow{\langle \mathsf{Alice}, \mathsf{enc}(\color{red}{\mathsf{s}}, \mathsf{k}) \rangle}$$



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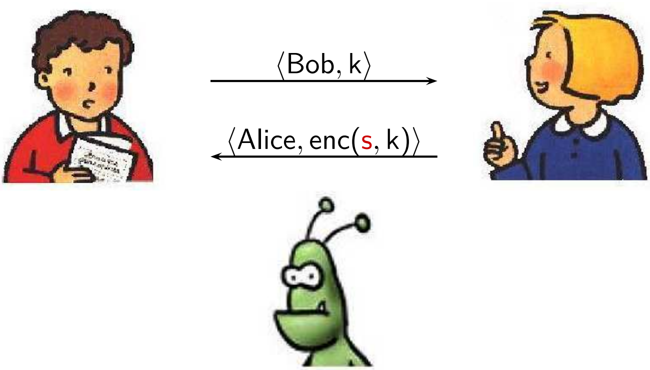


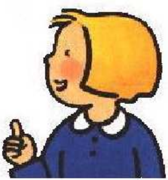
Question?

Can the attacker learn the secret s?

A simple protocol

$$\xrightarrow{\langle \mathsf{Bob}, \mathsf{k} \rangle}$$

$$\xleftarrow{\langle \mathsf{Alice}, \mathsf{enc}(\mathsf{s}, \mathsf{k}) \rangle}$$



Answer: Of course, Yes!

$$\frac{\dfrac{\langle \mathsf{Alice}, \mathsf{enc}(\mathsf{s}, \mathsf{k}) \rangle}{\mathsf{enc}(\mathsf{s}, \mathsf{k})} \qquad \dfrac{\langle \mathsf{Bob}, \mathsf{k} \rangle}{\mathsf{k}}}{\mathsf{s}}$$

Composition problem (part 2 of this talk)

$\longrightarrow$ sessions coming from the same protocol

$$\begin{array}{ll} A \rightarrow B: & \mathrm{enca}(\langle A, K, Na\rangle, \mathrm{pub}(B)),\ \mathrm{sign}(\mathrm{enca}(\langle A, Na\rangle, \mathrm{pub}(B)), \mathrm{priv}(A)) \\ B \rightarrow A: & Na, \mathrm{enc}(s, K) \end{array}$$

Question?

What about the secrecy of s?

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$\longrightarrow$ sessions coming from the same protocol

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\begin{array}{ll}
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Attack with 2 sessions:

$$\begin{array}{rl} A \rightarrow B: & \mathsf{enca}(\langle A, K, Na\rangle, \mathsf{pub}(B)),\ \mathsf{sign}(\mathsf{enca}(\langle A, Na\rangle, \mathsf{pub}(B)), \mathsf{priv}(A)) \\ B \rightarrow A: & Na, \mathsf{enc}(s_1, K) \\ I(A) \rightarrow B: & \mathsf{enca}(\langle A, Ki, Na\rangle, \mathsf{pub}(B)),\ \mathsf{sign}(\mathsf{enca}(\langle A, Na\rangle, \mathsf{pub}(B)), \mathsf{priv}(A)) \\ B \rightarrow A: & Na, \mathsf{enc}(s_2, Ki) \end{array}$$

Question?

What about the secrecy of s?

Composition problem (part 1 of this talk)

Protocol 1

$$P_1 : \quad A \to B : \quad \mathrm{enca}(s, \mathrm{pub}(B))$$

Question?

What about the secrecy of s?

Composition problem (part 1 of this talk)

$\longrightarrow$ sessions coming from different protocols

Protocol 1

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

Protocol 2

$$\begin{array}{lll} P_2: & A \rightarrow B: & \mathrm{enca}(N_a, \mathrm{pub}(B)) \\ & B \rightarrow A: & N_a \end{array}$$

Question?

