

# Extending Session Types to Model Security Properties

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# 1 | Introduction

The purpose of this report, is to establish a foundation for the future thesis by the author, in regards of extending session types to model security properties with the introduction of adversaries.

In the report I will first introduce the motivation for exploring this field, as well as the current research done in the area. Secondly, I will introduce different research areas, all related to the field, and how these work together as background knowledge for the further thesis, by which I will explain further about in the final section of this report.

## 1.1 Motivation

With IT becoming an ever bigger part of our lives, the need for stronger and better security measurements, has grown with it. In recent years we have seen the introduction of voting machines in the USA and a digitalisation of our hospitals here in Denmark. With this comes the importance of being able to restrict access to ensure acceptable behaviour especially in the presence of malicious adversaries where it becomes paramount. To solve this many researchers have suggested using security protocols to ensure these security guarantees. In this report I will highlight some of the research that has made it easier to program these security protocols, as it can be a complex and error prone task.

A lot of research has gone into communication protocols in the recent years, and fields such as Session Types, has made it a lot easier to build such protocols and ensure they are correct by construction. This idea however falls apart, when we introduce an adversary, as an attacker would be able to block messages from being delivered. This creates the motivation for doing the future thesis of introducing cryptography to Session Types, and with this report, create a basic understanding

of the different fields.

Security measurements has not only been introduced through protocols, but also through physical hardware, adding another layer of authentication. The company Trusted Computing Group introduced the Trusted Platform Module (TPM), a physical chip implemented on the motherboard, that provides a safe space for generating cryptographic keys, which is now used in a lot of modern computers and as a part of the Microsoft BitLocker. The TPM will be used as case in the thesis and is therefore also presented and explained in the following report.

## 1.2 Current research

The project relies heavily on the research done within the field of Security protocols and Session types. A lot of research has already gone into the field of the TPM specifications, especially by Ryan, Delaune, Kremer *et al.* [4], and will work as a foundation for the TPM's commands and protocols. Furthermore the report will use Cortier and Kremer to formally model security protocols and their goals.

## 1.3 Intended outcome

The intended outcome of the thesis, will be to take the idea of session types and choreography programming, and consider them in an adversarial environment. This will be done by extending session types to model properties, and from this produce protocols that are secure by construction. Furthermore a compiler will be constructed to automate the process of producing these programs afterwards.

## 2 | Work Done

This section describes the work carried out so far. Most of it will be highlighting research done within the different fields, and showcasing examples of its use. The section ends in a summary of how the different fields come together, and how they can be used further in the coming thesis.

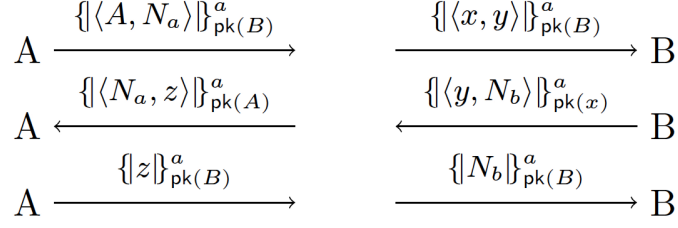
### 2.1 Security Protocols

Security protocols is an abstract or concrete protocol, that characterise the security related functions and applies cryptographic methods. It describes how the algorithm should be used to ensure the security and integrity of data transmitted. The security protocol is a protocol that runs in an untrusted environment where it assumes channels are untrusted and participants are dishonest. In academic examples, they are often described with the Alice and Bob notation, which will also be used in the following examples to create a better understanding of how security protocols work and can be reasoned about.

#### 2.1.1 Needham-Schroeder Protocol

The Needham-Schroeder Public Key Protocol, was first proposed by Roger Needham and Michael Schroeder in 1978, and will be used as a running example in this and the following two sections.

