Equivalence Properties by Typing in Cryptographic Branching Protocols

Joseph Lallemand (Loria)

joint work with Véronique Cortier, Niklas Grimm, Matteo Maffei

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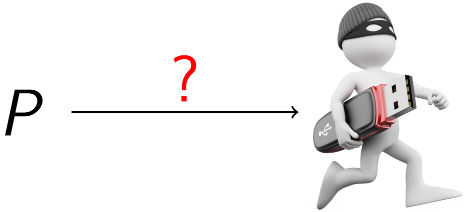
Trace properties

Trace properties = satisfied by all traces of a protocol

Example: reachability properties:

Can the attacker learn a given message ?

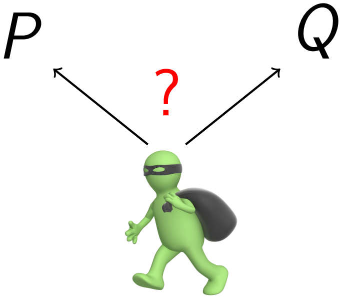


$\Longrightarrow$ secrecy, authentication, . . .

Equivalence

Some properties require the notion of equivalence:

Are two protocols indistinguishable for an attacker?

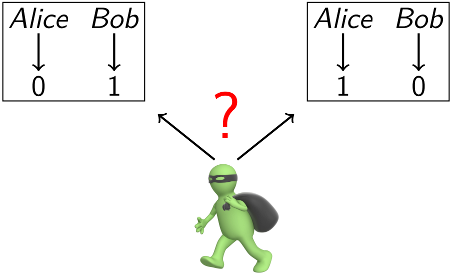


Example:

vote privacy, strong flavours of secrecy, anonymity, unlinkability, . . .

Example: vote privacy

Example: Privacy of the vote in voting protocols



Alice and Bob vote for either 0 or 1.

The values of the votes = 0 and 1 are not secret

The votes are secret if:

$$Alice(0) \mid Bob(1) \approx Alice(1) \mid Bob(0)$$

Type systems

Idea: design a type system that ensures protocols satisfy security properties

- Type systems: already applied to trace properties

$$M : \mathit{Secret} \vdash P \implies M \text{ is not deducible in } P$$

- Now: for equivalence

$$\vdash P \sim Q \quad \implies \quad P \approx Q$$

- Efficient (though incomplete) procedures
- Modularity

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Problem:

- Usually: typing $\rightarrow$ overapproximate the set of traces.
- Sound for trace properties, but not equivalence
  $\rightarrow$ might miss that some traces are only possible for P and not Q

Main idea

- Step 1: $\vdash P \sim Q : C$
  typing to ensure no leaks in behaviours
  collect all symbolic messages sent on the network into a *constraint*

- Step 2: $check(C)$
  ensure there are no leaks in the messages sent
  $\longrightarrow$ checking for repetitions

  Example:

  $$C = \{\mathtt{enc}(x, k) \sim \mathtt{enc}(a, k),\ \mathtt{enc}(y, k) \sim \mathtt{enc}(b, k)\}$$

  If in some execution we can have $x = y$, equivalence is broken.

Main result: Soundness

Theorem (Soundness)

If $\Gamma \vdash P \sim Q : C$ *and* $\forall\theta.\ C\theta$ *does not leak information, then*

$$P \approx Q$$

Theorem (Procedure to check constraints)

$$check(C) \Rightarrow \forall\theta.\ C\theta \textit{ does not leak information.}$$

Hypotheses:

- atomic keys only
- fixed cryptographic primitives: symmetric and asymmetric encryption, signature, hash, pairing
- no replication (bounded number of sessions only)

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From two to unbounded number of sessions

If one session typechecks, then any number of sessions typecheck:

Theorem (informal)

$$\Gamma \vdash P \sim Q : C \implies \Gamma \vdash !P \sim !Q : !C$$

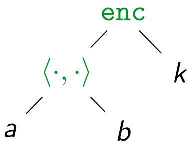
How to check that $!C$ does not leak information?
$\longrightarrow$ It is sufficient to check two copies of C:

Theorem (informal)

$$\mathit{check}(C \cup C') \implies \mathit{check}(!C)$$

Symbolic model

- Messages are terms
  constructed using abstract cryptographic primitives,



- Symbolic attacker
  with abilities defined by deduction rules

$$\frac{\mathtt{enc}(x, y) \qquad y}{x} \qquad\qquad \frac{x \qquad y}{\langle x, y \rangle}$$

Symbolic model

Process algebra similar to the applied pi-calculus

$$
\begin{array}{rcl}
P, Q & ::= & \\
 & & 0 \\
 & \mid & \mathtt{new}\ n.P \\
 & \mid & \mathtt{out}(M).P \\
 & \mid & \mathtt{in}(x).P \\
 & \mid & P \mid Q \\
 & \mid & \mathtt{let}\ x = d(y)\ \mathtt{in}\ P\ \mathtt{else}\ Q \\
 & \mid & \mathtt{if}\ M = N\ \mathtt{then}\ P\ \mathtt{else}\ Q \\
 & \mid & !P
\end{array}
$$

Static equivalence

Frames are sequences of messages modelling the attacker's knowledge

$$\phi = \{x_1 \mapsto k,\ x_2 \mapsto a,\ x_3 \mapsto \mathtt{enc}(b, k)\}$$

Static equivalence = indistinguishability of frames

$$\phi \approx \phi' \quad \iff \quad \forall R, S.\ R\phi = S\phi \Leftrightarrow R\phi' = S\phi'$$

Example:

$$\{\mathtt{enc}(a, k)\} \quad \approx \quad \{\mathtt{enc}(b, k)\}$$

but

$$\{\mathtt{enc}(a, k), \mathtt{enc}(a, k)\} \quad \not\approx \quad \{\mathtt{enc}(a, k), \mathtt{enc}(b, k)\}$$

and

$$\{k, \mathtt{enc}(a, k)\} \quad \not\approx \quad \{k, \mathtt{enc}(b, k)\}$$

Trace equivalence

A trace (tr, ϕ) is a sequence of observable actions
$+$ a frame of messages sent on the network

Definition (Trace equivalence)

P and Q are trace equivalent if any trace of P can be mimicked by a trace of Q (and conversely)

i.e.

$$\forall (tr, \phi) \in \mathrm{trace}(P).\ \exists (tr, \phi') \in \mathrm{trace}(Q).\ \phi \approx \phi'$$

and

$$\forall (tr, \phi) \in \mathrm{trace}(Q).\ \exists (tr, \phi') \in \mathrm{trace}(P).\ \phi \approx \phi'$$

Typing messages

Types for messages :

$$
\begin{array}{lcl}
l & ::= & \mathtt{LL} \mid \mathtt{HL} \mid \mathtt{HH} \\
T & ::= & l \\
 & \mid & \text{key}^{l}(T) \\
 & \mid & T * T \\
 & \mid & T \vee T \\
 & \mid & \dots
\end{array}
$$

- labels = levels of confidentiality and integrity
  - $\mathtt{LL}$ for public messages
  - $\mathtt{HH}$ for secret values
- key types $\text{key}^{l}(T)$

  Example:

$$\text{key}^{\mathtt{HH}}(\mathtt{LL} * \mathtt{HH})$$

Typing messages

$$\frac{\Gamma \vdash M \sim N : T \qquad \Gamma(k) = key^{\mathtt{HH}}(T)}{\Gamma \vdash \mathtt{enc}(M, k) \sim \mathtt{enc}(N, k) : \mathtt{LL}}$$

Ensure the messages sent are safe to output:
$\longrightarrow$ similar structure

$$\langle a, b \rangle \quad \not\sim \quad a$$

$$\mathtt{enc}(\langle a, b \rangle, k) \quad \sim \quad \mathtt{enc}(a, k) \quad \text{only if } k \text{ is secret}$$

