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Implementing Security Protocol Monitors

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Cryptographic protocols are often specified by narrations, i.e., finite sequences of message exchanges that show the intended execution of the protocol. Another use of narrations is to describe attacks. We propose in this paper to compile, when possible, attack describing narrations into a set of tests that honest participants can perform to exclude these executions. These tests can be implemented in monitors to protect existing implementations from rogue behaviour.

1 Introduction

Cryptographic protocols are designed to prescribe message exchanges between agents in a hostile environment in order to guarantee some security properties. In particular security properties such as confidentiality or authentication are violated when there exists an execution of the protocol in which they do not hold. However it has often been found that under certain circumstances, and after its deployment, a protocol failed to adequately protect its participants. These circumstances usually involve one or more sessions, and the participation of a dishonest agent hereafter called the intruder. When the attack is on a specific implementation of a protocol, its mitigation usually amounts to fixing this implementation.

However, some attacks are related to the exchanges of messages prescribed by the protocol, and not in the actual handling of these messages by participants. In that case, the only recourse is—when available—to alter the sequence of acceptable messages. This can be implemented by changing the format of the messages exchanged or by stopping an execution once it has been detected that the attack may be under way. We consider in this paper only the second approach, in which the participants behaviour is altered in order to reject some possible executions of the protocol.

Let us consider for example the Needham-Schroder Public Key (NSPK) mutual authentication protocol [11] described by the following sequence of messages between roles A and B:

\[
\begin{align*}
A \text{ knows} & \quad A, B, K_A, K_B, K_A^{-1} \\
B \text{ knows} & \quad A, B, K_A, K_B, K_B^{-1} \\
A \rightarrow B : & \quad \text{enc}(A, N_A, K_B) \\
B \rightarrow A : & \quad \text{enc}(N_A, N_B, K_A) \\
A \rightarrow B : & \quad \text{enc}(N_B, K_B)
\end{align*}
\]

The attack on this protocol discovered by Lowe [10] is described as follows, where \( I(A) \) denotes the
intruder impersonating the agent $A$:

$$
A \rightarrow I : \text{enc}(A, N_A, K_I) \\
I(A) \rightarrow B : \text{enc}(A, N_A, K_B) \\
B \rightarrow I(A) : \text{enc}(N_A, N_B, K_A) \\
I \rightarrow A : \text{enc}(N_A, N_B, K_A) \\
A \rightarrow I : \text{enc}(N_B, K_I) \\
I(A) \rightarrow B : \text{enc}(N_B, K_B)
$$

This execution is an attack because $B$ believes he has participated in a session with $A$ whereas $A$ never exchanged a message with $B$. As is the case in this attack narration, we assume from now on and without loss of generality [8] that in an attack, every message is sent to or received from the intruder. A fix, proposed in [10], consisting in altering the second message to include the name of the sender. The only drawback to such fixes is that implementations of the amended protocol are not interoperable with implementations of the original protocol. For widely deployed real-life protocols, interoperability must be maintained and thus the amended version coexists with the original one for years, leaving open an attack vector for attackers.

Our proposal aims at keeping the original version, but extended with additional tests. This extension involves the creation of a monitor for the actions of honest participants that furthermore may have access to some secret pieces of information held by these participants. In the case of Lowe’s attack, this access is unnecessary, as it suffices for $B$ to check that the message he receives at the third step is equal to the message sent by $A$.

We present in this paper an algorithm to implement a security protocol monitor. Given the input messages that participants are willing to share with the monitor, it basically amounts to computing the conditions to be checked in order to exclude a given narration from the possible executions of the protocol.

**Related works** This article is based on the refinement relation between traces introduced in [4]. An extension to the case where an attack can be excluded based on the information in only one session of a participant has been proposed in [9].

By contrast our approach stems from the line of work initiated in [3, 2] where the authors advocate for the prevention of attacks through detection and eventually retaliation against the attacker. Also, [7] presents in more details an architecture in which the analysis we present in this paper can be conducted with a better control on the messages, and also introduce the idea of applicative firewalls for security protocols.

**Outline** We recall in Sec. 2 how to represent protocols and roles and how to implement them as active frames. In Sec. 3 we formally introduce protocol monitors to control messages and manage knowledge shared by collaborating agents, in order to detect and block attacks. In Sec. 4 we show how to synthesize monitors from tests that can be derived automatically. We conclude in Sec. 6.

## 2 Role-based Protocol Specifications

### 2.1 Messages and basic operations

We consider an infinite set of free constants $\mathcal{C}$ and an infinite set of variables $\mathcal{X}$. For each signature $\mathcal{F}$ (i.e. a set of function symbols with arities), we denote by $T(\mathcal{F})$ (resp. $T(\mathcal{F}, \mathcal{X})$) the set of terms
over $F \cup C$ (resp. $F \cup C \cup \mathcal{X}$). The former is called the set of ground terms over $F$, while the latter is simply called the set of terms over $F$. Variables are denoted by $x$ and decorations thereof, but for a distinguished subset $(v_i)_{i \in \mathbb{N}}$ employed to denote positions in a sequence. Terms are denoted by $s$, $t$, and finite sets of terms are written $E, F, \ldots$, and decorations thereof, respectively. In a signature $F$ a constant is either a free constant or a function symbol of arity 0 in $F$. Given a term $t$ we denote by $\text{Var}(t)$ the set of variables occurring in $t$ and $\text{Cons}(t)$ the set of free constants occurring in $t$. A (ground) substitution $\sigma$ is an idempotent mapping from $\mathcal{X}$ to $\text{T}(F, \mathcal{X})$ and its support $\text{Supp}^1(\sigma) = \{x \mid \sigma(x) \neq x\}$ is a finite set. The application of a substitution $\sigma$ on a term $t$ (resp. a set of terms $E$) is denoted $t\sigma$ (resp. $E\sigma$) and is equal to the term $t$ (resp. the set of terms $E$) where all variables $x \in \text{Supp}^1(\sigma)$ have been replaced by the term $x\sigma$.