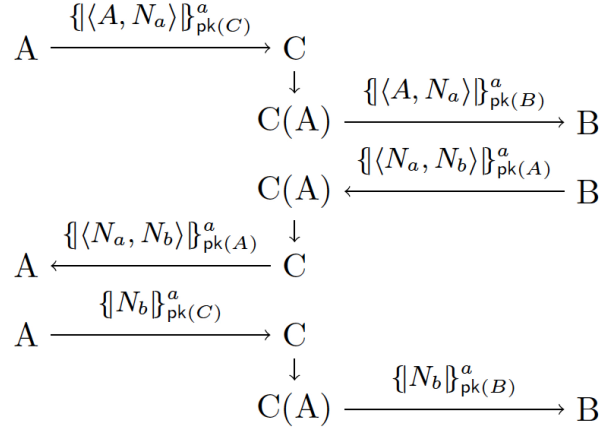
The Needham-Schroeder Public Key Protocol can be illustrated by the before mentioned Alice and Bob notation in the following way, as done by Cortier and Kremer



The A and B each represent Alice and Bob, while the arrows indicates the direction of the sent and received messages, by which are illustrated above each line. The notation  $\{|m|\}_{pk(B)}^a$  denotes that the message  $m$  is created with an asymmetric encryption of Bob's public key, while the  $\langle m_1, m_2 \rangle$  illustrates a pairing or concatenation of the two messages. The  $A$  and  $B$  in the messages each represent the identities of Alice and Bob, while  $N_a$  denotes the freshly generated nonce, a random number generated each session. The variables  $x, y, z$  are used for the unknown values of the message.

In the first exchange, Alice sends her identity and nonce asymmetrically encrypted with Bob's public key. Bob receives the message, with variables  $x$  and  $y$ , illustrating the unknown values of the message. Bob decrypts the message to check that it is well-formed. He then generate his own nonce, pair it with Alice's nonce, and then encrypts it with Alice's public key. Alice then decrypts Bob's message, to verify that it contains her previously sent nonce, which proves that Bob received her first message. This way of sending and receiving nonces is often called a *challenge-response* authentication [7], and is also what you see when using passwords, where the challenger asks for a password and then checks that the response is valid.

The gap left between the two participants illustrate the challenge of this protocol in an untrusted network, as an attacker may instigate a *man-in-the-middle* attack. This vulnerability of the protocol, was first described by Gavin Lowe in his paper published in 1995, where also a fix was purposed. Again the Alice and Bob notation is used, but now we introduce an adversary  $C$ , as illustrated here by Cortier and Kremer.



If the attacker can persuade  $A$  to initiate a session with him, he relay the messages to  $B$ , and thus convince him he is communicating with  $A$ . Lowe suggest a simple solution to this problem, by adding the identity of the sender in the second message so that  $\{\langle N_a, N_b \rangle\}_{pk(a)}^a$  would now look as such  $\{\langle N_a, \langle N_b, B \rangle \rangle\}_{pk(a)}^a$

### 2.1.2 Message deduction

Message deduction is a formal way of figuring out wether a message can be deduced from a priori given set of messages by using induction rules and derivation sequences. Most important is the use of *terms* representing messages. This allows for a better illustration of the keys, identities and nonces, but abstract away the exact values, while still keeping the structure as a special labelled graph.

**Terms** Functions symbols  $f$  are used to capture cryptographic primitives such as encryption and one-way hash functions, each with an associated integer as its arity. Function symbols with arity 0 are seen as a constant, while a finite set of functions symbols is called a *signature*. Terms are build by applying function symbols to a infinite set of names  $N$  (used for keys, nonces or identities), variables  $X$  and other terms  $F$ , and can be defined as such  $T(F, X, N)$ . As can be seen later, variables are often used to represent unknown variables, e.g. components received from another participant of the protocol.

**Inference rules** Inference rules uses the following notation  $\frac{u_l \quad \dots \quad u_n}{u}$  with  $u_l, \dots, u_n, u$  as terms with variables. Having a set of inference rules is also called

an inference system, and often contains both *composition rules* and *decomposition rules*. Below can be seen an inference system for the Dolev-Yao model ( $\mathcal{I}_{DY}$ ) with the composition rules presented first in each line, and the following being the decomposition rules.

$$\mathcal{I}_{DY} : \left\{ \begin{array}{l} \frac{x, y}{\langle x, y \rangle} \quad \frac{\langle x, y \rangle}{x} \quad \frac{\langle x, y \rangle}{y} \\[10pt] \frac{x \ y}{\text{senc}(x, y)} \quad \frac{\text{senc}(x, y) \ y}{x} \\[10pt] \frac{x \ y}{\text{aenc}(x, y)} \quad \frac{\text{aenc}(x, \text{pk}(y)) \ y}{x} \end{array} \right.$$

In the first line we have the rules for concatenation. It shows that anyone have the possibility of concatenating two terms (first rule), while the next two rules show that it is possible to retrieve the individual terms from a concatenation. On the second line we have the rules for symmetric encrypting and decrypting, showing that anyone can decrypt a message if they have the corresponding key. The same goes for the asymmetric encryption and decryption, with the rules shown in the third line.