Typing messages

$$\frac{\Gamma \vdash M \sim N : T \to c \qquad \Gamma(k) = key^{\mathtt{HH}}(T)}{\Gamma \vdash \mathtt{enc}(M, k) \sim \mathtt{enc}(N, k) : \mathtt{LL} \to c \cup \{\mathtt{enc}(M, k) \sim \mathtt{enc}(N, k)\}}$$

- Establish invariants regarding the types of keys
  If k is secret, the type of M, N must match the type of k
- Collect constraints
  Here we add the couple $\mathtt{enc}(M, k) \sim \mathtt{enc}(N, k)$ to the constraint

Typing processes

- All output messages must be of type $\mathtt{LL}$
- Their constraints are collected

$$\frac{\Gamma \vdash M \sim N : \mathtt{LL} \to c \qquad \Gamma \vdash P \sim Q : C}{\Gamma \vdash \mathtt{out}(M).P \sim \mathtt{out}(N).Q : C \cup c}$$

- All input messages are considered to be of type $\mathtt{LL}$:

$$\frac{\Gamma, x : \mathtt{LL} \vdash P \sim Q : C}{\Gamma \vdash \mathtt{in}(x).P \sim \mathtt{in}(x).Q : C}$$

Typing processes (2)

$\longrightarrow$ Processes have to progress the same way:

accept inputs/outputs at the same time,
follow (typably) equivalent branches

Example: applying destructors

$$\frac{\Gamma(x) = \mathtt{LL} \qquad \Gamma(k) = \mathsf{key}^{\mathtt{HH}}(T) \qquad \Gamma, y : T \vdash P \sim Q : C \qquad \Gamma \vdash P' \sim Q' : C'}{\Gamma \vdash \mathtt{let}\ y = \mathtt{dec}(x, k)\ \mathtt{in}\ P\ \mathtt{else}\ P' \sim \mathtt{let}\ y = \mathtt{dec}(x, k)\ \mathtt{in}\ Q\ \mathtt{else}\ Q' : C \cup C'}$$

Constraints

Why do we need constraints?

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Example: If k is a secret key

$$\begin{array}{lcll} \mathtt{out}(\mathtt{enc}(a, k)) & \sim & \mathtt{out}(\mathtt{enc}(b, k)) & \text{is fine} \\ \mathtt{out}(\mathtt{enc}(a, k)) & \sim & \mathtt{out}(\mathtt{enc}(a, k)) & \text{is fine} \end{array}$$

but not both together

$$\mathtt{out}(\mathtt{enc}(a, k)) \mid \mathtt{out}(\mathtt{enc}(a, k)) \not\sim \mathtt{out}(\mathtt{enc}(b, k)) \mid \mathtt{out}(\mathtt{enc}(a, k))$$

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$$\mathcal{C} = \{\mathtt{enc}(a,k) \sim \mathtt{enc}(b,k), \mathtt{enc}(a,k) \sim \mathtt{enc}(a,k)\}$$

Constraints

Collect symbolic messages in a constraint C while typing
and check that it is consistent

i.e. for any possible instantiation, C instantiated does not leak anything:

$$C = \{u_1 \sim v_1, \ldots, u_n \sim v_n\}$$

must satisfy

$$\forall \theta, \theta'. \quad \{u_1\theta, \ldots, u_n\theta\} \approx \{v_1\theta', \ldots, v_n\theta'\}$$

Constraints: Checking consistency

- Open messages as much as possible:

$$\begin{array}{rcll} \langle M, N \rangle & \longrightarrow & M, N & \\ \mathtt{enc}(M, k) & \longrightarrow & M & \text{if } k \text{ has type } \mathrm{key}^{\mathtt{LL}}(\cdot) \\ \ldots & & & \end{array}$$

- Check that both sides of the opened constraint satisfy the same equalities once instantiated (unification)

$$M \sim N, M' \sim N' \in C$$

$$\forall \theta, \theta'.\ M\theta = M'\theta \iff N\theta' = N'\theta'$$

- Actually only consider well-typed θ, θ'
i.e.

$$\forall x.\ \vdash \theta(x) \sim \theta'(x) : \Gamma(x)$$

The case of different keys

In the rules shown before, the keys were the same on both sides

$$\frac{\Gamma \vdash M \sim N : T \to c \qquad \Gamma(k) = \text{key}^{\text{HH}}(T)}{\Gamma \vdash \texttt{enc}(M, k) \sim \texttt{enc}(N, k) : \texttt{LL} \to c \cup \{\texttt{enc}(M, k) \sim \texttt{enc}(N, k)\}}$$

$\longrightarrow$ How to handle more complex cases where different keys are used?

