Equivalence Properties by Typing in Cryptographic Branching Protocols

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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?

\[ P \rightarrow ? \]

\[ \Rightarrow \text{secrecy, authentication, ...} \]
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:

\[ Alice(0) | Bob(1) \approx Alice(1) | Bob(0) \]
Type systems

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

- Type systems: already applied to trace properties

  \[ M : \text{Secret} \vdash P \implies M \text{ is not deducible in } P \]

- Now: for equivalence

  \[ \vdash P \sim Q \implies P \approx Q \]

- Efficient (though incomplete) procedures
- Modularity
Type systems

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- Modularity

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 \textit{constraint}

- **Step 2:** \textit{check}(C)
  ensure there are no leaks in the messages sent
  \(\rightarrow\) checking for repetitions

Example:

\[ C = \{ \text{enc}(x, k) \sim \text{enc}(a, k), \text{enc}(y, k) \sim \text{enc}(b, k) \} \]

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)

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

**Hypotheses:**

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

$\text{check}(C) \Rightarrow \forall \theta. C\theta$ 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)
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?

→ It is sufficient to check two copies of \( C \):

**Theorem (informal)**

\[ \text{check}(C \cup C') \implies \text{check}(!C) \]
Messages are terms constructed using abstract cryptographic primitives,

\[
\text{enc} \quad \langle \cdot, \cdot \rangle \quad k \\
\quad \quad \quad \quad \quad \quad \quad a \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad b
\]

Symbolic attacker with abilities defined by deduction rules

\[
\begin{align*}
\text{enc}(x, y) & \quad y \\
& \quad x \quad y \\
& \quad \langle x, y \rangle
\end{align*}
\]
Symbolic model

Process algebra similar to the applied pi-calculus

\[
P, Q ::=  \\
\quad 0  \\
\quad \text{new } n.P  \\
\quad \text{out}(M).P  \\
\quad \text{in}(x).P  \\
\quad P \mid Q  \\
\quad \text{let } x = d(y) \text{ in } P \text{ else } Q  \\
\quad \text{if } M = N \text{ then } P \text{ else } Q  \\
\quad !P
\]
Static equivalence

Frames are sequences of messages modelling the attacker’s knowledge

\[ \phi = \{ x_1 \mapsto k, \; x_2 \mapsto a, \; x_3 \mapsto \text{enc}(b, k) \} \]

Static equivalence = indistinguishability of frames

\[ \phi \approx \phi' \iff \forall R, S. \; R\phi = S\phi \iff R\phi' = S\phi' \]

Example:

\[ \{ \text{enc}(a, k) \} \approx \{ \text{enc}(b, k) \} \]

but

\[ \{ \text{enc}(a, k), \text{enc}(a, k) \} \not\approx \{ \text{enc}(a, k), \text{enc}(b, k) \} \]

and

\[ \{ k, \text{enc}(a, k) \} \not\approx \{ k, \text{enc}(b, k) \} \]
A trace \((tr, \phi)\) 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.

\[
\forall (tr, \phi) \in \text{trace}(P). \exists (tr, \phi') \in \text{trace}(Q). \phi \approx \phi'
\]

and

\[
\forall (tr, \phi) \in \text{trace}(Q). \exists (tr, \phi') \in \text{trace}(P). \phi \approx \phi'
\]
Typing messages

Types for messages:

\[
\begin{align*}
I & ::= \text{LL} | \text{HL} | \text{HH} \\
T & ::= I \\
& \quad | \text{key}^{I}(T) \\
& \quad | T \ast T \\
& \quad | T \lor T \\
& \quad | \ldots
\end{align*}
\]

- **labels** = levels of **confidentiality** and **integrity**
  - LL for public messages
  - HH for secret values
- **key types** key\(^I\)(T)

**Example:**

\[
\text{key}^{HH}(\text{LL} \ast \text{HH})
\]
Typing messages

\[ \Gamma \vdash M \sim N : T \quad \Gamma(k) = \text{key}^{\text{HH}}(T) \]

\[ \Gamma \vdash \text{enc}(M, k) \sim \text{enc}(N, k) : \text{LL} \]

Ensure the messages sent are safe to output:

\[ \rightarrow \text{similar structure} \]

\[ \langle a, b \rangle \not\sim a \]

\[ \text{enc}(\langle a, b \rangle, k) \sim \text{enc}(a, k) \quad \text{only if } k \text{ is secret} \]
Typing messages

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

- 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 $\text{enc}(M, k) \sim \text{enc}(N, k)$ to the constraint
• All output messages must be of type $\text{LL}$

• Their constraints are collected

\[
\frac{\Gamma \vdash M \sim N : \text{LL} \rightarrow c \quad \Gamma \vdash P \sim Q : C}{\Gamma \vdash \text{out}(M).P \sim \text{out}(N).Q : C \cup c}
\]

• All input messages are considered to be of type $\text{LL}$:

\[
\frac{\Gamma, x : \text{LL} \vdash P \sim Q : C}{\Gamma \vdash \text{in}(x).P \sim \text{in}(x).Q : C}
\]
Processes have to progress the same way: accept inputs/outputs at the same time, follow (typably) equivalent branches.