**Derivation sequence** By combining inference rule, we are able to derive new messages. An example is given by Cortier and Kremer, illustrating how a set of messages can be derived by an attacker, through the use of the before mentioned inference rules (here represented by a proof tree):

$$\frac{\frac{\frac{\langle k_1, k_2 \rangle}{k_1} \quad \frac{\langle k_3, a \rangle}{k_3}}{\langle k_1, k_3 \rangle} \quad \frac{\langle k_3, a \rangle}{a}}{\frac{\{n\}_{\langle k_1, k_3 \rangle}^s \quad n}{\langle n, a \rangle}}$$

From  $\langle k_1, k_2 \rangle$  the attacker can use the second rule shown, to learn  $k_1$ . Using the same rule, he is also able to obtain  $k_3$  from  $\langle k_3, a \rangle$ . From these two he is now able to decrypt message  $n$  from  $\{n\}_{\langle k_1, k_3 \rangle}^s$ , and thus get the encrypted message sent.



For further illustration it is shown that the attacker is also able to get hold of  $a$ , which in turn is called that  $\langle n, a \rangle$  is *deducible* from the set of messages.

This way of formalising whether a message is *deducible* can .... (STILL MISSING ROUND!!)

## 2.2 Applied $\pi$ -Calculus

The applied pi-calculus is based upon the language pi-calculus, but offers a more convenient use for modelling security protocols to be specified, by allowing for a more wide variety of complex primitives. It is used for describing and analysing security protocols, as it provides a more intuitive process syntax for detailing the actions of the participants in a protocol [1]. This is done by introducing the before mentioned rich term algebra for modelling the cryptographic operations used in security protocols, where function symbols represent cryptographic protocols.

Tools such as ProVerif [9] uses a syntax closely related to the applied pi-calculus, and offers a way of automated reasoning about the security properties found in cryptographic protocols. The ProVerif tool is however not used for this report, but is mentioned as it is often used when analysing security protocols, and will most likely be used in the following thesis.

### 2.2.1 Syntax

The applied pi-calculus has two types of process, the *plain* and *extended* processes. First we introduce the grammar for the *plain* process:

$P, Q, R ::=$	plain processes
$0$	null process
$P \mid Q$	parallel composition
$!P$	replication
$\nu n.P$	name restriction
if $M = N$ then $P$ else $Q$	conditional
$u(x).P$	message input
$\bar{u}\langle M \rangle.P$	message output

The 0 process is the process that does nothing;  $P \mid Q$  is the parallel composition of the processes  $P$  and  $Q$  executed in parallel;  $!P$  is the replication of  $P$  that allows for an infinite composition of  $P \mid P \mid \dots$ , which is often used for illustrating an unbound number of sessions; Name restriction  $\nu n.P$  acts as a binder which generates a restricted name  $n$  inside  $P$ . This is often used for capturing fresh random numbers such as nonces and keys, or private channels, which we will see later when we apply it to the Needham-Schroeder public key Protocol; The conditional  $\text{if } M = N \text{ then } P \text{ else } Q$  is like the one we know from normal conditioning in data types, where it behaves as  $P$  whenever  $M = N$  (representing equality), and as  $Q$  otherwise; Last we have the message input and output, where  $u(x).P$  expects an input on channel  $u$  and binds it to variable  $x$  in  $P$ , and  $\bar{u}\langle M \rangle.P$  outputs term  $M$  on channel  $u$  and then behaves as  $P$ . It should be noted that message input and output will also be written as  $\text{in}(u, x).P$  and  $\text{out}(u, M).P$  as done by Cortier and Kremer

The *extended* process uses *active substitutions* to capture the knowledge exposed to the adversarial environment:

$A, B, C ::=$	extended processes
$\mid P$	plain process
$\mid A \mid B$	parallel composition
$\mid \nu n.A$	name restriction
$\mid \nu x.P$	variable restriction
$\mid \{M/x\}$	active substitution

With *active substitution* we allow for  $M$  to be available in the environment through the 'handle'  $x$ . In other words,  $M$  can now be replaced by  $x$  in every process it is related to, and is only controlled by the variable restriction, i.e.  $\nu x.(\{M/x\} \mid P)$  is exactly the same as writing  $x = M$  in  $P$ .