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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
  $\longrightarrow$ this is not sufficient

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  $\longrightarrow$ 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;

$\longrightarrow$ 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 (1st part)
4. Composition result (2nd part): ongoing work
5. Conclusion

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Deduction capabilities of the attacker

Composition rules

$$\frac{T \vdash u \quad T \vdash v}{T \vdash \langle u, v \rangle} \qquad \frac{T \vdash u \quad T \vdash v}{T \vdash \mathsf{f}(u, v)} \ \textit{with}\ \mathsf{f} \in \{\mathsf{enc}, \mathsf{enca}, \mathsf{sign}\}$$

Decomposition rules

$$\frac{}{T \vdash u}\ u \in T \qquad \frac{T \vdash \langle u, v \rangle}{T \vdash u} \qquad \frac{T \vdash \langle u, v \rangle}{T \vdash v} \qquad \frac{T \vdash \mathsf{enc}(u, v) \quad T \vdash v}{T \vdash u}$$

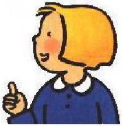
$$\frac{T \vdash \mathsf{enca}(u, \mathsf{pub}(v)) \quad T \vdash \mathsf{priv}(v)}{T \vdash u} \qquad \frac{T \vdash \mathsf{sign}(u, \mathsf{priv}(v))}{T \vdash u}\ \textit{(optional)}$$

Deducibility relation

A term u is deducible from a set of terms T, denoted by $T \vdash u$, if there exists a prooftree witnessing this fact.

Protocol – Example: Needham Schroeder protocol (1978)

Needham Schroeder protocol:



$$\begin{array}{rcrr} A & \rightarrow & B: & \{N_a, A\}_{\mathrm{pub}(B)} \\ B & \rightarrow & A: & \{N_a, N_b\}_{\mathrm{pub}(A)} \\ A & \rightarrow & B: & \{N_b\}_{\mathrm{pub}(B)} \end{array}$$

A protocol is a finite set of roles:

Exemple:

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

$$\mathrm{init} \xrightarrow{N} \mathrm{enca}(\langle N, a\rangle, \mathrm{pub}(b))$$
$$\mathrm{enca}(\langle N, x\rangle, \mathrm{pub}(a)) \rightarrow \mathrm{enca}(x, \mathrm{pub}(b)).$$

Secrecy via constraint solving

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

Scenario

$$
\begin{array}{ccc}
\mathrm{rcv}(u_1) & \xrightarrow{N_1} & \mathrm{snd}(v_1) \\
\mathrm{rcv}(u_2) & \xrightarrow{N_2} & \mathrm{snd}(v_2) \\
 & \dots & \\
\mathrm{rcv}(u_n) & \xrightarrow{N_n} & \mathrm{snd}(v_n)
\end{array}
$$

Constraint System

$$
\mathcal{C} = \begin{cases} T_0 \Vdash u_1 \\ T_0, v_1 \Vdash u_2 \\ \quad \dots \\ T_0, v_1, .., v_n \Vdash s \end{cases}
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Solution of a constraint system

A substitution σ such that

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

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T_0, v_1 \Vdash u_2 \\
\quad \dots \\
T_0, v_1, .., v_n \Vdash s
\end{array} \right.
$$

Well-formed constraint system

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

$\longrightarrow$ to discard some weird protocols, we also require plaintext origination

Procedure due to H. Comon-Lundh

Input: A (well-formed) constraint system
Output: Either $\perp$ or a constraint system in solved form
$\longrightarrow$ systems in solved form always have a solution

R_5 : $\mathcal{C} \wedge T \Vdash f(u,v) \rightsquigarrow \mathcal{C} \wedge T \Vdash u \wedge T \Vdash v$
for $f \in \{\langle\rangle, \mathrm{enc}, \mathrm{enca}, \mathrm{sign}\}$

R_4 : $\mathcal{C} \wedge T \Vdash u \rightsquigarrow \perp$ if $vars(T,u) = \emptyset$ and $T \nvdash u$

R_1 : $\mathcal{C} \wedge T \Vdash u \rightsquigarrow \mathcal{C}$ if $T \cup \{x \mid T' \Vdash x \in \mathcal{C}, T' \subsetneq T\} \vdash u$

R_2 : $\mathcal{C} \wedge T \Vdash u \rightsquigarrow_\sigma \mathcal{C}\sigma \wedge T\sigma \Vdash u\sigma$ $u' \in st(T)$