Example: anonymity, unlinkability

Example: Private Authentication

$\longrightarrow$ Authenticating B to A anonymously to others

$$A \to B : \quad \mathtt{aenc}(\langle N_a, \mathtt{pk}(k_a)\rangle, \mathtt{pk}(k_b))$$

$$B \to A : \quad \begin{cases} \mathtt{aenc}(\langle N_a, \langle N_b, \mathtt{pk}(k_b)\rangle\rangle, \mathtt{pk}(k_a)) & \text{if } B \text{ accepts } A\text{'s request} \\ \mathtt{aenc}(N_b, \mathtt{pk}(k)) & \text{if } B \text{ declines } A\text{'s request} \end{cases}$$

$\mathtt{pk}(k) =$ decoy key. No one has the secret key k.

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Anonymity: an attacker cannot learn whether B is willing to talk to A or not

$$Alice \mid Bob(pk_{Alice}) \approx Alice \mid Bob(pk_{Charlie})$$

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Problems: different keys and non uniform branching

Bikeys

$\longrightarrow$ We introduce bikeys: pairs of keys with a type

Example:

$$\Gamma(k_1, k_2) = \mathsf{key}^{\mathtt{HH}}(\mathtt{LL} * \mathtt{HH})$$

There may be multiple bindings for the same key :

$$\begin{array}{rcl} \Gamma(k_1, k_2) & = & \mathsf{key}^{\mathtt{HH}}(\mathtt{LL} * \mathtt{HH}) \\ \Gamma(k_1, k_3) & = & \mathsf{key}^{\mathtt{HH}}(\mathtt{HH} * \mathtt{LL}) \end{array}$$

We also add a type specifying that the keys are actually the same:

$$\Gamma(k, k) = \mathsf{eqkey}^{\mathtt{HH}}(\mathtt{HH})$$

Bikeys: encrypting

$\longrightarrow$ The rules for encrypting go as expected:
allow any pair of keys that is valid in Γ

$$\frac{\Gamma \vdash M \sim N : T \to c \qquad \Gamma(k_1, k_2) = \mathsf{key}^{\mathtt{HH}}(T)}{\Gamma \vdash \mathtt{enc}(M, k_1) \sim \mathtt{enc}(N, k_2) : \mathtt{LL} \to c \cup \{\mathtt{enc}(M, k_1) \sim \mathtt{enc}(N, k_2)\}}$$

$\longrightarrow$ Similarly for asymmetric encryption and signature

Bikeys: decrypting

Previously:

$$\frac{\Gamma(x) = \mathtt{LL} \qquad \Gamma(k) = \mathsf{key}^{\mathtt{HH}}(T) \qquad \Gamma, x : T \vdash P \sim Q : C \qquad \Gamma \vdash P' \sim Q' : C'}{\Gamma \vdash \mathtt{let}\ y = \mathtt{dec}(x, k)\ \mathtt{in}\ P\ \mathtt{else}\ P' \sim \mathtt{let}\ y = \mathtt{dec}(x, k)\ \mathtt{in}\ Q\ \mathtt{else}\ Q' : C \cup C'}$$

Bikeys: decrypting

With different keys ?

$$\frac{\Gamma(x) = \texttt{LL} \qquad \Gamma(k_1, k_2) = \mathsf{key}^{\texttt{HH}}(T) \qquad \Gamma, x : T \vdash P \sim Q : C \qquad \Gamma \vdash P' \sim Q' : C'}{\Gamma \vdash \texttt{let } y = \texttt{dec}(x, k_1) \texttt{ in } P \texttt{ else } P' \sim \texttt{let } y = \texttt{dec}(x, k_2) \texttt{ in } Q \texttt{ else } Q' : C \cup C'}$$

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Problem: There may be several bindings for k_1 in Γ
x may be encrypted with k_1 on the left, $k_3 \neq k_2$ on the right

$\longrightarrow$ We do not know that decryption succeeds or fails equally

$=$ the processes may branch non uniformly *i.e.* follow different branches

The problem of non-uniform branching

How to handle cases where the processes follow different branches?