With terms we use function symbols to capture primitives such as encryption or decryption used by cryptographic protocols. It should be noted that functions with arity 0 are what we define as constants. For terms we apply function symbols to names, variable and other terms as such:

L, M, N, T, U, V ::=	terms
a, b, c,...,k,...,m, n,...,s	names
x, y, z	variables
g(M <sub>1</sub> ,...,M <sub>l</sub> )	function application

### 2.2.2 Re-visiting the Needham-Schroeder Protocol

Having established an understanding of the applied pi-calculus and its grammar, we now use it model the previously mentioned Needham-Schroeder public key protocol.

To make a more detailed illustration, the processes has been parametrised to represent the initiator (Alice) and responder (Bob). First we look at the process of Alice  $P_A$ :

$$\begin{aligned}
P_A(sk_i, pk_r) \quad \hat{=} \quad & \nu n_a. \text{out}(c, \text{aenc}(\langle \text{pk}(sk_i), n_a \rangle, \text{pk}_r)). \\
& \text{in}(c, x). \\
& \text{if } \text{fst}(\text{adec}(x, sk_i)) = n_a \text{ then} \\
& \text{let } x_{nb} = \text{snd}(\text{adec}(x, sk_i)) \text{ in} \\
& \text{out}(c, \text{aenc}(x_{nb}, \text{pk}_r))
\end{aligned}$$

First Alice generates a fresh random nonce and binds it to  $n_a$ , the process then continues to output the first message of an asymmetric encryption on channel  $c$ . Next she waits for a input message on the same channel, and binds the message to variable  $x$ . She then checks wether the message matches her previously sent nonce  $n_a$  shown as the conditional. For readability the  $x$  is then bound to a local variable  $x_{nb}$ , representing the nonce received by the sender (Bob). Last she sends out a message again on channel  $c$ .

The dual of the process can now be modelled from the responder's (Bob) point of view:

$$\begin{aligned}
P_B(sk_r) \triangleq & \text{in}(c, y). \\
& \text{let } pk_i = \text{fst}(\text{adec}(y, sk_r)) \text{ in} \\
& \text{let } y_{na} = \text{snd}(\text{adec}(y, sk_r)) \text{ in} \\
& \nu n_b. \text{out}(c, \text{aenc}(\langle y_{na}, n_b \rangle, pk_i)) \\
& \text{in}(c, z). \\
& \text{if } \text{adec}(z, sk_r) = n_b \text{ then } Q
\end{aligned}$$

Combining the two processes we are able to model the Needham-Schroeder public key protocol, done so by Cortier and Kremer, as a whole:

$$\begin{aligned}
P_{\text{nspk}}^1 \triangleq & \nu sk_a, sk_b. (P_A(sk_a, \text{pk}(sk_b)) \parallel P_B(sk_b) \parallel \\
& \text{out}(c, \text{pk}(sk_a)) \parallel \text{out}(c, \text{pk}(sk_b)))
\end{aligned}$$

This however represent the naive model of the protocol, so to add the Lowe fix, as mentioned earlier i then report, we add the identity to the encryptions:

$$\begin{aligned}
P_{\text{nspk}}^5 \triangleq & !\nu sk_a, sk_b. (!\text{in}(c, x_{pk}). P_A(sk_a, x_{pk}) \parallel !P_B(sk_a) \parallel \\
& !\text{in}(c, x_{pk}). P_A(sk_b, x_{pk}) \parallel !P_B(sk_b) \parallel \\
& \text{out}(c, \text{pk}(sk_a)) \parallel \text{out}(c, \text{pk}(sk_b)))
\end{aligned}$$

(TODO: needs further explanation!!) TODO: smooth transition to the next chapter  
+ don't forget reference to article!!!!

## 2.3 Session Types

As with the applied pi-calculus, session types also have its root in the process calculus, and can be thought of as types for protocols. The idea behind session types, is to describe the communication protocols as a type, that can be checked either at compile-time or runtime, and thus ensure that well-typed programs are well behaved. Essential to session types is the distinction between binary and multiparty communication channels where the binary sessions allow for only two participants, while the multiparty session types can have zero or more participants. Only the basic definitions of session types will be presented here and will refer the reader to articles such as Hüttel, Lanese, Vasconcelos *et al.* for a deeper introduction.