R_3 : $\mathcal{C} \wedge T \Vdash v \rightsquigarrow_\sigma \mathcal{C}\sigma \wedge T\sigma \Vdash v\sigma$ $u, u' \in st(T)$
if $\sigma = \mathrm{mgu}(u,u')$, $u, u' \notin \mathcal{X}$, $u \neq u'$

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

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

Refinement of the procedure

$$\mathsf{R}'_2: \quad \mathcal{C} \wedge T \Vdash u \quad \rightsquigarrow_\sigma \quad \mathcal{C}\sigma \wedge T\sigma \Vdash u\sigma \qquad\qquad u' \in st(T)$$

$$\mathsf{R}'_3: \quad \mathcal{C} \wedge T \Vdash v \quad \rightsquigarrow_\sigma \quad \mathcal{C}\sigma \wedge T\sigma \Vdash v\sigma \qquad\qquad u, u' \in st(T)$$

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

<u>u, u' are not pairs</u>

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
  $\longrightarrow$ of course, the theoretical complexity remains the same, i.e. NP

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$$\mathsf{R}_2' : \quad \mathcal{C} \wedge T \Vdash u \quad \rightsquigarrow_\sigma \quad \mathcal{C}\sigma \wedge T\sigma \Vdash u\sigma \qquad\qquad u' \in st(T)$$

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3. Composition result (1^{st} part)
4. Composition result (2^{nd} part): ongoing work
5. Conclusion

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.

$\longrightarrow$ this tagging policy will avoid interaction between two differents protocols.

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

Protocol P_1

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

Protocol P_2

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

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Condition 2 - No critical key in plaintext

Protocol P_1

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Protocol P_2

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

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.

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

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

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

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

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

where $\mathsf{KC} = (\mathsf{ExtNames}(P_1) \cup \mathsf{ExtNames}(P_2)) \smallsetminus T_0$

Let s be a α-tagged term such that $vars(s) \subseteq vars(P_1)$.

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

We have that $\mathcal{C}$ satisfiable implies $\mathcal{C}'$ satisfiable

1. If $\mathcal{C}$ satisfiable, there exists a solution θ without any mixing, i.e. terms in $\mathcal{C}\theta$ will be either α-tagged or β-tagged.
   $\longrightarrow$ refinement of the constraint solving procedure due to H. Comon-Lundh
2. Removing β-tagged terms from a left hand side of a constraint is safe

$$T_0, T_\alpha\theta, T_\beta\theta \vdash u_\alpha\theta \;\Rightarrow\; T_0, T_\alpha\theta \vdash u_\alpha\theta$$

$\longrightarrow$ proved by induction on the prooftree witnessing $T_0, T_\alpha\theta, T_\beta\theta \vdash u_\alpha\theta$

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

We have that $\mathcal{C}$ satisfiable implies $\mathcal{C}'$ satisfiable

1. If $\mathcal{C}$ satisfiable, there exists a solution θ without any mixing, i.e. terms in $\mathcal{C}\theta$ will be either α-tagged or β-tagged.
   $\longrightarrow$ refinement of the constraint solving procedure due to H. Comon-Lundh
2. Removing β-tagged terms from a left hand side of a constraint is safe

$$T_0, T_\alpha\theta, T_\beta\theta \vdash u_\alpha\theta \;\Rightarrow\; T_0, T_\alpha\theta \vdash u_\alpha\theta$$

$\longrightarrow$ proved by induction on the prooftree witnessing $T_0, T_\alpha\theta, T_\beta\theta \vdash u_\alpha\theta$

A little bit further ...