Terms are manipulated by applying operations on them. These operations are defined by a subset of the signature $F$ called the set of public constructors. A context $C[v_1, \ldots, v_n]$ is a term in which $\text{Var}(C[v_1, \ldots, v_n]) \subseteq \{v_1, \ldots, v_n\}$, $\text{Const}(C[v_1, \ldots, v_n]) = \emptyset$, and all non-variable symbols are public constructors, including possibly non-free constant. We will specify the effects of operations on the messages and the properties of messages by equations. When the index $n$ is clear, we omit the possible variables list and denote contexts $C$. An equational presentation $E = (F, E)$ is defined by a set $E$ of equations $u = v$ with $u, v \in \text{T}(F, \mathcal{X})$. The equational theory generated by $(F, E)$ on $\text{T}(F, \mathcal{X})$ is the smallest congruence containing all instances of axioms in $E$ (free constants can also be used for building instances) $[\mathcal{E}]$. We write $s =_E t$ as the congruence relation between two terms $s$ and $t$. By abuse of terminology we also call $E$ the equational theory generated by the presentation $E$ when there is no ambiguity.

A deduction system is defined by a triple $(E, F, \mathcal{F})$ where $E$ is an equational presentation on a signature $F$ and $\mathcal{F}$ a subset of public constructors in $F$.

**Example 1. Public key cryptography.** For instance the following deduction system models public key cryptography:

\[
\{\text{dec}(\text{enc}(x, y), y^{-1}) = x\}, \\
\{\text{dec}(\_, \_), \text{enc}(\_, \_), \_, -1\}, \\
\{\text{dec}(\_, \_), \text{enc}(\_, \_)\}
\]

The equational theory is reduced here to a single equation that expresses that one can decrypt a ciphertext when the inverse key is available. The inverse function $\text{dec}(\_, \_)$ is not public, as it cannot be computed in reasonable time by participants.

**Example 2. Nonce generation.** Nonces are random values that are critical to the analysis of cryptography and cryptographic protocols. To give an agent the capacity to generate new values, we assume the existence of an infinite set of constants $C_N^\mathcal{X}$ away from $C$ such that each value in this set can be generated:

\[\mathcal{N} = (\emptyset, C_N^\mathcal{X}, C_N^\mathcal{X})\]

Note this model makes sense only in the case where the attacker is only one agent, or a set of information sharing agents $[13]$, as an agent cannot otherwise construct nonces generated by another, independent, agent.

**Test systems.** In order to express verifications performed by an agent on received messages we introduce test systems:

**Definition 1.** (Test systems) Let $D$ be a deduction system with an equational theory $E$. A $D$-test system $S[v_1, \ldots, v_n]$ is a finite set of equations denoted by $(C_i = C'_i)_{i \in \{1, \ldots, n\}}$ with $D$-contexts $C[v_1, \ldots, v_n], C[v_1, \ldots, v_n]$. It is satisfied by a substitution $\sigma$, and we denote by $\sigma \models S[v_1, \ldots, v_n]$, if for all $i \in \{1, \ldots, n\}$ the equality $C[v_1, \ldots, v_n] \sigma =_E C'_i[v_1, \ldots, v_n] \sigma$ holds.

As usual we simply denote a test system $S$ if the maximal indice $n$ is clear from the context.
2.2 Traces and active frames

We model messages with terms. The sequence of messages received and sent by a principal is a trace, and is thus a finite sequence of labeled messages:

Definition 2. (Trace) A trace is a finite sequence of messages each with label (or polarity) ! or ?.

Messages with label ! (resp. ?) are said to be “sent” (resp. “received”). Given a trace $\Lambda = /t_1, \ldots, /t_n$ we write $?\Lambda$ (resp. $!\Lambda$) as a short-hand for $?m_1, \ldots, ?m_n$ (resp. $!m_1, \ldots, !m_n$). Given a trace $\Lambda = /m_1, \ldots, /m_n$ we denote by $\sigma_\Lambda = \{v_1 \mapsto m_1, v_n \mapsto m_n\}$ the substitution mapping each variable $v_i$ to the $i$th message occurring in $\Lambda$. To simplify notation we also denote by $C[v_1, \ldots, v_n] : \Lambda$, or more simply $C \cdot \Lambda$, the application of the substitution $\sigma_\Lambda$ on the context $C[v_1, \ldots, v_n]$. Accordingly, we say that a trace $\Lambda$ satisfies an equality $C_1 = C_2$, and denote it by $\Lambda \models C_1 \equiv C_2$, whenever $C_1 \cdot \Lambda =_\sigma C_2 \cdot \Lambda$.

Operations on traces Let $\Lambda$ be a trace. We say that a $\Lambda$ is positive (resp. negative) if all its labels are $!$ (resp. ?). We denote $\Lambda^2$ (resp. $\Lambda^1$) the subsequence of $\Lambda$ of terms labeled with ? (resp. !). We denote $-\Lambda$ the trace in which all the labels in $\Lambda$ are inverted. Finally, we denote input($\Lambda$) (resp. output($\Lambda$)) the trace $-\Lambda^1$ (resp. $-\Lambda^2$).