- when decrypting with bikeys
- conditional branching where uniform execution cannot be ensured

$\longrightarrow$ We have to take all cases into account:

$$\frac{\begin{array}{c}\Gamma(y) = \mathtt{LL} \qquad \Gamma(k_1, k_2) = \mathsf{key}^{\mathtt{HH}}(T) \\ \Gamma, x : T \vdash P \sim Q \to C \qquad \Gamma \vdash P' \sim Q' \to C' \\ (\forall T'.\forall k_3 \neq k_2.\ \Gamma(k_1, k_3) = \mathsf{key}^{\mathtt{HH}}(T') \Rightarrow \Gamma, x : T' \vdash P \sim Q' \to C_{k_3}) \\ (\forall T'.\forall k_3 \neq k_1.\ \Gamma(k_3, k_2) = \mathsf{key}^{\mathtt{HH}}(T') \Rightarrow \Gamma, x : T' \vdash P' \sim Q \to C'_{k_3})\end{array}}{\begin{array}{c}\Gamma \vdash \mathtt{let}\ x = \mathtt{dec}(y, k_1)\ \mathtt{in}\ P\ \mathtt{else}\ P' \sim \mathtt{let}\ x = \mathtt{dec}(y, k_2)\ \mathtt{in}\ Q\ \mathtt{else}\ Q' \\ \to C \cup C' \cup (\bigcup_{k_3} C_{k_3}) \cup (\bigcup_{k_3} {C'}_{k_3})\end{array}}$$

Note: the simple rule still applies when keys have type $\mathsf{eqkey}^{l}(T)$

Back to Private Authentication

$$A \to B: \quad \mathtt{aenc}(\langle N_a, \mathtt{pk}(k_a)\rangle, \mathtt{pk}(k_b))$$

$$B \to A: \quad \begin{cases} \mathtt{aenc}(\langle N_a, \langle N_b, \mathtt{pk}(k_b)\rangle\rangle, \mathtt{pk}(k_a)) & \text{if } B \text{ accepts } A\text{'s request} \\ \mathtt{aenc}(N_b, \mathtt{pk}(k)) & \text{if } B \text{ declines } A\text{'s request} \end{cases}$$

$$Alice \mid Bob(pk_a) \approx Alice \mid Bob(pk_c)$$

We can typecheck Bob's response by having bindings in Γ for all cases

- (k_a, k) authentication succeeds on the left, fails on the right
- (k, k_c) authentication succeeds on the right, fails on the left
- (k_a, k_c) authentication succeeds on both sides
- (k, k) authentication fails on both sides

Done?

Done? Not. Yet.

The case of dynamic keys

In the rules shown before, the keys were all fixed, long-term keys

$\longrightarrow$ We also want to consider key distribution mechanisms, where keys are

- generated (session keys)
- received from the network and then used to encrypt, decrypt, sign

The case of dynamic keys (2)

$\longrightarrow$ A new type for session keys

$$\text{seskey}^l(T)$$

Processes can

- generate session keys (must specify a type annotation)

$$\frac{\Gamma, (k, k) : \text{seskey}^l(T) \vdash P \sim Q : C}{\Gamma \vdash \texttt{new}\ k : \text{seskey}^l(T).\ P \sim \texttt{new}\ k : \text{seskey}^l(T).\ Q : C}$$

- receive and store session keys in variables of type $\text{seskey}^l(T)$
- use these variables as keys to encrypt, decrypt, ...