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
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$$\begin{array}{rcl}\psi & := & \mathsf{true} \mid P(t_1, \ldots, t_n) \mid \neg\psi \mid \psi_1 \wedge \psi_2 \mid \psi_1 \vee \psi_2 \mid \mathrm{Y}\psi \mid \psi_1 \,\mathrm{S}\, \psi_2 \\ & & \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \mid \exists x.\psi \mid \forall x.\psi \\ \phi & := & \psi \mid \mathsf{learn}(m) \mid \neg\phi \mid \phi_1 \wedge \phi_2 \mid \phi_1 \vee \phi_2 \mid \exists x.\phi \mid \forall x.\phi\end{array}$$

This logic allows us to express:

- secrecy of a nonce: $\forall x. (\Box\, \mathsf{nonce}(x)) \Rightarrow \neg \mathsf{learn}(x)$
- several notions of authentication, e.g. aliveness:
  $\mathsf{end}(a, b) \Rightarrow \Box\, \mathsf{start}(b)) \wedge (\mathsf{end}(b, a) \Rightarrow \Box\, \mathsf{start}(a))$

Related Works

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]
  $\longrightarrow$ asymmetric condition allowing one to deal with protocols with ticket (e.g. Neuman-Strubblebine protocol)
  $\longrightarrow$ their condition has to hold on any valid execution of the protocol
- *Sufficient conditions for composing security protocols* [Andova *et al.*,07]
  $\longrightarrow$ different kinds of composition (parallel, sequential)
  $\longrightarrow$ 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^{st} part)
4. Composition result (2^{nd} part): ongoing work
5. Conclusion

Summary

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.

$\longrightarrow$ side-effect: we also caracterise 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.

$\longrightarrow$ we will use dynamic tags

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Our transformation

Let P be a protocol with ℓ participants as given below:

$$\begin{array}{rcl} A_{i_1} \longrightarrow A_{j_1} & : & m_1 \\ A_{i_2} \longrightarrow A_{j_2} & : & m_2 \\ & \vdots & \\ A_{i_k} \longrightarrow A_{j_k} & : & m_k \end{array}$$

Our transformation

The protocol $\overline{P}$ (with ℓ participants) is decribed below:

Initialisation phase: broadcast of fresh nonces

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\begin{array}{rl}
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{array}
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Main phase:

$$\begin{array}{rl} A_{i_1} \rightarrow A_{j_1}: & \overline{m_1} \\ A_{i_2} \rightarrow A_{j_2}: & \overline{m_2} \\ \vdots & \\ A_{i_k} \rightarrow A_{j_k}: & \overline{m_k} \end{array}$$

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

$$\begin{cases} \overline{\langle u_1, u_2 \rangle} & \rightarrow \quad \langle \overline{u_1}, \overline{u_2} \rangle \\ \overline{f(u_1, u_2)} & \rightarrow \quad f(\langle \mathsf{tag}, \overline{u_1} \rangle, \overline{u_2}) \\ & \qquad \text{when } f \in \{\mathsf{enc}, \mathsf{enca}, \mathsf{sign}\} \\ \overline{u} & \rightarrow \quad u \qquad \text{otherwise} \end{cases}$$

Example

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

$$\begin{array}{rl} A \rightarrow B: & \mathsf{enca}(\langle A, K, Na\rangle, \mathsf{pub}(B)), \\ & \mathsf{sign}(\mathsf{enca}(\langle A, Na\rangle, \mathsf{pub}(B)), \mathsf{priv}(A)) \\ B \rightarrow A: & Na, \mathsf{enc}(s, K) \end{array}$$

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

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Composition result

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

> *If P preserves the secrecy of s for a single honest session then $\overline{P}$ preserves the secrecy of s for an unbounded number of sessions.*

$\longrightarrow$ 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]
  $\longrightarrow$ their notion of security for P is very weak (essentially with no adversary)
  $\longrightarrow$ 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]
  $\longrightarrow$ PTIME decision procedure
  $\longrightarrow$ 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]
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How to combine both results ?

$\longrightarrow$ by using tags of the form 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

$$\begin{array}{ll} A \rightarrow B: & A, N_1 \\ B \rightarrow A: & B, N_2 \\ A \rightarrow B: & \mathrm{enca}(\langle A, N_1, B, N_2, s \rangle, \\ & \qquad \mathrm{pub}(B)) \end{array}$$

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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Conclusion

Conclusion: Two composition results

- one that can be used to compose protocols that satisfy disjoint encryption
  $\longrightarrow$ 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

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