Active frames An active frame represents the actions of a principal participating in a protocol. It is a sequence of steps, and at step $i$ the principal either sends a message, constructed from the messages received at steps $j < i$, or receives and message, and accepts it if it satisfies some tests constructed from it and messages received at steps $j < i$. To simplify exposition, at a step $i$, we call these messages received at steps $j < i$ the messages already known at step $i$, or just already known if the step is clear from context. As in the case of traces, messages sent are labeled $!v_i$ (and $v_i$ is an output variable) and those received are labeled $?v_i$ (and $v_i$ is an input variable). Since the available contexts depend upon the deduction system, the notion of active frame is also parameterised by a deduction system.

Definition 3. Given a deduction system $\mathcal{D}$, a $\mathcal{D}$-active frame is a sequence $(T_i)_{1 \leq i \leq k}$ where

$$T_i = \begin{cases} 
!v_i \text{ with } v_i \models C_i[v_1, \ldots, v_{i-1}] & \text{(send)} \\
?v_i \text{ with } S_i[v_1, \ldots, v_i] & \text{(receive)} 
\end{cases}$$

Without loss of generality and reusing the above notations, a simple recursion shows that we can assume that all variables in $C_i[v_1, \ldots, v_{i-1}]$ are labeled with ? at a step $j < i$, and that all variables in $S_i[v_1, \ldots, v_i]$ are labeled with ? at a step $j < i$. Without loss of generality, from now on we assume that this is the case for all the active frames we consider.

Example 3. The principal $A$ in the description of the NSPK protocol can be modeled by an active frame as follows, with the caveat that we have renamed the $v_i$ variables for more clarity:

$$(?x_{N_A} \text{ with } \emptyset, ?x_A \text{ with } \emptyset, ?x_B \text{ with } \emptyset, ?x_{K_A} \text{ with } \emptyset, ?x_{K_B} \text{ with } \emptyset, ?x_{K_A^{-1}} \text{ with } \emptyset,$$  
$!x_{msg1} \text{ with } x_{msg1} \models \text{enc}(x_A, x_{N_A}, x_{K_B}),$  
$?x_r \text{ with } \emptyset$  
$!x_{msg2} \text{ with } x_{msg2} \models \text{enc}(\pi_2(\text{dec}(x_r, x_{K_A^{-1}})), x_{K_B}))$  

Algebraically, by describing a principal’s actions, active frames are partial operations on the set of traces and map a sequence of messages sent by someone else and accepted to the sequence of received and sent messages by a principal. We formalize these notions as follows:
Definition 4. Let $\mathcal{D}$ be a deduction system with equational theory $\mathcal{E}$. Let $\phi = (T_i)_{1 \leq i \leq n}$ be an active frame, where the $T_i$’s are as in Definition[3] and where the input variables are $\{v_{a_1}, \ldots, v_{a_m}\}$. Let $\Lambda$ be a positive trace of length $k$, $\theta$ be the renaming of variables $\{v_{a_1} \mapsto v_j\}_{1 \leq j \leq k}$, and $S$ be the union of the test systems in $\phi$. The evaluation of $\phi$ on $\Lambda$ is denoted $\phi \cdot \Lambda$. It is defined, and we say that $\phi$ accepts $s$, if $S \cdot s$ is satisfiable. In that case, it is the trace $(m_1, \ldots, m_n)$ where:

$$m_i = \begin{cases} !C_i \cdot \theta \sigma \Lambda & \text{if } v_i \text{ has label } ! \text{ in } T_i \\ ?v_i \cdot \theta \sigma \Lambda & \text{if } v_i \text{ has label } ? \text{ in } T_i \end{cases}$$

Example 4. Let $\Lambda_A$ be the trace of the principal $A$ in the the specification of the NSPK protocol in the introduction, $r = \text{tr}(A)$, and $\phi_A$ be the active frame of Ex. [3]. Let $M$ be the message $\text{msg}(B, \text{enc}(\langle N_A, N_B \rangle, K_A))$. We have:

$$\text{input}(\Lambda_A) = (!N_A, !A, !B, !K_A, !K_B, !K_A^{-1}, !M)$$

and $\phi_A \cdot \text{input}(\Lambda_A)$ is the trace:

$$(!N_A, !A, !B, !K_A, !K_B, !K_A^{-1},
!\text{msg}(B, \text{enc}(\langle A, N_A \rangle, K_B)),
?M, !\text{msg}(B, \text{enc}(\frac{\pi}{2}(\text{dec}(\text{payload}(M), K_A^{-1})), K_B)))$$

Modulo the equational theory, this trace is equal to:

$$(!N_A, !A, !B, !K_A, !K_B, !K_A^{-1},
!\text{msg}(B, \text{enc}(\langle A, N_A \rangle, K_B)), ?M, !\text{msg}(B, \text{enc}(N_B, K_B)))$$

It is not coincidental that in Ex. [4] the traces $\phi_A \cdot \text{input}(\Lambda_A)$ and $\Lambda_A$ are equal as it means that within the active frame, the sent messages are composed from received ones in such a way that when someone sends the messages expected in $\Lambda_A$, the execution of $A$ is described by $\Lambda_A$. This relation gives us a criterion to define what an implementation of a trace is.

Definition 5. An active frame $\phi$ is an implementation of a trace $\Lambda$ if $\phi$ accepts input$(\Lambda)$ and $\phi \cdot \text{input}(\Lambda) =_e \Lambda$.

If a trace admits an implementation we say this trace is executable. Conversely we say that a trace $t$ is an execution of an active frame $\phi$ whenever $\phi$ is an implementation of $t$.