Example: applying destructors

\[
\begin{align*}
\Gamma(x) &= \text{LL} & \Gamma(k) &= \text{key}^{\text{HH}}(T) \\
\Gamma, y : T &\vdash P \sim Q : C & \Gamma &\vdash P' \sim Q' : C' \\
\Gamma &\vdash \text{let } y = \text{dec}(x, k) \text{ in } P \text{ else } P' \sim \text{let } y = \text{dec}(x, k) \text{ in } Q \text{ else } Q' : C \cup C'
\end{align*}
\]
Why do we need constraints?

−→

Example: If $k$ is a secret key

$\text{out}(\text{enc}(a, k)) \sim \text{out}(\text{enc}(b, k))$

is fine

but not both together

$\text{out}(\text{enc}(a, k)) | \text{out}(\text{enc}(a, k)) \not\sim \text{out}(\text{enc}(b, k)) | \text{out}(\text{enc}(a, k))$

$C = \{\text{enc}(a, k) \sim \text{enc}(b, k), \text{enc}(a, k) \sim \text{enc}(a, k)\}$
Why do we need constraints?

→ Local checks on the messages are not sufficient for equivalence
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Local checks on the messages are not sufficient for equivalence.

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\text{out} (\text{enc}(a, k)) & \sim \text{out} (\text{enc}(b, k)) \quad \text{is fine} \\
\text{out} (\text{enc}(a, k)) & \sim \text{out} (\text{enc}(a, k)) \quad \text{is fine}
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Why do we need constraints?

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\]

\[
\mathcal{C} = \{\text{enc}(a, k) \sim \text{enc}(b, k), \text{enc}(a, k) \sim \text{enc}(a, k)\}
\]
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:

\[
\langle M, N \rangle \quad \longrightarrow \quad M, N \\
\text{enc}(M, k) \quad \longrightarrow \quad M \quad \text{if } k \text{ has type } \text{key}^\text{LL}(\cdot)
\]

\[
\ldots
\]

- 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** \( \theta, \theta' \)

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

\[ \Gamma \vdash M \sim N : T \rightarrow c \quad \Gamma(k) = \text{key}^{HH}(T) \]

\[ \Gamma \vdash \text{enc}(M, k) \sim \text{enc}(N, k) : LL \rightarrow c \cup \{\text{enc}(M, k) \sim \text{enc}(N, k)\} \]

→ How to handle more complex cases where different keys are used?

Example: anonymity, unlinkability
Example: Private Authentication

→ Authenticating B to A anonymously to others

\[ A \rightarrow B : \text{aenc}(\langle N_a, \text{pk}(k_a) \rangle, \text{pk}(k_b)) \]

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

\text{pk}(k) = \text{decoy key}. \text{No one has the secret key } k.
Example: Private Authentication

→ Authenticating $B$ to $A$ anonymously to others

$A \rightarrow B : \ aenc(\langle N_a, pk(k_a) \rangle, pk(k_b))$

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

$pk(k) =$ decoy key. No one has the secret key $k$.

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

$Alice \mid Bob(pk_{Alice}) \approx Alice \mid Bob(pk_{Charlie})$
Example: Private Authentication

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

$\text{Alice} | \text{Bob}(pk_{\text{Alice}}) \approx \text{Alice} | \text{Bob}(pk_{\text{Charlie}})$

Problems: different keys and non uniform branching
We introduce **bikeys**: pairs of keys with a type

**Example:**

\[ \Gamma(k_1, k_2) = \text{key}^{HH}(LL \ast HH) \]

There may be multiple bindings for the same key:

\[ \Gamma(k_1, k_2) = \text{key}^{HH}(LL \ast HH) \]
\[ \Gamma(k_1, k_3) = \text{key}^{HH}(HH \ast LL) \]

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

\[ \Gamma(k, k) = \text{eqkey}^{HH}(HH) \]
The rules for encrypting go as expected: allow any pair of keys that is valid in $\Gamma$.

\[
\Gamma \vdash M \sim N : T \rightarrow c \\
\Gamma(k_1, k_2) = \text{key}^{HH}(T) \\
\Gamma \vdash \text{enc}(M, k_1) \sim \text{enc}(N, k_2) : \text{LL} \rightarrow c \cup \{\text{enc}(M, k_1) \sim \text{enc}(N, k_2)\}
\]