### 2.3.1 Binary Session Types

Session types allow for more structure to channel types, by defining the input, output and linear types. With pi calculus we are only able to keep track of the number of arguments passed through a channel, so preventing that the number of channels send by a participant is different from the recipients expectations. With session type we can define the types passed i.e.  $(nat, (nat))$  that describes a channel where the recipient expects a pair of values of natural numbers and a channel on which it will reply another natural number.

#### Input and Output types

Furthermore it allows for even more refinement, by including information on how channels are used in relation to input and output types. For the input types (processes that can only write on channels) the following notation is used  $!(T_1, \dots, T_n)$ . For output types (processes that can only read on channels) the following notation is used  $?(T_1, \dots, T_n)$ . With the previous mentioned channel we can now define it in more detail  $?(nat, !(nat))$  where the channel can only read a pair of nat values, and write a natural number.

#### Linear types *duality*

#### Binary session types

### 2.3.2 Multiparty Session Types

Multiparty session types extend the theory of binary session types to include more than two participants. It does so by describing interactions of a session in a top-down manner as a *global description* of all the messages exchanged, instead of separately looking at the behaviour of each individual channel endpoint, as done so in binary session types. This can ensure protocol conformance and preventing deadlocks, while making it easier to detect errors both manually and by automatic means.

Taking an example made by Hüttel, Lanese, Vasconcelos *et al.* of an interaction

between three participants of a Client, ATM and the Bank, we can here show how an implementation of global session types look:

Client  $\rightarrow$  ATM(string). *rec a.*

$$\text{Client} \rightarrow \text{ATM} \left\{ \begin{array}{l} \text{deposit} : \text{Client} \rightarrow \text{ATM}(\text{nat}). \text{ATM} \rightarrow \text{Bank}\{\text{deposit} : a\}, \\ \text{withdraw} : \text{Client} \rightarrow \text{ATM}(\text{nat}). \\ \quad \text{ATM} \rightarrow \text{Bank} \left\{ \text{withdraw} : \text{ATM} \rightarrow \text{Client} \left\{ \begin{array}{l} \text{dispense} : a, \\ \text{overdraft} : a \end{array} \right\} \right\}, \\ \text{balance} : \text{ATM} \rightarrow \text{Client}(\text{nat}). \text{ATM} \rightarrow \text{Bank}\{\text{balance} : a\}, \\ \text{quit} : \text{ATM} \rightarrow \text{Bank}\{\text{quit} : \text{end}\}. \end{array} \right\}.$$

First we have that the Client interacts with the ATM, here expecting a string input from the Client, which is one of the key interactions operations of *global types*. The ATM then branches and gives the Client four different options to choose from; *deposit*, *withdraw*, *balance* or *quit*, from which the ATM further reports the selected branch to the Bank. Looking at *deposit*, we can tell that the ATM expects a natural number from the client, and then reports the branch picked by the Client, to the Bank. The same happens in *withdraw*, but here the ATM further branches into the selection of *dispence* or *overdraft*.

Thus *global types* helps specify the order of the interaction between the three participants in relation to exchanging messages and the order of requests involved.

TODO: short description of choreography programming

## 2.4 TPM

The Trusted Platform Module (TPM) is a specialised chip that stores RSA encryption keys specific for the host system for hardware authentication. It is used as a component on an endpoint device and is used for the Windows BitLocker. The TPM contains an RSA key pair of the Endorsement Key (EK) and the owner-specified password. When a user takes ownership of the TPM, a *Storage Root Key* (SRK) is generated. The SRK works as the root of a tree like structure, where future keys are stored, by which are used for encrypting data. To each TPM key a 160-bit string is associated called the *authdata*, and works like a password to authorise the use of a key.