2.3 Computation of an implementation

We present in this section a method, parameterised by the deduction system $\mathcal{D}$, to compute an active frame implementing an executable trace. To build such an implementation we need to compute, given a message $t$ sent at step $i$, a $\mathcal{D}$-context $C_i$ that evaluates to $t$ when applied to the previously received messages. This reachability problem is unsolvable in general. Hence we have to consider systems that admit a reachability algorithm, formally defined below:

Definition 6. Given a deduction system $\mathcal{D}$ with equational theory $\mathcal{E}$, a $\mathcal{D}$-reachability algorithm $\mathcal{A}_\mathcal{D}$ computes, given a positive trace $\Lambda$ of length $n$ and a term $t$, a $\mathcal{D}$-context $\mathcal{A}_\mathcal{D}(s, t) = C[v_1, \ldots, v_n]$ such that $C \cdot \Lambda =_e t$ iff there exists such a context and $\perp$ otherwise.

For the many theories that admit a reachability algorithm, it can be employed as an oracle to compute the contexts in sent messages and therefore to derive an implementation of a trace $s$. We thus have the following theorem (see a proof in [4]).

Theorem 1. If a $\mathcal{D}$-reachability algorithm exists then it can be decided whether a trace $s$ is executable and if so one can compute an implementation of $s$. 
2.4 Computation of a prudent implementation

An implementation does not necessarily checks the conformity of the messages with the intended patterns, e.g., the active frame in Ex. 3 neither checks that $x_1$ is really an encryption with the public key $x_{K_1}$ of a pair, nor that the first argument of the encrypted pair has the same value as the nonce $x_{N_1}$.

Any of the algorithms proposed so far in the literature for the compilation of cryptographic protocols would require at least these tests. We now present an algorithm that computes these kinds of checks for an arbitrary deduction system. It formalizes a check as an equation between $\mathcal{D}$-contexts over messages received so far, including the initial knowledge. For example, and using the notations of Ex. 3 it computes that upon reception of the message the initiator must, among other tests, check the validity of the equation:

$$\pi_1(\text{dec}(x_r, x_{K_1})) \equiv x_{N_1}$$

We formalize in the definition below which traces $\Lambda'$ are acceptable by an agent expecting a trace $\Lambda$. We define the acceptable traces as the refinements of $\Lambda$, that is traces $\Lambda'$ such that every test system accepting $\Lambda$ also accepts $\Lambda'$.

**Definition 7.** Let $\Lambda, \Lambda'$ be two positive traces of identical length. We say that $\Lambda'$ refines $\Lambda$ if, for any pair of $\mathcal{D}$-contexts $(C_1, C_2)$ one has $C_1 \cdot \Lambda = C_2 \cdot \Lambda$ implies $C_1 \cdot \Lambda' = C_2 \cdot \Lambda'$.

Consider for example the following traces $\Lambda$ and $\Lambda'$:

\[
\begin{align*}
\Lambda' &= (!\text{enc}(a, k), !\text{enc}(a, k'), !k, !k', !a) \\
\Lambda &= (!\text{enc}(a, k), !\text{enc}(a, k'), !k, !k', !a)
\end{align*}
\]

since all equalities that can be checked on $\sigma$ can be checked on $\sigma'$. Two traces $s, s'$ that refine one another are equivalent. This definition is an adaptation to our setting of the classic notion of static equivalence [1].

When the behaviour of a principal is defined by a trace $\Lambda$, we expect that any implementation of that principal accepts the trace $\text{input}(\Lambda)$. Thus, and as long as only equality tests are considered, we expect any implementation of the trace $\Lambda$ to accept any refinement of input(\Lambda). We define a prudent implementation of $\Lambda$ as an implementation that only accepts inputs that refine the inputs in $\Lambda$.

**Definition 8.** An active frame $\varphi$ is a prudent implementation of a trace $\Lambda$ if $\varphi$ is an implementation of $\Lambda$ and any trace $\Lambda'$ accepted by $\varphi$ is a refinement of $\text{input}(\Lambda)$.

As already noted in [1], most deduction systems considered in the context of cryptographic protocols analysis have the property that it is possible to compute, given a positive trace, a finite set of context pairs that summarizes all possible equalities. Given a positive trace $\Lambda$ we denote $P_\Lambda$ the (infinite) set of context pairs $(C_1, C_2)$ such that $C_1 \cdot s = C_2 \cdot s$.

**Definition 9.** A deduction system $\mathcal{D}$ has the finite basis property if for each positive trace $\Lambda$ one can compute a finite set $P_\Lambda^f$ of pairs of $\mathcal{D}$-contexts such that, for each positive trace $\Lambda'$:

$$P_\Lambda \subseteq P_\Lambda^f \iff P_\Lambda^f \subseteq P_{\Lambda'}$$

Let us now consider a deduction system $\mathcal{D}$ that has the finite basis property. There thus exists an algorithm $\mathcal{A}_\mathcal{D}$ that takes a positive trace $\Lambda$ as input, computes a finite set $P_\Lambda^f$ of context pairs $(C, C')$ and returns as a result the test system $S_\Lambda : \{C \equiv C' \mid (C, C') \in P_\Lambda^f\}$. For any positive trace $\Lambda'$ of length $n$, by definition of $S_\Lambda$ we have that $S_\Lambda \cdot \Lambda'$ is satisfiable if and only if $s'$ is a refinement of $s$. We are now ready to present our algorithm for the compilation of strands into active frames.
**Algorithm** Given a trace $\Lambda$ and assuming that the deduction system $\mathcal{D}$ has a reachability algorithm and the finite basis property, and let $\Lambda$ be a trace of length $n$, and let us denote $\Lambda^i$ for $1 \leq i \leq n$ the prefix of length $i$ of $\Lambda$, and $\Lambda(i)$ the $i$th element of $\Lambda$. We construct a prudent implementation $\varphi_\Lambda = (T_i)_{i=1,...,n}$ of $\Lambda$ as follows:

$$T_i = \begin{cases} !v_i = \mathcal{A}_\mathcal{D}(\Lambda^{i-1}, t_i) & \text{If } \Lambda(i) = !t_i \\ ?v_i = \mathcal{A}_\mathcal{D}'(\Lambda^i) & \text{If } \Lambda(i) = ?t_i \end{cases}$$