The case of dynamic keys (3)

$\longrightarrow$ Tricky point: consistency of the constraints

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Example: If $x : \mathtt{LL}$ (key provided by the attacker), typechecking

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yields the constraint

$$\mathtt{enc}(a, x) \sim \mathtt{enc}(a, x)$$

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$$\mathtt{out}(\mathtt{enc}(a, x)) \sim \mathtt{out}(\mathtt{enc}(a, x))$$

yields the constraint

$$\mathtt{enc}(a, x) \sim \mathtt{enc}(a, x)$$

If we proceed as before and open the messages we get

$$x \sim x$$

which typically renders the constraint inconsistent

The case of dynamic keys (4)

Indeed: as soon as C contains

$$x \sim x \text{ and } M \sim N$$

if we choose $\theta(x) = M$ and $\theta'(x) \neq N$,

C instantiated with θ, θ' is not statically equivalent

The case of dynamic keys (4)

Indeed: as soon as C contains

$$x \sim x \text{ and } M \sim N$$

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C instantiated with θ, θ' is not statically equivalent

$\longrightarrow$ We need to further restrict the θ we consider

The case of dynamic keys (4)

Indeed: as soon as C contains

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if we choose $\theta(x) = M$ and $\theta'(x) \neq N$,

C instantiated with θ, θ' is not statically equivalent

$\longrightarrow$ We need to further restrict the θ we consider

$\longrightarrow$ Invariant: variables of type $\mathtt{LL}$ only contain messages
the attacker can construct from the remainder of the constraint

The case of dynamic keys (4)

Indeed: as soon as C contains

$$x \sim x \text{ and } M \sim N$$

if we choose $\theta(x) = M$ and $\theta'(x) \neq N$,

C instantiated with θ, θ' is not statically equivalent

$\longrightarrow$ We need to further restrict the θ we consider

$\longrightarrow$ Invariant: variables of type $\mathtt{LL}$ only contain messages the attacker can construct from the remainder of the constraint

$\longrightarrow$ Prevents the previous θ, θ' and solves the problem

Experimental results

- Prototype implementation for our type system
- We implement a typechecker,
  together with the procedure for constraints
- Very efficient
- But requires some type annotations

Protocol	Akiss	Apte	Apte-POR	Spec	Sat-Eq	TypeEq
Denning-Sacco	10	6	12	7	>30	>30
Wide Mouth Frog	14	7	12	7	>30	>30
Needham-Schroeder Symmetric Key	10	6	10	6	>30	>30
Yahalom-Lowe	10	6	10	7	>30	>30
Otway-Rees	6	3	6	6	-	>30
Needham-Schroeder-Lowe	8	4	4	4	-	>20

Number of sessions treated when proving secrecy
(bounded case)

Experimental results

Closer look for the Needham-Schroeder symmetric key protocol:

# sessions	Akiss	Apte	Apte-POR	Spec	Sat-Eq	TypeEq
3	0.1s	0.4s	0.02s	52s	0.2s	0.003s
6	20s	TO	4s	MO	0.4s	0.003s
7	2m		8m		1.3s	0.003s
10	SO		TO		2.3s	0.005s
12					4s	0.005s
14					7s	0.007s
30					1m6s	0.01s

Experimental results (unbounded)

We also compare to ProVerif for unbounded numbers of sessions:

Protocols	ProVerif	TypeEq
Helios	x	0.005s
Needham-Schroeder (sym)	0.23s	0.016s
Needham-Schroeder-Lowe	0.08s	0.008s
Yahalom-Lowe	0.48s	0.020s
Private Authentication	0.034s	0.008s
BAC	0.038s	0.005s

- Performances comparable to ProVerif for unbounded numbers of sessions
- First automated proof for Helios with unbounded number of sessions without private channels

Conclusion and future work

- a new approach to automatic proofs of equivalence properties for cryptographic protocols
- based on type systems + constraints
- handle bounded and unbounded number of sessions (CCS'17), dynamic keys, bikeys and non uniform branching (POST'18)
- efficient implementation

Future work:

- type inference
- computational soundness
- composition