### 2.4.1 The API and its commands

The API offers operations related to; *Secure key management and storage*, which generates new key and impose restrictions on their use; *Platform configuration registers (PCR)* which stores hashes of measurements taken by external software and later lock those by signing them with a specified key. This allows for the TPM to provide *root of trust* for a variety of applications such as:

- *Secure storage*: allows the user to securely store content which is encrypted with a key only available to the TPM
- *Platform authentication*: a platform can obtain keys by which it can authenticate itself reliably (rewrite)
- *Platform measurement and reporting*: A platform can create reports of its integrity and configuration state that can be relied on by a remote verifier (rewirte)

The TPM's application program interface (API) offers a wide variety of commands, that e.g. allow the user to load new keys or certify a key by another one. As the TPM offers more than 90 different commands through its application program interface (API), the report will only focus on a small sample of these. Each command has to be called inside an *authorisation session*, so the user will first have to choose between one of the following sessions:

- Object Independent Authorisation Protocol (OIAP)
- Object Specific Authorisation Protocol (OSAP)

The OIAP creates a session that can manipulate any object, but will only work with certain commands. When setting up the session, the TPM will send back a *session handle* and a fresh *even nonce* as part of its arguments. The OSAP creates a session that can only manipulate a specific object, specified at the session start, so when starting the session, the user will have to send with it the *key handle* of the object and an *odd nonce*.

This rotation of nonces, with the user's defined as *odd nonces* and the TPM's as *even nonce*, guarantees freshness of the commands and responses, which are then encrypted with an HMAC and works as a *shared secret*  $\text{hmac}(\text{auth}, \langle Ne^{OSAP}, No^{OSAP} \rangle)$ .