By construction we have the following theorem:\footnote{4}

**Theorem 2.** Let $\mathcal{D}$ be a deduction system that has a $\mathcal{D}$-ground reachability algorithm and has the finite basis property. Then for any executable trace $\Lambda$ one can compute a prudent implementation $\varphi_\Lambda$ of $\Lambda$.

### 2.5 Protocol implementation and execution

It is customary to describe a protocol by giving its intended execution, either using a message sequence chart or an Alice\&Bob notation. We note that the same notation is also employed to described e.g. attacks on that protocol. Beyond their syntax, the characteristic of such description is to associate to a generic principal (a rôles, in the case of a protocol specification, a participant in the case of an attack description) a trace describing its actions, and how these actions interact with the other principal actions. This association of a participant with a trace is formalised by a function mapping strands \footnote{14}, i.e. principals, rôles, etc., to traces. We define a protocol to be just one such mapping.

**Definition 10.** (Protocol) A protocol is a couple $P = (\Xi_P, \text{tr}_P)$ where $\Xi_P$ is a finite set of strands and $\text{tr}_P$ maps $\Xi_P$ to the set of traces.

When a protocol is intended to be a protocol specification, we refer to strands as the rôles of that protocol (e.g. the rôles $A$ and $B$ in the NSPK protocol). A strand $\xi$ is positive in a protocol $P$ if $\text{tr}_P(\xi)$ is a positive trace.

In the preceding definition the function $\text{tr}_P$ prescribes for each role $\xi \in \Xi_P$ the sequence of actions to be performed by an agent playing this role in any protocol instance. In the following, when there is no ambiguity in the considered protocol, we identify a strand $\xi$ with its trace $\text{tr}(\xi)$.

We have worked so far on the implementation of the trace of a role in a protocol, but the definitions lift to the level of an implementation of a protocol as follows.

**Definition 11.** (Protocol implementation) An implementation of a protocol $P = (\Xi_P, \text{tr}_P)$ is a couple $(\Xi_P, \Phi_P)$ where $\Phi$ maps each role $\xi \in \Xi_P$ to an active frame such that $\Phi(\xi)$ is an implementation of $\text{tr}_P(\xi)$. It is prudent if moreover for each $\xi \in \Xi_P$, $\Phi(\xi)$ is a prudent implementation of $\text{tr}_P(\xi)$.

From now on we consider only prudent implementations of protocols, i.e. implementations whose execution is a refinement of the protocol specification.

**Definition 12.** (Protocol execution) Let $P = (\Xi_P, \Phi_P)$ be a protocol implementation. A triple $E = (\Xi_E, \text{tr}_E, R_E)$ where:

1. $\Xi_E$ is a set of strands away from $\Xi_P$;
2. $(\Xi_E, \text{tr}_E)$ is a protocol;
3. $R_E : \Xi_E \rightarrow \Xi_P \cup \{I\}$.

is a protocol execution of $P$ if, for each $\xi \in \Xi_E$, if $R_E(\xi) \neq I$ then $\text{tr}_E(\xi)$ is an execution of $\Phi_P(R_E(\xi))$.

The strand $I$ denotes an Intruder who does not necessarily follows the directions prescribed by the protocol. A protocol execution is honest if $R_E(\Xi_E) \subseteq \Xi_P$. Strands in $\Xi_E$ are called the participants of the protocol execution $E$. The function $R_E$ maps each (honest) participant to its rôle in the protocol.
3 Protocol monitor

To mitigate an attack on a protocol, a monitor has to coordinate the participants to detect and stop an instance of a known flaw. This coordination is built according to data the participants are willing to share to prevent the attack. Our monitor construction relies on the description of the data the participants are willing to share, a description of the attack, and a description of the expected behaviour of the participants, and we compute tests (when possible) to distinguish an instance of the attack from the normal execution.

In Def.13 for each participant A, tr_M(A) contains the same inputs as tr_P(A), and the messages sent in tr_M(A) are the pieces of data shared by A with the monitor.

Definition 13. (Protocol Monitor) Let P = (Ξ_P, tr_P) and M = (Ξ_M, tr_M) be two protocols. We say that M is a monitor for P if 1. Ξ_M = Ξ_P; 2. M is executable; and 3. For each ξ ∈ Ξ_M we have input(tr_M(ξ)) = input(tr_P(ξ)).

Proposition 2. Let P = (Ξ_P, tr_P) be a protocol, M = (Ξ_P, tr_M) be a monitor of P, I_X = (Ξ_P, Φ_X) be any implementation of X ∈ {P, M}, and E = (Ξ_E, Φ_E, R_E) be an honest execution of I_P.

If I_P is prudent and Φ_M(R_E(ξ)) accepts input(tr_E(ξ)), then Φ_M(R_E(ξ)) · input(tr_E(ξ)) is a refinement of tr_M(R_E(ξ)).