Similarly for asymmetric encryption and signature.
Previously:

\[
\Gamma(x) = \text{LL} \quad \Gamma(k) = \text{key}^{\text{HH}}(T)
\]

\[
\Gamma, x : T \vdash P \sim Q : C \quad \Gamma \vdash P' \sim Q' : C'
\]

\[
\Gamma \vdash \text{let } y = \text{dec}(x, k) \text{ in } P \text{ else } P' \sim \text{let } y = \text{dec}(x, k) \text{ in } Q \text{ else } Q' : C \cup C'
\]
Bikeys: decrypting

With different keys?

\[ \Gamma(x) = LL \quad \Gamma(k_1, k_2) = \text{key}^{HH}(T) \]
\[ \Gamma, x : T \vdash P \sim Q : C \quad \Gamma \vdash P' \sim Q' : C' \]
\[ \Gamma \vdash \text{let } y = \text{dec}(x, k_1) \text{ in } P \text{ else } P' \sim \text{let } y = \text{dec}(x, k_2) \text{ in } Q \text{ else } Q' : C \cup C' \]
Bikeys: decrypting

With different keys?

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**Problem:** There may be several bindings for \( k_1 \) in \( \Gamma \)
\( x \) may be encrypted with \( k_1 \) on the left, \( k_3 \neq k_2 \) on the right

\[ \rightarrow \text{ We do not know that decryption succeeds or fails equally} \]

\[ = \text{ the processes may branch non uniformly i.e. follow different branches} \]
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

→ We have to take all cases into account:

\[
\Gamma(y) = LL \\
\Gamma(k_1, k_2) = \text{key}^{HH}(T) \\
\Gamma, x : T ⊢ P \sim Q \rightarrow C \\
\Gamma ⊢ P' \sim Q' \rightarrow C' \\
(∀ T'.∀ k_3 \neq k_2. \Gamma(k_1, k_3) = \text{key}^{HH}(T') \Rightarrow \Gamma, x : T' ⊢ P \sim Q' \rightarrow C_{k_3}) \\
(∀ T'.∀ k_3 \neq k_1. \Gamma(k_3, k_2) = \text{key}^{HH}(T') \Rightarrow \Gamma, x : T' ⊢ P' \sim Q \rightarrow C'_{k_3})
\]

\[
\Gamma ⊢ \text{let } x = \text{dec}(y, k_1) \text{ in } P \text{ else } P' \sim \text{let } x = \text{dec}(y, k_2) \text{ in } Q \text{ else } Q' \\
\rightarrow C \cup C' \cup (\bigcup_{k_3} C_{k_3}) \cup (\bigcup_{k_3} C'_{k_3})
\]

Note: the simple rule still applies when keys have type eqkey$^l(T)$
Back to Private Authentication

\[ A \rightarrow B : \text{aenc}(\langle N_a, \text{pk}(k_a) \rangle, \text{pk}(k_b)) \]

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

\[ Alice \mid Bob(pk_a) \approx Alice \mid Bob(pk_c) \]

We can typecheck Bob’s response by having bindings in $\Gamma$ for all cases

- $\langle k_a, k \rangle$ authentication succeeds on the left, fails on the right
- $\langle k, k_c \rangle$ authentication succeeds on the right, fails on the left
- $\langle k_a, k_c \rangle$ authentication succeeds on both sides
- $\langle k, k \rangle$ 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.

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)

→ A new type for session keys

\[ \text{seskey}^l(T) \]

Processes can

- **generate** session keys (must specify a type annotation)

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

- **receive** and store session keys in variables of type \( \text{seskey}^l(T) \)

- **use these variables as keys** to encrypt, decrypt, \ldots
Tricky point: consistency of the constraints
The case of dynamic keys (3)

→ Tricky point: consistency of the constraints

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

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

yields the constraint

$$\text{enc}(a, x) \sim \text{enc}(a, x)$$
The case of dynamic keys (3)

→ Tricky point: **consistency of the constraints**

**Example:** If $x : LL$ (key provided by the attacker), typechecking

\[
\text{out(}\text{enc}(a, x)) \sim \text{out(}\text{enc}(a, x))
\]

yields the constraint

\[
\text{enc}(a, x) \sim \text{enc}(a, x)
\]

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 $\theta$, $\theta'$ is not statically equivalent
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$\rightarrow$ We need to further restrict the $\theta$ we consider
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$\rightarrow$ We need to further restrict the $\theta$ we consider

$\rightarrow$ Invariant: variables of type LL only contain messages the attacker can construct from the remainder of the constraint
The case of dynamic keys (4)

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$\rightarrow$ We need to further restrict the $\theta$ we consider

$\rightarrow$ Invariant: variables of type LL only contain messages
  the attacker can construct from the remainder of the constraint

$\rightarrow$ Prevents the previous $\theta$, $\theta'$ and solves the problem
Experimental results

- Prototype implementation for our type system
- We implement a type checker, 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)
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    | SO   | 8m       |      | 1.3s   | 0.003s |
| 10         |       |      | 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                        |          | 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