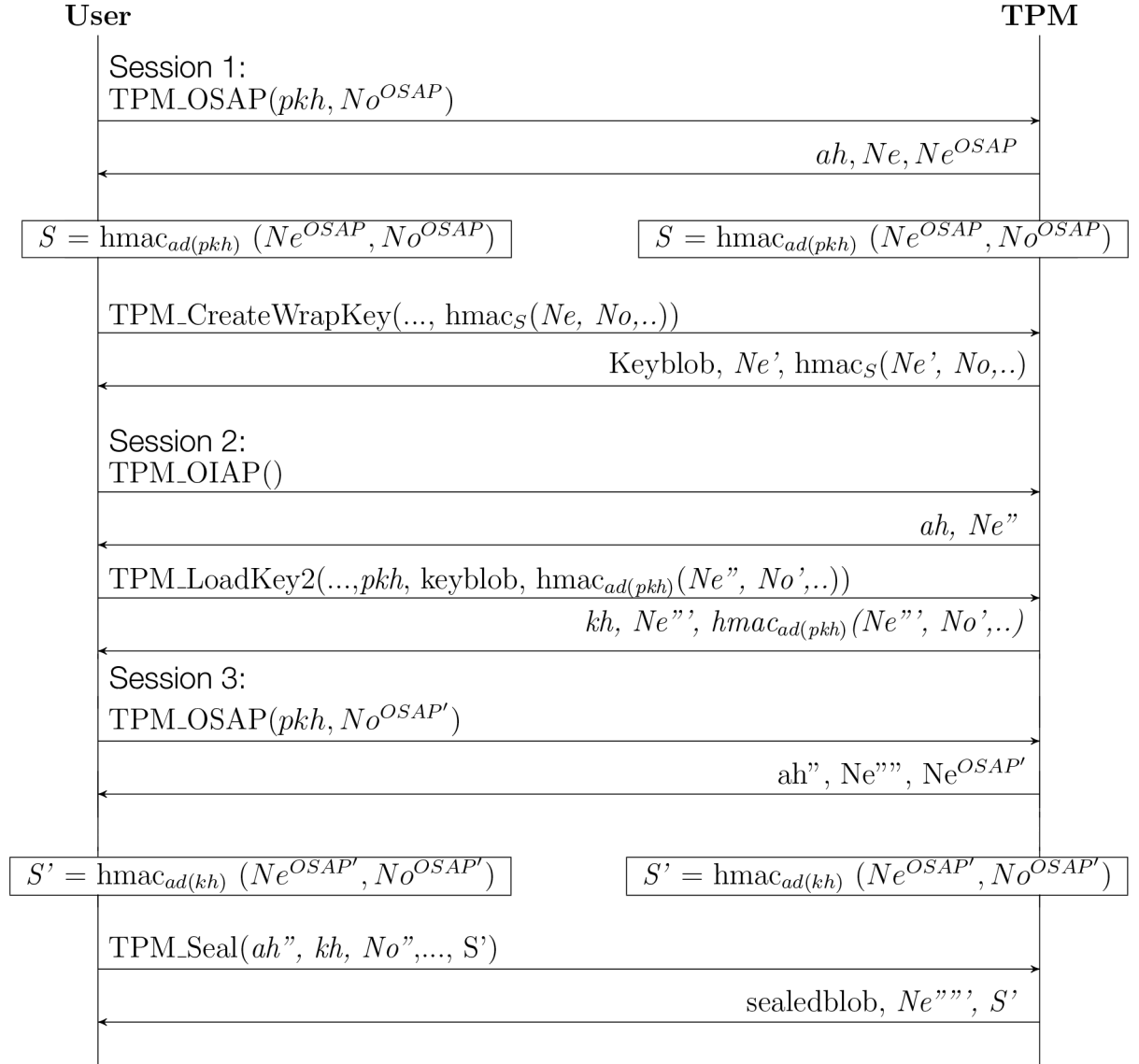
### 2.4.2 Example of commands

To illustrate the exchange of message between the TPM and a user, three commands besides the OIAP and OSAP has been chosen to get a better look at the authorisation going on:

- *TPM\_CreateWrapKey*: Creates a new key in the storage key tree
- *TPM\_LoadKey2*: Load key from tree into the TPM internal memory
- *TPM\_Seal*: Uses key to encrypt data

TODO: describe pkh! In the following illustration, the user starts with creating an OSAP session with the TPM to generate a *shared secret*  $= S$ .





## 2.5 Evaluation

- How they all come together
- Examples of TPM commands with session types

### 2.5.1 TPM as Session Types

TPM  $\rightarrow$  KeyStorage (parameters)

TPM  $\rightarrow$  Alice : PrivateKey. rec a

<i>Read:</i>	Alice $\rightarrow$ TPM : read. PCR $\rightarrow$ TPM : value. TPM $\rightarrow$ PCR : value. TPM $\rightarrow$ Alice : value. rec a
<i>Quote:</i>	Alice $\rightarrow$ TPM : quote. PCR $\rightarrow$ TPM : value. TPM $\rightarrow$ PCR : value. TPM $\rightarrow$ Alice : CertPCR. rec a
<i>CreateWrapKey:</i>	Alice $\rightarrow$ TPM : CreateWrapKey. PCR $\rightarrow$ TPM : value. TPM $\rightarrow$ PCR : value. KeyTable $\rightarrow$ TPM : KeyLoaded. <b>?(new key)?</b> . TPM $\rightarrow$ Alice : data. rec a
<i>LoadKey2:</i>	Alice $\rightarrow$ TPM : LoadKey2. PCR $\rightarrow$ TPM : value. TPM $\rightarrow$ PCR : value. KeyTable $\rightarrow$ TPM : KeyLoaded. TPM $\rightarrow$ KeyTable : KeyLoaded. rec a
<i>CertifyKey:</i>	Alice $\rightarrow$ TPM : data. KeyTable $\rightarrow$ TPM : KeyLoaded. TPM $\rightarrow$ Alice : Cert. rec a
<i>Unbind:</i>	Alice $\rightarrow$ TPM : unbind. PCR $\rightarrow$ TPM : value. TPM $\rightarrow$ PCR : value. KeyTable $\rightarrow$ TPM : KeyLoaded. TPM $\rightarrow$ Alice : adec. rec a
<i>Seal:</i>	Alice $\rightarrow$ TPM : data. PCR $\rightarrow$ TPM : value. TPM $\rightarrow$ PCR : value. KeyTable $\rightarrow$ TPM : KeyLoaded. TPM $\rightarrow$ Alice : data. rec a
<i>Unseal:</i>	Alice $\rightarrow$ TPM : unseal. PCR $\rightarrow$ TPM : value. TPM $\rightarrow$ PCR : value. KeyTable $\rightarrow$ TPM : KeyLoaded. TPM $\rightarrow$ Alice : KeyLoaded. rec a
<i>Extend:</i>	Alice $\rightarrow$ TPM : extend. PCR $\rightarrow$ TPM : value. TPM $\rightarrow$ PCR : hpcr. rec a

TODO: Description of above (+ code in appendix? for refs.)

## **3 | Future Plan**

In the previous chapter I slightly touched upon applying session types to the TPM commands. As could be deducted from this, global session types still exhibits some limitations of its expressivity, which is the prime motivation for the future thesis.

### **3.1 Introducing an adversary**

### **3.2 Compiler**

As part of my thesis, I will also be developing a compiler in F# for the findings.

Farewell

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