Proof. Assume there exists ξ_R ∈ Ξ_M and ξ_e ∈ Ξ_E with R_E(ξ_e) = ξ_R such that Φ_M(ξ_R) · input(tr_E(ξ_e)) is not a refinement of tr_M(ξ_R). That is, there exists pairs of contexts C_1, C_2 such that tr_M(ξ) |= C_1 = C_2 but Φ_M(ξ_R) · input(tr_E(ξ_e)) /∈ C_1 = C_2. Without loss of generality we can assume that C_1, C_2 are built upon the input variables of Φ_M(R_E(ξ)), that is, with θ : {v_j = v_j}_{1 ≤ j ≤ k}, where i_j is the jth input step of tr_M(ξ_R):

\[
\begin{align*}
\{ & \text{input(tr_M(ξ_R))} \models C_1 \theta = C_2 \theta \\
& \text{input(Φ_M(ξ_R) · input(tr_E(ξ_e)))} \not\models C_1 \theta = C_2 \theta
\end{align*}
\]

Since I_M is an implementation of M, by definition the second assertion is equal to input(tr_E(ξ_e)) /∈ C_1 \theta = C_2 \theta. By definition of a monitor, we have input(tr_M(ξ_R)) = input(tr_P(ξ_R)). Thus, we have:

\[
\begin{align*}
\{ & \text{input(tr_P(ξ_R))} \models C_1 \theta = C_2 \theta \\
& \text{input(tr_E(ξ_R))} \not\models C_1 \theta = C_2 \theta
\end{align*}
\]

Hence input(tr_E(ξ_R)) is not a refinement of input(tr_P(ξ_R)), and thus Φ_P(ξ_R) cannot be a prudent implementation of tr_P(ξ_R).

Definition 14. (Execution Log) Let P = (Ξ_P, tr_P) be a protocol, I_P = (Ξ_P, Φ_P) be an implementation of P, E = (Ξ_E, tr_E, R_E) be an execution of I_P, <_E be an arbitrary total order on the participants, and I_M = (Ξ_P, Φ_M) be an implementation of a monitor M of P. The execution log of E for monitor M is the concatenation of the traces:

\[
\text{output(Φ_M(R_E(ξ_e) · input(tr_E(ξ_e))))}
\]

for ξ_e ∈ Ξ_E such that R_E(ξ_e) \not= I in the increasing order with respect to <_E.

Proposition 2. Let P = (Ξ_P, tr_P) be a protocol, I_P = (Ξ_P, Φ_P) be an implementation of P, E = (Ξ_E, tr_E, R_E) be an execution of I_P, <_E be an arbitrary total order on the participants, and I_M = (Ξ_P, Φ_M) be an implementation of a monitor M of P. Then there exists a unique execution log of E for M.
Proof. For each $\xi_{e} \in \Sigma_{E}$ let $\varphi_{e} = \Phi_{M}(R_{E}(\xi_{e}))$ be the active frame executed by $\xi_{e}$, and let $in_{e} = \text{input}(tr_{E}(\xi_{e}))$ denote the messages received by $\xi_{e}$. Since sent messages are built by a context over preceding messages an easy recurrence shows that the value of each message in $\varphi_{e} \cdot in_{e}$ is uniquely defined by the values in $\text{input}(tr_{E}(\xi_{e}))$. Thus output($\varphi_{e} \cdot in_{e}$) is uniquely defined for each participant $\xi_{e} \in \Xi_{E}$. Since the order $<_{E}$ is total the concatenation of these traces is unique. \(\square\)

Since the ordering $<_{E}$ is arbitrary, we usually omit any reference to it. By Prop. 2 the execution log depends only on the monitor, not on its implementation. Accordingly we denote it $\log_{I_{p},M}(E)$. Assuming there exists a $\mathcal{R}$-reachability algorithm, it is possible to compute an implementation of $M$ whenever $M$ is executable. Thus given a monitor $M$ the function $\log_{I_{p},M}(E)$ can be effectively computed.

4 Generating an attack-preventing monitor

4.1 Attack presentation

In our setting attacks are simply specified as protocol executions without reference to any violated security property. The flexibility entailed by this choice however implies that, in order to prevent the given execution, one also has to provide what should have been the correct execution for the subset of participants involved in the attack. This setting leads to the definition of an attack presentation sharing the same set of participants playing the same roles, but having different traces.

Definition 15. (Attack definition) Let $I_{p} = (\Xi_{p}, \Phi_{p})$ be a protocol implementation. An attack definition on $I_{p}$ is a tuple $(\Xi_{E}, tr_{A}, tr_{N}, R_{E})$ such that $(\Xi_{E}, tr_{A}, R_{E})$ is an execution of $I_{p}$ and $(\Xi_{E} \setminus R_{E}^{-1}(I), tr_{N}, R_{E})$ is an honest execution of $I_{p}$.

Given an attack definition $(\Xi_{E}, tr_{A}, tr_{N}, R_{E})$, $(\Xi_{E}, tr_{A}, R_{E})$ refers to the attack execution while $(\Xi_{E}, tr_{N}, R_{E})$ refers to the normal execution of the protocol expected for the honest participants involved. Though this is not enforced by the definition and not needed in the rest of this paper, it is expected that the initial segments of the traces corresponding to the initial knowledge and the generation of nonces should be the same for each participant in the two executions.

Definition 16. (Attack presentation) Let $P = (\Xi_{p}, tr_{p})$ be a protocol, $I_{p} = (\Xi_{p}, \Phi_{p})$ be an implementation of $P$, $M = (\Xi_{p}, tr_{M})$ be a monitor of $P$, and $\mathcal{A} = (\Xi_{E}, tr_{A}, tr_{N}, R_{E})$ be an attack definition on $I_{p}$. Then the presentation of $\mathcal{A}$ to $M$ is the couple $(\log_{I_{p},M}(\Xi_{E} \setminus R_{E}^{-1}(I), tr_{A}, R_{E})), \log_{I_{p},M}(\Xi_{E} \setminus R_{E}^{-1}(I), tr_{N}, R_{E}))$

Detectable attacks. We note that the two traces in an attack presentation may be equivalent. In this case, no test performed by the monitor could enable it to distinguish between the normal and the attack execution, and the latter would not be preventable. We say that an attack $\mathcal{A}$ is detectable by the monitor $M$ if its presentation $(\Lambda, \Lambda')$ to $M$ is such that $\Lambda$ and $\Lambda'$ are not equivalent.

This definition leads to the problem of deciding whether an attack is detectable by a monitor.

Decision Problem 1. AttackDetectability $\mathcal{A}(s,s')$

Input: The presentation $(\Lambda, \Lambda')$ of an attack $\mathcal{A}$ on the protocol implementation $I_{p}$ with a monitor $M$;

Output: YES if $\mathcal{A}$ is detectable by $M$

This problem is related to the classic static equivalence problem by the following theorem, proved in the appendix.
Theorem 3. Let $\mathcal{D}$ be a deduction system, and $\mathcal{N}$ be the deduction system of Ex. 2. Then AttackDetectability $\mathcal{D} \cup \mathcal{N}$ on strands that do not contain symbols of $\mathcal{C}_\mathcal{N}$ is polynomial-time reducible to StaticEquivalence $\mathcal{D}$.

The latter StaticEquivalence $\mathcal{D}$ decision problem is well-studied and in most cases of deduction systems of interest was found to be decidable, which implies that the AttackDetectability $\mathcal{D} \cup \mathcal{N}$ problem is also decidable for most deduction systems of interest.

4.2 Monitor Synthesis

In our setting an attack definition relies on humans to specify also the intended execution, but this execution is not present when searching whether a concrete execution is an attack. Thus we need to synthesize tests that will detect whether an execution is an attack by relying solely on the contents of the actual execution.

Let $(A, A')$ be a detectable attack presentation. By definition there exists at least one equation $C_1 \rightarrow C_2$ either in $P_A'$ or in $P_{A'}$ that is not satisfied by the other trace. We add it to the tests of the monitor. If the equation is in $P_{A'}$, the monitor interrupts the protocol if it is not satisfied, whereas if it is in $P_A'$ the monitor interrupts the protocol if it is satisfied.

5 Attack detection in practice

We present in this section a simple example, the ISO/IEC 9797-1 protocol, especially its manual authentication mechanism 7a described in [12]. The normal run of the protocol is, after a human user sent $D$ and $R$ to the two devices $A$ and $B$:

- **$A$ knows** $A, B, D, R$
- **$B$ knows** $A, B, D, R$
- $A \rightarrow B : h(A, D, k_A, R)$
- $B \rightarrow A : h(B, D, k_B, R)$
- $A \rightarrow B : k_A$
- $B \rightarrow A : k_B$

A dishonest participant $i$ can sent back the first message directly to a honest participant $a$ willing to play the rôle $A$, and completely impersonate $B$ during the session:

- $a \rightarrow I : h(A, D, k_A, R)$
- $I \rightarrow a : h(A, D, k_A, R)$
- $a \rightarrow I : k_A$
- $I \rightarrow a : k_A$

We let $P = \{A, B\}, \text{tr}_P$ be the definition of the protocol, $E = \{\{a, i\}, \text{tr}_E, \{a \rightarrow A, i \rightarrow I\}\}$ be the execution of the protocol $P$ describing the attack, and $M = \{A, B\}, \text{tr}_M$ with:

\[
\begin{align*}
\text{tr}_M(A) &= (\text{?A, ?B, ?D, ?R, ?k}_A, \text{?h}(A, D, k_A, R), \text{!h}(A, D, k_B, R), \text{!h}(A, D, k_B, R), ?k_B) \\
\text{tr}_M(B) &= \text{input(tr}_P(B)\text{)}
\end{align*}
\]

The implementation of this monitor would be:

\[
\Phi_M(A) = (\text{?v}_1; ?v_2; ?v_3; ?v_4; !v_6 \text{ with } \{x_6 \equiv h(x_1, x_3, x_5, x_4)\}; ?v_7; !v_8 \text{ with } \{x_8 \equiv x_7\})
\]
Implementing Security Protocol Monitors

The two logs for the regular execution and the attack are respectively, with this implementation:

\[
\begin{align*}
\{ (!h(A, D, k_A, R); !h(B, D, k_B, R)) & \quad \text{(normal)} \\
(!h(A, D, k_A, R); !h(B, D, k_A, R)) & \quad \text{(attack)}
\end{align*}
\]

and the test \( x_1 = x_2 \) is satisfied by the log of attack trace but not by the log of the normal execution. Thus the monitor can reject the attack from the log when this equality is satisfied. A more robust monitor would send the last two messages \( k_A \) and \( k_B \) as in that case we know of no other attack even when keys are guessable or the hash function is weak [5].

6 Conclusion

In future work we plan to generate monitor implementations from several roles, and to study test simplification techniques for efficiency. We also need to extend the monitor construction in order to protect a protocol from all the refinements of an attack.

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A Relation with the notion of static equivalence

The notions of equivalence \( \text{wrt} \) the refinement relation and static equivalence are strongly related. The different setting is justified by the different handling of nonces: in \([1]\) contexts can contain any constant, so the secret constants in a trace have to be protected using \( \pi \)-calculus’ \( \nu \) operator, while we disallow non-public constants in contexts, which means that no constants can be used but the ones in the deduction system or those published (explicitly or implicitly) in the sequence of messages. We prove in Theo.\([3]\) that the two notions are identical modulo the generation of new constants with the deduction system \( \mathcal{N} \) of Ex.\([2]\).

The \( \text{AttackDetectability} \) problem defined in this paper is new, but it is strongly related to the static equivalence problem. In order to show this relation, let us introduce \textit{frames}, which are strands with a hidden set of constants.

\textbf{Definition 17.} (Frames, \([1]\)) A \textit{frame} is a couple \((\bar{n}, s)\) where \(\bar{n}\) is a set of constants and \(s\) is a positive trace, and is usually denoted \(v\bar{n}.s\).

Technically the definition in \([1]\) replaces \textit{positive trace} \(s\) by a substitution of domain \(x_1,\ldots,x_n\) that we have noted \(\sigma_s\). The application of a context \(C\) on a frame \(v\bar{n}.s\) is equal to the application of \(C\) on \(s\). We are now ready to define the static equivalence problem for a deduction system \(\mathcal{D}\).

\textbf{Decision Problem 2.} \textbf{StaticEquivalence} \(\varphi_1, \varphi_2\)

\textbf{Input:} Two frames \(\varphi_i = v\text{Const}(s_i)\) for \(i = 1,2\)

\textbf{Output:} \textbf{YES} if the frames have an equal length and for all pair \(C_1, C_2\) of public contexts and all function \(\theta : \text{Var}(C_1) \cup \text{Var}(C_2) \rightarrow \{x_1,\ldots,x_n\} \cup (\mathcal{C} \setminus (\bar{n}_1 \cup \bar{n}_2))\) we have \(C_1\theta\sigma_{s_1} = C_2\theta\sigma_{s_2}\) if, and only if, \(C_1\theta\sigma_{s_2} = C_2\theta\sigma_{s_2}\).

\(\text{Attack detectability}\) is related to \textit{static equivalence} with the following theorem:

\textbf{Theorem 3} Let \(\mathcal{D}\) be a deduction system, and \(\mathcal{N}\) be the deduction system of Ex.\([2]\). Then \(\text{AttackDetectability}_{\mathcal{D}, \mathcal{N}}\) on strands that do not contain symbols of \(\mathcal{C}, \mathcal{N}\) is polynomial-time reducible to \textit{StaticEquivalence} \(\varphi_1, \varphi_2\).

\textbf{Proof.} Given a trace \(s\) we let \(\varphi_v = v\text{Const}(s)\). This construction is clearly polynomial time. Let \(t_1, t_2\) be the two traces in the presentation of the attack \(\mathcal{A}\) on \(\mathcal{I}_p\) to \(\mathcal{M}\).

First, if \(t_1\) and \(t_2\) are of different length or have different label sequence, one can respond to the \(\text{AttackDetectability}\) in polynomial time. So let us assume the two strands have the same length and the same label sequence. Also, we assume that \(t_1, t_2\) do not contain the symbols of the \(\mathcal{N}\) deduction system.
Let us prove that $t_1$ and $t_2$ are discernable wrt the deduction system $\mathcal{D} \cup \mathcal{N}$ if, and only if, the frames $\phi_{s_1}, \phi_{s_2}$ are not statically equivalent wrt the deduction system $\mathcal{D}$.

First let us assume that the attack presentation $(t_1, t_2)$ is detectable, and wlog assume that $t_1$ does not refine $t_1$ for the deduction system $\mathcal{D} \cup \mathcal{N}$. Thus there exist two $\mathcal{D} \cup \mathcal{N}$-contexts $\mathcal{C}_1 t_1 = \mathcal{E} \mathcal{C}_2 t_1$ but $\mathcal{C}_1 t_2 \neq \mathcal{E} \mathcal{C}_2 t_2$. Since we assume that constants occurring in $s_1, s_2$ are away from $\mathcal{E} \mathcal{N}$, we construct $\mathcal{C}'_1, \mathcal{C}'_2$ and $\theta'$ as follows. For each constant $c \in \mathcal{E} \mathcal{N}$ occurring in $C_1$ or $C_2$:

- replace in the contexts $c$ with a new variable $x_c$;
- define $\theta$ as follows:

$$\theta(x) = \begin{cases} x_i & \text{if } x \in \text{Var}(C_1) \cup \text{Var}(C_2) \\ c & \text{if } x = x_c \end{cases}$$

By construction $\mathcal{C}'_1, \mathcal{C}'_2$ are $\mathcal{D}$-public contexts and $\theta$ maps each variable of these contexts to either a variable or to a constant away from $s_1, s_2$. Thus $\mathcal{C}'_1, \mathcal{C}'_2$ and $\theta'$ are witnesses that the frames $\phi_s$ and $\phi'_s$ are not $\mathcal{D}$-statically equivalent.

Conversely assume that the two frames $\phi_{s_1}, \phi_{s_2}$ are not statically equivalent. Then there exist $\mathcal{D}$ contexts $C_1, C_2$ and $\theta : \text{Var}(C_1) \cup \text{Var}(C_2) \rightarrow \mathcal{E} \setminus (\text{Const}(s_1) \cup \text{Const}(s_2))$ such that wlog $C_1 \theta \phi_{s_1} = \mathcal{E} C_2 \theta \phi_{s_1}$. Replacing each free constant $c$ by a constant in $\mathcal{E} \mathcal{N}$ yields appropriate contexts for the $\mathcal{D} \cup \mathcal{N}$ attack detectability. \(\square\)